Examining the Physical Demands of Elite Rugby League Match-Play

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Abstract

The work undertaken from the studies in this thesis provides novel information in relation to the physical match demands of the European Super League (ESL) competition, focusing on a newly promoted ESL franchise. Specifically, this is the first work to examine the physical demands of competition for an entire squad of players across an entire competitive season in the ESL, the first to examine the physical demands of match-play over multiple longitudinal seasons, and the first to examine the effects of different between match recovery periods on the running demands for a large sample of ESL teams. Methodological work in this thesis has also highlighted the importance of quantifying and interpreting errors associated with GPS devices to quantify player movements and collisions.

Chapter 4 examined the physical match demands for the newly promoted team over the entirety of a competitive season. Significant positional differences were evident, with Outside Backs (OB, 421 ± 89 m) and Pivots (PIV, 306 ± 108 m) performing more sprinting than Middle Unit Forwards (MUF, 185 ± 58 m) and Wide Running Forwards (296 ± 82 m). Conversely, MUF (35 ± 6) and WRF (36 ± 5) performed more collisions than PIV (23 ± 3) and OB (20 ± 3). Practitioners need to be aware of these differences when designing training and conditioning programmes for players. The high speed running (HSR) and number of collisions were greater for the newly promoted team than previously reported for higher ranked ESL teams, but are still lower than those experienced in the southern hemisphere National Rugby League (NRL).

Chapter 5 examined the level of agreement between two different models of GPS device in measuring the total distance, and distance covered at high speed (> 5.0 $m.s^{-1}$) in order that these could be examined in following chapters where two different models of device were

used. The two devices showed acceptable levels of agreement in relation to specific analytical goals using positional data from Chapter 4 (total distance CV 0.8%, HSR CV 2.2%) and in relation to the differences between games won and lost at the elite level (mean bias [95% LoA] -0.29 $m.min^{-1}$ [-1.6 m to 1.01 $m.min^{-1}$] for total distance per minute, and 0.01 $m.min^{-1}$ [-0.27 to 0.29 $m.min^{-1}$] for HSR distance per minute) concluding the two devices could be used interchangeably to measure these parameters.

Chapter 6 examined the physical demands of match-play for the newly promoted franchise over a three season period (2012-2014). There was an increase in the physical demands of competition in terms of the total distance coverer per minute (87.0 ± 2.4 $m.min^{-1}$ – 96.6 ± 2.4 $m.min^{-1}$), HSR distance covered per minute (6.3 ± 1.3 $m.min^{-1}$ – 8.1 ± 0.5 $m.min^{-1}$), and number of collisions per minute (0.43 ± 0.05 $no.min^{-1}$ – 0.53 ± 0.04 $m.min^{-1}$). These findings highlight that newly promoted teams need time to develop and adapt to the increasing demands of competition, which is a pertinent issue given the re-introduction of promotion and relegation from 2015. With the current structure, newly promoted teams will not have the chance to plan and develop over the long term, which could leads to teams spending over their means to attract the players required to keep them in the competition rather than focussing on long term player development.

Chapter 7 examined the effectiveness of a wearable GPS device to automatically detect collision events during elite Rugby League match-play. The overall error of the device (19%) was associated with not correctly identifying a collision has occurred. Ball carries (97%) were more accurately detected than when compared to tackles (73%). First man tackles (83%) were more accurately detected than second man tackles (72%), and third man tackles (51%). This data suggests the microsensor device has the ability to automatically detect the majority of collision events in Rugby League match-play.

However given the collision detection algorithm was originally developed for use in Rugby Union; this may need refinement for use in Rugby League, especially for detecting tackle events.

Chapter 8 examined the effect of different between match recovery cycles (short, medium, and long) on the movement demands in subsequent matches on a larger sample of six elite ESL teams. Matches after a short turnaround were associated with greater HSR distance covered per minute of play (13.2 ± 6.9 $m.min^{-1}$) than when compared to medium (11.6 ± 5.8 $m.min^{-1}$) and long turnarounds (10.6 ± 5.6 $m.min^{-1}$). Matches with long turnarounds were associated with increased low speed distance (< 3.8 $m.s^{-1}$) covered per minute of play (84.8 ± 18.2 $m.min^{-1}$) than both medium (79.3 ± 19.6 $m.min^{-1}$) and short turnarounds (80.3 ± 17.7 $m.min^{-1}$). The total distance covered per minute was only greater on a long turnaround (96.1 ± 16.9 $m.min^{-1}$) when compared to a medium turnaround (72.9 ± 21.8 $m.min^{-1}$). These data demonstrate that running performance is affected by the length of the between match recovery cycle, and coaches and conditioning staff working within the ESL should be mindful of these demands when developing recovery and training strategies for their players.

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List of Abbreviations

2DPL	2D PlayerLoad™
4G	fourth generation
ANOVA	analysis of variance
AU	arbitrary units
$b.min^{-1}$	beats per minute
cm	centimetres
CV	co-efficient of variation
EIMD	exercise induced muscle damage
ES	effect size
ESL	European Super League
HDOP	horizontal dilution of precision
G	G-force
GPS	Global Positioning System
HR	heart rate
HSR	high speed running
HUF	Hit Up Forwards
Hz	hertz

ISAK	International Society for the Advancement of Kinanthropometry
kcal/min	kilocalories per minute
kg	kilograms
$km.h^{-1}$	kilometres per hour
LoA	Limits of Agreement
m	metres
mm	millimetres
$mM.l^{-1}$	millimoles per litre
MUF	Middle Unit Forwards
$m.min^{-1}$	metres per minute
$m.s^{-1}$	metres per second
$no.min^{-1}$	numbers per minute
NASA	National Aeronautics and Space Administration
NRL	National Rugby League
NSWC	New South Wales Cup
NYC	National Youth Competition
OB	Outside Backs
PL	PlayerLoad™

PL Slow	PlayerLoad Slow^{TM}
QC	Queensland Cup
r	Pearson's correlation coefficient
RFL	Rugby Football League
SD	standard deviation
SPSS	Statistical Package for Social Sciences
TE	typical error
W/kg	Watts per kilogram
WRF	Wide Running Forwards

Chapter 1

General Introduction

In this Chapter the reader is presented with a background of Rugby League, an introduction to the development of scientific research within the game, and why there is the need for such research in this thesis to be undertaken. Based upon this, the objectives and aims of the research will be outlined.

1.1 Background

Rugby League is a high speed collision sport, played by two teams consisting of 13 players over two halves of 40 minutes with a 10 minute intermission (Gabbett, 2005b). The physical demands of the game are characterised by frequent bouts of high intensity exercise (running, sprinting, collision and wrestle) interspersed by more prolonged bouts of low intensity exercise (standing, walking, and jogging) (Gabbett, King, & Jenkins, 2008). The sport originated in the North of England in 1895 and is played at junior and senior levels as a high participation sport in Australia, New Zealand, England, and the Pacific Islands (Hausler, Halaki, & Orr, 2015), with Rugby League being the national sport of Papua New Guinea.

At the elite level two major competitions exist, namely the National Rugby League (NRL) which is the highest standard of competition in Australia and New Zealand, and the European Super League (ESL) which is its counterpart in Europe. The NRL is widely claimed to be a better standard of competition than the ESL (Eaves & Broad, 2007; Gabbett, 2013b; Twist et al., 2014). The NRL clubs also field a team of players under 20 years of age in the sub-elite National Youth Competition (NYC). Similarly, the New South Wales Cup (NSWC) and Queensland Cup (QC) form sub-elite, open-age competitions. Together the NYC, NWSC, and QC, provide player pathways to NRL selection (Hausler et al., 2015). The ESL competition has recently re-introduced promotion and relegation for the 2015 season after operating on a franchise system for the previous six seasons (2009-2014). This has enabled clubs from the second-tier of European competition (The Championship; many of whom operate on a part-time basis) to have the chance to gain promotion and compete in Europe's top flight of Rugby League competition. Since 2015, following the regular season games in the ESL and the Championship, the 24 teams from both competitions are split into three groups of eight, based on their league position finish.

After 23 games of the regular ESL season, the top eight teams split into the ‘Super 8’ group, playing seven more games each as they compete for a place in the ESL grand final. The bottom four ESL teams join the top four teams from the Championship into the ‘Middle 8’ group. These teams also play seven more games for a place in next year’s ESL competition, with the bottom 8 teams in the Championship competing in the Championship Shield.

Since 2008, there have been a number of advancements in player movement tracking systems, in particular global positioning systems (GPS). Generally, studies have concluded that GPS devices have an acceptable level of validity and reliability for assessing movement patterns in team sports, including Rugby League (Sykes, Nicholas, Lamb, & Twist, 2013; Waldron, Highton, & Twist, 2013). Validity has been defined as the ability of the measurement tool to reflect what it is designed to measure (Atkinson & Nevill, 1998). Reliability has been defined as the consistency of measurements, or the absence of measurement error (Atkinson & Nevill, 1998). GPS devices are now commonly used amongst NRL and ESL clubs and have helped to provide more detailed information regarding the physical demands of the game (Johnston, Gabbett, & Jenkins, 2014). Post 2013, this has led to a significant increase (250%) in the research describing activity profiles of competitive Rugby League performance from the elite level to junior competitions (Hausler et al., 2015). At the elite level, the vast majority of this research has been conducted within the NRL competition and therefore our understanding of the ESL competition is far behind what we know about the NRL.

The only published data examining the competitive physical demands of the ESL using GPS is limited by a small sample size of players and games (Waldron, Twist, Highton, Worsfold, & Daniels, 2011), and limited to successful teams competing at the top of the competition (Twist et al., 2014; Waldron, Twist, et al., 2011). Currently, there are no data examining the match demands for lower ranked or newly promoted teams. Given that lower ranked NRL teams have been shown to experience greater physical match demands than their higher ranked counterparts (Gabbett, 2013b), establishing such information for ESL teams is a pertinent issue given the re-introduction of promotion and relegation. It maybe that newly promoted clubs (who may have been part time in the league below) may have to withstand greater physical rigours than the rest of the competition, although to date this suggestion has not been investigated. Establishing such information could help inform the conditioning practices for those working with newly promoted or lower ranked teams in the future.

What is also evident from the literature is that much of the research has adopted a reductionist approach, which in this case refers to physical match performance indicators being examined over short time periods, i.e. over a single, or a limited number of games. Examining physical trends longitudinally would aid in understanding the development of match-play, providing useful information for coaches and conditioning staff alike in order to best prepare their players for the changing demands of the game. Currently, there are no published data on the physical demands of the ESL over a longer period than a single season. Anecdotally, there is a widely held belief that the speed and physical intensity of the game is increasing season on season, but there are no published data to support such a notion. There is evidence in soccer within the English Premier League that the physical demands of the game have increased substantially over a seven season period from 2006 to 2013 (Barnes, Archer, Hogg, Bush, & Bradley, 2014; Bush, Barnes, Archer, Hogg, & Bradley, 2015) which the authors attributed to the development of players' physical performance capabilities, and concluded that coaches and sport scientists should be mindful of these increasing demands when developing training and conditioning practices.

In addition to the movement demands, the game of Rugby League also requires players to engage in frequent physically demanding collisions (Gabbett, Jenkins, & Abernethy, 2011). As a result of the multiple physical collisions during the game, musculoskeletal injuries are extremely common (Gabbett et al., 2011). However, success in the game also depends on tackling ability, the ability to withstand physical collisions, and the ability to "win" the tackle contest (Gabbett, 2013c). Consequently, tackling is one of the most practiced skills in Rugby League as the ability or inability to effectively perform tackles may prove critical to the outcome of the game. Monitoring the number of collisions that players perform in competition and training gives a greater understanding of the physical demands imposed and has implications for injury risk (Gabbett & Ryan, 2009; Gabbett, Jenkins, & Abernethy, 2010), muscle damage (McLellan, Lovell, & Gass, 2011a), recovery (Oxendale, Twist, Daniels, & Highton, 2016), and training load prescription (Gabbett et al., 2010; Gabbett et al., 2011; Gabbett, Jenkins, & Abernethy, 2012). Traditionally, the number of collisions during match-play have been identified retrospectively using video replays (King, Jenkins, & Gabbett, 2009; Sirotic, Coutts, Knowles, & Catterick, 2009; Sykes, Twist, Nicholas, & Lamb, 2011). However the manual coding of collisions from video footage is labour intensive, taking considerable time to analyse such data. Recent advancements in GPS technology for player movement tracking has seen the introduction of accelerometers, gyroscopes and magnetometers housed within the devices making it possible to measure accelerations associated with sporting movements, including physical collisions in contact sports (Gabbett et al., 2010; Gastin, McLean, Spittle, & Breed, 2013; Kelly, Coughlan, Green, & Caulfield, 2012). Thus, GPS devices for use in team sports could potentially provide a less labour intensive method to investigate the collision demands of the sport than retrospective video analysis. Currently only two models of GPS device for use in team sports (Catapult MinimaxX, Catapult Optimeye S5) have been validated to automatically detect collision events and their associated intensity in Rugby League (Gabbett et al., 2010; Hulin, Gabbett, Johnston, & Jenkins, 2017). As such, most of the Rugby League research using GPS has overlooked the collision element of the game. Early work examining the collision demands in the ESL was published in 2001 using retrospective video footage (Gissane, Jennings, Jennings, White, & Kerr, 2001; Gissane, White, Kerr, & Jennings, 2001). However, with the numerous rule changes and improvements in professionalism within the game since then (Gabbett et al., 2008), this research is clearly outdated. Further work in the ESL has also examined the number of collisions players perform in game quarters using a semi-automated camera system (Sykes et al., 2011), and has used the manual coding of video footage to examine the relationship between the number of collisions performed and post-game fatigue responses (Twist, Waldron, Highton, Burt, & Daniels, 2012). More recently, GPS was used to identify the relationship between the number of collisions performed by ESL players and indirect markers of muscle damage (Oxendale et al., 2016). A limitation of the aforementioned studies is that they are limited to a limited number of games analysed. With the rapid advancements in GPS technology, new devices are continually being developed and produced for use in team sports that claim to be able to automatically detect collisions and their associated load. However, manufacturer claims need to be scientifically validated before they can be considered fit for purpose (Gabbett, 2013c).

Teams who gain promotion to the ESL from the Championship face the additional challenge at the higher competitive standard of coping with different recovery periods between games. In the Championship, regular season games are always played at weekends as some teams operate on a part-time basis with players from these clubs working full-time jobs during the week. Thus, the turnaround between games tends to remain consistent at 6 or 7 days. Fixture turnarounds in the ESL can vary from between 5 to 10 days with the subsequent effects on match performance unknown. The live television coverage of ESL games can also complicate the fixture schedule further. Conflicting findings in the NRL have shown high-intensity running outputs not to differ between short (5-6 days), medium (7-8 days) and long (9-10 days) between game recovery periods (Murray, Gabbett, & Chamari, 2014), but also to be significantly lower after a short recovery cycle (Kempton & Coutts, 2016). Many coaches of ESL teams have used the British press to criticise periods of fixture congestion such as the traditional ESL Easter weekend (Clubcall.com, 2014; Express, 2017; SkySports, 2016). It has been reported that for a single ESL team over a period of fixture congestion (four games in 22 days with between match periods of 6, 2, and 5 days) that reductions in high-intensity running (≥ 5.5 $m.s^{-1}$) and increases in low speed activity (< 5.4 $m.s^{-1}$) were evident in the later matches, indicative of an overall slowing of movement speed (Twist, Highton, Daniels, Mill, & Close, 2017). With these studies being limited to single teams, further research is needed in order to generalise the findings. Obtaining such information on multiple ESL teams may help them in their preparation for coping with differing recovery cycles between games.

1.2 Aims and Objectives

Based upon the aforementioned background, the overall aim of this thesis is to examine and further increase our understanding of the physical match demands of elite Rugby League match-play in the ESL focusing on a newly promoted franchise. This aim will be accomplished by the following objectives:

1. To profile the physical demands of ESL match-play over the course of an entire season within specific positional groups for a newly promoted team.

2. To establish if any differences exist between two current commercially available GPS devices to measure movement demands in order that they can be assessed interchangeably with the two different models of device. (Throughout the course of this PhD research, two different models of GPS device are to be used as the thesis progresses).
3. To examine if there is an evolution in competitive physical demands over a three season period for the newly promoted team with increased exposure to training and ESL competition.
4. To establish if the most recently developed model of GPS device to be used in this thesis can automatically detect collision events during Rugby League match-play against those coded from video footage.
5. To examine the differences in match movement intensity across different recovery periods between games for multiple ESL teams.

Chapter 2

Literature Review

In this Chapter the reader is presented with a further understanding of Rugby League, mainly concerning the positions on the field. The methods of quantifying the physical demands of competition are then examined including video time-motion analysis, GPS, and heart rate. Lastly, a succinct overview of the literature to date that has examined the physical demands of Rugby League match-play is presented.

2.1 Overview of Rugby League

Teams consist of 13 players that may be classified into two major playing groups, namely the forwards and backs. Positions can also be classified according to the specific individual position played (i.e. prop, hooker, second row, loose forward, scrum-half, stand-off, centre, wing, and full-back). There have also been attempts to sub-categorise positions further reflecting similar positional roles (hit-up forwards [HUF], wide-running forwards [WRF], pivots [PIV], and outside backs [OB]) (Gabbett et al., 2012). However, such categories do not have universal definitions and may differ between teams employing different tactics.

Typically (but not always) junior and amateur Rugby League matches are played under an unlimited interchange rule (Gabbett, 2005b). In the NRL and ESL competitions, teams are permitted to pick 17 players for a game (with four being on the interchange bench at any time) and are allowed a maximum of 10 interchanges during a game.

2.2 Methods of Quantifying Match Demands

To develop sports specific training and conditioning programmes, an accurate and comprehensive understanding is required of the physical demands placed on the players (Hughes & Franks, 2008). Given the recent focus on game specific and individualised conditioning for Rugby League players (Gabbett et al., 2008), specifying the content of training periods based upon the information sampled from competition offers an appropriate approach to match preparation. Methods that have been used to assess the demands of competition will now be examined.

2.2.1 Notational Analysis

Notational analysis is an inexpensive way of providing insight into the physical, technical and tactical demands of teams. This involves the subjective quantification of movement patterns or technical actions for individual players from video recordings (King et al., 2009). The validity and reliability of the process can vary depending on a number of factors, including how many observers are used, their experience, and the quality of their viewing perspective (Barris & Button, 2008). Whilst studies examining the physical demands of Rugby League using such a methodology have reported the process as reliable (King et al., 2009; Sirotic et al., 2009; Sirotic, Knowles, Catterick, & Coutts, 2011), due to the considerable time required to manually collect and analyse such data, these studies have focussed on only a small number of games and players.

All of the ESL clubs currently use a post-game video performance analysis service provided by Opta (Leeds, UK). Opta provide data primarily relating to the technical and tactical actions of teams, however it is also possible to obtain the number of physical collisions players experience through examining the number of ball caries and tackles. Currently no reliability data exists for Opta rugby analysis, although the reliability of the data collection process in football has been reported (Liu, Hopkins, Gómez, & Molinuevo, 2013). Data coded by independent Opta operators reached a very good agreement (intra-class correlation co-efficient ranged from 0.88 to 1.00 and low standardised typical errors varied from 0.00 to 0.37) (Liu et al., 2013). Furthermore, personal communication with Opta revealed they employ the same expert assessor for each team in the ESL to increase reliability.

Previous work has shown the measurement error for notational video analysis in terms of frequency, mean duration, and total time of individual movement events to be around 5-10% (Duthie, Pyne, & Hooper, 2003).

More recently, automatic computer visual tracking systems have been developed. These systems do not require human operators to locate manually and continually record the position of the tracked object. Such systems can provide feedback on the movement demands of competition to athletes and coaches; however these still require substantial operator intervention to process the data after capture. Also, they are often limited by the restricted capture environments that can be used (e.g. within stadiums) which makes longitudinal analysis difficult if all stadiums within the league of competition do not have the system installed. Studies using such methodologies in Rugby League have utilised the computer based systems Trak Performance (New South Wales, Australia) (Sirotic et al., 2009; Sirotic et al., 2011) and Prozone (Leeds, UK) (Sykes, Twist, Hall, Nicholas, & Lamb, 2009). The validity and reliability of these systems has been well established (Di Salvo, Collins, McNeill, & Cardinale, 2006; Edgecomb & Norton, 2006). The Prozone study involved six participants performing a series of runs in straight lines and different directions at different speeds within two football stadiums, and used timing gates as the criterion measure to examine displacement velocities (Di Salvo et al., 2006). The authors concluded that Prozone represents a valid motion analysis system for analysing movement patterns on a football pitch (Di Salvo et al., 2006). Interestingly, the Trak Performance system was compared to GPS to measure the total distance covered by Australian Football players (Edgecomb & Norton, 2006) using a calibrated trundle wheel as the criterion measure. The GPS system overestimated the total distance covered by 4.8%, whereas the computer based system overestimated by 5.8%, concluding both systems showed relatively small errors in true distances. Randers and colleagues compared four different match analysis systems, which included video based time-motion analysis, a semi-automated camera system (Amisco, Nice, France), and two different models of GPS device (1 Hz and 5 Hz) over the course of the same 90 minute soccer game (Randers et al., 2010). Although all four systems were able to detect similar performance decrements over the course of a game indicated by reductions in total distance and high-intensity running, large between-systems were present in the absolute distances covered. The Amisco system and 5 Hz GPS measured the total distance covered at around 1000 m higher than the video based time-motion analysis and 1 Hz GPS. The Amisco system measured 600 – 1000 m more high-intensity running than the other systems, indicating caution needs to be applied when comparing results from studies using different systems (Randers et al., 2010). Given that GPS can be used to analyse a whole squad of players with relative ease compared to computer based systems in any location, such a method of quantifying the movement demands of players may be more appealing to coaches and sport scientists than fixed computer based systems.

2.2.2 GPS Technology

2.2.2.1 History and Development

GPS were developed in the late 1960s for use by departments within the US government, specifically the department of defence and the National Aeronautics and Space Administration (NASA) (Steede-Terry, 2000). The goal of developing GPS was at any time for a GPS receiver to determine a three-dimensional position on Earth in any weather conditions with a high level of accuracy. This position was important in a military context (missile delivery, search and rescue) (Kaplan & Hegarty, 2005). GPS relies on a constellation of 27 satellites orbiting at varying trajectories that are combined to cover surface of the earth. At any one time there are only a fraction of these satellites visible and to determine the global position the GPS receiver unit uses a simple calculation of how long a signal from a satellite takes to reach it and by using the signal from three satellites, the position can be obtained using a synchronised clock (Steede-Terry, 2000). Manufacturers using GPS units within a sporting context have programmed software to examine data achieving a minimum of four satellites as an acceptable level whereby movement data can be collected, however the more satellites the receiver can "lock on" to, the more accurate the movement data will be (Cummins, Orr, O'Connor, & West, 2013). The distribution of satellites within the sky can provide an indication of the geometric quality of the data obtained. This measure is more commonly known as the horizontal dilution of precision (HDOP) (Hoppe, Baumgart, Polglaze, & Freiwald, 2018). The lower the HDOP value, the better the geometry of the satellite configuration (Williams & Morgan, 2009). The development of commercial sporting GPS technology began with devices sampling at 1 Hertz (Hz) and limited software to accompany them. More recently, 5 Hz, 10 Hz, and 15 Hz units have been available and the technology has been incorporated with tri-axial accelerometers to provide additional information by factoring in impacts and ground reaction forces measured in "G force" (G). These systems allow for individual workloads (distance covered and time/distance spent at different velocities) to be recorded and also allows for real time analysis opening up a number of applications in performance assessment (Williams & Morgan, 2009). The current 15 Hz units typically report interpolated values, upgrading a 5-10 Hz raw GPS signal (Aughey, 2011; Johnston, Watsford, Kelly, Pine, & Spurrs, 2014). The term "interpolation" essentially refers to a method of constructing new data points within the range of a discrete set of known data points (Maffiuletti et al., 2016). Currently, the leading manufacturers who supply such devices are GPSports (Canberra, Australia), Catapult (Victoria, Australia), and Statsports

(Co. Down, Ireland). In modern day team sports, the GPS devices are typically housed within a vest worn by the player, with the devices being located on the players back between the shoulder blades. A wealth of literature exists examining the validity and reliability of the devices for use in sport. Such studies are outlined in Table 2.1.

Minimal measurement error during the collection of data is critically important in sport science research. The main components of measurement error are systematic bias (e.g. general learning or fatigue effects on tests) and random error due to biological or mechanical variation. Both error components should be meaningfully quantified for the sport scientist to relate the described error to judgments regarding ‘analytical goals’ (the requirements of the measurement tool for effective practical use) rather than statistical significance of any reliability indicators (Atkinson & Nevill, 1998).

Methods based on correlation coefficients and regression provides an indication of ‘relative reliability’. Relative reliability is the degree to which individuals maintain their position in a sample with repeated measurements (Baumgartner, 1989). Absolute reliability is the degree to which repeated measurements vary for individuals (Baumgartner, 1989), and is expressed in the actual units of measurement or as a proportion of the measured values. Common statistical methods include the coefficient of variation (CV) or typical error (TE) and limits of agreement (LoA).

Table 2.1: Summary of validity and reliability studies undertaken on GPS specific to field sports.

Authors	**GPS Device(s) (Sampling Rate)**	**Task(s)**	**Criterion Measure(s)**	**Parameter(s)**	***Statistics*/Results**	**Conclusion**
MacLeod, Morris, Nevill, and Sunderland (2009)	SPI Elite (1 Hz)	Simulated team sport circuit (hockey)	Trundle wheel Timing gates	Distance Mean Speed	***Mean difference ± LOA*** Distance 2.5 ± 15.8 m Speed 0.0 ± 0.9 $km.h^{-1}$ ***Pearson's correlation*** 0.99 ($P < 0.001$) for distance and speed	Valid tool for measuring speed and total distance during hockey
Petersen, Pyne, Portus, and Dawson (2009)	MinimaxX v2.0 (5 Hz SPI Pro (5 Hz) SPI 10 (1 Hz)	Cricket specific movement	Timing gates 400 m athletics track	Distance Various speeds from walk to sprint	***Pearson's correlation*** 0.99 ($P < 0.001$) ***TE (%) for walk to stride (1 to 5 $m.s^{-1}$*** 1 Hz: 0.5 to 2.1 5 Hz SPI Pro: 0.4 to 3.7 5 Hz MinimaxX: 1.7 to 3.8 ***TE (%) sprinting > 5 $m.s^{-1}$*** 1 Hz: No result 5 Hz SPI Pro: 2.6 to 10.5 5 Hz MinimaxX: 5.3 to 23.8	Acceptable validity and reliability for estimating distances in walking to striding, further development needed for shorter cricket specific sprints
Barbero-Alvarez, Coutts, Granda, Barbero-Alvarez, and Castagna (2010)	SPI Elite (1 Hz)	15 m sprint 30 m sprint	Timing gates	Peak velocity	***Pearson's correlation*** 15 m sprint: 0.87, $P < 0.001$ 30 m sprint: 0.94, $P < 0.001$	Valid and reliable tool to asses both single and repeated sprint performance over distances of ≥ 30 m, further development needed to validate performance < 30 m
Coutts and Duffield (2010)	SPI Elite (1 Hz) SPI 10 (1 Hz) Wi SPI (1 Hz)	Simulated team sport circuit	Timing gates Measuring tape	Distance	***Bias (%)*** 1 Hz SPI 10: -4.1 ± 4.6 SPI Elite: -2.0 ± 3.7 Wi SPI: +0.7 ± 0.6	Accurate and reliable information on total distance travelled during team sport running patterns; however data from different devices should not be used interchangeably. 1 Hz may not be valid for defining high intensity activities, especially if they are completed over a non-linear path

Table 2.1 Continued.

Authors	GPS Device(s) (Sampling Rate)	Task(s)	Criterion Measure(s)	Parameter(s)	*Statistics*/Results	Conclusion
Duffield, Reid, Baker, and Spratford (2010)	MinimaxX v2.0 (5 Hz) SPI Elite (1 Hz)	Simulated court based movements	VICON	Distance Mean velocity Peak velocity	***TE (%)*** Not reported Calculated from reported data to be ~ 7 to 31%	GPS underestimated distance and speeds recorded during court based confined movements. The same device should be used for the same player to avoid inter-unit error
Gray, Jenkins, Andrews, Taaffe, and Glover (2010)	SPI Elite (1 Hz)	Linear 200 m course Non-linear 200 m course	Theodolite	Distance	***Bias (95% LOA)*** Linear course: + 2.0% (5.25 to -1.23) Multidirectional course: -6.0% (2.0 to -13.4)	GPS distance demonstrates reduced validity in non-linear movement patterns, including curved or circular paths, as movement intensity increases. Although 1 Hz GPS units should be considered a reliable tool for measuring total distance travelled by athletes in field based team sports, multiple changes in direction at high speed may reduce reliability and validity
Jennings, Cormack, Coutts, Boyd, and Aughey (2010)	MinimaxX v2.0 (1 Hz and 5 Hz)	Straight line course COD course Simulated team sport course	Timing gates Measuring tape Goniometer	Distance	***TE (%)*** Linear course: 1 Hz MinimaxX: 9.6 ± 2.0 to 32.4 ± 6.9 5 Hz MinimaxX: 9.8 ± 2.0 to 30.9 ± 5.8 Multidirectional course: 1 Hz MinimaxX: 9.0 ± 2.3 to 12.7 ± 3.0 5 Hz MinimaxX: 8.9 ± 2.3 to 11.7 ± 3.0 Team sport circuit: 1 Hz MinimaxX: 3.6 ± 0.6 5 Hz MinimaxX: 3.8 ± 0.6	The reliability and validity of GPS to estimate longer distances appears to be acceptable (<10% error). However, currently available GPS systems maybe limited for the assessment of brief, high speed straight line running, accelerations or efforts involving a change of direction. An increased sample rate improves the reliability and validity

Table 2.1 Continued.

Authors	GPS Device(s) (Sampling Rate)	Task(s)	Criterion Measure(s)	Parameter(s)	*Statistics*/Results	Conclusion
Portas, Harley, Barnes, and Rush (2010)	MinimaxX v2.5 (1 Hz and 5 Hz)	Linear course Multidirectional course Soccer specific movement	Trundle wheel	Distance	***Pearson correlation*** 0.99 for both 1 and 5 Hz ***TE (%)*** 1 Hz Walk: 1.8 to 4.2 5 Hz Walk: 2.2 to 4.4 1 Hz Run: 2.4 to 6.8 5 Hz Run: 2.2 to 3.6 1 Hz soccer specific: 1.3 to 3.0 1 Hz soccer specific 1.5 to 2.2	Both methods produced valid and reliable measures of linear motion and could be used to precisely quantify total distance motion in linear sport activity such as running. For multidirectional motion, both 1 Hz and 5 Hz were valid and reliable in less challenging scenarios but not in the more complex where reliability decreased
Castellano, Casamichana, Calleja-Gonzalez, Roman, and Ostojic (2011)	MinimaxX v2.0 (10 Hz)	Linear running, 15 and 30 m	Timing gates Measuring tape	Distance	***SEM (%)*** 15 m: 1.9 30 m : 5.1 ***Bias (%)*** 15 m: -11.9% 30m: -6.5% ***95% CI*** 15m: 12.9 to 13.6 m 30m: 28.4 to 27.7m	10 Hz GPS is valid for measuring distance during linear running motion, with accuracy improving as distance increases. High intra-device reliability was observed and it was concluded because of the small variations between devices it is not always necessary to monitor players with the same device
Waldron, Worsfold, Twist, and Lamb (2011)	SPI Pro (5 Hz)	Straight line sprinting	Timing gates Measuring tape	Distance Peak speed	***CV (%)*** Distance: 5.0 to 8.1 Speed: 6.6 to 9.8	5 Hz GPS can be used to quantify small, yet practically significant changes in sprint performance, particularly with reference to measures of peak speed in young rugby players. However, it appears that calculations made using either a GPS device or timing gates can differ markedly

Table 2.1 Continued.

Authors	GPS Device(s) (Sampling Rate)	Task(s)	Criterion Measure(s)	Parameter(s)	*Statistics*/Results	Conclusion
Johnston et al. (2012b)	MinimaxX v2.5 (5 Hz)	Simulated team sport circuit (as per Coutts & Duffield, 2010) Flying 50 m sprint	Timing gates Measuring tape	Distance Peak speed	***T-test*** GPS and criterion for total distance and peak speed both (P> 0.05)	5 Hz GPS units are capable of measuring total distance and peak speed. Because of the levels of reliability revealed in this study it is recommended that they are only used to measure the distance covered, time spent, and number of efforts performed at < 5.5 ms^{-1}
Varley, Fairweather, and Aughey (2012)	MinimaxX v2.0 (5 Hz) MinimaxX v4.0 (10 Hz)	Straight line running	Instantaneous velocity using a tripod mounted laser	Acceleration, Deceleration Constant velocity	***CV%, [correlation]*** Constant velocity 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] Acceleration 1 to 3 $m.s^{-1}$: 5.9 ± 0.23, [0.98] 3 to 5 $m.s^{-1}$: 4.9 ± 0.21, [0.95] 5 to 8 $m.s^{-1}$: 3.6 ± 0.18 [0.92] Deceleration 5 to 8 $m.s^{-1}$: 11.3 ± 0.44 [0.98]	Superior validity and inter unit reliability of 10 Hz compared to 5 Hz. The 10 Hz provide sufficient accuracy to quantify acceleration, deceleration and constant velocity running phases in team sports
Johnston, Watsford, et al. (2014)	MinimaxX S4 (10 Hz) SPI Pro XII (15 Hz)	Team sport circuit	Timing gates Measuring tape	Distance Peak speed	***TE (%)*** Distance 10 Hz MinimaxX: 1.3% 15 Hz SPI-ProX: 1.9% Peak speed 10 Hz MinimaxX: 1.6% 15 Hz SPI-ProX: 8.1%	No significant differences between GPS distance and criterion. High correlations between GPS and peak speed criterion. No advantage of using 15 Hz GPS over 10 Hz

2.2.2.2 Validity

The first commercially available GPS device designed specifically for sporting application became available in 2003 (Edgecomb & Norton, 2006). This device (GPSports Systems, SPI-10) sampled at 1 Hz in the first study to specifically investigate GPS application in team sports. The validity of GPS for distance measurement in a series of predetermined circuits was established via comparison with a calibrated trundle wheel. There was a systematic overestimation of distance by GPS of approximately 5%, despite high correlations (r = .998) to criterion distance.

Further validation of GPS for team sports did not occur until 2009 (MacLeod et al., 2009; Petersen et al., 2009), but since then numerous studies have attempted to examine the accuracy of GPS for recording movement during sport. The relatively rapid advances in GPS technology has warranted further investigation as new devices require validation prior to being used for research (Buchheit et al., 2014). Direct comparisons across these studies is difficult however if the aim is an all-encompassing statement on the validity of GPS in team sports, due to the variety of exercise tasks, GPS devices, sample rates and statistical methods applied (Table 2.1). Consequently, practitioners working with GPS must take steps to understand the validity and reliability of their own devices within their own settings and usage.

Researchers have used different methods when determining the gold standard criterion measure that GPS is compared with. The most popular method is to measure a course with a trundle wheel or tape measure, and then set up electronic timing gates at the start and finish. Researchers then estimate the starting point in the GPS data, add the measured length of time to complete the course, and attain distance over that period from the GPS software (Barbero-Alvarez et al., 2010; Castellano et al., 2011; Coutts & Duffield, 2010; MacLeod et al., 2009; Petersen et al., 2009; Waldron, Worsfold, et al., 2011).

The higher the sample rate, the more valid GPS becomes. When comparing similar high-velocity sprinting tasks across several studies, the error in distance reported for 1 Hz GPS is higher than for 5 Hz (Coutts & Duffield, 2010; Duffield et al., 2010; Jennings et al., 2010) and 10 Hz is lower again (Castellano et al., 2011). The typical error (TE) for distance covered was as great as 32.4% for 1 Hz GPS in a standing start 10 m sprint, with 5 Hz GPS marginally better at 30.9% (Jennings et al., 2010). By contrast, a 10 Hz GPS demonstrated a 10.9% TE over a 15 m sprint (Castellano et al., 2011). In another study, 1 Hz GPS underestimated distance in a high velocity tennis specific drill by approximately 31%, whereas 5 Hz GPS only underestimated by approximately 6% (Duffield et al., 2010). It has been shown that GPS units sampling at 1 Hz may be unable to record movement taking less than 1 second to complete (Coutts & Duffield, 2010). The newer 10 Hz units are capable of measuring the smallest worthwhile change in acceleration, whereas the 5 Hz unit is unable to do so (Varley et al., 2012). The greater errors associated with measurement of distance with the 1 Hz and 5 Hz vs the 10 Hz units indicate that sampling rate may be limiting the accuracy of distance and velocity measurements. The findings into the validity and reliability of 15 Hz interpolated devices suggests there is no advantage to using these devices over 10 Hz devices when comparing total distance, or high speed running distance (HSR) (3.8 – 5.5 $m.s^{-1}$) (Johnston, Watsford, et al., 2014).

Not surprisingly the velocity of a task directly influences the validity of distance measured by GPS. Perhaps the best illustrations of this occur in studies where the same devices are tested at a range of velocities. Portas et al. (2010) showed the TE to be lowest during walking (around 1.8 $m.s^{-1}$, TE 0.7%) and highest during running (around 6 $m.s^{-1}$, TE 5.6%). Similarly Johnston et al. (2012b) reported that 5 Hz GPS is capable of measuring movement performed at velocities lower or equal to 5.5 $m.s^{-1}$; however recommended caution when analysing movement performed at velocities of above 5.5 $m.s^{-1}$.

Although it has been reported that GPS can provide a valid measure of distance during change of direction tasks at low to moderate speeds for both 1 Hz and 5 Hz GPS (Jennings et al., 2010), validity has been shown to decrease with change of direction tasks as velocity increases, and the complexity of the change of direction increases; the TE for 1 Hz and 5 Hz GPS for walking through a gradual change of direction course was 2% and 0.6% respectively, however increased to 17.4 % and 12.9% for sprinting. For a course where the change of direction was tighter, the TE for 1 Hz and 5 Hz was 9.2% and 5.2% respectively, which increased to 22.2% and 15.8% for sprinting. It should be noted however, that when designing validation protocols including changes of direction, human locomotion around a marked circuit may not be a sufficiently reliable mode for criterion validity studies. Given the very small measurement error of the Vicon criterion motion analysis system (< 0.0008%) used by Duffield et al. (2010), the distance measured by this system whilst jogging around a 26 m perimeter rectangle was 25.8 m. Humans do not rigidly adhere to a marked trajectory, but rather lean around corners in order to maintain balance and speed and exhibit a sinusoidal pathway due to alternating limb support (Gray et al., 2010). Given that the GPS unit is worn on the upper thoracic region, it is logical that during change of direction tasks the GPS unit does not follow the prescribed path exactly. Furthermore, the deficit between the path of the device and the prescribed path is likely exacerbated at higher speeds and greater turning angles (Jennings et al., 2010). Although this may be possible to control during low-speed linear tasks, increasing speed and course complexity by introducing changes of direction make verification of receiver path almost impossible.

The longer the duration of a measured task, the more valid GPS measured distance becomes. For example, the TE for 5 Hz is reduced from 32.4% to 9.0% for sprint distances of 10 m and 40 m respectively (Jennings et al., 2010). This is reduced even more to just 3.8% over a 140 m modified team sport running circuit that included a range of tasks of differing velocities and change of direction (Jennings et al., 2010). Similarly, in a 197 m simulated high intensity soccer activity, the TE was just 1.5% for 5 Hz GPS again (Portas et al., 2010).

Thus, in the application of current GPS technology, more confidence is possible in measures of a longer duration, even if they contain periods of high-velocity activity. Furthermore, researchers and practitioners should aim to use GPS with a higher sampling rate to enhance the validity of findings. It is unlikely that 1 Hz GPS can detect anything other than total distance moved by players and therefore higher sampling rates should be used to quantify the high intensity measures arguably of most interest to team sports.

2.2.2.3 Reliability

The factors of sampling frequency, speed of movement, and duration of task which affect GPS validity, similarly affect the reliability of GPS. The co-efficient of variation (CV) of a 10 m sprint was 77% with 1 Hz GPS and 39.5% with 5 Hz (Jennings et al., 2010). However in linear soccer tasks, the CV was 4.4 – 4.5% for 1 Hz and 4.6 – 5.3% for 5 Hz (Portas et al., 2010). For longer duration tasks, the CV was reported as 1.4%-2.6% for 5 Hz measurement of walking 8800 m, yet only 0.3-0.7% for 1 Hz GPS (Petersen et al., 2009). However, more recently 10 Hz GPS has demonstrated improved reliability during the constant velocity (CV < 5.3%) and acceleration or deceleration phase (CV < 6%) (Varley et al., 2012). It is possible that different models and manufacturers can partially explain these differences in reliability, however it appears an increased sampling rate appears to improve the reliability of GPS measures.

One thing that is clear, is that the higher the velocity of movement, the lower the reliability of GPS. Jennings et al. (2010) showed the CV for a 1 Hz unit to increase from 30.8% (walking over 10 m) to 77.2 % (sprinting over 10 m) GPS. With 5 Hz GPS, the CV increased from 23.3% (walking over 10 m) to 39.5% (sprinting over 10 m). Similarly Petersen et al. (2009) showed with 5 Hz units that walking 8800 m had a CV of 1.4% – 2.6%, but sprinting 20 m had a CV of 19.7 % - 30%. The reliability of GPS devices is also negatively affected by movements requiring changes in direction. The CV for gradual and tight change of direction movements at walking pace has been reported as 11.5% and 15.2% respectively (Jennings et al., 2010). The tight change of direction movements may demonstrate a decreased reliability due to the increased number of speed changes performed.

Interestingly, the variability between two GPS units on the same player for total distance and high intensity running distance in a hockey match were similar at approximately 10% (Jennings et al., 2010) using 5 Hz GPS (Catapult MinimaxX), however it was concluded in a sports setting that players should wear the same GPS unit every training session or game to avoid inter-unit error. However Castellano et al. (2011) found that with 10 Hz GPS it was not always necessary to monitor players with the same GPS device every training session or game due to the small variability between devices for 15 m and 30 m runs (CV 1.3% and 0.7% respectively).

The studies from the literature conclude GPS devices for use in team sports have an acceptable level of validity and reliability for assessing movement patterns in team sports; however caution should be taken when analysing movement patterns when the speed of movement exceeds 5.5 $m.s^{-1}$, especially for devices with a low sampling rate. This caution should be interpreted with the specific analytical goal of the study taken into account (the requirements of the measurement tool for effective practical use) rather than statistical significance of any reliability indicators. These analytical goals' in relation to the reliability of GPS are explored in the later Chapters of this thesis. GPS units with increased sampling frequency demonstrate improved reliability and validity. It should be noted however that there is no additional benefit to using a 15 Hz (5 Hz with 15 Hz interpolation) unit over a 10 Hz unit (Scott, Scott, & Kelly, 2016) when measuring total distance or distance covered at speeds up to 5.5 $m.s^{-1}$. The commercial availability of current 10 Hz devices, with a more sensitive GPS receiver and improved algorithms, justifies their utilisation within current research examining the movement demands of intermittent, field based sports such as Rugby League.

2.2.2.4 Use of GPS in Detecting Collisions in Collision Sports

In addition to the non-running demands, currently commercially available GPS devices now contain accelerometers, gyroscopes and magnetometers making it possible to measure accelerations associated with sporting movements, including physical collisions in contact sports (Gabbett et al., 2010; Gastin et al., 2013; Kelly et al., 2012). Historically, the numbers of collisions during match-play have been identified retrospectively using video replays (King et al., 2009; Sirotic et al., 2009; Sykes et al., 2009). However, similar to examining movement demands this way, the manual coding of collisions from video footage is labour intensive, taking club video analysts and sport scientists considerable time to analyse such data. A real-time or immediate post-event system that could automatically identify collisions would be beneficial to provide information that could be used to give practical guidance on training loads. Therefore, there is a clear need for a system that can both automatically and accurately monitor collision loads during games and training.

Studies utilising GPSports SPI Pro devices have traditionally reported the level of impacts as a G force which has a poor relationship with tackles and ball carries in Rugby League (McLellan et al., 2011a). A number of studies from varying collision-based sports (Australian Football, Rugby Union, Rugby League) have attempted to quantify collision events using both microsensor technology and video-based notational analysis (Cummins & Orr, 2015; Gabbett, 2013c; Gastin et al., 2013; McLellan et al., 2011a). Although reporting impacts in G may have limitations in accurately quantifying collisions, an algorithm has been developed which can detect collision events using the tri-axial accelerometer in the GPSports devices when used in Rugby Union (Kelly et al., 2012). The authors used static window features and a mathematic learning grid to detect collisions using the tri-axial accelerometer, which enabled collisions to be consistently detected with very few false positives and false negatives (Kelly et al., 2012). Early work in Rugby League has shown that the Catapult MinimaxX GPS device can automatically detect collisions (Gabbett et al., 2010). Using a specially designed manufacturer algorithm, analysis of 237 collision events from 21 training sessions and a single trial game showed no significant differences and strong correlations between the total number, number of mild, moderate, and heavy collisions detected by the device and those subjectively coded from video footage (Gabbett et al., 2010). For a collision to be detected, the GPS unit was required to be in a non-vertical position, meaning the player was leaning forwards, backwards, or to the left or right. Instantaneous PlayerLoad™ (PL) (a parameter specific to Catapult GPS devices) which is determined as a vector magnitude from the instantaneous rate of change in acceleration in the three axes of acceleration (Boyd, Ball, & Aughey, 2011; Young, Hepner, & Robbins, 2012) was calculated by the device. A spike in the instantaneous player load shortly before the change in orientation of the unit was also required for the collision to be detected (Gabbett et al., 2010). Clearly a limitation of this study is that the majority of collisions were coded from training observations, where the frequency and intensity of collisions have been shown to be considerably lower than those experienced in competition (Gabbett et al., 2012). Whilst descriptors were described for the video coding of mild, moderate, and heavy collisions, the authors did not state how the GPS device was able to differentiate between these differences in collision intensity. Although the authors state there were no significant differences and strong correlations between GPS and video detection, they provided no information on how undetected collisions and false detections were handled.

Further work has shown that the same GPS device and manufacturer algorithm was unable to detect collisions in Australian Rules Football, with a 78% success rate (Gastin, McLean, Breed, & Spittle, 2014), however unlike in the Gabbett and colleagues study (Gabbett et al., 2010) all of these collisions were from four competitive games. The authors stated the less successful detections than when compared to rugby league may be due to the differences in tackle dynamics. In rugby, a tackle is generally considered complete when the player carrying the ball is brought to the ground or the ball touches the ground whilst the player is being held. To accommodate this objective, the algorithm requires a considerable change in orientation of the GPS unit. In Australian Rules Football, the objective of a tackle is to impede the progress of the player with the ball, to prevent the ball being disposed of or to force an ineffective disposal; which can be achieved without necessarily brining the player to ground. Therefore, a number of completed tackles may not have been detected as the change in orientation criteria was not met (Gastin et al., 2014). The device was more sensitive in detecting tackles against (90%) rather than tackles made (66%) (Gastin et al., 2014), which may be due to the difference in intensity of carrying the ball into contact compared with making a tackle (Gastin et al., 2014).

More recently, GPSports SPI HPU units were used to detect collisions against those coded from video footage in men's and women's rugby sevens (Clarke, Anson, & Pyne, 2016). A collision was detected by the device when all three acceleration vectors exceeded 3.5 G. Unlike the success of the same device in Rugby Union (Kelly et al., 2012) the device only had modest utility in rugby sevens, with 45% of collisions for men, and 62% of collisions for women being incorrectly detected. The difference in collision detection algorithm may account for some of the differences observed when compared to Rugby Union (Kelly et al., 2012), however it was also recognised that possibly due to tackles being one-on-one events or because the ball is quickly removed from a breakdown in rugby sevens, ball contests following a tackle are minimised (Clarke et al., 2016) The authors attributed differences in measures between the men's and women's game as being a result of physical size, strength, physicality and technical and/or tactical factors (Clarke et al., 2016). Collectively, these findings show that to allow the detection of a range of collision events within contact sports requires sophisticated sport and event-specific algorithms, and until these are further refined and validated the use of microtechnology data is best when used in combination with other technologies such as video coding.

More recently, the Catapult Optimeye S5 device was used to detect collisions during NRL match-play compared with 380 collisions coded by video footage. In order for a collision to be detected by the GPS device, a spike in instantaneous PL above or equal to 2 arbitrary units (AU) is required to occur along with a change in orientation of the device (Hulin et al., 2017). The number of true-positives (player involved in a collision and the device reported collision) and false-negatives (player involved in a collision and the device did not report a collision) were used to calculate sensitivity (reporting a collision event when collisions do occur), whilst the number of true-negatives (collision detection algorithm conditions were met, the player was not involved in a collision, and a collision was not recorded by GPS) and false-positives (player not involved in a collision and the GPS device reported a collision) was used to calculate specificity (not reporting collision events when collisions did not occur) (Hulin et al., 2017). The device was sensitive to detect 97.6% of collision events during Rugby League match-play, with the specificity of the device being lower at 91.7% (Hulin et al., 2017), which highlights the error associated with the devices are due to not reporting collision events when collision events do not occur.

As previously eluded to, PL is an accelerometer derived parameter specific to Catapult GPS devices. More recently, variants of the PL metric have been developed with regards to providing greater insights into some of the high acceleration, low velocity movements (such as collisions, tackles, and wrestling) that occur during Rugby League. Given the strong relationship between PL and measures of total distance (Boyd et al., 2010), the vertical vector of the PL equation can be removed, providing a measure of accelerations in the medio-lateral and anterio-posterior planes (i.e. 2D PlayerLoad™ [2DPL]) (Johnston, Gabbett, & Jenkins, 2015). Given that Rugby League players are required to perform substantial amounts of wrestling and grappling both while standing and on the ground, these physically demanding activities can be quantified using the PlayerLoad Slow™ (PL Slow) metric. PL Slow quantifies all accelerations from the accelerometer that occur at speeds of less than 2 $m.s^{-1}$ (Gabbett, 2015b). It has been shown that there are weak relationships between PL, 2DPL, and PL Slow and the number of collisions and repeated high-intensity efforts performed for OB ($r = 0.13 – 0.30$) and PIV ($r = 0.20 – 0.34$) , i.e. players that are involved with greater HSR demands than forwards groups (Gabbett, 2015b). However these relationships were significantly greater for the forwards ($r = 0.52 – 0.69$) and hookers ($r = 0.32 – 0.65$). These findings suggest that PL, 2DPL, and PL Slow offer measures of providing collision activity in positional groups such as the forwards and hookers, but are limited in describing the collision activities for positions such as OB and PIV.

With regards to collision intensity, Wundersitz and colleagues attempted to validate the Catapult MinimaxX S4 unit to measure peak impact accelerations in a laboratory setting using three-dimensional motion analysis as the criterion measure during tackling and bumping activities (Wundersitz, Gastin, Robertson, & Netto, 2015). Twenty five players wore the device, attached to which was a single retro-reflective marker recorded by a 12 camera motion analysis system during a tackle bag drill, a bump pad drill, and a one on one tackle drill. Peak impact accelerations as recorded by the GPS device overestimated (mean bias 0.6 G) when compared to those recorded by the motion analysis system, with the tackle bag drill providing the greatest validity with the motion analysis system. Accuracy of the device was increased when a cut off filter of 20 Hz was applied (mean bias 0.01 G) (Wundersitz et al., 2015). With the continuous development in microtechnology used to assess athlete demands, the manufactures of such devices claim to be able to automatically detect collisions and their associated load in collision sports. Indeed one such is the Statsports Viper device; however these claims are yet to be scientifically validated.

2.3 Quantifying the Physical Demands of Rugby League Match-Play

2.3.1 Introduction

Most of the research examining the physical demands of Rugby League match-play has focused on the movement demands measured with GPS. There are a few points to consider when comparing across studies. Firstly, there has been little consistency across the literature in the velocity zones used for low-speed (ranging from 0-1.9, 1-3, 0-2.7, 0-3.3, and 0-5 $m.s^{-1}$), moderate-speed (1.9-3.9, 2.7-5, 3-5 and 3.3-5 $m.s^{-1}$), high-speed (3.9-5.8, 5-5.5, 5-6.1 and 5-7 $m.s^{-1}$) and very high-speed/sprinting activity (>5.5, >5.6, >5.8, >6.1, and 7 $m.s^{-1}$) (Austin & Kelly, 2013, 2014; Gabbett, 2012b; McLellan & Lovell, 2013; McLellan, Lovell, & Gass, 2011c; Waldron, Twist, et al., 2011). Secondly, universal definitions for positional groupings between studies are difficult, and will largely depend on the tactics employed for the team(s) under investigation. It maybe that different studies use the same positional categories but they consist of different positions within those categories. For example "HUF" compromise of only props in some studies (Gabbett et al., 2010; Gabbett et al., 2011, 2012), whereas the same category includes all of props, second rows, and loose forward in others (Twist et al., 2014), or sometimes just props and second rows (Waldron, Twist, et al., 2011). Full-backs have been classified as both OB (Twist et al., 2014; Waldron, Twist, et al., 2011) and PIV (Gabbett et al., 2010; Gabbett et al., 2011, 2012). Similarly Waldron, Twist, et al. (2011) classifies the loose forward position as a PIV, whereas (Gabbett et al., 2010; Gabbett et al., 2011, 2012) classify the position as a WRF. Such examples highlight the difficulty of grouping individual positions, and should be taken into account when comparing values across studies.

What is also clear from reviewing the literature is that the vast majority of studies at the elite level have examined the demands of the NRL competition, which is regarded as the highest level of competition in the world (Eaves & Broad, 2007; Gabbett, 2013b; Twist et al., 2014). In addition to our in-depth understanding of the positional demands over the course of 80 minutes of match-play in the NRL (Austin & Kelly, 2013, 2014; Cummins & Orr, 2015; Gabbett, 2012b; Gabbett et al., 2012; Kempton, Sirotic, & Coutts, 2014; King et al., 2009; McLellan et al., 2011c; Sirotic et al., 2011; Twist et al., 2014), the physical demands have been broken down to examine the most demanding passages of play (Austin, Gabbett, & Jenkins, 2011; Johnston & Gabbett, 2011), influence of field position and phase of play (Gabbett, Polley, Dwyer, Kearney, & Corvo, 2014), influence of the opposing team (Gabbett, 2013b), fatigue and pacing strategies (Black & Gabbett, 2014), and demands of successful and less successful teams (Hulin, Gabbett, Kearney, & Corvo, 2014). There are few studies examining the basic positional demands in the ESL from a limited number of games and players from teams competing at the top of the table (Twist et al., 2014; Waldron, Twist, et al., 2011), clearly our understanding of ESL match-play is far behind what we know about the NRL. In the only study to directly compare the demands of the NRL and ESL, it is perhaps not surprising that NRL players performed more HSR than those competing in the ESL, and NRL players managed to better preserve HSR between the first and second half of matches (Twist et al., 2014). Studies that have examined the movement demands of match-play at the elite level (i.e. NRL and ESL competitions) are summarised in Table 2.2.

Table 2.2: Studies describing the movement demands of Rugby League match-play.

Authors	Competition /Positional Group	Playing Time (Min)	Distance (m)	Relative Distance (m.min^{-1})	Low-Speed Activity (m)	High-Speed Running (m)
(Sykes et al., 2009) *	ESL OB	-	8142 ± 630	-	-	-
	ESL PIV	-	8800 ± 581	-	-	-
	ESL Props	-	8688 ± 405	-	-	-
	ESL Back Row	-	8685 ± 547	-	-	-
(Sykes et al., 2011) **	ESL OB	-		89 ± 11 – 97 ± 9		
	ESL PIV	-		100 ± 8 – 105 ± 5		
	ESL Props	-		102 ± 6 – 107 ± 17		
	ESL Back Row	-		96 ± 9 – 102 ± 9		
Austin and Kelly (2013)	NRL forwards	-	5964 ± 696	85 ± 4	4655 ± 568	432 ± 127
	NRL backs	-	7628 ± 744	86 ± 5	5844 ± 549	749 ± 205
Gabbett et al. (2012)	NRL HUF	38.0 ± 10.8	3569 ± 1177	94 ± 10	3334 ± 1082	235 ± 122
	NRL WRF	58.5 ± 16.7	5561 ± 1579	96 ± 13	5143 ± 1474	418 ± 154
	NRL PIV	64.1 ± 23.0	6411 ± 2468	101 ± 19	5974 ± 2299	436 ± 198
	NRL OB	73.5 ± 14.9	6819 ± 1421	93 ± 13	6235 ± 1325	583 ± 139
Gabbett (2013a)	NRL HUF	50.7 ± 13.1	5129 ± 1652	105 ± 21	4878 ± 1541	251 ± 157
	NRL PIV	74.9 ± 14.6	7834 ± 2207	99 ± 8	7513 ± 2138	320 ± 176
	NRL OB	77.8 ± 10.1	7575 ± 850	94 ± 10	7123 ± 830	452 ± 113
McLellan et al. (2011c)	NRL forwards	-	4982 ± 1185	-	4664 ± 1165	232 ± 60
	NRL backs	-	5573 ± 1128	-	4879 ± 1339	440 ± 101
McLellan and Lovell (2013)	NRL forwards	-	8442 ± 812	98 ± 12	-	-
	NRL backs	-	8158 ± 673	101 ± 8	-	-
Varley, Gabbett, and Aughey (2014)	NRL	64.9 ± 18.8	6276 ± 1950	96 ± 16	5950 ± 1845	327 ± 168

Table 2.2 Continued

Authors	Competition /Positional Group	Playing Time (Min)	Distance (m)	Relative Distance (m.min^{-1})	Low-Speed Activity (m)	High-Speed Running (m)
Twist et al. (2014)	NRL HUF	56.7 ± 16.4	4948 ± 1370	88 ± 8	-	-
	NRL PIV	82.8 ± 8.9	7973 ± 1160	96 ± 8	-	-
	NRL OB	85.8 ± 3.9	7381 ± 518	87 ± 6	-	-
	ESL HUF	57. 9 ± 15.8	5733 ± 1158	102 ± 14	-	-
	ESL PIV	69.7 ± 23.4	6766 ± 1495	104 ± 27	-	-
	ESL OB	83.9 ± 12.9	7133 ± 1204	86 ± 11	-	-
Waldron, Twist, et al. (2011)	ESL HUF	44.2 ± 19.2	4181 ± 1829	95 ± 7	1723 ± 743	513 ± 298
	ESL PIV	65.2 ± 12.4	6093 ± 1232	94 ± 8	2365 ± 667	907 ± 255
	ESL OB	77.5 ± 12.3	6917 ± 1130	89 ± 4	3262 ± 505	926 ± 291
(Oxendale et al., 2016)	ESL forwards	55:2 ± 21:4	4675 ± 1678	82 ± 7	-	307 ± 194
	ESL backs	67:1 ± 25:2	5640 ± 2191	83 ± 10	-	481 ± 262

*In the Sykes et al. (2009) study, interchange players were analysed together to give a total value for that position, e.g. props were shown to cover the highest distance even though they spend less time on the field

** In the Sykes et al. (2011) study, relative distances are reported as ranges over game quarters

2.3.2 Total Distance

During a game, the total distance covered is typically between 4000-8000 m which can vary depending on playing position and standard of competition (Table 2.2). OB have been shown to cover greater distances (5550-8000 m) than PIV (6000-7000 m) and HUF (3500-6000 m). Differences between positions for the total distance covered are less evident when expressed relative to playing time (Table 2.2). Relative distances (m.min^{-1}) show trivial differences between positions with most research (Austin & Kelly, 2013; Gabbett, 2013a; McLellan & Lovell, 2013; Twist et al., 2014; Waldron, Twist, et al., 2011) suggesting forwards cover slightly greater distances relative to playing time, which may be attributable to forwards typically spending less time on the field than other positions, usually around 40-50 min (Gabbett et al., 2012; Twist et al., 2014; Waldron, Twist, et al., 2011). At the elite level (NRL and ESL) players typically cover 90-100 $m.min^{-1}$ (McLellan & Lovell, 2013; Twist et al., 2014; Waldron, Twist, et al., 2011). Semi-elite and junior elite match intensities are typically lower than elite matches (88 vs 95 $m.min^{-1}$) (Black & Gabbett, 2014; Gabbett, 2013a, 2014a; Johnston et al., 2013), and are lower again for non-elite matches (75-83 $m.min^{-1}$) (Duffield, Murphy, Snape, Minett, & Skein, 2012; Gabbett, 2014b; Johnston et al., 2013). Reasons for these differences could be attributable to reduced physical (Gabbett, 2005a; Gabbett, Kelly, Ralph, & Driscoll, 2009) and skill qualities (Gabbett, Kelly, & Pezet, 2007) in non-elite players leading to lower work rates, more errors, and stoppages during play.

The relative distance covered appears important to the outcome of matches. In elite (NRL) and semi-elite (QC) competition, greater relative distances are covered by winning sides (Black & Gabbett, 2014; Gabbett, 2013b), which suggests the ability to maintain high work rates is linked to match outcome. However, a more recent study disputes such findings. Hulin et al. (2014) suggest that success in the NRL is not indicative of greater running workloads, in fact less successful teams were involved in greater relative distances in the "mean 5 minute period" of match-play than their more successful counterparts and concluded more successful teams are involved in a greater number of collisions. Whilst the average match intensity ($m.min^{-1}$ for the games duration) is useful for profiling the general demands of the sport, and has shown relationships between match outcome, the average demands of the game do not highlight the most demanding passages of match-play (Austin et al., 2011; Gabbett, 2015a; Gabbett et al., 2014), and thus conditioning players based on such movement demands in training is likely to result in players being underprepared for competition (Gabbett et al., 2014; Kempton, Sirotic, Cameron, & Coutts, 2013). There is support for such a notion given that when only assessing ball in play time rather than the whole game (including stoppages), average NRL match running intensity is significantly greater (125 ± 16.1 vs. 86.7 ± 9.8 $m.min^{-1}$) (Gabbett, 2015a).

Field position and phase of play (attack or defence) has also been shown to be a determinant of the relative distance covered in the NRL. Greater relative distances are evident when defending in the final third of the field (70-100 m zone) compared with 0-30 m (117 ± 29.1 vs. 100.4 ± 28.9 $m.min^{-1}$) (Gabbett et al., 2014). Collectively, these data show the importance of players maintaining high match intensity, as well as possessing the ability to increase intensity at critical match periods.

2.3.3 High-Speed Running

At critical parts in the game, players are required to perform high-speed activities (Austin et al., 2011; Gabbett, 2013b, 2014a). When comparing positions, OB have been shown to perform the greatest volumes of HSR (452 ± 113 m) compared with PIV (320 ± 176 m), and HUF (251 ± 157 m) (Gabbett, 2013a) (Table 2.2). OB perform significantly more high-speed runs over 10-20 m than HUF, and over 20-30 m than PIV and HUF (Sykes et al., 2011).

A recent study has reported that less successful elite NRL teams perform more HSR than successful teams in the same competition (Hulin et al., 2014), however this study was limited to two teams (one with a high and one with a low success rate) and therefore may be limited by the tactical approach of these teams. Other findings suggest there is little difference in the amount of HSR between winning and losing teams in Southern hemisphere competitions at the elite level (Gabbett, 2013b), and semi-elite level (Gabbett, 2014a). In the only study to date to directly compare NRL and ESL competition, NRL players were found to perform more HSR, and better maintain HSR between first and second halves of the game (Twist et al., 2014). What is currently unclear is how players achieve these distances (e.g. good kick chase in winning teams vs. covering line breaks in losing teams). It may be in fact less successful teams are equally equipped as their more successful counterparts to perform HSR efforts, but perhaps cannot recover as quickly (Gabbett, 2013b). Indeed such data examining these demands for less successful ESL teams has not been investigated. Examining additional data such as line breaks also may provide more useful information into how these distances are achieved.

2.3.4 Sprinting

The distribution of sprints between positions mirrors the HSR demands (Gabbett, 2012b). In the NRL, only 1.4% of sprints are deemed "high velocity" (> 7.0 $m.s^{-1}$) with remaining sprints made up of low (≤ 1.11 $m.s^{-2}$), moderate (1.12 – 2.77 $m.s^{-2}$) and high (≥ 2.78 $m.s^{-2}$) acceleration efforts (Gabbett, 2012b). Standing (24.3%) and forward walking (28.1%) are the most common activities players perform prior to a sprint (Gabbett, 2012b). Training the acceleration ability of players over 0-20 m from a number of starting positions is thought to be imperative. Longer sprints focusing on maximal velocity are also important for OB (Gabbett, 2012b; Waldron, Twist, et al., 2011). It has been shown at semi-elite standard (QC), that the top four sides in the competition perform more sprinting than the bottom four sides (Gabbett, 2014a).

2.3.5 Collisions

Players require the ability to perform and withstand physical collisions during both attacking and defensive phases of play (Gabbett et al., 2010). The defensive play of tackling is integral to performance, where the ability to effectively perform a winning tackle may prove critical in determining match outcome (Gabbett, 2013c). The attacking play of ball carrying and the ability to tolerate being tackled is important for gaining distance and field position. Not only is the total number of collisions sustained important, but also the collision type and magnitude are vital considerations for match outcome (Cummins & Orr, 2015). Whilst forwards HSR demands are typically lower than other positions, their collision demands are the greatest. In the NRL, WRF have been shown to perform the greatest number of collisions over the course of a game (47 ± 12), followed by HUF (36 ± 8), PIV (29 ± 6) and OB (24 ± 6) (Gabbett et al., 2011). When expressed relative to playing time, HUF experience the greatest frequency of collisions over the course of match-play (Gabbett et al., 2012; Sykes et al., 2011). HUF (16; range 14 to 18) and WRF (17; range 15 to 20) have been shown to perform a significantly greater number of “heavy” collisions when compared to PIV (11; range 9 to 14), but not OB (14; range 12 to 16) measured through the Catapult MinimaxX device (Gabbett et al., 2012), however as in a previous investigation (Gabbett et al., 2010), the authors provided no information on how the device was able to differentiate between the intensity of the collisions. Hulin et al. (2014) have showed that teams in the NRL who perform the greatest numbers of collisions have improved chances of winning. This finding has been confirmed by others investigating semi-elite competition (QC) (Hulin & Gabbett, 2015). The number of collisions manually coded from video footage during ESL match-play has been reported as 38 ± 19 for forwards and 25 ± 8 for backs (Twist et al., 2012). Later work using GPS has reported higher collision counts in the ESL for forwards (54 ± 37) and backs (31 ± 13)

(Oxendale et al., 2016). The data reported in these studies were from the same team, but collected four seasons apart. This may suggest that the demands of the game are increasing, however it is also possible that the small number of games analysed in these ESL studies (Oxendale et al., 2016; Twist et al., 2012) may account for some of the differences and large variations observed.

2.3.6 Physiological Response to Match-Play

Thus far in this literature review, methods of measuring the movement and contact demands of the game have been outlined. Such demands can be defined as the "external" demands or the work completed by the player, measured independently of their internal characteristics (Wallace, Slattery, & Coutts, 2009). The internal demands may be defined as the relative physiological stress imposed on the player as a result of the external demands (Halson, 2014). Traditionally, heart rate (HR) chest monitors have been used to measure such demands since their inception 30 years ago. Studies demonstrating a strong positive correlation between HR and oxygen utilisation during continuous steady state running underpin the rationale for using HR as an indirect measure of exercise intensity (Achten & Jeukendrup, 2003) and is a highly popular method due to the ease and non-invasive nature of obtaining HR data during team sport activities. However, the strength of this linear relationship is compromised during intermittent and high-intensity exercise (Borresen & Lambert, 2009; Dellal et al., 2010; Impellizzeri, Rampinini, & Marcora, 2005). In such situations HR elevation in response to exercise is delayed as a large proportion of the required energy is initially supplied via anaerobic metabolism (Borresen & Lambert, 2009). Despite this evidence of identifying HR as being potentially unsuitable for reflecting the physiological demands of high-intensity intermittent activity, it remains prevalent in the majority of studies examining the physiological response to match-play in Rugby League.

Elite players have been shown to experience average HR's over the course of match-play similar to those of semi-elite players (Coutts, Reaburn, & Abt, 2003), with trivial differences between OB (83.5 ± 1.9 % max), PIV (81.5 ± 4.1 % max) and HUF (84.1 ± 8.2 % max). Average HR is reduced in the second half of the game for elite players, which can be likely attributed to reductions in playing intensity (Waldron, Highton, Daniels, & Twist, 2013). Although the relative intensity appears to be similar between positions, the physiological load over the course of the game measured through Edwards training impulse (Edwards, 1993) is greater in OB (279.4 ± 71.8 arbitrary units [AU]) than HUF (198.3 ± 82.3 AU), but not different to PIV (270.6 ± 63.5 AU), likely attributable to greater playing times for these groups (Waldron, Twist, et al., 2011). However greater overall and HSR distances have also been shown to influence perception of effort (Lovell, Sirotic, Impellizzeri, & Coutts, 2013). Coutts and colleagues have also described the blood lactate, and estimated energy expenditure of semi-elite players competing in the QC Cup (Coutts et al., 2003). HR 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 players' match HR combined with the HR-VO_2 regression equation derived from an incremental treadmill test. The mean blood lactate concentration during the semi-elite game was reported to be 7.2 ± 2.5 $mM.l^{-1}$, with a significant reduction between first (8.4 ± 1.8 $mM.l^{-1}$) and second (5.9 ± 2.5 $mM.l^{-1}$) halves (Coutts et al., 2003). The invasive nature and logistical difficulties of blood lactate collection have limited the use of this measure at the elite level. Blood lactate values are also likely to be influenced by the intensity of exercise performed immediately before sampling and the potentially limited role blood lactate plays in fatigue during prolonged intermittent exercise (Krustrup et al., 2006). Nevertheless, the data from the above studies have confirmed that there is both a large aerobic and anaerobic glycolytic component to Rugby League match-play (Meir, Newton, Curtis, Fardell, & Butler, 2001).

2.3.7 A New Energetic Approach

One relatively recent approach has been to estimate the metabolic or internal cost of activities performed during games based upon players' external movement profiles. The approach proposed by di Prampero and colleagues considers accelerated running on a flat surface to be metabolically equivalent to incline running at a constant speed where the incline is equal to the forward acceleration (di Prampero et al., 2005). The 'equivalent slope' obtained from this method is then used to provide an instantaneous estimate of the energy cost of accelerated running. This approach has since been adapted for use in team sports (Osgnach, Poser, Bernardini, Rinaldo, & di Prampero, 2010). In the first study to examine the metabolic power demands of Rugby League match-play, metabolic power values of ~ 9-11 W/kg were reported (Kempton, Sirotic, Rampinini, & Coutts, 2015). In this study, speed-derived methods underestimated when compared to metabolic power-derived indices from as little as 37% for OB, up to 76% for HUF, with the authors proposing metabolic power is a more appropriate method than the traditional speed based approach (Kempton et al., 2015). However, the validity of metabolic power to quantify the internal load of team-sport activity has recently been questioned due to a reported underestimation of energy expenditure owing to an inability to detect non-ambulatory related activities (Buchheit, Manouvrier, Cassirame, & Morin, 2015). Indeed, during a repeated-effort rugby protocol comprising of 3 sets of 6 collisions, metabolic power based methods (7.2 ± 1.0 kcal/min) underestimated the total energy expenditure when compared to that obtained from open-circuit spirometry (13.2 ± 2.3 kcal/min) (Highton, Mullen, Norris, Oxendale, & Twist, 2017), concluding energy expenditure is underestimated from GPS based methods and should be applied with caution during intermittent team sports that involve collisions.

2.4 Fatigue Following Match-Play Demands

Post-game, players experience immediate and delayed symptoms of fatigue that persist for a number of days. Several investigations have reported impairments in whole-body neuromuscular function (Duffield et al., 2012; Johnston et al., 2013; McLean, Coutts, Kelly, McGuigan, & Cormack, 2010; McLellan, Lovell, & Gass, 2011b; Twist et al., 2017; Twist et al., 2012), increases in markers of skeletal muscle damage (Johnston, Gabbett, Jenkins, & Hulin, 2015; Johnston et al., 2013; McLellan, Lovell, & Gass, 2010; McLellan et al., 2011a, 2011b; Twist et al., 2012) and reductions in perceived well-being (Johnston et al., 2013; McLean et al., 2010; Twist et al., 2017; Twist et al., 2012) following Rugby League match-play. Muscle damage resulting from competition has been shown to remain throughout the entire season (Fletcher et al., 2016). It is outside the scope of this thesis to comprehensively review the literature on post-match fatigue responses of Rugby League players; rather the aim of this section is to look at the match-play demands that may contribute to such responses. A comprehensive review of the mechanisms of fatigue in professional Rugby League players has been conducted previously (Twist & Highton, 2013).

At the elite level, competition does not coincide with a standardised amount of recovery between games which can be separated by as many as 10 days and as few as 5 days over an eight month season. Thus, coaching and conditioning staff need to be mindful of the recovery time course in order to prepare optimally for the subsequent match. In the first study to analyse the effect of different between-match recovery times on the activity profiles of NRL players (from a single team), matches after short turnarounds (5-6 days) were associated with greater relative total distance than matches with longer recovery (9-10 days) (Murray et al., 2014). The authors attributed these findings to the increases in low-speed activity, with interestingly no differences between moderate- and high-speed activities (Murray et al., 2014). Although the authors did not record ball in play time, they suggest greater relative total and low speed distance may have been observed in shorter turnarounds due to lower ball in play times. The authors offered a potential explanation that players attempted to manage fatigue in short turnarounds by kicking the ball out of play more often, thereby reducing ball in play time (Murray et al., 2014). Consistent with previous findings into winning and losing in Southern hemisphere competition games (Black & Gabbett, 2014; Gabbett, 2013b), the relative intensity in terms of the distance covered per minute was higher when games were won after a short turnarounds (Murray et al., 2014). This again emphasises that the competitive advantage of teams is closely linked to their ability to maintain a higher playing intensity, and suggests successful teams can overcome the physical and mental challenge of short between match recovery cycles. Conflicting findings were reported in a later study, again for a single NRL team where it was shown that matches following short recovery cycles (5-6 days) were associated with reduced relative total and HSR distances, which were also evident when matches were won (Kempton & Coutts, 2016). The total time the ball was out of play reduced the relative total distance, but not HSR distance. It has been reported that for a single ESL team over a period of fixture congestion (four games in 22 days with between match periods of 6, 2, and 5 days) that reductions in high-intensity running ($\geq 5.5 \text{ m.s}^{-1}$) and increases in low speed activity ($< 5.4 \text{ m.s}^{-1}$) were evident in the later matches, indicative of an overall slowing of movement speed (Twist et al., 2017). The reduction in high-intensity running coincided with reductions in countermovement jump flight time, indicative of lower body neuromuscular fatigue (Twist et al., 2017). Large reductions in between-match training loads (measured through session rating of perceived exertion multiplied by session duration) were reported for the periods of fixture congestion between matches 2 and 3 (2 days), and matches 3 and 4 (5 days). Clearly a limitation of these studies is the limited sample size in regards to the fact they only recruited players from single teams. Establishing such information in a greater sample of teams could increase our understanding of the match demands for games during different between match recovery periods.

2.5 Summary

In summary, this chapter has reviewed the methods commonly used to assess physical match demands in Rugby League including video time-motion analysis, GPS, and HR, all of which will be used throughout this thesis. The literature that currently exists examining the physical demands of the game has also been outlined, the vast majority of which focuses on the elite level NRL competition. Our understanding of ESL match-play clearly is far behind what we know about the NRL and hence this thesis will attempt to increase our understanding of ESL competition, examine the recent developments in the physical intensity of ESL match-play, provide evidence for the best methods of quantifying collisions, and examine the effect of different between match recovery periods on the running performance of the subsequent match.

Chapter 3

General Methods

Methods that are common to multiple studies within this thesis have been included in this section. Details of methods that were exclusive to a particular study can be found in the relevant chapter.

3.1 Ethical Approval and Location of Testing

Ethical approval for all experimental procedures outlined in this thesis was granted by the Liverpool John Moores University Ethics Committee. The governing body of Rugby League in the UK, the Rugby Football League (RFL) have also passed the GPS devices to be used as safe to wear during training and competition. Chapter 4 (2012 season) and Chapter 6 (2012, 2013, 2014 season) testing took place at every ESL stadium over these seasons (13 home games, 13 away games, 1 neutral ground). All away fixtures were played on grass. The teams and stadiums in the league remained the same over this period. Chapter 5 testing took place at the stadium of an ESL club based in North West England. The pitch at the home ground of the club under investigation was a 4^{th} generation (4G) artificial Desso surface. Chapter 7 data was from the same team as in Chapters 4 and 6, and took place at an ESL stadium in Yorkshire, England during the 2014 season. Chapter 8 data was collected from six ESL clubs during official ESL regular season games in the 2015 season, which were played at various stadiums throughout the league.

3.2 Assessing Player Movement Patterns

In all chapters where player movements were assessed, GPS technology was used. Two different models of GPS device were used throughout this thesis; the characteristics of which can be seen in Table 3.1.

Table 3.1: GPS device characteristics of those to be used in this thesis.

Manufacturer (unit name)	Chapters featured	Mass (g)	Size (mm)	GPS sampling rate (Hz)	Accelerometer sampling rate (Hz)	Additional features
GPSports (SPI Pro XII)	4,5,6,	76	48 x 20 x 87	5 with 15 interpolation	100	
Statsports (Viper)	5,6,7,8	50	21 x 18 x 77	10	100	Gyroscope, digital compass

In Chapter 4 participants wore the GPSports SPI Pro XII unit in a custom designed vest in addition to a compatible HR chest monitor. In Chapter 5, the participants wore both models of unit simultaneously in a custom designed vest with the units being located on the upper thoracic region approximately 15 cm apart (Figure 3.1). In Chapters 6 and 7, participants wore the Statsports Viper unit in a custom designed vest. In Chapter 6, participants also wore the GPSports SPI Pro XII unit in a custom designed vest. In the aforementioned chapters, a tightly fitted squad shirt was worn over the vest. In Chapter 8, participants wore the Statsports device with either a tightly fitting squad shirt over the vest, or the unit was placed in a small purposely made pouch in the squad playing shirt. In all Chapters where GPS was used, the devices were switched on and left for 20 minutes to acquire satellite locks before the commencement of movement activity as per manufacturer instructions. Players underwent a familiarisation period using the GPS devices during training sessions that included Rugby League specific training, game simulated contact activities and pre-season friendly games.

Figure 3.1: Participant wearing both models of device in a custom designed vest.

After the units were collected from the players post testing, data were downloaded to a computer via multi-unit docking ports. Data from the GPSports units were downloaded using Team AMS Release R1 2012.4 (GPSports, Canberra, Australia). Data from the Statsports units were downloaded using Statsports v.2.0.2.5 (Statsports, Dundalk, Ireland) before being exported into Microsoft Excel (Microsoft Corporation, USA) for further analysis.

3.4 Assessing Player Collisions

Notational analysis was used to gather data on the collision demands of match-play in both Chapters 4 and 6. This data was provided by Opta, an independent analysis service who provide performance data to every ESL club through examination of video footage. Currently no reliability data exists for Opta Rugby analysis specifically, although the reliability of the data collection process in football has been reported (Liu et al., 2013). Results showed that data coded by independent Opta operators reached a very good agreement (intra-class correlation co-efficient ranged from 0.88 to 1.00 and low standardised typical errors varied from 0.00 to 0.37) (Liu et al., 2013). Furthermore, personal communication with Opta revealed they employ the same expert assessor for each team in the ESL to increase reliability. Previous work has shown the measurement error for notational video analysis in terms of frequency, mean duration, and total time of individual movement events to be around 5-10% (Duthie et al., 2003). Opta variables included the number of ball carries and tackles. The total number of collisions was calculated by summing the number of ball carries and tackles. The number of carries only included those that resulted in a collision with an opposing player through either the ball carrier being tackled by a defending player, or the ball carrier going into a tackle and offloading the ball in the process of being tackled. Tackles did not include missed tackles, which were discarded from the analysis given that the data from Opta cannot distinguish which missed tackles resulted in a collision or not. Notational analysis was used again to quantify collisions in Chapter 7, however rather than using Opta data, collisions were manually coded by the author of this thesis from observation of video footage. Collisions were defined as “a player making contact with either another player or the ground, which resulted in an alteration to the player’s momentum or the player’s direction of travel” (Gabbett et al., 2010; Hulin et al., 2017). All offensive, defensive, and collisions off the ball were coded. A repeated analysis was conducted on the sample three weeks later to assess intra-individual test-retest reliability using Cohen’s kappa statistic, which assesses the level of agreement for variables assessed on nominal scales. These were then compared against the number of collisions automatically detected by the Statsports Viper device. The Cohen’s Kappa statistic can be used for both inter- and intra-rater reliability tests, and is similar to a correlation co-efficient ranging from -1 to +1, where 0 represents the amount of agreement that can be expected from random chance, and 1 represents perfect agreement between the observations. As with correlation statistics, the Kappa is a standardised value and thus interpreted the same across multiple studies (McHugh, 2012). Cohen suggested the Kappa result be interpreted as follows: values ≤0 as indicating no agreement, 0.01-0.20 as none to slight, 0.21 to 0.40 as fair, 0.41 to 0.60 as moderate, 0.61 to 0.81 as substantial, and 0.81 to 1.00 as almost perfect agreement (Cohen, 1960). A 3 x 3 cross tabulation approach was used to assess whether a collision was a ball carry, tackle, or collision off the ball. Further cross tabulations where then conducted to assess ball carries to ground vs. ball carries not to ground (2 x 2), tackles to ground vs. tackles not to ground (2 x 2), and first man tackle vs. second man tackle vs. third man tackle (3 x 3). The Kappa statistic for each of these cross tabulations was then computed using the Statistical Package for Social Sciences (SPSS), version 21 (Chicago, IL, USA). For every category the Kappa statistic was 1.0, indicating a perfect level of agreement for each of the collision categories.

3.5 Determination of Positional Groups

In Chapters 4 and 6, data for positional groups were examined. The definitions of these groups are outlined in Table 3.2.

Table 3.2: Positional group definitions for use in Chapters 4 and 6.

Positional group	Individual positions within that group
Outside Backs (OB)	Full-back, wingers, centres
Pivots (PIV)	Hooker, stand-off, scrum-half
Middle Unit Forwards (MUF)	Props, loose forwards
Wide Running Forwards (WRF)	Second rows

Two forwards groups (MUF and WRF) were used rather than grouping the forwards as a whole, which has largely been the case in previous research (Twist et al., 2014; Waldron, Twist, et al., 2011). This was because the tactical requirements imposed on these positions by the coaching staff at the club were substantially different and it was likely that the MUF would play significantly less game time than the WRF.

3.6 Determination of Time on Pitch

In Chapters 4, 6 and 8, only "time on pitch" was used for analysis. "Time on pitch" encompassed how much time the player was on the playing pitch for during the game. Time where players were off the field, such as when on the interchange bench were removed from analysis. "Time off" during match-play, such as injury time or video referee was included, hence "time on pitch" may, in some cases exceed the standard 80 minutes of match-play.

Chapter 4

The competitive physical demands for a low ranked newly promoted ESL team with regards to differences in position

There are limited insights into the physical demands of ESL competition for newly promoted low ranked teams. Obtaining such information is of practical and pertinent importance given the ESL has re-introduced promotion and relegation after operating on a franchise system for the past six seasons. Current ESL research is also limited to a small number of players and games. Therefore the aim of the current study was to provide comprehensive positional profiles of the physical match demands for a newly promoted low ranked ESL team, over the entirety of a competitive season. This study has been published in a special edition of the European Journal of Sport Science:

Evans, S. D., Brewer, C., Haigh, J. D., Lake, M., Morton, J. P., & Close, G. L. (2015). The physical demands of Super League rugby: Experiences of a newly promoted franchise. *Eur J Sport Sci*, 1-9. doi: 10.1080/17461391.2015.1041064

4.1 Introduction

There are limited insights into understanding the physical demands of elite ESL competition. Most of the research at the elite level has been conducted within the NRL which is widely perceived to be a better standard of competition (Eaves & Broad, 2007; Gabbett, 2013b; Twist et al., 2014). The only studies examining the movement demands of the ESL competition using GPS are limited to a small number of games and players (Oxendale et al., 2016; Twist et al., 2014; Waldron, Highton, Daniels, et al., 2013; Waldron, Twist, et al., 2011). Research into the NRL competition has shown that analysing demands from an entire competitive season produced significantly different results to previous investigations using data collected over fewer games where there were underestimations in total distance and distance covered at high-speeds (Austin & Kelly, 2013). Analysing a higher number of players and games would allow for a greater understanding of the physical demands of match-play allowing for higher variance in playing styles of opposition and referee interpretation.

Furthermore, all of the ESL studies are also limited to high ranked teams competing at the top of the table (Oxendale et al., 2016; Twist et al., 2014; Waldron, Highton, Daniels, et al., 2013; Waldron, Twist, et al., 2011). Given that in the NRL, lower ranked teams have been shown to experience greater physical match demands than their higher ranked counterparts (Gabbett, 2013b), establishing such information for newly promoted low ranked ESL teams is a pertinent issue given that the ESL has only recently re-introduced promotion and relegation for the 2015 season. It maybe that newly promoted clubs (who may have been run on a part time basis in the league below) may have to withstand greater physical demands than the rest of the competition, although to date this suggestion has not been investigated. Establishing such information could help inform the conditioning practices for those working with newly promoted and lower ranked teams in the future.

In addition to the movement demands, there is also limited information examining the non-running demands of ESL competition. These include the collision demands, and the relative internal physiological cost of the movement and collision demands. Therefore the aim of the current study was to provide comprehensive positional profiles of the movement, collision, and physiological demands for a newly promoted low ranked ESL team, over the entirety of a competitive season. It was hypothesised that there would be significant differences between positions when examining the physical demands of competition.

4.2 Methods

4.2.1 Participants

Thirty-three male elite Rugby League players from the English ESL club under investigation participated in this study. Players were sub-categorised into the four positional groups as described in Chapter 3 for each game based on which position they would feature predominantly during that game. A summary of the anthropometric profiles of the positional groups, based upon the players that featured the most in that group throughout the season can be seen in Table 4.1.

Table 4.1: Mean (SD) anthropometric details for positional groups. These were taken at the start of the ESL season.

	n	**Height (cm)**	**Weight (kg)**	**Age (Years)**	**Sum of seven skinfold sites (mm)** [a]
OB	8	180 (5)	96 (4)	24 (3)	61 (14)
PIV	11	176 (6)	86 (8)	23 (5)	47 (8)
MUF	10	184 (4)	106 (5)	26 (4)	74 (11)
WRF	4	184 (4)	99 (7)	24 (4)	58 (6)

[a] Sum of seven skinfold sites: Abdominal, iliac crest, subscapula, bicep, tricep, thigh, calf. All measurements were taken according to the International Society for the Advancement of Kinanthropometry (ISAK) protocols by an ISAK-accredited practitioner.

4.2.2 Procedures

Players wore an individual GPS device (SPI Pro XII, GPSports, Canberra, Australia) as described in Chapter 3 with a compatible HR monitor attached to the thoracic region. Maximum HR was obtained prior to data collection, defined as the highest value reached during a modified 150 metre maximal anaerobic shuttle test (Brewer, 2008). The procedure for switching on devices and downloading data is described in Chapter 3.

A total of 459 data files from all 27 regular season ESL games (17 players per game) from the 2012 season were originally considered for analysis. If players were not on the pitch for more than two standard deviations away from the average for that positional group for that particular game, they were discarded from the analysis (since this was likely the result of an injury rather than a tactical substitution). This left 399 data files that were included in the analysis. The number of performances for each position were 116 (OB), 79 (PIV), 124 (MUF), and 80 (WRF). Throughout the testing period a mean of 8 satellites (range 7-11) were available for signal transmission.

4.2.3 Variables

Time on pitch was determined as described in Chapter 3. Movement variables included those outlined in Table 4.2 in addition to these variables expressed per minute of time on pitch. Additional movement variables included peak speed ($m.s^{-1}$), number of sprints (>5.5 $m.s^{-1}$), number of sprints per minute of time on pitch, average sprint distance (m), and maximum sprint distance (m). The speed thresholds were determined according to methods used previously investigating the demands of elite Rugby League match-play using GPS technology (Austin & Kelly, 2013; McLellan et al., 2011c).

Table 4.2: Speed thresholds for use in the current study (Austin & Kelly, 2013; McLellan et al., 2011c).

Movement	Speed ($m.s^{-1}$)	Speed ($km.h^{-1}$)
Walking	0 – 1.6	0 – 6.0
Jogging	1.6 – 2.7	6.0 – 12.0
Cruising	2.7 – 3.8	12.0 – 14.0
Striding	3.8 – 5.0	14.0 – 18.0
High intensity running (HIR)	5.0 – 5.5	18.0 – 20.0
Sprinting	>5.5	>20.0

In order for ease of comparison with previous investigations, the total distance covered above 5.0 $m.s^{-1}$ (the sum of HIR and sprint distance) was termed as HSR and expressed per minute of time on pitch. This however was excluded from statistical analysis, and used rather to provide a comparison across studies.

HR zones used are outlined in Table 4.3. These were based on methods used investigating the physiological demands of Rugby Union (Cunniffe, Proctor, Baker, & Davies, 2009). As well as the total time spent in HR zones, percentage of the total time spent in zones were also analysed.

The number of collisions, including ball carries and tackles was calculated as described in Chapter 3. Whilst these were examined for each positional group, the Opta data also allows collisions to be examined for opposition sides. Therefore the data were examined for the team under investigation and their opposition over the course of the season in order for comparison. The variables were expressed as the total number of carries per game, total number of tackles per game, and total number of collisions per game (for the team under investigation and opposition sides).

Table 4.3: Heart rate zones for use in the current study (Cunniffe et al., 2009).

Zone Number	% of HR Max
1	< 60%
2	60 – 70%
3	70 – 80%
4	80 – 90%
5	90 – 95%
6	> 95%

In addition to the number of collisions, the quantification of accelerometer "impacts" measured in G-force from the GPS were also examined. It should be stressed that this model of device has not been validated to detect collisions outright. The impact zones examined are outline in Table 4.4, and set up according to system manufacturer guidelines. As well as the total number of impacts in each zone, these were also expressed per minute of time on pitch. High intensity impacts (above 7G) commonly occur in sport such as aggressive changes in direction, falling to the ground, landing from jumping and collisions, therefore impacts less than 7G were excluded from the analysis as these were likely to represent foot contacts from walking, running, or gentle changes in direction (GPSports, 2012).

Table 4.4: Impact zones for use in the current study.

Zone Number	Intensity of Impact (G-Force)
1	7-9
2	9-11
3	11-13
4	13-15

Additional data provided by Opta was also examined in order to contextualise the physical data and to compare the newly promoted team against their opposition. These variables included the mean time that the ball was "in play", the mean time in possession of the ball, the mean number of line breaks, and mean number of errors. An error in this case is defined as "a player making an error which leads to the opposition gaining possession of the ball, either in open play or in the form of a scrum" (Opta, 2011).

4.2.4 Statistical Analysis

Before using parametric statistical procedures, the assumptions of normality and sphericity were verified using the Shapiro-Wilk and Mauchley test respectively. One-way analyses of variance (ANOVA) were performed to assess differences between positions for all variables. Where a significant difference was observed, post-hoc Tukey Honest Significant Difference (HSD) tests were conducted to identify the location of the differences. Independent T-tests were performed to assess differences between the team under investigation and the opposition for additional Opta data. Statistical significance was set at $P < 0.05$ throughout. All parametric statistical procedures were carried out using the Statistical Package for Social Sciences (SPSS), version 21 (Chicago, IL, USA). To adopt a practical approach, differences between positions were also analysed using Cohen's effect size (ES). ES were calculated as trivial (<0.2), small (0.2-0.6), moderate (0.6-1.2), large (1.2-2.0), and very large (>2.0) (Hopkins, Marshall, Batterham, & Hanin, 2009).

4.3 Results

For the 27 games analysed, 6 of these were won with 21 being lost. The league record for the team over the 2012 season is outlined in Table 4.5.

Table 4.5: A summary of the team's league record over the 2012 season. Data presented as mean (SD) where appropriate.

League Position Finish (Out of 14)	Total Points per Game	Points Scored Per Game	Points Conceded Per Game	Total Tries Per Game	Tries Scored Per Game	Tries Conceded Per Game
14	60 (13)	20 (13)	40 (18)	11 (3)	4 (2)	7 (3)

4.3.1 Movement Demands

Table 4.6 shows the movement demands over the season presented as mean (SD). MUF spent less time on the pitch than all other positions (P = 0.001; ES = 2.9-7.8). As a result, they covered less total distance (P = 0.001; ES = 3.1-6.5), walking distance (P = 0.001; ES = 2.9-8.9), jogging distance (P = 0.001; ES = 2.6-3.9), cruising distance (P = 0.001; ES = 1.7-3.0), striding distance (P = 0.001; ES = 1.7-3.4), HIR distance (P = 0.001; ES = 1.5-2.9), and sprint distance (P = 0.001; ES = 1.7-3.4) than all other positions. By contrast OB covered greater distances in HIR than PIV (P = 0.001; ES = 1.2) and MUF (P = 0.001; ES = 2.9), greater distances sprinting than all other positions (P = 0.001; ES = 1.2-3.2) and performed more sprint efforts than all other positions (P = 0.001; ES = 1.4-3.5). OB recorded greater peak speeds than MUF (P = 0.001; ES = 2.3), and WRF (P = 0.001; ES = 1.7); however there only a small difference between OB and PIV (P = 0.46; ES = 0.4).

Differences between positions were less evident when absolute measures were expressed per minute of time on pitch (Table 4.6). MUF covered greater total distance per minute than OB (P = 0.001; ES = 2.9) and WRF (P = 0.001; ES = 3.2), with WRF also being lower than PIV (P = 0.001; ES = 2.4). MUF covered greater cruising (P = 0.001; ES = 3.3-

4.1) and striding (P = 0.018; ES = 1.6-2.1) distances per minute than OB and WRF. Greater distances per minute for cruising (P = 0.001; ES = 2.7-3.4) were also observed for the PIV compared to OB and WRF, and for striding (P = 0.02; ES = 1.5) when compared to WRF.

4.3.2 Collision Demands

WRF performed more total collisions than OB (P = 0.001; ES = 4.0) and PIV (P = 0.001; ES = 3.3), whilst similar trends were observed for MUF (P = 0.001; ES = 2.7-3.3). There was only a small difference between MUF and WRF for total number of collisions (P = 0.926; ES = 0.2). OB performed less tackles than all other positions (P = 0.001; ES = 2.7-3.8), with WRF (P = 0.001; ES = 1.8) and MUF (P = 0.001; ES = 1.8) performing more tackles than PIV. PIV performed less carries than all other positional groups (P = 0.001; ES = 1.4-1.7). When expressed per minute, MUF performed more carries per minute (P = 0.001; ES = 2.3-5.3), tackles per minute (P = 0.001; ES = 2.1-5.7), and subsequently collisions per minute (P = 0.001; ES = 2.7-5.9) than all other positions (Table 4.7).

Absolute number of impacts from the accelerometer revealed trivial to moderate between positions for 7-9 G (P = 0.136; ES = 0.2-1.2), 9-11 G (P = 0.66; ES = 0.1-1.3), 11-13 G (P = 0.251; ES = 0.0-1.0), or 13-15 G (P = 0.316; ES = 0.2-1.0). Differences in impact intensity between positions were more evident when impacts were expressed per minute. MUF experienced a greater number of impacts per minute for 7-9 G than OB (P = 0.001; ES = 2.5) and WRF (P = 0.029; ES = 1.4), with a moderate difference to PIV (P = 0.378; ES = 0.6). For 9-11 G (P = 0.001; ES = 1.5-3.2) and 11-13 G (P = 0.001; ES = 1.1-2.0), MUF experienced greater impacts per minute than all other positions. There were trivial to moderate differences between positions in the impacts experienced per minute for 13-15 G (P = 0.249; ES = 0.0-0.9) (Table 4.7).

4.3.3 Physiological Demands

MUF spent less absolute time between 70-80% HR max (P = 0.001; ES = 1.8-2.8) and 80-90% HR max (P = 0.001; ES = 1.5-2.5) than all other positional groups, likely attributable to less playing time. When percentage of times on pitch were examined, MUF spent less percentage time between 70-80% HR max than OB (P = 0.002; ES = 2.5) and WRF (P = 0.022; ES = 5.1), and less percentage time between 80-90% HR max than WRF (P = 0.02; ES = 6.2). MUF did however spend more percentage time above 95% HR max than both WRF (P = 0.001; ES = 5.1) and OB (P = 0.02; ES = 2.4) (Table 4.8).

4.3.4 Additional Opta Data

Opta data revealed the mean ball in play time was 48.6 ± 3.5 min. The team under investigation (23.4 ± 3.1 min) spent less time in possession of the ball (P = 0.03; ES = 0.6) than opposition sides (25.2 ± 2.6 min). Opposition sides (10 ± 4) made a greater number of line breaks (P = 0.01; ES = 1.4) than the team under examination (5 ± 3). The mean number of errors per game was 28 ± 4 with a moderate difference (P = 0.07; ES = 0.6) between the number of errors made by the team under investigation (13 ± 3) and opposition sides (15 ± 4). The team performed more carries (188 ± 26) per game than opposition sides (136 ± 15) (P = 0.01, ES = 2.5). Although the team under investigation performed more tackles per game (289 ± 38) than opposition sides (280 ± 42), this difference was found to be small (P = 0.4, ES = 0.2). Overall, the team experienced a greater number of collisions per game (477 ± 40) than opposition sides (417 ± 40) (P = 0.01, ES = 1.5).

4.3.5 Comparison of Selected Variables across Studies

Table 4.9 shows the total distance, distance covered per minute, HSR distance per minute, and total number of collisions across positional groups in the current investigation compared with previous research. Whilst the total distance covered is similar across studies, the distance covered per minute was lower in the current investigation compared with all of those previously published. HSR distance per minute in the current study was higher than previously reported in NRL competition. Total numbers of collisions in the current investigation are lower than those reported in the NRL.

Table 4.6: Movement demand data for positional groups presented as mean (SD).

	Outside Backs	Pivots	Middle Unit Forwards	Wide Running Forwards
Absolute measures				
Time on pitch (Min)	86.7 (3.4) †	72.8 (10.6)	47.8 (6.6) * † ‡	77.0 (9.0)
Total distance (m)	7246 (333) ‡	6549 (853)	4318 (570) * † ‡	6408 (629)
Walking (m)	2737 (107) †	2229 (377)	1400 (195) * † ‡	2418 (307)
Jogging (m)	1689 (119)	1667 (252)	1094 (187) * † ‡	1620 (221)
Cruising (m)	1452 (94)	1520 (140) ‡	1061 (169) * † ‡	1304 (120)
Striding (m)	749 (71) ‡	676 (79)	481 (86) * † ‡	609 (64)
HIR (m)	197 (43) †	147 (41)	98 (26) * † ‡	161 (26)
Sprinting (m)	421 (89) ‡†	306 (108)	185 (58) * † ‡	296 (82)
Peak speed ($m \cdot s^{-1}$)	8.3 (0.5)	8.1 (0.4)	7.4 (0.3) * †	7.7 (0.2) *
No. of sprints	25 (4) ‡†	18 (6)	11 (4) * † ‡	19 (4)
Average sprint distance (m)	20 (2)	19 (2)	18 (2)	18 (2)
Maximum sprint distance (m)	60 (11)	38 (16) *	38 (4) *	40 (7)
Per minute measures				
Overall ($m.min^{-1}$)	83.6 (2.8) †	90.2 (3.3) ‡	90.8 (2.2) * ‡	83.4 (2.4)
Walking ($m.min^{-1}$)	31.6 (1.0)	30.3 (1.5)	29.2 (1.0) * ‡	31.5 (1.4)
Jogging ($m.min^{-1}$)	19.5 (1.3) †	23.0 (1.7)	23.2 (2.4) *	20.9 (1.5)
Cruising ($m.min^{-1}$)	16.8 (1.1) †	21.4 (1.6) ‡	22.4 (1.6) * ‡	17.1 (1.6)
Striding ($m.min^{-1}$)	8.6 (0.7)	9.4 (1.1) ‡	10.1 (1.2) * ‡	8.0 (0.8)
HIR ($m.min^{-1}$)	2.3 (0.5)	2.0 (0.5)	2.1 (0.4)	2.1 (0.4)
Sprinting ($m.min^{-1}$)	4.9 (1.0)	4.2 (1.2)	3.9 (1.1)	3.9 (1.1)
Sprints per minute	0.28 (0.04)	0.25 (0.07)	0.24 (0.06)	0.25 (0.06)

* Significantly different from outside backs ($P < 0.05$).
† Significantly different from pivots ($P < 0.05$).
‡ Significantly different from wide running forwards ($P < 0.05$).

Table 4.7: Collision demand data for positional groups presented as mean (SD).

	Outside Backs	Pivots	Middle Unit Forwards	Wide Running Forwards
Absolute measures				
Impacts 7-9 G	135 (41)	200 (67)	166 (70)	177 (48)
Impacts 9-11 G	17 (3)	18 (4)	23 (8)	24 (8)
Impacts 11-13 G	6 (2)	5 (2)	7 (2)	6 (3)
Impacts 13-15 G	0.7 (0.4)	0.3 (0.4)	0.5 (0.2)	0.6 (0.5)
Carries	10 (2)	5 (2) * × ‡	10 (2)	11 (2)
Tackles	10 (3)	18 (3) * × ‡	25 (5) *	25 (5) *
Total no. of collisions	20 (3) × ‡	23 (3) × ‡	35 (6)	36 (5)
Per minute measures				
Impacts 7-9 G	1.55 (0.47) †	2.75 (0.79)	3.29 (0.95) * ‡	2.31 (0.49)
Impacts 9-11 G	0.20 (0.03)	0.26 (0.07)	0.47 (0.14) * † ‡	0.31 (0.07)
Impacts 11-13 G	0.06 (0.02)	0.06 (0.03)	0.15 (0.07) * † ‡	0.09 (0.04)
Impacts 13-15 G	0.01 (0.00)	0.00 (0.01)	0.01 (0.01)	0.01 (0.01)
Carries	0.11 (0.02)	0.06 (0.02) * × ‡	0.22 (0.04) *	0.14 (0.03) * ×
Tackles	0.11 (0.03)	0.25 (0.04)	0.51 (0.11) * † ‡	0.33 (0.06) * †
Total no. of collisions	0.23 (0.04)	0.31 (0.04) * × ‡	0.73 (0.13) *	0.46 (0.07) * ×

* Significantly different from outside backs ($P < 0.05$).
† Significantly different from pivots ($P < 0.05$).
‡ Significantly different from wide running forwards ($P < 0.05$).
× Significantly different from middle unit forwards ($P < 0.05$).

Table 4.8: Physiological demand data for positional groups presented as mean (SD).

	Outside Backs	Pivots	Middle Unit Forwards	Wide Running Forwards
Absolute times (minutes)				
< 60% HR Max	1.8 (1.7)	1.5 (3.0)	0.6 (1.1)	0.0 (0.0)
60-70% HR Max	2.8 (1.6) †	1.1 (1.1)	1.2 (0.2) *	1.4 (1.3)
70-80% HR Max	18.5 (7.4) †	11.1 (4.7)	4.7 (2.5) * † ‡	13.7 (5.8)
80-90% HR Max	36.5 (6.1)	29.9 (8.3)	16.4 (9.9) * † ‡	40.2 (12.7)
90-95% HR Max	20.3 (7.6)	20.4 (9.5)	15.1 (4.2)	17.7 (10.5)
> 95% HR Max	6.6 (3.5)	7.5 (4.8)	8.3 (5.1) ‡	2.4 (2.4)
Percentage of time on pitch				
< 60% HR Max	0.9 (1.8)	2.3 (4.6)	1.3 (0.0)	0.0 (0.0)
60-70% HR Max	3.2 (1.8)	1.6 (1.6)	0.6 (0.0) *	1.8 (0.0)
70-80% HR Max	21.6 (9.0)	15.5 (7.1)	10.3 (2.0) * ‡	18.2 (1.1)
80-90% HR Max	42.8 (7.0)	40.8 (9.0)	33.7 (0.2) ‡	52.6 (0.2)
90-95% HR Max	23.8 (8.5)	27.2 (11.1)	32.5 (0.1)	22.6 (0.1)
> 95% HR Max	7.6 (4.1)	10.6 (7.9)	17.7 (0.1) * ‡	3.1 (0.1)

* Significantly different from outside backs ($P < 0.05$).
† Significantly different from pivots ($P < 0.05$).
‡ Significantly different from wide running forwards ($P < 0.05$).

Table 4.9: Mean total distance, metres per minute, HSR distance per minute and total number of collisions across positional groups in the current investigation and previous ESL and NRL investigations.

Investigation	Competition	Variable	Outside Backs	Pivots	Middle Unit Forwards	Wide Running Forwards	Hit Up Forwards	Forwards	Backs
Current investigation	ESL	Total distance	7246	6549	4318	6408			
Twist et al. (2014)	ESL	Total distance	7133	6766			5733		
Twist et al. (2014)	NRL	Total distance	7381	7973			4948		
Gabbett et al. (2012)	NRL	Total distance	6819	6411		5561	3569		
Waldron, Twist, et al. (2011)	ESL	Total distance	6917	6093			4181		
Current investigation	ESL	Distance per minute	83.6	90.2	90.8	83.4			
Twist et al. (2014)	ESL	Distance per minute	85.6	104.4			101.7		
Twist et al. (2014)	NRL	Distance per minute	86.5	96.2			88.0		
Gabbett et al. (2012)	NRL	Distance per minute	93	101		96	94		
Waldron, Twist, et al. (2011)	ESL	Distance per minute	89	94			95		
Current investigation	ESL	Distance > 5.0 m·s^{-1} per minute	7.1	6.2	5.9	5.9			
Twist et al. (2014)	ESL	Distance > 5.0 m·s^{-1} per minute	6.6	5.9			5.6		
Twist et al. (2014)	NRL	Distance > 5.0 m·s^{-1} per minute	7.8	8.2			5.5		
Gabbett et al. (2012)	NRL	Distance > 5.0 m·s^{-1} per minute	7.9	6.8		7.1	6.2		
Waldron, Twist, et al. (2011)	ESL	Distance > 5.8 m.s^{-1} per minute	4	4			2		
Current investigation	ESL	Number of collisions	20	23	35	36	36		
Gabbett et al. (2011)	NRL	Number of collisions	24	29		47	42		
Gabbett et al. (2012)	NRL	Number of collisions	28	34		45			
(Twist et al., 2012)	ESL	Number of collisions						38	25
(Oxendale et al., 2016)	ESL	Number of collisions						54	31

4.4 Discussion

The primary aim of the study was for the first time, to report a full seasons' worth of data regarding the external and internal physical match demands of ESL rugby within different positional groups for a newly promoted team. The data highlights that for all positions, the majority of match-play is spent in low intensity movement activities, but at a considerable internal physiological demand at, or above 80% of HR max. OB spend more time on the pitch, cover greater total distance, and cover more distance sprinting than other positions. MUF conversely spend the least time on the pitch but were required to operate at higher relative intensities in terms of the total distance covered per minute, and with WRF were involved in more collisions than other positions. The total distances outlined in the current study are similar to previous investigations into ESL and NRL match-play. However the newly promoted team operated at substantially lower overall movement intensities in terms of the distance covered per minute, but covered more HSR distance per minute than previously reported for higher ranked ESL sides. The number of collision involvements was also greater for the team under investigation when compared to their opposition ESL sides over the course of the season. These data therefore suggest that the newly promoted ESL teams may be subject to increased HSR and collision demands, potentially as a result of being unable to control the speed of play as well as established ESL teams. This is something that the coaching staff of newly promoted teams should be aware of and attempt to address in training.

The distance covered per minute was lower for all positions in the current study when compared to previous investigations into elite match-play. Given the mean number of tries scored per game was 11, the mean errors per game was 28, and the ball was only "in play" for ~48 minutes per game (which is considerably lower than previously reported in ESL at around 55 min (Sykes et al., 2009) and NRL at around 55 min (Gabbett, 2012a)), it is likely that the lower distance per minute is a direct result of the numerous stoppages in play. Contrastingly, the HSR distance covered per minute is higher in this study than previously reported in the ESL. It should be noted that in the Waldron, Twist, et al. (2011) study, 5.8 $m.s^{-1}$ was used as the most comparable speed threshold. When comparing these values to sprint distances per minute in the current study (> 5.5 $m.s^{-1}$), the values in the current investigation are still considerably higher. Due to the considerable number of game stoppages reported in the present study, it could be argued that players were given more time to recover between passages of play, which could increase their ability to perform high speed efforts in a more stop-start game. It could also be argued that due to on average 40 points per game being scored against the team under investigation, their defensive line was broken frequently, and hence a lot of the HSR was achieved in chasing back trying to stop opposition attackers who have broken the line. This suggestion is supported by the fact that the opposition made more line breaks than the team under investigation. Although this study provides preliminary evidence that the HSR demands are greater for lower ranked ESL teams, the HSR demands are still lower than for those reported in the NRL. Thus, in agreement with previous research (Twist et al., 2014), there is more evidence to suggest that across the course of match-play, NRL matches are of greater high speed intensities than ESL. It has been previously been shown that the difference between the amounts of HSR between ESL and NRL players is due to a lower reduction for NRL players between the first and second half (9% vs. 27%) (Twist et al., 2014). Differences in physical capacity are known to influence HSR performance during Rugby League match-play (Gabbett, Stein, Kemp, & Lorenzen, 2013) which might explain some of the observed differences between ESL and NRL. It may also be possible that pacing strategies adopted by players may account for some of the differences. It has been shown that ESL players typically adopt higher intensities in their first exercise bout, followed by a lower, maintainable intensity in the second (Waldron, Highton, Daniels, et al., 2013). Players in the NRL might therefore be encouraged to adopt an even pacing strategy that enables only small reductions in HSR during the second half of a game. Tactical strategies utilised by NRL coaches might also enable the maintenance of HSR during matches.

The collision demands for the team in the current study were greater than for opposition ESL sides. Again, the number of collisions is lower in the current investigation than those reported in the NRL. However, in the current study missed tackles and collisions off the ball were not reported as the Opta data available are not able to distinguish between which missed tackles resulted in a collision and which did not. These were included in previous investigations in determining the total number of collisions in the NRL (Gabbett et al., 2011, 2012) which could account for some of the observed differences. The number of collisions reported in the current study are comparable to those previously reported in the ESL for forwards and backs groups (Twist et al., 2012), however are considerably lower when compared to those more recently reported (Oxendale et al., 2016). Given that the data reported by Oxendale and colleagues are from four seasons after the data reported by Twist and colleagues (collected from the same team), and two seasons after the data reported in this study, this may reflect that the demands of the game are increasing. However, it is also possible that the very small number of games analysed in these ESL studies (Oxendale et al., 2016; Twist et al., 2012) may account for some of the differences and large variations observed.

For the newly promoted team, there were also significant positional differences. Greater overall movement intensities in terms of the distance covered per minute were observed for MUF despite lower absolute differences covered due to less playing time. Significantly greater distances per minute for MUF and PIV coincide with greater cruising and striding distances covered per minute. Sprint performance may be influenced by pitch position, whereby OB are offered larger areas of space with which to develop forward locomotion. In contrast, PIV and the forward groups are most often closer to the opposition gain line and so the capacity to generate high speed is less (Gabbett et al., 2014). It is also possible that the forwards are typically slower than backs (Meir et al., 2001), thus preventing the attainment of an arbitrary sprint category (>5.5 $m.s^{-1}$) with the same ease, and could explain why OB recorded significantly greater peak speeds in this study than the forwards groups.

The lower number of absolute and per minute carries for the PIV is expected, given that hookers usually pick up and pass the ball on to a teammate from the play the ball. The halfbacks are used mainly to pass and kick the ball rather than perform carries into the opposition defensive line. The absolute and per minute number of tackles for the PIV is mainly attributable to the hooker who defends in the centre of the field with the MUF in anticipation of being required as a playmaker if the ball is turned over (Gabbett, 2005b).

The greater number of collisions per minute (and subsequent periods of wrestle) combined with a greater overall distance covered per minute contributed to MUF experiencing a greater internal physiological stress in terms of the percentage time spent above 95% of HR max than other positions and supports why this group is interchanged frequently during games (mean time on pitch 42.8 ± 6.6 min). Given that WRF were involved in a similar number of total collisions it seems somewhat surprising they spend the least percentage time > 95% max HR. This may reflect that their total distance per minute was the lowest (83 $m.min^{-1}$).

Impact data from the GPS devices revealed no differences in the number of impacts in each of the four zones between positions. This raises doubts regarding the use of the current model of device to quantify collision load in Rugby League. With the rapid new advancements in GPS technology, new models of device claim to be able to quantify collisions during rugby match-play. Therefore future studies should aim to examine if this technology can provide accurate information on the collision demands.

The study highlights significant practical applications for the sport science support team working within Rugby League clubs, especially for those working in the future with newly promoted ESL sides. For newly promoted squads as a whole, it is important to expose players to typical HSR and collision volumes and intensities that they may expect to encounter in games to ensure that players are robust enough to handle the demands of competition. The pre-season period therefore is of utmost importance to expose players to such demands in training. Furthermore the nature of conditioning work should differ between positions. MUF and WRF should be subject to repeated high intensity accelerations leading into, and arising from collisions. The need to be able to withstand approximately 35 collisions per game has significant implications for strength training requirements on the kinetic chain. The larger mass amongst these groups of players might also be explained by the role the play. PIV need to be able to achieve similar maximal sprint speeds to the OB, but typically over less distance and with less frequency, which is indicative of a greater need of a multi-directional speed component within their programme. This conforms to the interaction of hookers play around the breakdown and the role of halfbacks in creating line breaks of others around them. Conditioning programmes for OB should focus on the development of repeated prolonged sprint ability over distances typically between 20-60 m, with a lesser emphasis on collision.

In conclusion, the current study has for the first time provided a comprehensive overview of the positional external and internal physical match demands for a newly established ESL franchise and has provided preliminary evidence that the HSR and collision demands are greater for lower ranked ESL teams than higher ranked teams. However, the HSR and collision demands are still lower than those experienced in the NRL. The positional differences observed provide a reference for Rugby League practitioners to follow when designing conditioning and training regimes. The comparison of data from training drills to the data outlined in this study can inform coaches of newly promoted sides if they are adequately preparing their players for the physical demands of elite level competition.

Despite contributing valuable new data to the literature, the present study is not without its limitations, most of which are due to collecting data in the real world alongside the movement data from the GPS being limited to one ESL team. Subsequent follow-up longitudinal studies with the same team are required in future seasons to further our understanding of the development of match-play and to establish if there is an evolution in match-play demands with increased exposure to training and ESL competition given the team were granted a minimum three year licence to continue competing in the league regardless of position finish.

Chapter 5

Differences between two GPS devices for use in team sports in measuring selected movement demand parameters

There have recently been rapid advancements in the development of GPS devices used to track player movements in team sports. In order to collect longitudinal data over multiple seasons, teams are likely to change the GPS equipment being used in order to keep up with the latest advancements. As such, in this thesis two different models of GPS device are used as the thesis progresses. The only direct comparison between the devices was required for two selected movement parameters in Chapter 6 which have been identified in the literature as showing a relationship with team performance. Therefore the aim of this agreement study was to examine if there were any differences between the two models of unit to measure the total distance and the distance covered at high-speed (> 5.0 $m.s^{-1}$) in relation to specific analytical goals.

5.1 Introduction

The importance of collecting and analysing the movement demand data of team sport athletes during training sessions and matches has been established (Coutts, Quinn, Hocking, Castagna, & Rampinini, 2010; Di Salvo et al., 2007; Sirotic et al., 2009). In addition, movement demand parameters such as the total distance and the distance covered whilst performing HSR have shown a relationship to the match performance of teams (Johnston et al., 2012a; Rampinini, Impellizzeri, Castagna, Coutts, & Wisloff, 2009). As a result, the instruments that are used to measure such data need to be valid and reliable. GPS units are currently being used by professional sporting teams to collect movement data from their players because of the ease of data collection and the quality of analysis provided (Aughey, 2011; Gabbett et al., 2012; Johnston et al., 2012a), and so the validity and reliability of these units is of primary importance. There have recently been rapid technological advancements in the GPS devices used to track players movements, and in order for longitudinal data to be collected across multiple seasons teams are likely to switch to newer devices in order to keep up with the latest developments. Therefore, the level of agreement between devices when teams do switch devices is vital to establish.

Previous research has concluded that 10 Hz and 5 Hz with 15 Hz interpolation GPS devices have an acceptable level of validity and reliability for assessing total distance and movement demands up to speeds of 5.5 $m.s^{-1}$ (Johnston, Watsford, et al., 2014; Portas et al., 2010; Randers et al., 2010; Varley et al., 2012; Waldron, Worsfold, et al., 2011). It has also been shown specifically that there are no differences between the 5 Hz with 15 Hz interpolation device used in this thesis (GPSports SPI Pro XII) and a 10 Hz device (Catapult MinimaxX) when comparing total distance and distance covered whilst performing HSR (between 3.8 and 5.5 $m.s^{-1}$) (Johnston, Watsford, et al., 2014). Whilst this suggests the two devices used in this thesis could potentially be used interchangeably to assess such movement demands, it was vital to perform similar tests specifically for the devices that will be used throughout this thesis in the settings that they will primarily be used.

The statistical philosophy for assessing agreement between two measurements can be considered to be different from that surrounding the testing of research hypotheses (Altman, 1990; Morrow & Jackson, 1993). The two components of measurement error are systematic bias (general trend for measurements to be different in a particular direction, either positive or negative) and random error due to biological or mechanical variation. These errors should be meaningfully quantified for the sport scientist to relate the described error to judgements regarding analytical goals, i.e. the requirements of the measurement tool for effective practical use (Atkinson & Nevill, 1998). The data from Chapter 4 has revealed there were differences between positions for the total distance and HSR distance covered. These parameters have also shown to differ between games that are won and lost at the elite level (Gabbett, 2013b). Thus, this information can be used to develop specific analytical goals which can then be used as an appropriate level for determining measurement error.

Therefore the aim of this pilot study was to examine if there were any differences between the two models of unit to measure the total distance and the distance covered at high-speed (> 5.0 $m.s^{-1}$) during Rugby League specific training in relation to specific analytical goals.

5.2 Methods

5.2.1 Participants

Two players from a North West based ESL club (age 21 ± 2 years; height 180 ± 4 cm; body mass 87 ± 8 kg) took part in the study. Both participants were members of the first team squad, and were fit and injury free during the testing period.

5.2.2. Procedures

The participants wore both models of unit simultaneously as described in Chapter 3 and in Figure 3.1. The process of switching on units and downloading data was as described in Chapter 3. The participants wore the units during ten team training sessions during the in-season period of the 2013 ESL season. The coaching staff at the club provided input into the design and content of the sessions. The sessions were typically between 50 and 100 minutes in length and consisted of a warm up lead by the clubs' strength and conditioning coach, Rugby League specific skills (catching and passing, tackling technique, support play, defensive line speed and shape, and ball control), and conditioning games.

5.2.3 Variables

The total distance and distance covered at high speed (> 5.0 $m.s^{-1}$) were compared between the two different models of device. These were also expressed per minute of training time. Whilst Chapter 4 provided a comprehensive overview of a multitude of distance and velocity parameters during match-play, the current study only aims to examine the two aforementioned due to their importance in determining match outcome (Black & Gabbett, 2014; Gabbett, 2013b, 2014a; Hulin & Gabbett, 2015; Hulin et al., 2014), and will be examined in future chapters of this thesis.

5.2.5 Statistical Analysis

Relative Reliability:

The strength of the relationship between the two different devices was analysed according to the methods of Hopkins (2015) to produce a Pearson correlation score using a spreadsheet. A correlation system of trivial (0.0), small (0.1), moderate (0.3), large (0.5), very large (0.7), nearly perfect (0.9), and perfect (1.0) scores were used (Hopkins, 2000). Differences between units were further assessed using a paired t-test. The paired t-test was carried out using SPSS version 21.

Absolute Reliability:

The typical error between units was calculated and expressed as a CV%. The CV% was calculated by dividing the SD of the data by the mean and multiplying by 100 (Atkinson & Nevill, 1998). Values were then interpreted in relation to specific analytical goals, developed using the positional data from Chapter 4, and in relation to winning and losing games in the NRL (Gabbett, 2013b). Positional data from Chapter 4 for the parameters to be investigated in this study expressed "per minute" are outlined in Table 5.1.

Table 5.1: Total distance per minute and HSR distance per minute for positional groups in Chapter 4.

Positional Group	Total distance per minute ($m.min^{-1}$)	HSR per minute ($m.min^{-1}$)
OB	84	7.1
PIV	90	6.2
MUF	91	5.9
WRF	83	5.9
Average (SD)	87 (4)	6.3 (0.6)
CV%	4.7	9.1

Data for the total distance covered per minute, and HSR per minute in games that were won and lost in the NRL (Gabbett, 2013b) are shown in Table 5.2.

Table 5.2: Total distance per minute and HSR distance per minute for games that are won and lost in the NRL. Data reproduced from (Gabbett, 2013b).

Match Outcome	Total distance per minute ($m.min^{-1}$)	HSR per minute ($m.min^{-1}$)
Win	107.9	5.0
Loss	100.5	5.7
Average (SD)	104.2 (5.2)	5.4 (0.5)
Difference	7.4	0.7
CV%	5.0	9.3

The level of variability between positions as expressed by the CV% was shown to be 4.7% for total distance per minute, and 9.1% for HSR distance per minute. The absolute difference (bias) between winning and losing was shown to be 7.4 $m.min^{-1}$ for total distance per minute and 0.7 $m.min^{-1}$ for HSR distance per minute. Collectively, these data provide references towards analytical goals for an appropriate level of measurement error in the current study.

The data between devices was further examined using Bland-Altman method (Bland & Altman, 1986). Bias (mean error) and limits of agreement (LoA) are presented for each movement parameter. LoA was calculated as the standard deviation of the mean differences between the devices, multiplied by 1.96. Graphical interpretation was conducted according to recommended methods (Bland & Altman, 1986).

5.3 Results

Data from the ten training sessions are outlined in Table 5.3 and are presented as an average for both participants. Over the course of testing a mean of 9 satellites were available for signal transmission (range 8-11) as picked up by the GPSports device.

Relative Reliability:

For both variables nearly perfect correlations were observed (total distance $r = 0.99$; HSR $r = 0.99$). There were no significant differences between the two models of device for total distance ($P = 0.96$), or HSR distance ($P = 0.93$).

Absolute Reliability:

The CV% revealed low typical errors between units, with 0.8 % for total distance and total distance per minute, and 2.2 % for HSR distance and HSR distance per minute. The Bland Altman LoA for total distance and HSR distance are presented in Figure 5.1. For total distance the mean bias (95% LoA) was -18.9 m (-111.6 to 73.8 m). For HSR the mean bias (95% LoA) was 1.3 m (-18.5 m to 21.0 m). When expressed per minute, the mean bias (95% LoA) was -0.29 m.min^{-1} (-1.6 m to 1.01 m.min^{-1}) for total distance, and 0.01 m.min^{-1} (-0.27 to 0.29 m.min^{-1}) for HSR distance.

Table 5.3: Total distance and HSR distance measured by the two models of device for two participants over ten Rugby League training sessions. Data presented as mean (SD).

Movement demands	**Statsports**	**GPSports**	***p***	**Pearson's *r***	**CV (%)**
Total distance (m)	3789.6 (1291.3)	3770.7 (1308.3)	0.96	0.99	0.8
HSR distance (m)	280.6 (211.0)	281.9 (209.4)	0.93	0.99	2.2
Total distance per minute (m.min^{-1})	50.1 (11.7)	49.9 (11.9)	0.95	0.99	0.8
HSR distance per minute (m.min^{-1})	4.0 (3.1)	4.0 (3.2)	0.93	0.99	2.2

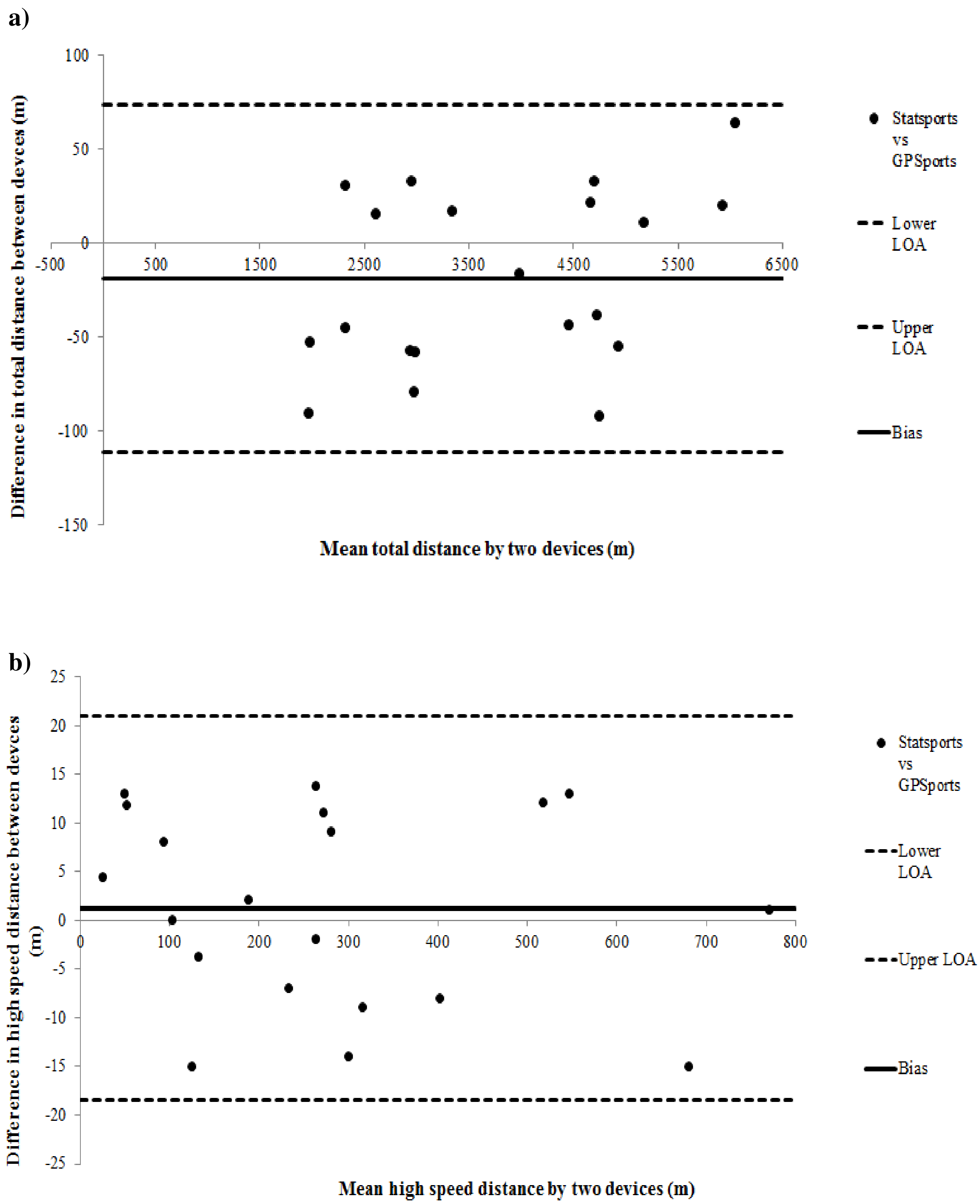

Figure 5.1: Bland-Altman plots determining the difference between the two models of GPS device for measuring a) total distance; b) high speed distance.

5.4 Discussion

The aim of this agreement study was to establish if differences existed between two current commercially available GPS athlete tracking devices in measuring the selected movement demand parameters of total distance and HSR distance. The data demonstrated there were no significant differences, low typical errors and strong correlations between the devices for the variables under investigation. Furthermore, the measurement error between devices was shown to be lower than the variation shown between positions from the data obtained in Chapter 4, and the bias (and range between the LoA) between devices was shown to be lower than the differences reported between winning and losing games. Collectively this data shows that the two models of device can be used interchangeably to assess the selected movement demand variables outlined in the current study.

The Pearson's correlation coefficient has been the most common technique for assessing reliability (Atkinson & Nevill, 1998). The idea behind this approach is that if a high (>0.8) correlation is obtained, the equipment is deemed to be sufficiently reliable (Coolican, 2009), which is the case for both of the parameters investigated in this current study. However, Bland and Altman (1986) considered the use of the correlation coefficient as being inappropriate, since it cannot, on its own, assess systematic bias and it depends greatly on the range of values in the sample (Bates, Zhang, Dufek, & Chen, 1996).

As such, a paired t-test was used in this study to assess whether there is any statistically significant bias between the tests. Although it was reported that there were no significant differences between devices for either of the parameters, Bland and Altman (1986) have stressed caution needs to be taken in the interpretation of a paired t-test to assess reliability, since the detection of a significant difference is actually dependent on the amount of random variation between tests. Specifically, if there are large amounts of random error between the tests, significant systematic bias will less likely to be detected (Atkinson & Nevill, 1998). To overcome this, Bland-Altman plots were used to provide a visual representation of systematic bias and random error. Inspection of the plots revealed no trend for systematic bias in favour of either device for both parameters, with the error between devices remaining consistent as the measured values increased. When expressed per minute, the bias values between devices were considerably lower than the differences reported between winning and losing games. Furthermore the range between the LoA for both parameters expressed per minute are also lower than the differences between winning and losing games. The CV% reported in the current study for both parameters are also lower than the analytical goals determined from positional data in Chapter 4. Thus, it can be concluded that the measurement error between the devices is acceptable for measuring the total distance and HSR distance, which will be examined in the following Chapter.

Previously it has been shown that an alternative 10 Hz (Catapult MinimaxX) and the 5 Hz with 15 Hz interpolation devices are valid and reliable for measuring total distance and distances covered at velocities of up to 5.5 $m.s^{-1}$ (Johnston, Watsford, et al., 2014). Furthermore the authors showed that for the parameters of total distance and HSR distance (3.3-5.5 $m.s^{-1}$) there were no significant differences between 10 Hz and 5 Hz with 15 Hz interpolation devices (Johnston, Watsford, et al., 2014), thus in agreement with the current study. This questions the benefits of increasing sampling rate of 10 Hz units to 15 Hz interpolated units.

Due to an agreement between one of the Rugby League clubs under investigation in this thesis and the GPS manufacturer, two different models of unit were used to assess player movement demands during the writing period. Whilst this is clearly a limitation of any study planning to utilise both models of unit, the data in this chapter concludes that the two devices can be used interchangeably to asses measures of total distance and HSR distance.

Therefore, this provides rationale for the use of both models device for the analysis of longitudinal data of the newly promoted ESL team in Chapter 6. Examining trends longitudinally would aid in the understanding the development of match-play, as there are no published data that has examined the evolution of physical game performance indicators over any longer period than a single season.

Chapter 6

The evolution in in competitive physical demands for a newly promoted ESL team over a three season period

The data from Chapter 4 profiled the physical demands of ESL competition for a newly promoted side that finished bottom of the table over an entire season. Much of the previous research examining the physical demands of Rugby League match-play has adopted a reductionist approach whereby physical key performance indicators are examined with limited data over a small number of games. Examining trends longitudinally would aid in the understanding the development of match-play. Currently there are no published data that has examined the evolution of physical game performance indicators over any longer period than a single season. Therefore, the aim of the current study was to examine parameters relating to the physical intensity of match-play for a newly promoted ESL franchise longitudinally over a three season period.. This study has been published by Science and Medicine in Football, available online at

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6.1 Introduction

There is conflicting evidence relating to differences in the physical intensity of match-play between successful and less successful Rugby League teams. In a study of one elite NRL team, it was shown that competitive success was associated with the ability to maintain a higher running intensity in terms of the total distance covered per minute (Gabbett, 2013b). Such findings have been confirmed by others who investigated match intensities between successful and less successful southern hemisphere semi-elite Rugby League teams (Black & Gabbett, 2014). Another study of semi-elite teams in the same competition has shown that top four ranked sides perform more sprinting than bottom four ranked sides (Gabbett, 2014a). However, more recent evidence comparing separate elite NRL teams with high and low success rates demonstrated that greater running workloads were not indicative of success, and that teams with higher success rates were involved in a greater number of collisions (Hulin et al., 2014). No such data has been examined in the ESL competition.

The data from Chapter 4 has shown that for a newly promoted ESL side finishing bottom of the table, the distance covered per minute was lower than reported previously for higher ranked teams, however, the HSR distance (> 5.0 $m.s^{-1}$) per minute were substantially higher. The number of collision involvements (as established from Opta data) was also significantly greater for the newly promoted team compared with their opposition over the course of the season. Such findings have significant pertinent and practical implications for the conditioning staff of newly promoted teams given that the ESL competition has just re-introduced promotion and relegation for the 2015 season after operating on a licensing franchise system for the past six seasons. Coaching staff only have a short time to prepare players (some of whom may be part-time professionals in the league below) for the increased demands of ESL competition. What is not known currently is if there is an evolution in competitive physical demands with increased full-time training and ESL competition exposure for newly promoted teams under the ESL franchise system and if it is possible to get up to speed with the rest of competition in a three year licence period.

Much of the research examining the physical demands of Rugby League match-play has adopted a reductionist approach whereby physical demands are examined with limited data over a small number of games. Examining trends longitudinally would aid in understanding the development of Rugby League match-play. There is evidence in soccer which shows the physical demands of the game have increased substantially over a seven season period (Barnes et al., 2014; Bush et al., 2015). Indeed there is no study which has examined the evolution of Rugby League game performance indicators over any longer period than a single season. Therefore the aim of the current study was to examine parameters relating to the physical intensity of match-play for a newly promoted ESL franchise longitudinally over a three season period (2012 – 2014). It was hypothesised that there would be an increase in the physical intensity of match-play (total distance per minute, high-speed distance per minute, and number of collisions per minute) over this time period with increased exposure to full time training and experience of ESL competition.

6.2 Methods

6.2.1 Participants

Forty-two male elite Rugby League players (mean ± SD age 26 ± 4 years; height 183 ± 6 cm; body mass 96 ± 7 kg) from the same English ESL club were originally considered to participate in the study. Players (n=22) who did not participate in the 3 complete seasons were excluded from statistical analysis, and therefore a total of 20 players (mean ± SD age

25 ± 3 years; height 184 ± 7 cm; body mass 96 ± 6 kg) were examined. The percentage turnover of the squad, total number of match appearances for the players' analysed, and total number of these appearances expressed as a percentage of the total possible match appearances are shown in Table 6.1. In addition to examining means for the squad, players were also sub-categorised into the positional groups for physical data as outlined in Chapter 3 (OB, n=6; PIV, n=5; MUF, n=5; WRF, n=4). Specific differences between positions were not specifically investigated in this study as these have been previously reported in Chapter 4; the aim rather was to examine how the demands changed over the three season period.

Table 6.1: Percentage turnover and match appearances for the players examined over the three seasons.

Season	Percentage turnover of squad from previous season	Total match appearances for the players examined (Out of a possible 459)	Match appearances for players examined as a percentage of the total possible appearances
2012		360	78%
2013	24%	345	75%
2014	27%	330	72%

6.2.2 Procedures

Player's movement activities were examined using GPS. During every game in the 2012 season, and for the first 16 games in the 2013 season, players wore an individual GPS device (SPI Pro XII, GPSports, Canberra, Australia) as in Chapter 3. For the final 11 games in the 2013 season and during every game in the 2014 season, players wore a GPS unit (Viper, Statsports, Co. Down, Ireland) as described in Chapter 3. The different GPS device was introduced at this point in time due to a manufacturer deal with the club under investigation. The GPS units were worn by players in a custom designed vest. A standard tightly fitting squad shirt was worn over the top of the vest. Although the change in device is acknowledged as being a limitation, the data from Chapter 5 has provided evidence that both models of GPS device can be used interchangeably to assess the total distance and HSR distance (> 5.0 $m.s^{-1}$). Furthermore, such challenges exist when collecting longitudinal data in the real world where new technology is continually being developed for use by elite teams. The procedure for switching on devices and downloading data was as in those outlined in Chapter 3. All official ESL games were examined (27 rounds of games per season) over three consecutive seasons (first season: 2012; second season: 2013; third season: 2014).

6.2.3 Variables

The process of determining time on pitch was as described in Chapter 3. Movement variables consisted of the total distance covered per minute of time on pitch, and the total distance covered at high speed (> 5.0 $m.s^{-1}$) per minute of time on pitch. Expressing these values "per minute" allows any differences as a result of longer or shorter game durations to be removed (Burgess, Naughton, & Norton, 2006). Furthermore the approach of expressing movement variables per minute for a single team over three consecutive seasons has been used previously when profiling an Italian Serie A soccer team (Vigne et al., 2013) in a study similar in nature to the current investigation. Information on collisions was provided by Opta as described in Chapter 3.

Additional Opta data were included to contextualise the physical demands in terms of on-field performances over the three season period. These data included the mean time that the "ball was in play", the mean time in possession of the ball for the team under investigation and opposition sides, the mean number of line breaks per game (irrespective of team, for the team under investigation, and opposition sides), the mean number of penalties conceded per game (irrespective of team, for the team under investigation, and opposition sides), and the mean tackle success percentage per game (for the team under investigation).

6.2.4 Statistical Analysis

Before using parametric statistical procedures, the assumptions of normality and sphericity were verified using the Shapiro-Wilk and Mauchley test respectively All parametric statistical analyses were performed using SPSS version 21. Repeated measures ANOVAs were performed to assess differences between seasons. Where a significant main effect was observed, post-hoc Tukey HSD tests were conducted to identify the location of the differences. Statistical significance was set at $P < 0.05$ throughout. To adopt a practical approach, differences between seasons were also analysed using Cohen's ES statistic. ES were categorised as trivial (<0.2) small (0.2-0.6), moderate (0.6-1.2), large (1.2-2.0), and very large (>2.0) (Hopkins et al., 2009).

6.3 Results

Table 6.2 shows a summary of the newly promoted team's league record over the three seasons. There were no differences between seasons for playing times (P = 0.227) (Table

6.3). There was a significant increase in the total distance covered per minute over the three seasons (P = 0.001). Specifically there was a large increase between 2012 (87.0 $m.min^{-1}$) and 2013 (91.3 $m.min^{-1}$) (P = 0.005; ES = 1.6) and a very large increase from 2013 to 2014 (96.6 $m.min^{-1}$) (P = 0.001; ES = 2.0), resulting in players covering on average 11% more total distance when comparing 2012 and 2014 (P = 0.001; ES = 4.0) (Table 6.3).

Table 6.2: A summary of the newly promoted team's league record over the three season period.

Season	Played	Won	Drawn	Lost	League Position Finish (Out of 14)
2012	27	6	0	21	14
2013	27	10	2	15	10
2014	27	13	1	13	8 *

*Qualified for post-season play off finals

The HSR distance covered per minute increased over the three seasons (P = 0.002) with only moderate increases between both 2012 (6.3 $m.min^{-1}$) and 2013 (7.4 $m.min^{-1}$) (P = 0.081; ES = 0.9) and 2013 to 2014 (8.1 $m.min^{-1}$) (P = 0.237; ES = 1.1). This however resulted in a very large increase when comparing 2012 and 2014 (P = 0.002; ES = 2.0), resulting in players covering around 28% more HSR distance over this period. MUF were the only positional group not to show a significant increase in HSR across seasons, covering 5.9 $m.min^{-1}$ in 2012 and 6.6 $m.min^{-1}$ in 2014 (P = 0.569; ES = 0.5) (Table 6.3).

Players performed a significantly greater number of collisions over the three seasons (P = 0.001). Only a small increase was observed between 2012 (0.43 $no.min^{-1}$) and 2013 (0.44 $no.min^{-1}$) (P = 0.709; ES = 0.2), however there was a very large increase when comparing

2013 and 2014 (0.53 $no.min^{-1}$) (P = 0.001; ES = 2.5) and 2012 and 2014 (P = 0.001; ES = 2.1), which resulted in players performing approximately 23% more collisions in 2014 when compared with 2012 (Table 6.3).

Table 6.4 shows Opta data over the three seasons. The team showed a moderate increase in the number of points they scored per game when comparing 2012 (20) to 2014 (29) (P = 0.026; ES = 0.7), and a large reduction in the number of points opposition sides scored per game when comparing over the same period (from 40 to 21) (P = 0.001; ES = 1.2) and between 2013 (33) and 2014 (P = 0.014; ES = 0.8). Irrespective of team, the total number of points scored per game was lower in 2014 (49) compared with 2012 (60) (P = 0.039, ES = 0.7). The ball was in play longer in 2014 (51.79 min) than compared with both 2012 (48.63 min) (P = 0.004; ES = 0.9) and 2013 (49.19 min) (P = 0.023; ES = 0.7), attributable to opposition sides spending longer in ball possession in 2014 (26.66 min) than in 2013 (24.41 min) (P = 0.003; ES = 0.8). Irrespective of team, the number of penalties per game was lower in 2014 (13) than 2012 (17) (P = 0.001; ES = 1.0), attributable to the team under investigation reducing the number of penalties they conceded in 2014 (6) compared with 2012 (9) (P = 0.001; ES = 1.1). There was a reduction in the number of line breaks per game irrespective of team from 2012 (15) to 2014 (12) (P = 0.017; ES = 0.8), attributable to opposition sides making less line breaks per game in 2014 (7) than 2012 (10) (P = 0.003; ES = 1.0). The team under investigation increased their tackle success percentage per game from 90% in 2012 to 92% in 2013 (P = 0.003; ES = 0.7) with this remaining at 92% in 2014.

Table 6.3: Physical demand data over the three season period. Data presented as mean (SD).

	2012	2013	2014
Outside backs			
Playing Time (Min)	86.7 (3.4)	83.0 (4.71)	84.1 (6.05)
Total distance ($M.min^{-1}$)	83.6 (2.8)	86.2 (4.21)*	91.1 (3.41)*
HSR ($M.min^{-1}$)	7.1 (1.4)	8.6 (1.7)	9.2 (1.4)*
Collisions ($no.min^{-1}$)	0.23 (0.04)	0.26 (0.03) *	0.32 (0.05) * †
Pivots			
Playing Time (Min)	72.8 (10.6)	72.3 (9.04)	71.6 (6.62)
Total distance ($M.min^{-1}$)	90.2 (3.3)	94.1 (2.68) *	98.9 (2.85) * †
HSR ($M.min^{-1}$)	6.2 (1.6)	7.4 (0.9)	8.0 (1.0) *
Collisions ($no.min^{-1}$)	0.31 (0.04)	0.33 (0.05)	0.37 (0.05) * †
Middle Unit Forwards			
Playing Time (Min)	47.8 (6.6)	45.5 (2.72)	48.0 (7.14)
Total distance ($M.min^{-1}$)	90.8 (2.2)	93.0 (5.26) *	100.3 (3.87) *
HSR ($M.min^{-1}$)	5.9 (1.4)	6.1 (1.37)	6.6 (1.00)
Collisions ($no.min^{-1}$)	0.72 (0.13)	0.75 (0.09)	0.88 (0.1) * †
Wide Running Forwards			
Playing Time (Min)	77.0 (9.0)	72.0 (3.4)	72.42 (15.1)
Total distance ($M.min^{-1}$)	83.4 (2.4)	91.9 (3.0) *	95.9 (6.3) *
HSR ($M.min^{-1}$)	5.9 (1.4)	7.4 (0.81)	7.9 (1.22) *
Collisions ($no.min^{-1}$)	0.46 (0.07)	0.42 (0.09)	0.55 (0.09) * †
Mean			
Playing Time (Min)	71.0 (3.8)	68.2 (2.7)	69.0 (3.8)
Total Distance ($M.min^{-1}$)	87.0 (2.4)	91.3 (3.0) *	96.6 (2.4) * †
HSR ($M.min^{-1}$)	6.3 (1.3)	7.4 (0.9)	8.1 (0.5) *
Collisions ($no.min^{-1}$)	0.43 (0.05)	0.44 (0.03)	0.53 (0.04) * †

*Significantly different to 2012 ($P<0.05$)

†Significantly different to 2013 ($P<0.05$)

Table 6.4: Opta data over the three season period. Data presented as mean (SD).

	2012	2013	2014
Total points scored per game (irrespective of team)	60 (13)	57 (17)	49 (15) *
Team under investigation points scored per game	20 (13)	23 (11)	29 (14) *
Team under investigation points conceded per game	40 (18)	33 (17)	21 (13) * †
Time that the ball was in play (min)	48.63 (3.47)	49.19 (3.90)	51.79 (3.24) * †
Team under investigation possession Time (min)	23.42 (3.12)	24.78 (3.29)	25.13 (2.84)
Opposition possession time (min)	25.21 (2.57)	24.41 (2.00)	26.66 (2.60) †
Penalty count per game (irrespective of team)	17 (3)	14 (3)	13 (5) *
Team under investigation penalty count (against) per game	9 (3)	7 (2) *	6 (3) *
Opposition penalty count (against) per game	7 (2)	7 (2)	6 (3)
Line breaks per game (irrespective of team)	15 (4)	15 (4)	12 (4) * †
Team under investigation line breaks per game	5 (3)	7 (2)	5 (3)
Opposition line breaks per game	10 (4)	8 (4)	7 (3) *
Team under investigation tackle success percentage per game	90% (2%)	92% (3%) *	92% (2%) *

*Significantly different to 2012 (P<0.05)

†Significantly different to 2013 (P<0.05)

6.4 Discussion

The aim of the study was to be the first to examine the physical intensity of match-play over a consecutive three season period for a newly promoted ESL franchise. Across the three seasons there was a significant increase in the total distance covered per minute, and number of collisions performed per minute. There was also an increase in the HSR distance per minute for all positions except MUF. These data collectively highlight that there was an increase in the physical intensity of match-play. This data also highlights the need for newly promoted teams to have the chance to be able to develop and adapt to the demands of ESL competition over time, which is a pertinent issue given the recent re-introduction of promotion and relegation.

No differences for playing times for positions over the three seasons indicates the tactical approach to interchanges remained consistent, and increases in physical intensity measures cannot be attributed to differences in playing time. Both total and HSR distances, and number of collisions have been previously used to represent the physical demands of Rugby League match-play, with all three measures having been shown to differentiate between successful and less successful teams (Gabbett, 2013b, 2014a; Hulin et al., 2014). The findings of the present study may suggest that greater success in the ESL competition is reflective of increased physical demands given the team examined demonstrated a marked improvement in league position and the ability to lower the points conceded whilst increasing the points scored, however more specific research examining winning and losing games is required in a greater sample of ESL teams.

The data from Chapter 4 highlighted the fact that although the total distance covered per minute of match-play for the newly promoted team in 2012 was lower than previously reported in ESL, the HSR demands were higher. A significant increase in the total distance covered per minute over the three season period across all positions in the current study may be expected given that there was a reduction in the total points scored per game, total penalty count, and increase in ball in play time. Such data highlight a reduction in game stoppages which would increase relative movement activity but lower recovery periods in games. However, there was an increase for the collision involvements for all positions and HSR for all positions except MUF. This indicates an increased ability to perform high intensity activities despite fewer periods for recovery within games.

In Chapter 4, a substantial amount of HSR in the 2012 season was attributed to being the result of chasing back opposition players who had broken the defensive line. Given that there was a reduction in the total number of line breaks, and the number of line breaks performed against the team, with no difference in the number of line breaks performed by the team, this would suggest the increased HSR outputs will have been achieved in different ways. Potential suggestions for this include an increased ability to maintain high-speed kick chase activities, and the ability to sustain running into collision at greater speeds over the course of match-play. From a position specific perspective, MUF were the only positional group not to show a significant increase in HSR. This could be due to their specific role in the game whereby they are not offered the freedom of pitch position with which to develop forward locomotion as much as other positions. Being located in the middle of the field close to the opposition gain line means their capacity to generate high-speed is lower (Gabbett et al., 2014). It is also possible that forwards are typically slower than backs (Meir et al., 2001), thus preventing the attainment of an arbitrary HSR threshold (>5.0 $m.s^{-1}$) with the same ease. This highlights once again that training acceleration over short distances for this positional group should take precedence than developing prolonged HSR ability.

Players in the current investigation covered 96.6 $m.min^{-1}$ of total distance in 2014 which is higher than reported previously for higher ranked ESL teams at 95.8 $m.min^{-1}$ (Twist et al., 2014). Similarly players in the current investigation covered 8.1 $m.min^{-1}$ of HSR distance in 2014, again higher than previously reported for higher ranked ESL players at 6.1 $m.min^{-1}$ (Twist et al., 2014). It should be noted however that the comparative data (Twist et al., 2014) were from players competing in the 2011 season. Clearly more research is needed examining the evolution in demands for higher ranked teams in the competition. If in accordance with the current study competitive success is related to greater running intensities, (Black & Gabbett, 2014; Gabbett, 2013b, 2014a) it may be in fact the top teams in the competition are covering above and beyond the movement demands outlined in this investigation.

Increases for collision involvements could be attributable to the ball being in play for a longer time over the three seasons, which would be indicative of a greater number of collisions due to a relative increase in playing action over 80 minutes. A greater tackle success percentage over the three season period could also contribute to such increases. In addition to displaying greater tackle success, reductions in the penalties conceded and line breaks made against the team highlights their ability to better execute technical skills, control the ruck speed, and maintain defensive shape under game induced fatigue.

Despite contributing valuable new data to the literature, the present study is not without its limitations, the main one being a change in GPS equipment. Whilst this is a major limitation, such issues are part of dealing with collecting real world data in the applied setting and if longitudinal data are to be studied teams are likely to switch GPS equipment over time to keep up with the latest developments in the technology. Pilot data from Chapter 5 has revealed there were good levels of agreement between the two models of device for the movement variables to be used in this study. Furthermore, when considering the analytical goals in Chapter 5, the increase in movement demands in the current study are larger than the CV% and range between the LoA. The data is also limited to one ESL team, which makes league wide generalisations difficult. In conclusion, this study has shown that there is an increase in physical match intensity of ESL competition for a newly promoted team over a three season period. Coaches and conditioning staff need to be aware of the recent developments in match-play and highlights the importance of being able to continually monitor physical match outputs to re-evaluate positional data.

Secondly, the study shows that newly promoted teams need time to develop and adapt to the increasing demands of ESL competition. This is a pertinent issue for those responsible for organising the league structure given the recent re-introduction of promotion and relegation. With the current structure, newly promoted teams will not have the chance to plan and develop over the long term. Given that newly promoted teams may be greatly under resourced compared to teams who have been competing in the competition for a long time, this could potentially lead to teams spending over their means to attract the players required to keep them in the competition rather than focussing on long term player development.

Whilst in Chapter 4 and in the current chapter, the collision demands of ESL match-play have been profiled, there is a paucity of literature examining these when compared to the movement demands. Part of the reason for such may be the time consuming and labour intensive process of manually examining retrospective video footage for large numbers of players. A system that operates in real time or immediate post-event system that could automatically identify collisions would be beneficial to provide information that could be used to give practical guidance on training loads. Therefore, there is a clear need for a system that can both automatically and accurately monitor collision counts and their intensity during games and training.

Chapter 7

The ability of a GPS device for use in team sports to automatically detect collisions during Rugby League match-play

Although Chapters 4 and 6 have profiled the collision demands of ESL match-play, data examining such demands are less evident in the literature when compared to the movement demands. This may be due to the time consuming and labour intensive process of manually examining retrospective video footage to assess the number of collisions players have been exposed to. With the introduction of accelerometers, gyroscopes, and magnetometers into the modern GPS devices, the automatic detection of collision events is now a possibility, however such technology needs to be validated before being considered fit for purpose. Therefore the purpose of the study was to examine if the Statsports GPS device could automatically detect the number of physical collisions during ESL match-play compared with those manually coded from video footage.

7.1 Introduction

As a result of the multiple physical collisions players are exposed to over the course of an 80 minute match, musculoskeletal injuries are extremely common (Gabbett et al., 2011). However success in the game also depends on tackling ability, the ability to withstand physical collisions and the ability to "win" the tackle contest (Gabbett, 2013c). Consequently, tackling is one of the most practiced skills in Rugby League as the ability or inability to effectively perform tackles may prove critical to the outcome of the game (Gabbett, 2013c).

Inconsistency in language appears in the literature with the terms "tackle" and "collision" sometimes used interchangeably, despite tackles being a subset of collisions (Kelly et al., 2012). Their differentiation is important as the number of tackles is more of a tactical performance indicator, while monitoring the number of overall collisions gives a greater understanding of the physical demands imposed and has implications for injury risk (Gabbett et al., 2010), muscle damage (McLellan et al., 2010), recovery (Oxendale et al., 2016), and training load implications (Gabbett et al., 2010; Gabbett et al., 2011, 2012). Historically, the number of collisions during match-play have been identified retrospectively using video replays (King et al., 2009; Sirotic et al., 2009; Sykes et al., 2009). However, the manual coding of collisions from video footage is labour intensive, taking club video analysts and sport scientists considerable time to analyse such data. A real-time or immediate post-event system that could automatically identify collisions would be beneficial to provide information that could be used to give practical guidance on training loads and even tactical substitutions. Therefore, there is a clear need for a system that can both automatically and accurately monitor collisions and their associated intensity in games and training.

Commercially available wearable tracking devices have been developed for use in field based team sports and are typically worn by athletes on their upper back in a sports vest (Kelly et al., 2012). Such devices typically contain global positioning system (GPS) technologies which have been used to determine the running demands of Rugby League match-play, e.g. Chapter 4 and others (Austin & Kelly, 2013; Twist et al., 2014; Waldron, Twist, et al., 2011). The devices also contain accelerometers, gyroscopes and magnetometers making it possible to measure accelerations associated with sporting movements, including physical collisions in contact sports (Gabbett et al., 2010; Gastin et al., 2013; Kelly et al., 2012) and potentially provide a less labour intensive method to investigate the collision demands of the sport than retrospective video analysis.

Catapult MinimaxX S4 GPS devices are reported to have a good validity for measuring collision events in various tackling bag, bump bag and one on one tackle drills compared with video-based analysis, using both raw and smoothed data (CV 9-15%) (Wundersitz et al., 2015). GPSports devices have traditionally reported the level of impacts measured in G force, and have shown to have a poor relationship with tackles and ball carries in Rugby League (McLellan et al., 2011a), which is confirmed by the findings from Chapter 4. A number of studies from varying collision-based sports (Australian Football, Rugby Union, and Rugby League) have attempted to quantify collision events using both microsensor technology and video-based notational analysis (Cummins & Orr, 2015; Gabbett, 2013c; Gastin et al., 2013; McLellan et al., 2011a). Although reporting impacts in G may have limitations in accurately quantifying collisions, an algorithm has been developed which employs static window features and a mathematic learning grid to detect collision events using the tri-axial accelerometer in the GPSports devices when used in Rugby Union (Kelly et al., 2012). The Catapult MinimaxX device has been shown to successfully detect collisions in Rugby League (Gabbett et al., 2010). A collision detection algorithm was used to detect collision events. Analysis of 237 collision events from 21 training sessions and a single trial game showed no significant differences and strong correlations between the total number, number of mild, moderate, and heavy collisions detected by the device and those subjectively coded from video footage, however it has been shown that the frequency and intensity of collisions during training is far lower than those experienced during competition (Gabbett et al., 2012), thus limiting this study.

Further work has shown that the same GPS device and algorithm was unable to detect collisions in Australian Rules Football, with a 78% success rate (Gastin et al., 2014), however unlike in previous work (Gabbett et al., 2010) all of the collisions analysed were from competitive games. The less successful detections in Australian Rules Football were suggested to be due to the differences in tackle dynamics between the sports. The device was more sensitive in detecting tackles against (90%) than tackles made (66%) (Gastin et al., 2014). More recently, it has been shown that the automated collision detection system in GPSports devices has only modest utility in Rugby Sevens, especially for female players' (Clarke et al., 2016). Collectively, these findings show that to allow the detection of a range of collision events within collision sports requires sophisticated sport and event-specific algorithms, and until these are further refined and validated the use of microtechnology data is best when used in combination with other technologies such as video coding. The Catapult S5 device has been shown to correctly identify 97.6% of collision events during Rugby League match-play (Hulin et al., 2017), and that the error of the device is associated with not reporting a collision event when a collision does not occur.

The Statsports Viper athlete tracking device is now widely used amongst elite level ESL Rugby League teams to measure player's activities in training and competition. The manufacturers of the device have developed a collision detection algorithm for use in

Rugby Union. However, is it unknown whether the technology could be successful in automatically detecting collisions in Rugby League, given the laws of Rugby League differ to those of Rugby Union and Rugby Sevens pertaining to the breakdown of tackles (i.e. formation of rucks) (Hogarth, Burkett, & McKean, 2016). Therefore, the aim of this study was to examine if a currently commercially available athlete tracking device (Statsports Viper) could automatically detect the number of physical collisions during Rugby League match-play compared with those manually coded from video footage.

7.2 Methods

7.2.1 Participants

Seventeen elite male (age 25.4 ± 3.2 y, height 1.81 ± 0.04 m, mass 97.1 ± 9.0 kg) players who all played for the same ESL club during the 2014 season were included in the study. Testing took place over one game that all seventeen players participated in during a regular season game in the 2014 season.

7.2.2 Procedures

A cross-validation approach was used to evaluate the effectiveness of a wearable athlete tracking device (Statsports Viper, Ireland, 10 Hz GPS, tri-axial 100 Hz accelerometer) to automatically detect the total number of collisions during ESL match-play. Video observation of coded collisions during match-play was considered the criterion measure, and collisions that were automatically recorded via a collision detection algorithm within the Statsports Viper software were compared to those coded from video observations. For a collision to be detected by the algorithm, a combination of the magnitude of all three acceleration vectors (x, y, and z) must record an instantaneous impact of above 8 G (personal communications with Statsports). This coupled with the duration of the event is taken into account before the algorithm decides whether to register a collision or not. The speed of the player into the collision, and instantaneous initial impact is also factored in to produce a "collision load" score, however this parameter is not specifically investigated in the current study as it was determined that in order to validate this metric would require further work using three dimensional motion analysis in a laboratory setting. Further information specifically relating to the collision detection algorithm has not been published and these remain proprietary, however the present study is able to be replicated as the software and devices are commercially available. It should be stressed that the algorithm underwent most of its development to detect collisions in Rugby Union.

The process for manually coding collisions from video footage is outlined in Chapter 3. Manually coded collisions were matched with the Statsports data to determine if a collision had been detected. The process was then effectively reversed with all automatically detected collision events from the Statsports devices compared with the video footage to assess whether the collision events identified by the devices were collisions, other high-impact events or simply other events incorrectly detected. This approach provided an assessment of the number and level of agreement for events considered as a true positive (a microtechnology collision was detected alongside a manually coded collision), false positive (a microtechnology detected collision was recorded but not associated with a manually coded collision), and a false negative (a collision was manually coded but not recorded by the microtechnology device).

Manually coded collisions were classified as a ball carry, tackle, or collision off the ball. Furthermore, tackles were subdivided further into three subsequent classifications; first man into the tackle, second man into the tackle, and third man into the tackle. It was also noted whether the ball carry or tackle resulted in the ball carrier or tackler going to ground, or staying upright. A repeated analysis was conducted on the sample three weeks later to assess intra-individual test-retest reliability using Cohen's Kappa statistic. The Kappa statistic was computed using the methods outlined in Chapter 3, and for all collision categories a value of 1.0 was observed, indicating perfect agreement between the two observations.

7.2.3 Statistical Analysis

Recall and precision were calculated according to previous methods (Clarke et al., 2016; Garraway et al., 1999; Kelly et al., 2012). Recall is the ability to detect collisions with a low number of false negatives and was calculated as the number of true positives divided by the sum of the number of true positives and false negatives. Precision is the ability to correctly detect collisions with a low number of false positives and was calculated as the number of true positives divided by the sum of the number of true positives and false positives. A value of 1.0 is the best outcome that can be achieved for either precision or recall (i.e. no false positives or negatives). A value of 0.5 would indicate that 50% of collisions are either not captured (poor recall), or incorrectly labelled (poor precision). Further descriptive data of absolute numbers and percentage of total collisions, ball carries, and tackles detected are reported. In accordance with previous chapters, the level of agreement was considered against analytical goals. The CV% between positions for the number of collisions performed per minute was shown to be 51% from the data in Chapter 4. The CV% between the number of collisions performed per minute in games that were won and lost was shown to be considerably lower at 0% (Gabbett, 2013b).

7.3 Results

A total of 634 collisions were manually coded during the game. Of these, the Statsports device recorded 516 true positives, 118 false negatives, and 0 false positives (0.81 recall; 1.0 precision) (Table 7.1). There were 22 collisions “off the ball”, the descriptors of which are outlined in Table 7.2.

Table 7.1: Observed GPS detected collisions, compared to manually coded collisions for a team of 17 players in an ESL game during the 2014 season.

	Manually coded collisions (n)	True Positive (n)	False Positive (n)	False Negative (n)	Recall	Precision
Total collisions	634	516	0	118	0.81	1.0

Table 7.2: Counts of collisions “off the ball” with their collision descriptors.

Collision descriptor	Count
Collision with opposition player during kick chase	6
Falling on the ground for a loose ball	7
Slipping onto ground when attempting to change direction	3
Attempting to tackle opposition player but missing and colliding with the ground	3
Diving to score a try	2
Celebrating scoring a try with team mate	1

Ball carries were more accurately detected (197/203 = 97%) than tackles made (297/409 = 73%) (Table 7.3). Of the tackles manually coded, the majority were first man tackles (196/409). These were more accurately detected (162/196 = 83%), than both second man tackles (96/134 = 72%), and third man tackles (39/79 = 51%) (Table 7.4).

Table 7.3: Observed GPS detected total ball carries, total tackles, ball carries to ground and not to ground, and tackles to ground and not to ground compared to manually coded collisions for a team of 17 players in an ESL game during the 2014 season.

	Manually coded collisions (n)	**True positive (n)**	**False negative (n)**	**Percentage of collisions detected correctly**
Ball carries	203	197	6	97%
Tackles	409	297	112	73%
Collisions off the ball	22	22	0	100%
Ball carries to ground	171	167	4	97%
Ball carries not to ground	32	30	2	95%
Tackles to ground	374	276	98	74%
Tackles not to ground	35	21	14	65%

Table 7.4: Observed GPS detected first man, second man, and third man tackles compared to those manually coded for a team of 17 players in an ESL game during the 2014 season.

	Manually coded collisions (n)	**True positive (n)**	**False negative (n)**	**Percentage of collisions detected correctly**
First man tackles	196	162	34	83%
Second man tackles	134	96	38	72%
Third man tackles	79	39	40	51%

7.4 Discussion

The aim of the study was to evaluate the effectiveness of a wearable microtechnology device to automatically detect collision events in elite Rugby League match-play. Recall of the device (0.81), was lower than precision (1.0), which highlights the error (19%) associated with measuring collision events is related to the ability of the device not correctly identifying a collision. A perfect level of precision shows that there was no error in the device for incorrectly detecting a collision event. Ball carries were more accurately detected (97%) than when compared to tackles (73%), especially when detecting the third man into the tackle (51%). This data suggests the microsensor device has the ability to automatically detect the majority of collision events in Rugby League match-play. Whilst the level of error was shown to be lower than the differences between the number of collisions by positions reported in Chapter 4 (CV = 29%), the level of error was shown to be greater than the differences in the number of collisions performed between winning and losing games (CV = 1%) (Gabbett, 2013b). Given that the collision detection algorithm was originally developed for Rugby Union; this may need refinement for use in Rugby League, especially for detecting tackle events.

The results of the current investigation would suggest a lower success than previous work into detecting collisions in Rugby League (Gabbett et al., 2010) using an alternative microtechnology device (Catapult MinimaxX). No significant differences and strong correlations between the collisions detected by the Catapult MinimaxX device and those coded from video footage were reported (Gabbett et al., 2010). However this approach failed to take into consideration undetected tackles and false detections. The majority of collisions in the previous study (Gabbett et al., 2010) were also collected in a skills training environment, which makes comparisons to the current investigation where collisions from competition were analysed further difficult, as it has been shown that the frequency and intensity of collisions of those experienced in training are much lower than those in competition (Gabbett et al., 2012). The same algorithm that Gabbett and colleagues (Gabbett et al., 2010) used was less successful in detecting tackles in Australian Football, where 78% of tackles were detected, highlighting the need for a sport specific algorithm. The recall of the device in the current investigation was lower than the Catapult S5 device in NRL Rugby League match-play (0.81 vs. 0.97); however the precision in the current investigation was higher (1.0 vs. 0.88) (Hulin et al., 2017).

The recall of the device in the current investigation was lower than that reported for the GPSports SPI Pro device in Rugby Union (Kelly et al., 2012) (0.93) where an algorithm employing static window features and a mathematic learning grid was used, however precision in the current investigation was higher (1.0 vs 0.96). Similar devices (GPSports SPI HPU) were used to automatically detect collisions in men's and women's Rugby Sevens (Clarke et al., 2016), with the values for recall and precision in both the men's (0.69; 0.73) and women's codes (0.45; 0.71) being considerably lower than those reported in the current study. Clarke and colleagues identified that the collision detection algorithm was developed for original use in Rugby Union, and that the algorithm may need re-defining for use in Rugby Sevens due to less players being on the field resulting in fewer players being involved in each tackle.

In the current study, tackles (73%) were less successfully detected by the device than ball carries (97%). It would be expected that ball carries would produce a greater instantaneous impact than tackles, with the speed of forward locomotion the ball carrier would carry into the tackle. Given the algorithm was originally developed for Rugby Union, the lower tackle accuracy could also be attributable to the differences in Rugby League and Union codes with regards to the definitions of tackles. In Rugby Union, according to the World Rugby 2017 Laws of the game a tackle occurs when the ball carrier is held by one or more opponents and is brought to ground. In Rugby League, the Rugby Football League 2017 rules state a player in possession is tackled when he is held by one or more opposing players and the ball or the hand or arm holding the ball comes into contact with the ground. However, the ball carrier does not necessarily have to go to ground for a tackle to be deemed complete in Rugby League. The rules further state the ball carrier can be held upright by one or more opposing players in such a manner that he can make no further progress and cannot part with the ball. This of course may not lead to the criteria being fulfilled for a collision to be detected. It may be that the instantaneous impact is not registered on the vertical acceleration axis, as the player is not brought to ground. This is supported by the fact that collisions that resulted in players going to ground were more accurately detected than those which did not in the current investigation. Further work may need to refine the algorithm to better detect collisions which do not involve players going to ground.

Third man tackles (51%) were less successfully detected than second man tackles (72%), and first man tackles (83%). In Rugby League, the first man into the tackle will usually make the biggest impact with the ball carrier in order to stop the attacker's momentum. The second and third men then usually will wrap up and control the ball and ball carrier to prevent the attacker offloading the ball, and slowing the subsequent play the ball down by attempting to assist the first man in bringing the ball carrier to ground on their back. As quite often the second and third men will not hit the ball carrier with as much force as the first man, it would make sense less of these tackles would be detected as the instantaneous impact would be lower than that for the first man. Whilst lowering the G threshold used to classify a collision may reduce the number of false negatives (increasing recall), there is also the possibility that this would in turn increase the number of false positives that are observed (reducing precision). In order to identify the optimal threshold to use in the quantification of automatic collision detection in Rugby League, further research is warranted. Analysing a greater number of players, games, and teams (who may show variation in the tactical approach to carrying the ball and tackling) would be beneficial in understanding this area further as the current study is limited to one team over a single game. Whilst this study has attempted to quantify if the Statsports Viper device could automatically detect collision events, further research would also be beneficial in attempting to quantify the "collision load" score provided by the system; however research attempting to do this in the applied setting would prove difficult due to the gold standard criterion measure which the intensity of collisions could be compared with. Controlled conditions utilising three dimensional motion analyses in a similar method to a previous investigation (Wundersitz et al., 2015) may provide the best approach.

In conclusion the Statsports Viper device can detect the majority of collisions during Rugby League match-play. The error (19%) associated with measuring collision events is related to the ability of the device to not correctly identify a collision has occurred. A perfect level of precision shows that there was no error in the device for incorrectly detecting a collision event. Ball carries (97%) are more accurately detected than tackles (73%). Further work is needed to refine the algorithm to understand the accelerometer patterns that occur with tackles events during Rugby League match-play, especially those involving second and third men in order that this technology can be widely used in applied and research settings. Although second and third men into the tackle met the definition of a manually coded collision in the current study, future investigations may have to look at the definitions of such, and identify if these actually are collision events (as sometimes these will just involve a period of wrestle rather than a full-on collision).

Thus far, this thesis has examined in depth the movement and collision demands of ESL match-play and how these have changed over time for a newly promoted team competing under the ESL licencing system. Whilst the findings are useful for the conditioning and coaching staff of newly promoted teams to consider when planning training programmes for their players, newly promoted teams have the additional challenge of planning for different recovery periods between matches. Typically, in the Championship rest periods between games remain consistent at 6 to 7 days; however in the ESL the periods between games can range from 5 to 10 days. What would be useful to know is how these different periods impact on match day running performance and the match result. Such information could be utilised by coaches and conditioning staff in order to plan training and recovery strategies for players.

Chapter 8

Between match recovery duration and the impact on match running performance in European Super League players

The findings thus far in this thesis can help coaches and conditioning staff of newly promoted teams in the future to plan training intensities for their players. The additional challenge newly promoted ESL teams encounter is the inconsistent recovery periods between games. Game turnarounds can range from 5 to 10 days, with the effect of these different recovery periods on match running performance unknown. Such information could help in the planning and recovery strategies for players. Therefore the aim of the final study is to examine the effects of different between match recovery cycles on the running performance and result on a greater sample of ESL teams.

8.1 Introduction

Exercise induced muscle damage (EIMD) after Rugby League match-play has been well documented (Oxendale et al., 2016; Twist et al., 2012). It is characterised by elevations in myofibrillar proteins in plasma (Johnston et al., 2013; McLean et al., 2010; McLellan et al., 2010), decrements in neuromuscular function (Duffield et al., 2012; Johnston et al., 2013; McLellan & Lovell, 2012), and increased in perceived muscle soreness (Twist et al., 2012) that last several days after competition. Symptoms of EIMD might therefore compromise the quality of a player's performance in the days after the original damage, particularly where congested training and competitive schedules occur.

Congested fixture periods where multiple matches are experienced in short time periods are common in elite sporting competitions. The limited recovery time between these games has the potential to have an impact on the running performance of match-play. Rugby League players experience immediate and delayed symptoms of fatigue that persist for a number of days following a game (Johnston, Gabbett, et al., 2014). For teams participating in the second tier of European competition (The Championship), the turnaround period between games remains consistent between 6-7 days. At the elite level in the NRL and ESL, the recovery time between matches can differ in between 5-10 days as a result of live television coverage. Therefore, coaching and conditioning staff need to be mindful of the recovery time in order to prepare optimally for the subsequent match.

The first study to investigate the effect of short (5-6 days), medium (7-8 days), and long (9-10 days) between-match recovery cycles on activity profiles was conducted on a single team participating in the NRL competition (Murray et al., 2014). Interestingly, players covered greater total distance per minute of play after short between-match recovery cycles (5-6 days) than when compared to medium (7-8 days), and longer (9-10 days) between match turnarounds. This increase was attributed to increased low speed activity, with no differences in moderate or high speed distances covered by players (Murray et al., 2014). The authors also report that a greater total distance per minute was covered when matches were won after a short turnaround, consistent with previous findings that have shown greater relative intensity in winning teams (Gabbett, 2013b). Contrasting findings were reported in a more recent study (again from a single NRL team), where both the total distance covered per minute and high speed distance covered per minute were lower after short recovery cycles (Kempton & Coutts, 2016). When matches were won, the total distance per minute and high speed distance per minute were also lower (Kempton & Coutts, 2016). The different findings between the studies could be due to that in the Murray and colleagues study (Murray et al., 2014) the authors failed to account for contextual factors, such as time out of play, or alternatively may be due to differences in the recovery strategies and training schedules between the reference teams (Kempton & Coutts, 2016). Nevertheless, collectively the findings show that recovery strategies should be carefully planned during short between match recovery cycles to preserve running performance in subsequent matches.

A limitation of the aforementioned studies is that they are limited to single teams from the NRL, so these contrasting findings are difficult to generalise. Many coaches of ESL teams have used the British press to criticise periods of fixture congestion such as the traditional ESL Easter weekend (Clubcall.com, 2014; Express, 2017; SkySports, 2016). It has been reported that for a single ESL team over a period of fixture congestion (four games in 22 days with between match periods of 6, 2, and 5 days) that reductions in high-intensity running (≥ 5.5 m.s^{-1}) and increases in low speed activity (< 5.4 m.s^{-1}) were evident in the later matches, indicative of an overall slowing of movement speed (Twist et al., 2017). Obtaining such information on multiple ESL teams may help them in their preparation for coping with differing recovery cycles between games. Therefore the aim of the current study was to examine the effect of different between match recovery cycles (short, medium, and long) on the running performance in subsequent matches on a large sample of six elite ESL teams. It was hypothesised that movement demands would decrease in terms of the high speed distance covered per minute (indicative of fatigue) during matches with short between match recovery cycles, and conversely this would be greater after a long turnaround.

8.2 Methods

8.2.1 Participants and Procedures

A total of 795 individual performances from the 2015 ESL season were originally considered for analysis from six different teams. Players movements were examined using GPS (Statsports Viper, Ireland, 10 Hz GPS, tri-axial 100 Hz accelerometer) in either a custom designed vest with a tightly fitting squad shirt over the vest, or alternatively were fitted within a specially designed pouch housed within the tightly fitting squad shirt. The procedure for switching on devices and downloading data was as described in Chapter 3, as was the procedure for determining time on pitch. If players were on the pitch for less than 5 minutes, then these files were removed from the analysis as this likely represented an injury (rather than a tactical substitution). This left a total of 776 files for analysis.

The GPS variables analysed included the total distance covered per minute of time on pitch, low speed distance (< 3.8 $m.s^{-1}$) covered per minute of time on pitch, and high speed distance (> 3.8 $m.s^{-1}$) covered per time on pitch. As stated in previous chapters, expressing these values "per minute" allows any differences as a result of longer or shorter game durations to be removed (Burgess et al., 2006). The use of these broad speed categories is different to previous chapters as these best reflected the data that was able to be received by the researcher from the clubs participating in the study. The key GPS variables were analysed to investigate differences in movement demands between short turnarounds (ST) (5-6 days), medium turnarounds (MT) (7-8 days), and long turnarounds (LT) (9-10 days) between games. These periods were chosen based upon previous research (Kempton & Coutts, 2016; Murray et al., 2014), and best reflect the typical between match recovery periods in the ESL (5-10 days). The total number of files for each between match recovery period were; ST (271), MT (301), and LT (204). In addition, differences in movement demands for matches that were won and lost with the various between match recovery periods were also examined; ST win (140), ST lose (131), MT win (161), MT lose (141), LT win (105), LT lose (98). The number of files for games won and lost regardless of the between match recovery period was 406 (win) and 370 (loss).

8.2.2 Statistical Analysis

Before using parametric statistical procedures, the assumptions of normality and sphericity were verified using the Shapiro-Wilk and Mauchley test respectively. One-way ANOVAs were performed to assess differences between match recovery periods for all variables. Where a significant difference was observed, post-hoc Tukey HSD tests were conducted to identify the location of the differences. Differences in the movement demands between matches won and lost (regardless of the between match recovery period) were initially compared using an independent T-test. Further independent T-tests were then conducted to investigate the differences between movement demands when matches were won or lost during games after ST, MT, and LT. Statistical significance was set at $P < 0.05$ throughout.

All parametric statistical procedures were carried out using SPSS version 21. To adopt a practical approach, differences between match turnarounds were also analysed using Cohen's ES. ES were calculated as trivial (<0.2), small (0.2-0.6), moderate (0.6-1.2), large (1.2-2.0), and very large (>2.0) (Hopkins et al., 2009).

8.3 Results

8.3.1 Differences in movement demands

Differences in movement demands between different between match recovery periods are shown in Table 8.1. No differences were observed among different between match recovery cycles for playing time ($P = 0.073$). There was a small significant difference between match recovery cycles for the distance covered per minute ($P = 0.007$), where the distance per minute covered after games with LT (96.1 ± 16.9 $m.min^{-1}$) was greater than compared to games after MT (90.8 ± 20.4 $m.min^{-1}$) ($P = 0.005$; ES = 0.3). There was a small, significant increase in the low speed distance per minute covered after matches with LT (84.8 ± 18.2 $m.min^{-1}$) compared with both ST (80.3 ± 17.7 $m.min^{-1}$) ($P = 0.026$; ES = 0.2) and MT (79.3 ± 19.6 $m.min^{-1}$) ($P = 0.003$; ES = 0.3). There was a small, significant increase in the high speed distance covered per minute in matches after ST (13.2 ± 6.9 $m.min^{-1}$) when compared with both MT (11.6 ± 5.8 $m.min^{-1}$) ($P = 0.004$; ES = 0.3) and LT (10.6 ± 5.6 $m.min^{-1}$) ($P = 0.001$; ES = 0.4).

Table 8.1: Movement demands of ESL matches from the 2015 season with different between match recovery times. Data presented as mean (SD).

	ST	MT	LT
Playing Time (Min)	72.2 (22.3)	72.9 (21.8)	68.6 (21.5)
Distance per minute	93.5 (17.9)	90.8 (20.4)	96.1 (16.9) *
Low speed distance per minute	80.3 (17.7)	79.3 (19.6)	84.8 (18.2) * †
High speed distance per minute	13.2 (6.9) *	11.6 (5.8)	10.6 (5.6) †

*Significantly different to MT † Significantly different to ST

8.3.2 Differences in movement demands in matches won and lost and won and lost with different between match recovery cycles

Differences in movement demands for matches that were won and lost (regardless of the between match recovery cycle) are shown in Table 8.2. There were no significant differences for playing time (P = 0.172, ES = 0.1) or the high speed distance covered per minute (P = 0.139, ES = 0.1). There were small significant differences for the distance covered per minute (P = 0.024, ES = 0.2) and low speed distance covered per minute (P = 0.040, ES = 0.2) , with these both being higher in games won than in games lost (Table 8.2). Differences in movement demands for matches that were won and lost between different between match recovery periods are shown in Table 8.3. There were no differences between playing time for matches that were won and lost for ST (P = 0.552, ES = 0.2), MT (P = 0.779, ES = 0.1), and LT (P = 0.675, ES = 0.0). There was a small increase for the distance covered per minute after ST when matches were won (95.6 ± 91.3 $m.min^{-1}$) compared to when matches were lost (91.3 ± 19.9 $m.min^{-1}$) (P = 0.002, ES = 0.2). There were trivial differences between the high speed distance covered per minute after ST for matches that were won (13.1 ± 5.8 $m.min^{-1}$) compared to when matches were lost (13.4

± 8.0 m.min^{-1}) (P = 0.004; ES = 0.0). After MT matches, there were also trivial differences for the high speed distance per minute when matches were lost (11.2 ± 5.9 m.min^{-1}) compared to matches which were won (12.0 ± 5.5 m.min^{-1}) (P = 0.01, ES = 0.1). There was a small difference for the low speed distance covered per minute, being slightly higher for matches that were won (81.7 ± 21.1 m.min^{-1}) after MT than when in matches that were lost (76.4 ± 17.5 m.min^{-1}) (P = 0.022, ES = 0.3). There was a significant difference for the high speed distance covered per minute after LT, with this being moderately greater (P = 0.04, ES = 0.9) for matches that were won (12.6 ± 5.6 m.min^{-1}) than when compared to matches that were lost (8.0 ± 4.7 m.min^{-1}).

Table 8.2: Differences in movement demands for matches that were won and lost. Data presented as mean (SD).

	Win	**Loss**
Playing Time (Min)	71.5 (22.1)	72.7 (21.9)
Distance per minute	94.5 (18.6) *	91.4 (18.9)
Low speed distance per minute	82.3 (19.2) *	79.5 (18.1)
High speed distance per minute	12.2 (5.8)	11.5 (6.7)

*Significantly different to a loss

Table 8.3: Differences in movement demands for matches that were won and lost between different between match recovery periods. Data presented as mean (SD).

	ST		MT		LT	
	Win	**Lose**	**Win**	**Lose**	**Win**	**Lose**
Playing Time (Min)	70.0 (21.5)	74. 5 (23.0)	72.4 (21.5)	73.6 (22.2)	68.4 (23.7)	68.8 (19.4)
Distance per minute	95.6 (15.6)	91.3 (19.9) *	92. 9 (21.0)	88.4 (19.4)	95.3 (18.2)	96.2 (15.5)
Low speed distance per minute	82.6 (16.8)	77.9 (18.4)	81.7 (21.1)	76.4 (17.5) *	82.7 (19.4)	86.6 (16.8)
High speed distance per minute	13.1 (5.8)	13.4 (8.0) *	11.2 (5.9)	12.0 (5.5) *	12.6 (5.6)	8.0 (4.7)*

*Significantly different to winning

8.4 Discussion

The aim of the current study was to examine the effect of different between match recovery cycles (short, medium, and long) on the running performance of subsequent games from a representative sample of six ESL teams. The results of this study demonstrate that matches after ST were associated with greater high speed distance covered per minute of play than when compared to MT and LT. Matches with LT were associated with increased low speed distance covered per minute when compared to both ST and MT, with the total distance covered per minute only being greater in LT when compared to MT. These data demonstrate that running performance is affected by the length of the between match recovery cycles. Coaches and conditioning staff working within the ESL should be mindful of these demands, considering them when developing recovery and training strategies for players.

The overreaching hypothesis of the current study was that running performance in terms of the high speed distance covered per minute would be increased following long between match recovery cycles. Perhaps a surprising finding is the high speed distance covered per minute of play was higher after shorter turnarounds when compared to long turnarounds, with only the low speed distance covered per minute being higher in longer turnarounds when compared to short. It was reported that there were no significant differences between playing times over the recovery cycles, which indicates the tactical approach to interchanges remained consistent, and differences in running intensity measures cannot be attributed to differences in playing time. The increased high speed distance after short turnarounds in the current investigation is in contrast to previous research which reported reduced HSR following short turnarounds (Kempton & Coutts, 2016). The findings of the present study may therefore suggest that players are fatigued going into matches with longer between match recovery cycles, and therefore produce reduced running performances in terms of high speed efforts. A potential reason for this could be attributed to differences in training load relating to the recovery time before the next game, although this statement remains speculative. Typically between games with a short recovery cycle, the training week is characterised by an increase in recovery sessions and reduction in training intensity (SkySports, 2016). It may be that on longer turnarounds, coaches may feel players have sufficient recovery time and therefore increase the load placed on the players which may subsequently induce fatigue on the players, affecting their match day running performance. It has been previously reported that in different between match recovery cycles for an elite NRL team, that the mean daily training load was lower on a 5 day between match recovery cycle than on both 7 day, and 9 day cycles (McLean et al., 2010). Large reductions in between-match training loads (measured through session rating of perceived exertion multiplied by session duration) have also been reported for a single ESL team during periods of fixture congestion (4 games in 22 days) (Twist et al., 2017). This provides support that the reduced running performance after longer turnarounds in the current investigation may be due to increased training load, which potentially could result in inducing fatigue and therefore inhibiting running performance. NRL players' neuromuscular performance and perception of fatigue have been shown to be reduced for at least 48 hours following a Rugby League match, but can be recovered to baseline levels after four days with the appropriate training and recovery (McLean et al., 2010). It has been reported that in elite NRL players, plasma creatine kinase concentration remains elevated for 120 hours after a game and that five days of modified activity is required to achieve full recovery to baseline levels (McLellan et al., 2011a). Collectively these findings suggest that players are able to recover fully from the demands of the previous match in the five day recovery cycle, which is aided by decreased training load and thus may explain the present study reporting increased high speed distances after short turnarounds.

A small, but significant difference was evident for the distance covered per minute and low speed distance covered per minute between matches being won and lost, with these being higher for matches that were won. These results are in accordance with previous investigations that suggest competitive success of winning teams is linked closely to their ability to maintain a higher playing intensity in terms of the distance covered per minute over the course of the game (Black & Gabbett, 2014; Gabbett, 2013b). When considering the match result in relation to turnaround, the high speed distance covered per minute was different between winning and losing for each of the between match recovery cycles. An interesting finding is that the matches that were lost following long turnarounds were characterised by a significant reduction in high speed distance per minute than when compared to wins. This offers an explanation towards the difference between games that are won and lost on long turnarounds as when players are unable to cover the same relative high speed distances, the outcome of the game may be more likely to be a loss. This may suggest players are unable to carry out high speed activities with the same ease as on short or medium turnarounds, potentially with fatigue leading to a decreased ability to maintain high-speed kick chase activities and perform covering line breaks. Alternatively it could potentially be suggested that if players were fatigued leading into a game after a long between match turnaround that the players attempted to manage this by kicking the ball out of play more often. Although ball in play time was not investigated in the current study, this would in turn lower the ball in play time which has previously been shown to increase low speed activity (Gabbett, 2015a) which may explain the increase in low speed distance per minute on a long turnaround compared with both short and medium turnarounds in the current study.

Although this was the first study to examine the match running demands of players from multiple ESL teams (six) over different between match recovery periods, there are some limitations of this study that warrant discussion which mainly relate to the data available to be collected from the participating teams. Further data relating to the number of collisions during the games would have been interesting to examine in addition to the running demands outlined here. Secondly data relating to technical and tactical performance of the teams would have provided more information to be able to better contextualise the movement demands. As such, these data was not readily available to be shared by the teams under investigation.

Despite these limitations, the present study highlights significant practical implications for the sports science support team within Rugby League clubs, mainly relating to the structure of the training week throughout the competitive season. The composition of the training schedule in the weeks where the team has a longer turnaround should possibly be likened in some ways to that of a short turnaround to produce the best results and player performance in games. This may suggest that coaches should reduce the training load placed on players during long turnaround weeks in terms of session number and intensity, as well making sure not to neglect recovery protocols often used more rigorously during short turnaround weeks.

In conclusion, the current study has for the first time provided a comprehensive insight into the running demands during match-play of multiple teams in the ESL following different between match recovery lengths. Longer between match turnarounds are associated with a reduction in HSR performance. Moreover, games that are lost following long turnarounds are characterised by decreased HSR elicited by players in comparison to wins. The comparison of this data, along with the differences observed, provide a solid reference for Rugby League practitioners to consider in relation to the association between the length of the recovery period between games, the design of the training schedule for the preparation week and the production of optimal performance levels.

Chapter 9

Synthesis of findings

In this Chapter the reader is presented with a general discussion from the findings of the present thesis. The findings are then outlined in relation to the aims and objectives outlined in Chapter 1. The Chapter then progresses to examining the limitations and practical applications of the findings. Finally, future research directions are presented.

9.1 General Discussion

9.1.1 Knowledge on the analysis of physical demands using GPS

Applied scientific research continues to investigate methods of quantifying the physical demands of team sports. GPS technology is now widely used by elite sports teams to assess player movement patterns. Generally, studies have concluded that GPS devices sampling at 10 Hz and 15 Hz for use in team sports have an acceptable level of validity and reliability for assessing movement patterns in team sports, including Rugby League (Hausler et al., 2015), however 1 Hz and 5 Hz devices have limitations in the capability to quantify short distance linear and multi-directional running. Chapter 5 specifically assessed the level of agreement between two currently commercially available GPS devices (sampling at 10 Hz and 15 Hz) to measure the total distance and HSR distance (> 5.0 $m.s^{-1}$). Previous work has questioned the increase in sampling rate from 10 Hz to 15 Hz, suggesting this provides no additional benefit to the reliability of movement measures (Johnston, Watsford, et al., 2014). The findings from Chapter 5 support this notion given that there were no significant differences (Total distance P = 0.96; HSR P = 0.93), low typical errors (Total distance CV% = 0.8%; HSR CV% = 2.2%) and strong correlations (Total distance $r = 0.99$; HSR $r = 0.99$) between the two devices for both of the movement parameters under investigation. Furthermore the level of error between the two devices was lower than the variation in movement demands between positions in Chapter 4 (Total distance per minute CV% = 4.7%; HSR per minute CV% = 9.1%), and lower than the differences in movement demands between winning and losing teams (Total distance per minute CV% = 5.0%; HSR per minute CV% = 9.3%) (Gabbett, 2013b). The error between devices was quantified in relation to these specific ‘analytical goals’ in order to determine the effective practical use of the two devices (Atkinson & Nevill, 1998). Thus, it was concluded that the two models of GPS device could be used interchangeably to assess the total distance and distance covered at high speed (> 5.0 $m.s^{-1}$) for use in Chapter 6 of this thesis, and is in agreement with previous research that there is no benefit of improving sampling rate from 10 Hz to 15 Hz when assessing athlete movement demands (Johnston, Watsford, et al., 2014).

More recently, GPS technology has been developed to include accelerometers, gyroscopes and magnetometers, allowing the potential quantification of the non-locomotor demands such as physical collisions. GPSports devices traditionally have reported the number of 'impacts' recorded by the accelerometer in G force, however given early work has reported around 800 impacts during a Rugby League game (McLellan & Lovell, 2012), this approach clearly overestimates the number of physical collisions players perform. These findings are confirmed from the results in Chapter 4 of this thesis using the same device, where the total number of impacts above 7G totalled to around 195 per position. As such, manufacturers of GPS devices have developed specific collision detection algorithms using accelerometer data. The findings from Chapter 7 revealed that for the Statsports Viper device, recall (0.81), was lower than precision (1.0), which highlights the error (19%) associated with measuring collisions are related to the ability of the device not correctly identifying a collision. A perfect level of precision shows that there was no error in the device for incorrectly detecting a collision event. Ball carries were more accurately detected (97%) than when compared to tackles (73%), especially when detecting the third man into the tackle (51%). Whilst the level of error was shown to be lower than the differences between the number of collisions by positions reported in Chapter 4 (CV = 29%), the level of error was shown to be greater than the differences in the number of collisions performed between winning and losing games (CV = 1%) (Gabbett, 2013b). Given that the collision detection algorithm was originally developed for use in Rugby Union; this may need refinement for use in Rugby League, especially for detecting tackle events. Indeed, this notion is supported from previous investigations that have adopted collision detection algorithms from other football codes and applied it to others, only to find the algorithm was less successful (Clarke et al., 2016; Gastin et al., 2014).

9.1.2 ESL movement demands

What is clear from reviewing the literature examining the movement demands of elite level competition is that the vast majority of studies have been conducted within the Southern hemisphere NRL competition, with data being limited in the ESL. In addition to our in-depth understanding of the positional demands over the course of 80 minutes of match-play in the NRL (Austin & Kelly, 2013, 2014; Cummins & Orr, 2015; Gabbett, 2012b; Kempton et al., 2014; King et al., 2009; McLellan et al., 2011c; Sirotic et al., 2011; Twist et al., 2014), the physical demands have been analysed to examine the most demanding passages of play (Austin et al., 2011; Johnston & Gabbett, 2011), influence of field positon and phase of play (Gabbett et al., 2014), influence of the opposing team (Gabbett, 2013b), fatigue and pacing strategies (Black & Gabbett, 2014), and demands of successful and less successful teams (Hulin et al., 2014). As such, the overall aim of this thesis was to further increase our understanding of the demands of the ESL competition. Chapter 4 analysed the positional movement demands for a newly promoted ESL team over every game in the 2012 season. From a position specific perspective, the findings from Chapter 4 have confirmed the findings of others that OB typically cover greater distances than PIV and forwards groups (Table 2.2). Although MUF typically spend less time on the field than other positions, the findings from Chapters 4 and 6 together have showed that MUF cover greater distances relative to playing time, again consistent with previous findings (Table 2.2). The total distances reported in Chapter 4 are similar to previous investigations into ESL and NRL match-play (Table 4.9). However the newly promoted team operated at considerably lower overall movement intensities in terms of the distance covered per minute. The lower distance per minute was attributed to a considerable number of game stoppages (mean tries per game 11, mean errors per game 28, ball in play ~ 48 minutes). The distance covered per minute would appear important to match outcome, with greater relative distances covered by semi-elite winning sides (Black & Gabbett, 2014), and NRL winning sides (Gabbett, 2013b). This notion is further supported from the findings in this thesis. The total distance covered per minute for the newly promoted team over the course of match-play in Chapter 6 increased over three seasons, which coincided with increased levels of on-field performance (better league position, more points scored, less points conceded). Furthermore, the findings in Chapter 8 revealed that the distance covered per minute was greater for games that were won than when compared to when games that were lost in a larger sample of six ESL teams (regardless of the between match recovery period) and also when games were won after a short between match recovery period (5-6 days). Collectively, these findings suggest that the ability to maintain high work rates is linked to match outcome in the ESL.

While profiling the total distance travelled during a match is useful, it is also blunt in the information that it provides for practitioners in regards to the structure and intensity of this external activity. Therefore, a comprehensive evaluation of the demands of competition is difficult unless taking into account different 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. It has been established that players perform high-speed activities during critical periods of a match (Austin et al., 2011; Gabbett et al., 2014). The findings from Chapter 4 again confirm the findings of previous investigations that OB perform more HSR and sprinting than other positions, with MUF performing the least amounts. These differences between positions were mirrored in Chapter 6 over three seasons where the high speed distance was expressed per minute of play. Interestingly however, MUF were the only position not to show an increase in HSR over the three seasons. This could be due to their specific role in the game, whereby they are not offered the freedom of pitch position to develop forward locomotion as much as OB for example, who have a much larger area of space in which to progress at high speeds from game situations such as kick-returns and positions during attacking play. The MUF are located in the middle of the field, close to the opposition gain line, and so their capacity to generate high speed is less (Gabbett et al., 2014). Another potential suggestion is that forwards are slower than backs (Meir et al., 2001), preventing the attainment of an arbitrary HSR threshold (> 5.0 $m.s^{-1}$ in this case) with the same ease. The findings from Chapter 4 support these notions given that MUF performed greater cruising (2.7 – 3.8 $m.s^{-1}$), and striding (3.8 – 5.0 $m.s^{-1}$) distances covered per minute, and reached lower peak speeds when compared to other positions. Issues such as these then raise questions on the appropriate speed thresholds in order to assess player movements. There has been little consistency across the literature in the arbitrary velocity zones used for low-, and high-speed activity in Rugby League. Indeed even in the current thesis, the threshold used in Chapter 8 (3.8 $m.s^{-1}$) is lower than the threshold used in Chapters 4 and 6 (> 5.0 $m.s^{-1}$), however this was due to the data that was able to be received from the participating clubs in Chapter 8. There is an argument therefore, that individualised or position specific speed thresholds may provide more detailed information regarding the running demands of Rugby League. This issue is further discussed later in the limitations of the thesis section.

It has been reported that less successful NRL teams perform more HSR than successful teams (Hulin et al., 2014). Other findings suggest there is little difference in the amount of HSR between winning and losing teams (Gabbett, 2013b). The findings from Chapter 4 showed that the less successful, newly promoted ESL team performed more HSR than previously reported for higher ranked ESL teams; however this was still lower than when compared to NRL teams (Table 4.9). Direct comparisons between ESL and NRL competition has shown that NRL players perform more HSR, and better maintain HSR between first and second halves of the game (Twist et al., 2014). Differences in physical capacity are known to influence HSR performance during Rugby League match-play (Gabbett et al., 2013) which might explain some of the observed differences between ESL and NRL. Another factor to consider is players' may adopt pacing strategies. ESL players typically adopt higher intensities in their first exercise bout, followed by a lower, maintainable intensity in the second (Waldron, Highton, Daniels, et al., 2013). Players in the NRL might therefore be encouraged to adopt an even pacing strategy that enables only small reductions in HSR during the second half of a game. Tactical strategies utilised by NRL coaches might also enable the maintenance of HSR during matches.

It has been suggested that it is unclear how players achieve HSR distances in games (e.g. good kick chase in winning teams vs. covering line breaks in losing teams) (Johnston, Gabbett, et al., 2014). As such, Chapters 4 and 6 attempted to address such an issue by examining Opta data. In Chapter 4 a significant amount of HSR was attributed to chasing back players who had broken the newly promoted team's defensive line (given on average they conceded 40 points per game, and the opposition performed significantly more line breaks than they did). Also, given the high number of game stoppages (as previously discussed), players might have been able to perform more high speed efforts in a more stop start game. Indeed it has been suggested that less successful teams are equally equipped as their more successful counterparts to perform HSR efforts, but perhaps cannot recover as quickly (Gabbett, 2013b). This notion is supported from the evidence in Chapter 6 where it was shown that as performances improved, players from the newly promoted team were able to perform more HSR over the three seasons, even though the ball was in play for longer and game stoppages were reduced.

9.1.3 Collisions and their relevance

Players require the ability to perform and withstand physical collisions during both attacking and defensive phases of play (Gabbett et al., 2010). The defensive play of tackling is integral to performance, where the ability to effectively perform a winning tackle may prove critical in determining the outcome of the game (Gabbett, 2013c). The attacking play of ball carrying and the ability to tolerate being tackles is important for gaining distance and field position (Gabbett, 2013c). The previous section of this general discussion showed that the findings from this thesis indicate that forwards' (specifically MUF) HSR demands are lower than other positions. Chapter 4 has revealed that MUF and WRF perform a similar amount of collisions over the course of 80 minutes, more than PIV and OB. When expressed relative to playing time in Chapters 4 and 6, the amount of relative collisions MUF have to perform are far greater than any other position. Previous findings have shown that teams in the NRL who perform the greatest number of collisions have improved chances of winning (Hulin et al., 2014). This findings has been confirmed by others investigating semi-elite competition (Hulin & Gabbett, 2015). Findings into the number of collisions performed in relation to performance are somewhat equivocal in this thesis. In Chapter 4, it was shown that the newly promoted team performed more carries, tackles, and subsequently more collisions than their opposition, which may indicate less successful performances are characterised by a greater number of collisions. However, in Chapter 6, the number of collisions performed by the team increased over the three seasons, as did on-field performance. It has been suggested that successful teams who perform more collisions are better equipped at slowing the 'play-the-ball' while defending. This is potentially achieved by tactical strategies that employ more players to compete each tackle on more occasions (i.e. 2 and 3 players per tackle on a greater number of occasions), resulting in: (1) a greater number of collisions, as more players are involved in each tackle and (2) a slower 'play' that may not require the need for players to cover greater total distance or HSR (Hulin et al., 2014). In Chapter 6 the tackle success percentage of the team increased over the three seasons, therefore less tackles were being missed which would lead to a greater number of collisions. The ball was in play for longer over the three seasons, which as suggested in Chapter 6 would lead to a relative increase in playing action, also increasing the number of collisions. However, it is questionable whether this resulted in a 'slower play' as previously suggested (Hulin et al., 2014), as the relative distance and HSR distance also increased over the three seasons. Given the number of line breaks made against the team reduced over the three seasons, it would suggest the increased relative distance and HSR distance would not have been achieved as a result of poor defence and missed tackles, leading to players chasing back the opposition.

It has been suggested that in addition to the frequency of collisions, the magnitude of collisions is also vital in determining match outcome (Cummins & Orr, 2015), however there is no study to date that has specifically examined this relationship. The introduction of GPS embedded accelerometers, magnetometers and gyroscopes has led to practitioners being potentially able to measure collision magnitude, however given the 19% error for measuring a collision event outright in Chapter 7 using GPS, the algorithm used to detect a collision event outright needs to be improved before the magnitude of these collisions can be examined in relation to match outcome.

9.2 Achievement of aims and objectives

The overall aim of this thesis was to examine and further increase our understanding of the physical match demands of elite Rugby League match-play in the European Super League. The aims of the thesis have been realised through a series of interlinked studies evaluated in sequence.

Objective 1 - To profile the physical demands of ESL match-play over the course of an entire season within specific positional groups for a newly promoted team.

Objective 1 was addressed in Chapter 4. This chapter provided preliminary evidence that the HSR and collision demands are greater for lower ranked ESL teams than higher ranked teams, but these are still lower than those experienced in the NRL. Significant differences were observed between positions which can be used as a reference for Rugby League practitioners to follow when designing conditioning and training regimes. The comparison of data from training drills to the data outlined in this study can inform coaches of newly promoted sides if they are adequately preparing their players for the physical demands of elite level competition. It was therefore concluded that Objective 1 of the thesis was successfully achieved.

Objective 2 - To establish if any differences exist between two current commercially available GPS units to measure movement demands in order that they can be assessed interchangeably and seamlessly with the two different models of device.

Objective 2 was addressed in Chapter 5. The data demonstrated that there were no significant differences, low typical errors and strong correlations between the two devices in terms of the total distance covered and the high speed distance (above 5.0 $m.s^{-1}$). Furthermore the agreement between devices was considered acceptable in relation so specific analytical goals from positional data in Chapter 4, and considering the differences between games that are won and lost. This led to the conclusion that the two models of device could be used interchangeably to assess these movement demand variables in the following chapters. It was therefore concluded that Objective 2 of the thesis was successfully achieved.

Objective 3 - To examine if there is an evolution in competitive physical demands over a three season period for the newly promoted team with increased exposure to training and ESL competition.

Objective 3 was addressed in Chapter 6. The findings from this Chapter revealed there was an increase in physical match intensity of ESL competition for a newly promoted team over a three season period in terms of the total distance covered per minute, high speed distance covered per minute, and number of collisions per minute. Coaching and conditioning staff need to be aware of these increased demands when designing training and conditioning regimes, and newly promoted teams need time to develop and adapt to the increasing demands of ESL competition. It was therefore concluded that Objective 3 of the thesis was successfully achieved.

Objective 4 - To establish if the most recently developed model of GPS device to be used in this thesis can automatically detect collision events during Rugby League match-play against those coded from video footage.

Objective 4 was addressed in Chapter 7. The data from this Chapter concluded that the Statsports Viper device can detect the majority of collisions during Rugby League match-play. The error (19%) associated with measuring collision events is related to the ability of the device not correctly identifying a collision has occured. There was no error in the device for incorrectly detecting a collision event. Ball carries (97%) were more accurately detected than tackles (73%). It was therefore concluded that Objective 4 of the thesis was successfully achieved.

Objective 5 - To examine the differences in match movement intensity across different recovery periods between games for a greater number of ESL teams.

Objective 5 was assessed in Chapter 8. Longer between match turnarounds were associated with a reduction in HSR performance. Moreover, games that were lost following long turnarounds were characterised by decreased HSR elicited by players in comparison to wins. It was therefore concluded that Objective 5 of the thesis was successfully achieved.

9.3 Limitations of the thesis

Although this thesis has provided novel data for the literature it is not without limitations, many of which are a direct consequence of collecting data from elite athletes outside of the controlled laboratory environment. These limitations are now discussed.

Sample size

The findings from Chapters 4, 6 and 7 are from a single professional Rugby League team and this the findings are difficult to generalise for other teams. In Chapter 7 (collision detection study) analysing a greater number of players, games, and teams (who may show variation in the tactical approach to carrying the ball and tackling) would be beneficial in understanding this area further. Whilst data from multiple teams were used in Chapter 8, future studies might consider collecting data from a variety of teams to increase sample size and the statistical power of results, especially for examining longitudinal studies such as in Chapter 6.

Switch in GPS equipment

The switch in GPS equipment part way through the 2013 season for the club under investigation in Chapter 6 is a limitation of the data collected. However such challenges exist in applied professional sport, where new technology is currently being developed and distributed to elite teams. The switch to the Statsports device allowed the potential automatic detection of collisions as examined in Chapter 7, and the company signed a league wide deal in the following years which meant every team was using the same GPS device (as in Chapter 8). Whilst Chapter 5 attempted to address the issue of a switch in GPS equipment, this remains a limitation.

Absolute vs relative speed zones

In this thesis, absolute speed zones have been used to distinguish between the movement intensities of players. These have traditionally been used to analyse the movement demands of Rugby League match-play in the literature (Austin & Kelly, 2013, 2014; Gabbett, 2012b; McLellan & Lovell, 2013; McLellan et al., 2011c; Waldron, Twist, et al., 2011). Emerging research suggests the use of individualised speed thresholds may provide a more accurate picture of the positional running demands of Rugby (Dwyer & Gabbett, 2012; Reardon, Tobin, & Delahunt, 2015; Scott, Thornton, Scott, Dascombe, & Duthie, 2017) and Soccer players (Abt & Lovell, 2009), especially when examining the distance covered at high speed. The traditional method of using absolute thresholds has been shown to both underestimate and overestimate the distance covered at high intensity (Abt & Lovell, 2009; Reardon et al., 2015; Scott et al., 2017), which is dependent upon the individual player characteristics. Preliminary data on players' running abilities would be required to establish these individual thresholds, and these would have to be monitored and adjusted over the course of time based on the fitness status of the player. This approach may not always be possible especially during the in-season period, when assessments of players' fitness and speed qualities cannot be obtained on a regular basis due to the demands of the competitive schedule. However the approach of using individualised thresholds may allow for better prescription and monitoring of external training loads based on measured individual physical capabilities.

Analysing in-game epochs

Throughout this thesis, the physical demands of the game have been analysed over the full 80 minutes of match-play. Whilst this gives a global picture of the physical intensity of the game, the average match intensity over 80 minutes does not reflect the most demanding passages of match-play (Austin et al., 2011; Gabbett, 2015a; Gabbett et al., 2014). For example, the total distance covered per minute of match-play has been shown to be significantly greater when assessing only ball in play time (125 vs. 98 $m.min^{-1}$) (Gabbett, 2015a). In addition the total distance per minute can vary depending on field position and the phase of play. The total distance covered per minute is greatest when defending in the oppositions 0-30 m zone, compared with defending in the teams own 0-30 m zone (117 vs. 100 $m.min^{-1}$) (Gabbett et al., 2014). As such, examining this information for the newly promoted team over time may have increased our knowledge of the game demands even further.

Examining heart rate data in Chapter 6

As heart rate data was examined in Chapter 4, it would have been interesting to examine such data in the longitudinal follow up study (Chapter 6) in order to examine how the internal physiological demands had altered as a result of the increasing external demands. In the 2012 season the coaching staff at the club made it compulsory for all players to wear a heart rate device during games. Following on in 2013 and 2014, the coaching staff then made this optional due to considerable player dissatisfaction at having to wear the device, which unfortunately meant there was a considerable amount of data missing over the 2013 and 2014 seasons.

Examining collision and Opta data in Chapter 8

Whilst Chapters 4, 6, and 7 examined the collision demands of match-play, Chapter 8 only examined the movement demands. Unfortunately collision data (either from Opta or GPS), and Opta data to contextualise the movement demands was not ready available to be shared by the participating clubs. Examining such information would have increased the knowledge in this area.

9.4 Practical Implications

The following is a summary of key practical recommendations/findings that have been identified through completion of the present thesis:

1. There are significant positional differences in physical match demands and these should be accounted for when designing training regimes for players.
2. For newly promoted teams, it is important to expose players to typical HSR and collision volumes and intensities that they may expect to encounter in games to ensure that players are robust enough to handle the demands of competition. The pre-season period therefore is of utmost importance to expose players to such demands in training.
3. For practitioners who have collected longitudinal data over multiple seasons using the GPSports SPI Pro XII, and Statsports Viper GPS devices, these can be used interchangeably to assess the total distance covered and the distance covered at high-speed (above 5.0 $m.s^{-1}$).
4. Coaches and conditioning staff need to be aware of the recent increases in the physical demands of match-play and highlights the importance of being able to

continually monitor physical match outputs to provide and re-evaluate benchmark positional data.

5. Newly promoted teams need time to develop and adapt to the increasing demands of ESL competition. This is a pertinent issue for those responsible for organising the league structure given the recent re-introduction of promotion and relegation. With the current structure, newly promoted teams will not have the chance to plan and develop over the long term.
6. The Statsports Viper device can detect the majority of ball carries during Rugby League match-play (97%), however practitioners should be cautious when examining the number of tackles (73% accuracy) especially for second man, (72% accuracy) and third man tackles (51% accuracy).
7. The composition of the training schedule in the weeks where ESL teams have a longer between match recovery periods should possibly be likened in some ways to that of a short turnaround to produce the best results and player performance in games. This may suggest that coaches should reduce the training load placed on players during long turnaround weeks in terms of session number and intensity, as well making sure not to neglect recovery protocols often used more rigorously during short turnaround weeks.

9.5 Recommendations for future research

The studies completed within this thesis have provided novel information relating to the physical demands of elite rugby league match-play. In achieving the aim of the thesis, several issues and subsequent findings have promoted the formulation of recommendations for future research. These will now be discussed.

Suggestions arising from Chapter 4:

The work from this chapter revealed there were significant positional differences for the physical match demands for a newly promoted ESL team. Whilst the differences between positions are in line with previous work in this area, the novel findings from this chapter were that the HSR and collision demands were greater for the low ranked ESL team under investigation than higher ranked teams in previous research, but these were still lower than those experienced in the NRL. Whilst such a situation would be difficult to replicate in research at the moment given the return of promotion and relegation (as the team was competing under the franchise system), it would be interesting to profile the demands for a newly promoted team over an entire season who were not competing under the ESL franchise structure to see if there were any differences in the physical intensity of play compared with the current investigation.

Suggestions arising from Chapter 5:

The data from Chapter 5 revealed that the GPSports SPI Pro XII and Statsports Viper devices could be used interchangeably to assess the total distance covered and high-speed distance (> 5.0 $m.s^{-1}$). Whilst the level of agreement was important to establish for use of the two devices in Chapter 6, future research that examines longitudinal data where a change in technology was used should aim to conduct similar type investigations using the parameters specific to the research question and appropriate analytical goals.

Suggestions arising from Chapter 6:

The findings from this Chapter revealed there was an increase in the physical demands of ESL competition for a newly promoted team over a three season period in terms of the total distance covered per minute, high speed distance covered per minute, and number of collisions per minute. Future studies should now use a greater sample of ESL teams to determine if there has been a league wide increase in the physical demands of match-play in recent times.

Suggestions arising from Chapter 7:

The data from this Chapter concluded that the Statsports Viper device can detect the majority of collisions during Rugby League match-play. Ball carries (97%) were more accurately detected than tackles (73%). Whilst this suggests the device could potentially be used to assess the number of collisions during match-play, the manufacturers of the device also claim to be able to detect the intensity of collisions using a "collision load" metric. The speed of the player into the collision and instantaneous initial impact is factored in to produce the collision load score. Future studies should assess the accuracy of this claim in a controlled laboratory, using three-dimensional motion analysis as the criterion measure.

Suggestions arising from Chapter 8:

The findings from this study provided a comprehensive insight into the running demands during match-play of multiple teams in the ESL following different between match recovery lengths. Longer between match turnarounds were associated with a reduction in

HSR performance. Moreover, games that were lost following long turnarounds were characterised by decreased HSR elicited by players in comparison to wins. One of the suggestions for these differences was the composition of the training schedule, whereby an increased training load was prescribed to players during weeks with a long between match recovery periods, causing fatigue leading into the next game. Whilst this suggestion is speculative, this data could be examined in a follow up study where the training load of teams is examined over the different between match recovery schedules. The number of collisions during the games under investigation could also be examined providing further insights into the physical demands over these periods.

9.6 Conclusion

In conclusion, this applied thesis has provided novel information and successfully increased our knowledge of the physical demands of ESL match-play focusing on a newly promoted franchise. Specifically, this is the first work to examine the physical demands of competition for an entire squad of players across an entire competitive season in the ESL, the first to examine how the physical demands of match-play have changed over longitudinal seasons, and the first to examine the effects of different between match recovery periods on the running demands for a large sample of ESL teams. Methodological work in this thesis has also highlighted the importance of quantifying and interpreting errors associated with GPS devices to quantify player movements and collisions.

Chapter 10

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