THE DEVELOPMENT OF A NOVEL RUGBY LEAGUE MATCH SIMULATION PROTOCOL

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor of Philosophy

by Dave Sykes

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I certify that all work is in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

 **(Signature)**

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GLOBAL ABSTRACT

The effectiveness of recovery interventions following prolonged multiple sprint team sports matches has rarely been studied despite the potential for exercise-induced muscle damage to adversely affect training in the days following games. The lack of research related to this topic is probably owing to the wide variability that exists in the movement demands of players between matches and the impact that this has on the subsequent rate and magnitude of recovery which makes it difficult to detect meaningful differences when conducting research with small sample sizes. Therefore, the purpose of this thesis was to develop a rugby league-specific match simulation protocol that replicates the movement demands, physiological responses and subsequent recovery from matches in order to study the effectiveness of recovery interventions.

Hence, two time-motion analysis studies were conducted using a semi-automated image recognition system to inform the development of the rugby league match simulation protocol (RLMSP). Whilst mean total distance covered over the duration of the match was 8,503 m, ball in play and stoppage work-to-rest ratios were 1:6.9 and 1:87.4, respectively, for all players. Furthermore, a significant decline in high and very high intensity running locomotive rates were observed between the initial and final 20 min periods of the match.

Thus a RLMSP was devised to replicate the overall movement demands, intra-match fatigue and recovery from a senior elite rugby league match. Not only was there a low level of variability in the movement demands during the RLMSP over consecutive trials, but with the exception of creatine kinase, the rate and magnitude of recovery following the RLMSP was similar to that that has been published following competitive matches. Therefore, the RLMSP devised in this thesis may be a more appropriate research tool for assessing the effectiveness of recovery interventions following match related exercise than following actual match play.

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ABBREVIATIONS

%Δ	percentage change
% HR_{max}	percentage maximum heart rate
%TEM	relative technical error of measurement
%TT	percentage total time
%BM	percentage body mass
2D	2-dimensional
3D	3-dimensional
AIR	automated image-recognition
AMP	adenosine monophosphate
ANOVA	analysis of variance
ATP	adenosine triphosphate
BM	body mass
BURST	Bath University rugby shuttle test
CAPTAIN	computer all-purpose time-motion analysis integrated
CK	creatine kinase
CMJ	countermovement jump
COD	change of direction
CoV	coefficient of variation
dGPS	differential global positioning system
DJ	drop jump
DOMS	delayed onset muscle soreness
EIMD	exercise-induced muscle damage
FFA	free fatty acids
GPS	global positioning system
H:Q	hamstring: quadricep ratio
HR	heart rate
HR_{max}	maximum heart rate
HR-$\dot{V}O_2$	heart rate to oxygen uptake
HSR	high speed running
ICC	intraclass correlation coefficient
IMP	inosine monophosphate

LIST	Loughborough intermittent shuttle test
LoA	limits of agreement
Mb	myoglobin
MDA	malondaldehyde
MIVC	maximal isometric voluntary contraction
NdGPS	non-differential global positioning system
NH_3	ammonia
NMT	non-motorised treadmill
PHIR	prolonged high intensity intermittent running simulation protocol
PMSTS	prolonged multiple sprint team sports
POMS	profile of mood states
POWER	periods of work efforts and recovery
RFID	radio frequency identification
RLMSP	rugby league match simulation protocol
ROS	reactive oxygen species
RPE	rating of perceived exertion
SD	standard deviation
SAIR	semi-automated image-recognition
SEE	standard error of estimate
SJ	squat jump
SSC	stretch-shortening cycle
SSEP	soccer specific exercise protocol
SSIET	soccer specific intermittent exercise test
SSSP	soccer specific simulation protocol
TD	total distance
TE	typical error
TMA	time-motion analysis
UA	uric acid
$\dot{V}O_2$	oxygen uptake
$\dot{V}O_{2\max}$	maximal oxygen uptake
$v\dot{V}O_{2\max}$	speed at $\dot{V}O_{2\max}$
WRR	work-to-rest ratio

CHAPTER ONE

INTRODUCTION

1.1 Movement demands of competitive rugby league matches

Rugby league is an intermittent team sport played between two teams of 13 players with a maximum of 12 interchanges from a pre-determined 17 named players during the course of a match. Each team is allowed six tackles with the ball (referred to as a set) and following each tackle, a 'play-the-ball' takes place to reintroduce the ball back into play (Meir et al., 2001a) with the defending team required to retire 10 m from the point of the play-the-ball or to the team's goal line (Meir et al., 2001a). After the completion of each set of six tackles, or when an error or interception occurs, the ball is handed over to the opposition to commence its set of six tackles (Gabbett et al., 2008). The match is played over two 40 minute halves (excluding injury time) with a 10 minute interval between halves. Individuals are classified based on their positional roles into one of nine positions (props, hookers, second rowers, loose forwards, scrum halves, stand-offs, centres, wingers and fullbacks), or into subgroups as defined by Gabbett (2005) as props, back rowers (second row and loose forwards), pivots (hookers, scrum halves and stand offs) and outside backs (centres, wingers and full backs).

Based on the analysis of four players from two professional clubs, Meir et al. (2001a) suggested that prior to the introduction of the 'limited interchange' rule in 2001, the total distance (TD) covered was between 8,458 and 9,929 m during a competitive match, depending on playing position, and that work-to-rest ratios (WRRs) were 1:10 for hookers, 1:7 for props, 1:12 for scrum halves and 1:28 for wingers. In comparison, a post-2001 analysis conducted by King et al. (2009), reported relatively little positional variation (1:5-1:6). More recently, Sirotic et al. (2009) reported a mean locomotive rate of 106 $m \cdot min^{-1}$ for elite Australian players, which equates to a TD covered of 8,517 m for those playing the entire match. However, no attempt was made to explore whether there were positional differences due to the low sample size. Furthermore, the accuracy of the data for the aforementioned studies was heavily reliant on the ability of the observer (Di Salvo et al., 2006) with data generated either from subjective analysis of gait, with arbitrary velocities being associated with each locomotive category (Meir et al., 2001a; King et al., 2009), or using a scaled drawing tablet to track the movements of the players (Sirotic et al., 2009). Therefore, the use of time-motion analysis (TMA) methods with less subjectivity, for instance semi-automated image recognition (SAIR) tracking systems or global positioning systems (GPS), would be beneficial for assessing the overall movement demands of competitive matches. Whilst concerns over the safety of GPS in contact sports have, in the past, prevented their usage in official matches (Di Salvo et al., 2006), recent changes in the stance taken by national governing bodies have facilitated the use of a commercially available, non-differential GPS (NdGPS) to monitor the movement demands of rugby league matches (McLellan et al., 2010, 2011a, 2011c). Similar results were reported for both studies, with mean distances reported to range from 4,774-4,982 m for forwards and 5,573-5,747 m for backs, which is noticeably lower than previously reported via other TMA systems. Moreover, given the inconsistencies in the reported time-motion demands of competitive rugby league matches, the small sample sizes utilised, the questionable accuracy of the data and lack of analysis of the various phases of play within a match, a more in-depth analysis of the movement demands of competitive rugby league matches is warranted. Furthermore, following the demonstration of the validity (Di Salvo et al., 2006) and reliability (Bradley et al., 2009, 2010; Di Salvo et al., 2009) of SAIR tracking systems as a non-intrusive method for quantifying movement velocities of multiple players during match play (Di Salvo et al., 2006), SAIR tracking systems have been used to quantify the overall demands (Bradley et al., 2009, 2010; Di Salvo et al., 2007; Rampinini et al., 2007b) and monitor changes in exercise intensity (Bradley et al., 2009; Carling and Dupont, 2011; Di Salvo et al., 2009; Rampinini et al., 2009) throughout competitive soccer matches.

1.2 Recovery following competitive rugby league matches

Exercise-induced muscle damage (EIMD) is a well documented phenomenon following unaccustomed eccentric muscle actions (Byrne et al., 2004; Vaile et al., 2008), which are a common occurrence in intermittent team sports where there are a high number of accelerations and decelerations (Osgnach et al., 2010). Immediately following activities which incorporate eccentric muscle actions, electron microscopathy has demonstrated disruption to sarcomeres in myofibrils, t-tubule damage and Z-line streaming (Close et al., 2005). The level of muscle damage is then amplified in the subsequent 1-3 d by the inflammatory response (Armstrong et al., 1991). During this period, the increased membrane permeability results in an increased influx of fluid into the muscle (Smith, 1991), which together with hypersensitivity of sensory nerves (Newham et al., 1987) exacerbates muscle soreness. The result is a peak in muscle soreness 1-2 d post-exercise, a phenomenon known as delayed onset muscle soreness (DOMS; Cleak and Eston, 1992). In addition, unaccustomed eccentric muscle actions typically result in increases in intracellular proteins (e.g. creatine kinase; CK) in the blood (Vaile et al., 2008; Byrne and Eston, 2002), muscle stiffness (Cleak and Eston, 1992), reductions in muscle strength and power (Thompson et al., 1999; Cleak and Eston, 1992; Byrne and Eston, 2002; Twist and Eston, 2005; 2007), and impaired sprint and agility performance (Twist and Eston, 2005; Highton et al., 2009), in the days following exercise. Unsurprisingly, similar findings have been reported in the days following rugby league matches with general muscle soreness elevated 1 d following a competitive rugby league match (McLean et al., 2010) and CK raised for up to 5 d following (McLellan et al., 2010, 2011a, 2011b). In addition, muscle function has been reported to be impaired for up to 2 d following a competitive rugby league match (McLean et al., 2010; McLellan et al., 2011b).

From an applied perspective, this has obvious implications for the quality of training in the days following a match. Therefore, the identification of recovery strategies which can attenuate the severity of the muscle soreness and reduce the loss in muscle function or speed up the return to baseline would be hugely beneficial to practitioners. From a research perspective, the exercise stimulus used to stimulate muscle damage in studies should be related to the sports activity from which recovery is sought (Falvo and Bloomer, 2006). Therefore, in an ideal world the effectiveness of recovery interventions would be studied in the days following competitive matches. However, given the variability in match demands due to the opposition and the tactics employed, and the reluctance of professional sports players to change their regular training and recovery routines following matches, research into recovery strategies ‘in the field’ is problematic. Therefore, having an ecologically valid model of competitive matches with reproducible movement demands would enable controls to be put in place in order to isolate and study the effectiveness of recovery strategies in the days following match-related exercise. Furthermore, given the large inter-match variability of movement parameters observed in elite soccer matches (Gregson et al., 2010; Mohr et al., 2003; Rampinini et al., 2007b), a protocol that incorporates performance measures with low levels of variability, could be useful for measuring the impact of training leading up to matches on physical match performance.

1.3 Aims of the current research

Whilst previous studies have utilised downhill running (Eston et al., 1996; Chen et al., 2007), high volume plyometric (Avela et al., 1999; Twist and Eston, 2005; 2007) and resistance exercise (Byrne and Eston, 2002; Vaile et al., 2007), few have investigated the impact of sport-specific exercise on changes in muscle soreness, muscle function and other markers of EIMD (Falvo and Bloomer, 2006), despite eccentric muscle actions being a common occurrence in prolonged multiple sprint sports (PMSTS)-matches (Fridén et al., 1988). Therefore, the principal aim of the current programme of research was to develop an ecologically valid and reliable research tool for evaluating the effectiveness of interventions on recovery following rugby league matches.

Previous studies investigating the movement demands of competitive rugby league matches have been conducted prior to the aforementioned limited interchange rule in 2001 (Meir et al., 2001a), have been generated from subjective analysis of gait (King et al., 2009; Meir et al., 2001a), were based on a small data set (McLellan et al., 2010, 2011a; Meir et al., 2001a) or were based on players from just one team (King et al., 2009; McLellan et al., 2010, 2011a, 2011c; Meir et al., 2001a; Sirotic et al., 2009). In addition, studies have failed to differentiate between positions (Sirotic et al., 2009) and to date none has accounted for the differences in the movement demands of phases of the game. Therefore, Studies One and Two of this thesis set out to investigate the in-depth movement demands of competitive rugby league matches, which could be used by practitioners to (i) improve the specificity of their training and (ii) develop an ecologically valid and reliable match simulation protocol for use as a research tool.

Whilst indoor running (Nicholas et al., 2000) and motorised treadmill (Drust et al., 2000) simulation protocols exist for replicating the demands of soccer match-play, the game of rugby league is distinctive from soccer, not only by the inherent contact element, but in its movement demands and the duration of its matches. Therefore, the aim of Study Three was to report how the movement demands and physiological responses of non-elite, active sportsmen participating in the rugby league match simulation protocol (RLMSP) compared to those observed during competitive matches (Study One). In addition, Study Three aimed to evaluate the degree of variability in the movement demands and physiological responses elicited during the RLMSP over repeated trials.

Finally, Study Four was designed to evaluate the efficacy of the RLMSP for inducing EIMD to an extent similar to that observed following competitive matches (McLean et al., 2010; McLellan et al., 2010, 2011a, 2011b, 2011c). Changes in CK, perceived muscle soreness, neuromuscular function and perception of effort and heart rate (HR) during an intermittent running protocol were assessed at 1, 2, 3 and 7 d following the RLMSP.

CHAPTER 2

LITERATURE REVIEW

2.1 A historical perspective on the use of time-motion analysis systems in prolonged multiple sprint team sports

Prolonged multiple sprint team sports (PMSTS) (including: rugby league, rugby union, soccer, Australian rules football and hockey) incorporate maximal or close to maximal intensity sprints over relatively short distances, interspersed with periods of low intensity exercise or rest, over a duration of 80-108 min (excluding added time). However, the typical intensity and duration of work and rest periods, and duration of the match, is specific to each sport and also playing position. The various time-motion analysis (TMA) systems that have evolved in order to quantify the movement demands of match play during PMSTS are discussed in the following section.

2.1.1 Gait analysis

In one of the first studies to evaluate the movement demands of PMSTS, Mayhew and Wenger (1985) classified players into locomotive categories based on observer's subjective analysis of gait using the following operational definitions: standing (no locomotor movement); walking (forwards, sideways and backwards strolling locomotor movement); jogging (non-purposeful, slow running where the individual did not have a specific goal for his movements, such as to recover on defence); running (running with purpose and effort); utility (backwards running, sideways shuffling or jumping). This method necessitates that the pan and tilt function on the camera are used to track individual players at a focus that allows a field of view ~5 m either side of the player. This is to ensure adequate player resolution without the loss of frames as a result of the video analyst not being able to react quickly enough to rapid changes of direction by the player. As a result of the need to have one camera tracking each individual player it is likely that only one player can be tracked per match making this an extremely time consuming procedure.

Once classified into these movement classifications, data can either be reported as a percentage of total time (%TT) spent in each of the categories or generic arbitrary velocities applied to the absolute time in each category in order to calculate a distance covered in each locomotive category (Krustrup and Bangsbo, 2001). For example, Krustrup et al. (2002) assigned the following velocities to each locomotive category: standing (0 $km \cdot h^{-1}$), walking (6 $km \cdot h^{-1}$), jogging (8 $km \cdot h^{-1}$), low speed running (12 $km \cdot h^{-1}$), moderate speed running (15 $km \cdot h^{-1}$), high speed running (18 $km \cdot h^{-1}$), sprinting (25 $km \cdot h^{-1}$), sideways movements (12 $km \cdot h^{-1}$), and backwards movement (10 $km \cdot h^{-1}$) which were selected by calculating the mean speed for each locomotive activity from videotapes of participants moving between pitch markings of known distance. However, given that the velocity at which they perform the various locomotive movements are likely to be very specific to the individual, especially in the faster movement categories depending on participants' maximal speed, the estimation of distances from gait analysis may not be all that accurate. Indeed, through undertaking the same piloting process as Krustrup et al. (2002), Mohr et al. (2003) assigned a velocity of 30 $km \cdot h^{-1}$ to sprinting. Hence, an individual who was adjudged to have spent 50 s sprinting during the match, would be calculated as having sprinted 345 m using the method by Krustrup et al. (2002) and 415 m (20% greater) using that of Mohr et al. (2003). In addition, calculating distances not only assumes that the velocity is the same for all individuals classified into that locomotive category, but that the velocity is constant throughout the movement (Duthie et al., 2005).

Only recently has an attempt been made to assess the accuracy of the distances and velocities calculated from these analyses in comparison to criterion measurements (Doğramaci et al., 2011). Whilst the relative technical error of measurement (%TEM) for total distance (TD) covered was 2.1%, which according to Duthie et al. (2003) suggests good agreement, there is an assumption in calculating the criterion distance from the measured layout of the circuit that participants move in a straight line between markers and make 'tight' turns. Furthermore, as participants were required to change their locomotive movements in response to verbal commands to stand, walk, jog, run, sprint or move backwards or sideways, calculation of the criterion distances in each locomotive category using this method assumes that participants accurately respond to the audio cues and move at a constant velocity between locations. Therefore, the 'criterion' distances for each locomotive action may not be all that precise, making comparisons between the calculated and 'criterion' distances for discrete locomotive actions invalid.

In addition, the reliability of this method is reliant on the initial classification of the locomotive category correctly. Withers et al. (1982) reported that inter-operator correlation coefficients for distance covered in each locomotive category ranged from 0.989 to 0.815 with the lowest calculated for striding and sprinting (>5% difference between operators in distance covered sprinting). Similarly, mean inter-operator %TEM has been reported to be 4.7% for %TT spent in each of the locomotive categories (Deutsch et al., 2007) (Table 2.1). Furthermore, intra-operator %TEM has been reported to range from 2.4-10.2% for movement frequency (Deutsch et al., 2007; MacLeod et al., 2007; Spencer et al., 2004) and 3.4-9.5% for mean time in each locomotive category (Deutsch et al., 2007; MacLeod et al., 2007; Spencer et al., 2004) (Table 2.2). Given that a %TEM of 5-9% suggests moderate agreement (Duthie et al., 2003), the movement demands derived from gait analysis are for most locomotive categories moderately reliable but the inter- and intra-operator reliability of high intensity activities is poor (Duthie et al. 2003). Given that changes in the distance covered in locomotive categories within a match may be small, changes in locomotive categories (especially higher intensity activities) may not be detectable using gait analysis to monitor movement demands.

An evolution of manual gait analysis was the development of the Computerised All-Purpose Time-Motion Analysis Integrated (CAPTAIN) system (O'Donoghue, 1998) whereby operators coded the match verbally onto audio cassette using a portable dictation machine. However, the reliability of this system is poor as a result of the reaction time required to classify the movements together with the subjective classification of the movements (O'Donoghue, 2008).

Table 2.1 Inter-operator reliability of various manual-operated TMA systems

TMA system	Manufacturer (If applicable)	Study	Measure	Movement path	Movement velocity	Reliability statistics	Interpretation of reliability
Gait analysis	Not applicable	Withers et al. (1982)	Distance	Match	Intermittent	r=0.989-0.815	Good
		Deutsch et al. (2007)	%TT	Match	Intermittent range	%TEM: 4.7%	Good
Drawing tablet	Sportstech	Edgecomb and Norton (2006)	Distance	Match	Intermittent	%TEM: 6.1%	Moderate
	ProZone MatchViewer	Bradley et al. (2007)	Positional location	Match	Intermittent	95%LoA: 8.5 m TE: 3.1 m	Moderate
Manual digitisation in a calibrated area	Not applicable	Roberts et al. (2006)	Distance	Multi-directional circuit	Intermittent	95%LoA: 11.6 m TE: 4.2 m CoV: 0.9%	Moderate

Table 2.2 Intra-operator reliability of assessing match movement demands from gait analysis

Study	Measure	Movement velocity	Reliability statistics	Interpretation of reliability
MacLeod et al. (2007)	Movement frequency	Walking	%TEM: 2.4%	Good
		Jogging	%TEM: 2.9%	Good
		Sprinting	%TEM: 7.6%	Moderate
	Mean time	Walking	%TEM: 3.4%	Good
		Jogging	%TEM: 9.5%	Moderate
		Sprinting	%TEM: 5.7%	Moderate
Deutsch et al. (2007)	Movement frequency	Intermittent	%TEM: 4.6%	Good
	Mean time		%TEM: 1.8%	Good
	%TT in locomotive category		%TEM: 1.6%	Good
Spencer et al. (2007)	Movement frequency	Intermittent	%TEM: 5.4-10.2%	Moderate-poor
	Mean time		%TEM: 5.7-9.8%	Moderate
King et al. (2009)	%TT in locomotive category	Intermittent	TE: 2.2-11.8% 95%LoA: 6.1-32.7%	Moderate-poor
Dogramaci et al. (2011)	TD	Intermittent	%TEM: 11.1%	Poor

A further modification of this system was the simplification to the Periods of Work Efforts and Recovery (POWER) system (O'Donoghue et al., 2005), which involved simply coding the locomotive activity as either 'work' or 'rest' for quantification of work-to-rest ratios (WRRs). By reducing the number of movement classifications to just two, its reliability is likely to be better than the CAPTAIN system owing to fewer changes in movement activity. Indeed, an analysis of the reliability of the time spent in each movement classification in the POWER system revealed kappa values ranging from 0.7028 to 0.9327, which is indicative of good to very good reliability (Altman, 1991; O'Donoghue, 2007). Whilst this provides a good indication of the intermittent nature of the activity, including frequency and duration of high intensity bouts, recovery durations and repeated work bouts, the detail provided would not be sufficient enough to monitor changes in intensity throughout a match or develop match simulation protocols. For example, whilst a player might spend the same amount of time 'working' during successive 15 min periods of a match, the intensity at which work is performed during each 15 min period maybe somewhat different.

On the basis of intra- and inter- reliability issues and a lack of scientific evidence for its accuracy, the value of the data pertaining to distances obtained from subjective gait analysis may be questionable.

2.1.2 Manual digitisation on a drawing tablet

Pioneering work by Reilly and Thomas (1976) attempted to verbally record the locomotive action of soccer players and approximate distance of discrete locomotive movements using line markings from learned maps of the pitch whilst watching matches live. Thereafter, this method was performed retrospectively from video footage by plotting player path on a scaled plan of a pitch (McLean, 1992). Nowadays, this approach involves mimicking players' on field movements mechanically on a computerised drawing tablet using a drawing pen, attempting to match the velocity of movement and position as closely as possible and using visual cues to estimate field locations (Burgess et al., 2006). Having specified the location of the player on the pitch using X and Y coordinates, any displacement from a previous location can be calculated and divided by time to produce a movement velocity for the player.

However, this procedure appears to overestimate actual distances by an average of 5.8% (95 percent limits of agreement; 95%LoA=7.4%) compared to those measured using a calibrated trundle wheel pedometer (Edgecomb and Norton, 2006). This is likely to be as a result of sideways movements of the pen by just one pixel being translated into lateral movements resulting in an increase in the overall distance recorded.

Furthermore, the inter-operator %TEM for measurement of TD around circuits of varying lengths is 6.1% (Edgecomb and Norton, 2006) which suggests only moderate reliability (Duthie et al., 2003; McInnes et al., 1995) (Table 2.1). Indeed, Bradley et al. (2007) reported standard deviation (SD) of the difference values of ~0.05 s and 4.3 m, which when equating these to a player travelling 20 m in 4 s (5 $m \cdot s^{-1}$), would result in them having a calculated velocity between 3.9 and 6.1 $m \cdot s^{-1}$, suggesting that movement velocity cannot be consistently classified by different operators. Given that intra-operator reliability for TD is lower (%TEM ~2%; Sirotic et al., 2009) it may be advisable for the same operator to perform all the analysis if comparison between positions is required. Even so, Sirotic et al. (2009) reported that intra-operator TEM was greater at higher movement velocities with an absolute TEM of 0.92 $m \cdot min^{-1}$ (%TEM ~7%) for very high intensity running (>18.6 $km \cdot h^{-1}$),

In addition, whilst a single camera may not be required to track each player, all players must remain in the camera's field of view. Although quicker than classifying players based on their running gait, it is still an extremely time demanding method of analysing a large number of players as only one player's movements can be followed on the drawing tablet at a time. It must also be accepted that manual digitisation of a player's path on a scaled drawing tablet is likely to overestimate actual distance covered by ~6% and that this method of TMA has only moderate inter- and intra- operator reliability at higher movement velocities.

Manual digitisation in a calibrated area

Roberts et al. (2006) calibrated five fixed cameras by digitising four calibration poles (height = 1.0 m) positioned in known locations to create a two-dimensional (2D) plane 1.0 m above the playing surface of the rugby pitch. Cameras were fixed for the entirety of the data capture in the position used for calibration. The participants' hip centres were then digitised at a rate of 1 Hz and subsequent reconstruction provided positional pitch coordinates on a global 2D Cartesian coordinate system. The reliability and accuracy of this system was assessed by the digitisation of participants completing 4 to 8 intervals of a predefined running circuit. The distance travelled by the participant during each run was obtained by summing the individual displacements for each 1 s time interval with subsequent velocities obtained from the displacement analysis. Inter- (Table 2.1) and intra- operator reliability coefficient of variation (CoV) were 0.9 and 0.5% for distances travelled, respectively, which suggests acceptable reliability (Atkinson et al., 1999; Stokes, 1985). Furthermore, in comparison to known distances, the CoV was reported to be 1.8-2.1% with a relative standard error of the estimate (%SEE) of 6.0-7.4%, suggesting moderate accuracy.

Therefore, although the accuracy of manual digitisation in a calibrated area appears similar to digitising player's movement path on a scaled drawing tablet or subjectively analysing gait, the use of two or more operators to manually digitise matches appears more acceptable. Nevertheless, manual tracking remains a time-consuming and laborious task because of the time it takes to identify individuals from the footage and digitise each person on a frame by frame basis (Perš et al., 2002). Indeed, Roberts et al. (2006) reported that it takes ~8 h to analyse the movements of one player over a complete 80 min match.

2.1.3 Triangulation surveying

Triangulation surveying involves calculating the position of a player using the length of the baseline and two angles. The base of the triangle is composed of the distance between two cameras, each mounted on a tripod along the pitch sidelines (Castagna et al., 2003). By filming the same player with both cameras, an encoder at the base of each camera tracking the orientation of the cameras records the two angles needed for triangulation (D'Ottavio and Castagna, 2001). Analogue signals from the encoders are sequentially converted at a rate of 10 Hz into digital data and subsequently a player's location can be obtained from X and Y co-ordinates created from this data. Data on the accuracy and reliability of this form of TMA system is limited although two independent studies report no significant difference ($P>0.05$) between known distances during a match simulation protocol and distances obtained from triangulation surveying (Castagna et al., 2003; D'Ottavio and Castagna, 2001), with a relative error of <1%. Furthermore, distances calculated from simulated matches were <1% different ($P>0.05$), whether computed by the same or two different operators (Castagna et al., 2003; D'Ottavio and Castagna, 2001). Superficially, these findings suggest this TMA system is highly accurate and reliable. However, it is unclear whether the movements observed were similar in velocity to those observed during PMSTS as these have been shown to produce less favourable results than slow linear movements over longer distances in other TMA analysis systems (Duffield et al., 2010; Jennings et al., 2010; Petersen et al., 2009; Portas et al., 2010).

2.1.4 Global positioning systems

Global positioning systems (GPS) utilise freely available satellite systems to construct the geographical location of an individual. Each satellite broadcasts radio frequency signals which are detected by a receiver worn by the player. The time taken from the satellite to the receiver is then multiplied by the velocity of light and the exact distance to each satellite is calculated, with a minimum of three satellites required to produce a three-dimensional (3D) position calculated by trigonometry (Schutz and Herren, 2000). In addition, GPS receivers are able to validate the velocity of displacement by measuring the rate of change of the radio frequency signals, known as the Doppler Shift (Schutz and Herren, 2000). Although initially designed for military use and reported to be highly accurate, the United States Ministry of Defence (US MOD) introduced an intentional error into the signals detectable by civilians in order to protect security (Witte and Wilson, 2004). Subsequently, the introduction of the differential GPS (dGPS), which utilises a fixed permanent receiver placed at a known geographical location, can be utilised to calculate the inherent error introduced by the US MOD. Information is transmitted by radio waves to the dGPS receiver worn by the athlete, which continuously corrects for the known error. Using dGPS, Larsson and Henriksson-Larsen (2001), reported a mean error of 0.8 and 0.1 m over distances of 115 and 247 m, respectively, which equates to an extremely small systematic overestimation of 0.04-0.70% for distance covered. However, the assessment of the accuracy of dGPS for measurement of distances during sport-specific movements that are generally performed over short distances with frequent changes of direction (COD) is yet to be established. Therefore, the validity of dGPS for use in PMSTS is at present unjustified. More recently, the accuracy of measuring the movement demands of PMSTS using commercially available 1-5 Hz non-differential GPS (NdGPS) units incorporating 100 Hz tri-axial accelerometers have been assessed. These include the SPI 10, SPI Elite and WiSPI (GPSports, Canberra, Australia) sampling at 1 Hz, the SPI Pro (GPSports, Canberra, Australia) sampling at 5 Hz, and the Minimax X (Catapult Innovations, Melbourne, Australia) sampling at either 1 or 5 Hz.

Several studies have observed that NdGPS is accurate for measuring linear distance at slow movement velocities (Table 2.3), regardless of sampling frequency with <5.5% overestimation (Gray et al., 2010; Jennings et al., 2010; Portas et al., 2010). Indeed, Portas et al. (2010) reported <1% overestimation of distance using 1 and 5 Hz NdGPS (Minimax X) for linear walking (%SEE were 2.7 and 3.1%, respectively). Conversely, it has been reported that the measurement accuracy of NdGPS falls as movement velocity increases (Jennings et al., 2010; Peterson et al., 2009). Specifically, NdGPS consistently underestimates distance during short (10-40 m) linear sprints (Jennings et al., 2010; Petersen et al., 2010; Table 2.4).

However, peak velocity measured from NdGPS devices sampling at 1 Hz, have been shown to be moderately (r = -0.40 to -0.53 across GPS models; Coutts and Duffield, 2010) and strongly (r = -0.93, Barbero-Álvarez et al. 2010) correlated with static 20 and 30 m acceleration times, respectively. Furthermore, a 5 Hz system has been reported to result in a lower mean positional error than a 1 Hz system when measuring multidirectional movements with sharp COD (Duffield et al., 2010; Jennings et al., 2010; Portas et al., 2010; Table 2.5). Therefore, peak velocity during short (20-30 m) linear sprints are likely to be more accurate using a 5 Hz NdGPS unit than one sampling at a lower frequency. Measurement accuracy of NdGPs is improved as discrete distances increase when jogging, striding and sprinting at both 1 and 5 Hz (Jennings et al., 2010). Nevertheless, 5 Hz NdGPS is more accurate than 1 Hz, regardless of movement velocity, the number of COD or distance (Duffield et al., 2010; Jennings et al., 2010; Portas et al., 2010). Indeed, Duffield et al. (2010) observed that a 5 Hz NdGPS was substantially more accurate than a 1Hz NdGPS at measuring distances within a small (4-8 m) area (Table 2.5). Similarly, over short distances with large COD (180^{o}) a 1 Hz NdGPS underestimated distance by ~1-11% (%SEE: 2.4-6.8%) whilst a 5 Hz NdGPS calculated mean distance to within 2% of the criterion distance (%SEE: 2.4-3.6%; Portas et al., 2010). It is possible that the underestimation reported in multidirectional (Jennings et al., 2010; Petersen et al., 2009) and curvilinear (Gray et al., 2010) movements is due to participants ‘cutting the corners’ or the need to lean towards the middle to maintain balance, resulting in a shorter distance covered by the upper body (and thus GPS receiver also) than the lower body and delineated movement path used to calculate actual distance. However, in the case of multidirectional movements at least, it is more likely that the rapid changes in direction over a short time frame result in data points being ‘missed’ causing the system to misinterpret the movement back into the same space as being the individual remaining static.

Table 2.3 Accuracy of NdGPS for measuring linear walking distance

TMA system	Manufacturer	Study	Movement path	Systematic bias	Random error	Interpretation of validity
NdGPS (1Hz)	GPSports	Gray et al. (2010)	Long linear (200 m)	2.9% overestimation	Not reported	Good
	Catapult	Portas et al. (2010)	Short linear (51 m)	<1% overestimation	%SEE: 2.7%	Good
		Jennings et al. (2010)	Short linear (10-40 m)	0.4-4.3% overestimation	%SEE: 9.6-23.8%	Moderate-poor
NdGPS (5Hz)	GPSports	Pertersen et al. (2010)	Long linear (8,800 m)	0.8-1.1% underestimation	%SEE: 0.5-1.0%	Good
	Catapult	Jennings et al. (2010)	Short linear (10-40 m)	2.3-5.5% overestimation	%SEE: 11.9-21.3%	Moderate-poor
		Portas et al. (2010)	Short linear (51 m)	<1% overestimation	%SEE: 3.1%	Good
		Pertersen et al. (2010)	Long linear (8,800 m)	2.1-3.2% overestimation	%SEE: 2.0-3.8%	Good

Table 2.4 Accuracy of NdGPS for measuring linear sprinting distance

TMA system	Manufacturer	Study	Movement path	Movement velocity	Systematic bias	Random error	Interpretation of validity
NdGPS (1 Hz)	GPSports	Gray et al. (2010)	Long linear (200 m)	Sprinting	2.6% overestimation	Not reported	Good
		Jennings et al. (2010)	Short linear (10-40 m)	Sprinting	37.1% under- to 1.9% over-estimation	%SEE: 12.2-32.4%	Poor
NdGPS (5 Hz)	GPSports	Petersen et al. (2010)	Short linear (10-40 m)	Sprinting	7.4-20.0% underestimation	%SEE: 2.6-10.5%	Moderate-poor
	Catapult	Jennings et al. (2010)	Short linear (10-40 m)	Sprinting	26.0% under- to 0.7% over-estimation	%SEE: 12.9-30.9%	Poor
		Petersen et al. (2010)	Short linear (10-40 m)	Sprinting	19.5-37.3% underestimation	%SEE: 5.3-23.8%	Poor

Table 2.5 Accuracy of NdGPS for measuring distance during multidirectional short courses with 45-180 ^{o} COD

TMA system	Manufacturer	Study	Movement velocity	Systematic bias	Random error	Interpretation of validity
NdGPS (1 Hz)	GPSports	MacLeod et al. (2009)	Cruise to sprint	1.2% under- to 0.8% over-estimation	95% LoA: 2.1-9.5%	Good
		Duffield et al. (2010)	Maximal effort	14.8-37.6% underestimation	Not reported	Poor
NdGPS (1 Hz)	Catapult	Portas et al. (2010)	Running	~1% over- to ~11% under-estimation	%SEE: 2.4-6.8%	Good-moderate
		Jennings et al. (2010)	Stride to sprint	12.4-22.2% underestimation	%SEE: 10.4-12.5%	Poor
NdGPS (5 Hz)	GPSports	Petersen et al. (2009)	Sprint	6.1-20.0% underestimation	%SEE: 2.6-6.7%	Moderate-poor
	Catapult	Jennings et al. (2010)	Stride to sprint	7.8-15.8% underestimation	%SEE: 10.8-11.7%	Moderate-poor
		Petersen et al. (2009)	Sprint	28.1-28.9% underestimation	%SEE: 5.3-12.7%	Poor
		Portas et al. (2010)	Running	~1% over- to ~2% under-estimation	%SEE: 2.4-3.6%	Good
		Duffield et al. (2010)	Maximal effort	2.7% over- to 29.7% under- estimation	Not reported	Good-poor

In spite of these findings, over longer distance PMSTS-multidirectional circuits, Portas et al. (2010) reported no consistent bias for over- or under-estimation of TD covered with either 1 or 5 Hz NdGPS units and %SEE ranged from 1.3-3% and 1.5-2.2% in 1 and 5 Hz NdGPS, respectively (Table 2.6). Similarly, MacLeod et al. (2009) reported a small (0.04%) overestimation with a 95%LoA of 0.23% for TD covered over a 6,818 m multidirectional course. In contrast, Jennings et al. (2010) reported a consistent (5.7 and 3.7%) underestimation of TD covered around a multidirectional circuit using 1 and 5 Hz NdGPS, respectively. However, it is possible that some of the reported disparities are due to differences between the measured distance of the circuit and the movement path taken by participants.

Interestingly, Petersen et al. (2009) reported that despite both the SPI Pro and Minimax X sampling at the same frequency (5 Hz) and receiving the same satellite signals, the SPI Pro was generally more accurate than the Minimax X, especially at higher movement velocities (Tables 2.4 and 2.5). Whilst mean %SEE for sprinting ranged from 5.3.-23.8% for the Minimax X, the mean %SEE for the SPI Pro was 2.6-10.5% with distances underestimated by 7.4-20.0 and 19.5-37.3%, respectively (Petersen et al., 2009). The increased accuracy of the GPSports device would suggest that the manufacturer-specific calculations used to triangulate unit position and smooth the data are more affective at improving the accuracy of the measurement than those in the Catapult system. Therefore, in light of these collective findings, 5 Hz NdGPS units (ideally SPI Pro) should be used to accurately measure distances during PMSTS.

Table 2.6 Accuracy of TD covered during PMSTS-specific multidirectional circuits using various NdGPS

TMA system	Manufacturer (If applicable)	Study	Movement velocity	Systematic bias	Random error	Interpretation of validity
NdGPS (1 Hz)	GPSports	Edgecomb and Norton (2006)	Unspecified	4.8% overestimation	95%LoA: 7.2%	Moderate
		MacLeod et al. (2009)	Intermittent	0.04% overestimation	95%LoA: 0.23%	Good
		Coutts and Duffield (2010)	Intermittent	4.1% under- to 0.7% over- estimation	Not reported	Good
		Doğramaci et al. (2011)	Intermittent	12.6% underestimation	%TEM: 2.2%	Moderate
	Catapult	Jennings et al. (2010)	Intermittent	5.7% underestimation	%SEE: 3.6%	Good-moderate
		Portas et al. (2010)	Maximal effort	~1% under- to ~1% over- estimation	%SEE: 1.3-3.0%	Good
NdGPS (5 Hz)	Catapult	Jennings et al. (2010)	Intermittent	3.7% underestimation	%SEE: 3.8%	Good
		Portas et al. (2010)	Maximal effort	~1% under- to ~1% over- estimation	%SEE: 1.5-2.2%	Good

On a separate note, whilst GPS removes inter- and intra-operator error associated with other TMA systems, there is a reliability issue associated with the GPS unit itself. Specifically, researchers must critique not only the inter-unit reliability (i.e. the reliability of using two GPS units of identical model and manufacturer) but the intra-unit reliability, which refers to using the same unit to monitor a movement on two occasions. Whilst the inter-unit reliability has been shown to be acceptable for the measurement of individual endurance sports that require relatively linear movements (CoV<6.04%; Gray et al., 2010), the inter-unit reliability of measuring distances around multidirectional PMSTS-specific circuits appear better at slower velocities with CoV for overall, low (<14.4 $km \cdot h^{-1}$; 4.0 $m \cdot s^{-1}$), high (>14.4 $km \cdot h^{-1}$; 4.0 $m \cdot s^{-1}$) and very high intensity running (>20.0 $km \cdot h^{-1}$; 5.6 $m \cdot s^{-1}$) distances of 3.6, 4.3, 11.2 and 15.4%, respectively, for a 1 Hz NdGPS unit (Coutts and Duffield, 2010) (Table 2.7). In light of these findings, participants should wear the same NdGPS units during all conditions that researchers/practitioners wish to compare.

Interestingly, Duffield et al. (2010) observed that when measuring distance over multidirectional short courses with sharp (45-180^{o}) COD, the inter-unit reliability of a 1 Hz NdGPS (SPI Elite) was generally better (CoV: 3.5-9.5%) than the Minimax X collecting data at a rate of 5 Hz (CoV: 3.5-17.8%) (Table 2.8). This may be as a consequence of the increased volume of data collected by the 5 Hz model or differences in the way in which data is acquired by the manufacturers of the respective systems (Duffield et al., 2010). Nevertheless, as per accuracy of the systems, the inter-unit reliability of the NdGPS device by GPSports was more favourable than that manufactured by Catapult.

Table 2.7 Inter-unit reliability of distance measurements using NdGPS

TMA system	Manufacturer (If applicable)	Study	Movement path	Movement velocity	Reliability statistics	Interpretation of reliability
NdGPS (1 Hz)	GPSports	Coutts and Duffield (2010)	Multidirectional circuit	Overall	CoV: 3.6-7.1%	Good-moderate
				Low (<14.4 $km \cdot h^{-1}$)	CoV: 4.3-12.5%	Good-poor
				High (>14.4 $km \cdot h^{-1}$)	CoV: 11.2-32.4%	Poor
				Very high (>19.8 $km \cdot h^{-1}$)	CoV: 11.5-30.4%	Poor
		Duffield et al. (2010)	Multidirectional short course with 90-180^{o} COD	Jogging	CoV: 3.6-9.5%	Good-moderate
						Good
				Max effort	CoV: 3.6%	
		Edgecomb and Norton (2006)	Multidirectional circuit	Intermittent	%TEM: 5.5%	Moderate
		Gray et al. (2010)	Linear	Walking	CoV: 2.0%	Good
				Sprinting	CoV: 3.4%	Good
			Curvilinear	Walking	CoV: 2.8%	Good
				Sprinting	CoV: 6.0%	Moderate
NdGPS (5 Hz)	Catapult	Duffield et al. (2010)	Multidirectional short course with 90-180^{o} COD	Jogging	CoV: 9.8%	Moderate
				Max effort	CoV: 3.5-17.8%	Good-poor

In contrast to findings on the inter-unit reliability, intra-unit reliability is reported to be independent of sampling frequency for both linear (CoV = 4.4-5.3%) and multidirectional movements (3.9-7.7% and 3.4-6.7% for 1 and 5 Hz NdGPS, respectively; Portas et al., 2010) (Table 2.8) In addition, over longer PMSTS-specific multidirectional circuits, CoVs for distance covered in locomotive categories were comparable between units (2.0-4.9%; Portas et al., 2010). Whilst measuring the intra-unit reliability also takes into account the repeatability of the test itself, the test-retest reliability for the movements observed was <10% and therefore still deemed acceptable (Atkinson et al., 1999; Stokes, 1985).

Furthermore, acceptable intra-unit reliability have been reported for summated peak velocities during repeated 30 m maximal accelerations (CoV = 1.7%; Barbero-Álvarez et al., 2010) and peak velocity during 20 m maximal accelerations (CoV = 2.3%; Coutts and Duffield, 2010; CoV = 1.9%; Waldron et al., 2011), suggesting that, peak velocity in accelerations ≥20 m in distance maybe a reliable enough measure to detect small changes in performance if using the same NdGPS unit for repeated measurements.

Table 2.8 Intra-unit reliability of distance measurements using NdGPS

TMA system	Manufacturer (If applicable)	Study	Movement path	Movement velocity	Reliability statistics	Interpretation of reliability
NdGPS (1 Hz)	Catapult	Portas et al. (2010)	Linear	Walking	CoV: 4.4%	Good
				Running	CoV: 4.5%	Good
			Short 45-180^{o} COD	Walking	CoV: 3.9-5.7%	Good-moderate
				Running	CoV: 4.1-7.7%	Good-moderate
			Multidirectional circuits	Maximal effort	CoV: 2.0-4.9%	Good-moderate
		Gray et al. (2010)	Long Linear	Walking	CoV: 1.9%	Good
				Jogging	CoV: 2.5%	Good
				Sprinting	CoV: 2.7%	Good
			Long Curvilinear	Walking	CoV: 2.8%	Good
				Jogging	CoV: 2.0%	Good
				Sprinting	CoV: 4.8%	Good

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TMA system	Manufacturer (If applicable)	Study	Movement path	Movement velocity	Reliability statistics	Interpretation of reliability
NdGPS (5 Hz)	Catapult	Portas et al. (2010)	Linear	Walking	CoV: 5.3%	Moderate
				Running	CoV: 4.6%	Good
			Short 45-180^{o} COD	Walking	CoV: 3.4-6.7%	Good-moderate
				Running	CoV: 3.7-6.1%	Good-moderate
			Multidirectional circuits	Maximal effort	CoV: 2.2-4.5%	Good-moderate
		Duffield et al. (2010)	Short with 90-180^{o} COD	Maximal effort	CoV: 3.5-11.0%	Good-poor
			Multidirectional	Maximal effort	CoV: 16.8%	Poor

Although concerns over their safety in contact sports have, until recently, prevented the application of NdGPS units in official PMSTS games (Di Salvo et al., 2006), recent studies have used them to measure the movement demands of competitive Australian rules football (Aughey, 2010; Coutts et al., 2010; Wisbey et al., 2010), rugby union (Cunniffe et al., 2009) and rugby league (McLellan et al., 2010, 2011a, 2011c) matches. However, the equipment is costly (Witte and Wilson, 2004), and furthermore, would require an agreement to be made between teams to share information in order to develop a normative profile across multiple teams. As a result of the reluctance for teams to share confidential information on the physical performance of their players in matches, the majority of the studies published report data from just one team (Aughey, 2010; Coutts, et al., 2009; Cunniffe et al., 2009; McLellan et al., 2010, 2011a, 2011c), and therefore may not provide a true normative profile of the movement demands of the specific positions analysed. In addition, positional error of NdGPS has been reported to be inversely related to the number of satellites available during trials (r=-0.50, P<0.05; Gray et al., 2010), which may be lower in stadia due to signal obstructions (Williams and Morgan, 2009). Therefore, the validity of using NdGPS during matches is questionable as research under these conditions has yet to be tested. Furthermore, NdGPS cannot be used to quantify time spent in contact (i.e. tackles). Indeed, despite tackles being highly physically demanding components of rugby union (Roberts et al., 2008) and rugby league (McLellan et al., 2011a, 2011c) matches, NdGPS may register them as low intensity activity based on the movement velocity at which they are performed (Cunniffe et al., 2009; McLellan et al., 2011c).

2.1.5 Radio frequency identification

Radio frequency identification (RFID) utilises microchips worn in the players' vest and located in the ball that transmits radio signals to antennas located around the stadium (Cornell, 2006). The reception time to each antenna calculates the distance of the player and ball from each antenna. Information from multiple antennas is then triangulated to determine a single location (Wylie, 2006). Whilst the system samples at 1000 Hz, there is a reciprocal relationship between the sampling frequency and the number of transponders which would result in a sampling rate of 38 Hz (1000/26) for a rugby league match. Under static conditions, the average positional error in relation to a known location is 0.01 ± 0.00 m when static on the pitch or a maximum of 0.03 ± 0.01 m when worn by participants (Frencken et al., 2010). Under dynamic conditions RFID appears to underestimate distance covered and mean velocity (Table 2.9), especially at higher speeds with the CoV ranging from 2.0-2.7% for mean velocity during multidirectional short courses with sharp (45-90^{o}) COD compared to that recorded from timing gates (Frencken et al., 2010). Furthermore, the microchips are extremely robust, with manufacturers claiming that they can withstand blows greater than 3,000 times the force of gravity which is over four times the strength of a direct blow from a professional soccer kick (Austen, 2002). Unlike GPS, the size of the RFID microchip is small; approximately 15 mm in diameter and 12 grams in weight, making the potential uses of the RFID to sport promising. However, costing around €180,000 to install in a stadium (Lefeber, 2008), this technology is too expensive for many researchers. Furthermore, like GPS, in contact sports such as rugby league, RFID will register contacts as low intensity activity, hence substantially underestimating the intensity of competitive matches.

2.1.6 Automated image-recognition

This process incorporates an automatic tracking system to utilise colour and shape information to recognise player positions (Beetz et al., 2007). Beetz et al. (2007) describe how initially the automated image-recognition (AIR) system detects players by segmenting clusters of colours on the field that are not green. However, images which include partial player occlusion may contain more than one player. Thus, the image is then subdivided into an approximated multi-segmental model consisting of a shirt, shorts and socks region and uses colour recognition to match the colours of the respective sub-segments to the learned colour classes. To account for players being parallel to the floor (e.g. during a slide tackle) this template is shifted to five different configurations to find the best fit. For this process each pixel is tested for a colour match based on learned colour patterns. Colour models associated with players' clothing are learned semi-automatically using k-mean clustering on manually marked regions. Once detected, players are localised using their estimated centre of gravity as the centre between shirt and shorts and a pitch coordinate is assigned to their position.

The video input for this process is obtained from the main camera, which constantly adjusts its pan, tilt and zoom, in order to follow on-the-ball actions. As a result, the first stage of player detection is to estimate the camera parameters by matching the video image to a computer animated model of the field. The estimation is formulated through an iterative optimisation procedure using an Iterative Extended Kalman Filter. The optimisation software searches for images, such as field lines, which correspond to the computer animated model and allows the players' coordinates to be adjusted based on the camera view. Using the aforementioned methods, Beetz et al. (2007), claim that player position is typically accurate to within 0.5 m, however, no data have been published in support of this. Moreover, a disadvantage of this system is that players can only be detected when in the camera field of view, resulting in all off-the-ball activity being lost. Therefore, this method is unsuitable for obtaining TMA data for the entirety of a match. Furthermore, a disadvantage to any automatic tracking system is the misclassification of players and failure to detect players in crowded situations. Indeed, Beetz et al. (2007) examined corner situations from a single match and found players to be misclassified or undetected 3.68 and 17.53% of the time, respectively. The latter issue was largely attributed to the occlusion of players when clustered and may be reduced by using multiple cameras or by using cameras perpendicular to the playing surface. Barris (2008) collected data using a single fixed camera placed directly above an indoor court and perpendicular to the playing surface with a wide angle lens to allow full coverage of the court. The video was then transformed to remove the distortion at the extremes of the picture caused by using a wide angled lens. Further to this, radial distortion was addressed by applying an algorithm calculated using the coordinates of a series of known fixed points. Using a similar system as used by Beetz et al. (2007), players were automatically tracked using A-Eye motion analysis software, which adopts colour recognition to detect player positions (Barris, 2008). However, unlike the aforementioned study by Beetz et al. (2007), input from a single fixed camera overhead means multi-segmental models are not necessarily due to the relatively consistent colour pattern obtained from this field of view. Having located the player, the A-Eye tracking software draws a bounding box around the player and the centre of the bounding box is used as the player's centre of mass location. Furthermore, the system utilises predictive movement algorithms based on the location and velocities from previous frames to narrow the field of search. Whilst Barris (2008) reported that there was no significant difference ($P>0.05$) between the velocities obtained by automatic tracking and those obtained from timing gates over known distances, this is not necessarily indicative of agreement between individual results. Nevertheless, based on retrospective analysis of the published data, automatic tracking using the A-Eye system showed acceptable accuracy for measuring short (15-28.5 m) linear running distances (CoV=2.2%; TE=0.31 m; 95%LoA ± 0.86 m) with a systematic bias to overestimate distance by 1.8%. Although it is worth noting these values were greater in comparison to manual tracking of the same data set (CoV=1.2%, TE=0.17 m; 95%LoA ± 0.48 m). Furthermore, the automatic tracking using the A-Eye system showed perfect correlation across three trials (r=1.0; CoV=0.0%; TE=0.0 m; 95%LoA ± 0.0 m) and thus it was concluded that it was not possible for the A-Eye system to code the same footage in more than one way. Therefore, automatic tracking removes both inter- and intra- reliability issues.

However, because of the field of view of the single camera and the need to place the camera directly overhead, parallel to the plane of the playing surface, the apparatus is limited in its application to sports played on small indoor courts.

Similarly, Perš and Kovacic (2000) utilised two cameras equipped with wide angle lenses, each covering half of the court, to track players in a handball match. In order to reduce the previously outlined issue of radial distortion, a linear camera calibration model was utilised to determine the scaling factor.

Similar to the aforementioned AIR systems, this system uses template tracking to distinguish the player from the background, followed by colour detection and motion prediction algorithms. Perš and Kovacic (2000) concluded that a combination of all of these detection methods resulted in less human operator intervention than either of these methods in isolation. The need for an operator to intervene was reported to be almost exclusively the result of collisions between players or players' shadows contacting other players. Similar to Barris (2008), it was also noted that the precision was greater when manually tracking players than when using the automated tracking system. The mean positional error for the combined automated tracking method was 0.28 m in comparison to 0.07-0.10 m by human operators. This is possibly explained by the misclassification of each player's centre of mass due to the movement of his extremities. Therefore, a semi-automated tracking system appears to offer the most appropriate solution to balancing the need for accuracy with operator time. Furthermore, multiple camera coverage of the same area would reduce the likelihood of player occlusions.

2.1.7 Semi-automated image-recognition

Developments in multiple camera semi-automated image recognition (SAIR) tracking systems have provided a non-intrusive and relatively quick method for quantifying movement velocities of multiple players during match play (Di Salvo et al., 2006). This method generally uses six to eight fixed colour cameras installed along the roof of the venue with two opposing corners housing three cameras each and a further camera situated in each of the other two corners. The field of view of the camera is then positioned so that every area of the pitch is covered by a minimum of two cameras, as described by Di Salvo et al. (2006), for increased accuracy and to reduce the occurrence of occlusions. Consequently, the multiple camera systems have the advantage of largely removing the issue of players not being detected during crowded situations. On installation of the cameras, the playing area is calibrated and transformed into a 2D model to allow each player's position to be reported as an X and Y co-ordinate measured from the centre spot of the playing venue. Players are automatically tracked in a similar manner to AIR tracking systems, however, in the event of a tracking error, the system operator is able to manually stop the tracking, move back to the frame of error and re-initialise the automatic tracking (Di Salvo et al., 2009). The image co-ordinates are then converted into pitch co-ordinates using a linear 4-point transformation calibration followed by a proprietary 50 point algorithm that eliminates vision distortion with respect to optical errors (Hartley and Zisserman, 2002).

Generally, most commercially available SAIR tracking systems sample at a rate of 10-25 Hz. The average velocity across a 1 s period of time is then calculated by dividing the summated distance over the frames by time. From this, players' movements are then classified into a movement category based upon the velocity thresholds for each movement category. Given that these velocity thresholds have been generically assigned to all players, the appropriateness of these labels (e.g. high speed running; HSR) may be questionable for some individuals (Abt and Lovell, 2009). Nevertheless, distance and velocity are direct output measures and are not reliant on the subjective classification of movement or calculated from a subsequent assumption of their movement velocity. Therefore, distance in each of the locomotive categories is likely to be more accurate than those calculated from gait analysis. In fact, Di Salvo et al. (2006) evaluated the accuracy of mean velocities obtained from a multiple camera SAIR tracking system (ProZone 3, ProZone®, Leeds, England) compared to those obtained from timing gates. The mean CoV were 0.2, 0.3, 0.2 and 1.3% for a paced linear 60 m run, 50 m paced arced run, 15 m linear sprint and 20 m sprint with 90^{o} COD, respectively. Whilst accuracy of SAIR tracking systems is lower during high velocity movements with sharp COD, SAIR tracking systems appear more accurate than other TMA systems for measuring mean velocity during these movements (Table 2.9).

Table 2.9 Accuracy of mean velocity during multidirectional short courses with 45-180° COD using (semi) automated TMA systems

TMA system	Manufacturer (If applicable)	Study	Movement path	Movement velocity	Systematic bias	Random error	Interpretation of validity
NdGPS (1 Hz)	GPSports	MacLeod et al. (2009)	45-180° COD	Maximal effort	1.8% under- to 1.2% over-estimation	95%LoA: 0.5-1.2 $km{\cdot}h^{-1}$	Moderate
		Duffield et al. (2010)	90-180° COD	Maximal effort	10.3-35.3% underestimation	Not reported	Poor
NdGPS (5 Hz)	Catapult	Duffield et al. (2010)	90-180° COD	Maximal effort	27.6% under- to 5.9% over-estimation	Not reported	Moderate-poor
RFID (45 Hz)	Inmotio	Frencken et al. (2010)	45-90° COD	Sprinting	1.3-3.0% underestimation	CoV: 2.0-2.7%	Good
SAIR (10 Hz)	ProZone	Di Salvo et al. (2006)	90° COD	Sprinting	Not reported	CoV: 0.2-1.3% 95% LoA: 0.23 $km{\cdot}h^{-1}$ ICC: 0.950 TE: 0.23 $km{\cdot}h^{-1}$	Good

However, given that the system requires manual correction, its reliability is dependent on the operator. Therefore, Di Salvo et al. (2009) assessed the inter-observer reliability of the system resulting from the manual correction by ProZone 'in-house' quality control personnel. Two quality control personnel observed the same footage from two outfield soccer players and the total time spent and distance covered in each of the discrete locomotive categories as a result of calculating velocity for each 0.1 s of the match was analysed for each observer. No statistically significant differences (P>0.05) were observed between operators for time and distance and the highest CoV for any of the comparisons was ~5% for time spent sprinting (>25.2 $km \cdot h^{-1}$). Similarly, Bradley et al. (2009, 2010) reported inter- and intra-observer CoV for distance covered walking, running, HSR, high intensity running (>14.4 $km \cdot h^{-1}$) and very high intensity running (>19.8 $km \cdot h^{-1}$) to be <2%, with sprinting <3.5%, suggesting acceptable reliability (Stokes, 1985; Atkinson et al., 1999). Although it is worth noting that whilst the inter- (Table 2.10) and intra- (Table 2.11) operator reliability of calculating distance from SAIR tracking systems appear to be worse at higher movement velocities, there is less variability in the distances reported than those obtained from NdGPS units (Table 2.7 and 2.8).

Unlike both GPS and RFID technology, SAIR systems do not require players to wear any form of transmitter, thereby removing the potential for injury in contact sports as a consequence of wearing a receiver (Di Salvo et al., 2006). As a result, the use of this technology is permitted for use in official PMSTS matches, including those that involve contact, such as rugby league. In addition, SAIR tracking systems allow both teams to be tracked providing information on the away as well as the home team. As a result of which, a more normative profile can be achieved than when relying on the output from just one team, as is often the case when analysing the movement demands of matches using NdGPS (Aughey, 2010; Coutts et al., 2009; Cunniffe et al., 2009; McLellan et al., 2010, 2011a, 2011c).

Table 2.10 Inter-operator reliability of SAIR tracking systems for measuring distance during competitive matches

TMA system	Manufacturer (If applicable)	Study	Movement velocity	Reliability statistics	Interpretation of reliability
SAIR (10 Hz)	ProZone	Bradley et al. (2009)	Overall	CoV: <3.5%	Good
			Walking	CoV: <2%	Good
			Jogging	CoV: <2%	Good
			Sprinting	CoV: 3.5%	Good
			High (>14.4 $km \cdot h^{-1}$)	CoV: <2%	Good
			Very high (>19.8 $km \cdot h^{-1}$)	CoV: <2%	Good
		Di Salvo et al. (2009)	Walking	CoV: ~1.5%	Good
			Jogging	CoV: ~2.0%	Good
			Sprinting	CoV: ~ 4.8%	Good
		Bradley et al. (2010)	Walking	CoV: <2%	Good
			Running	CoV: <2%	Good
			Sprinting	CoV: 3%	Good
			High (>14.4 $km \cdot h^{-1}$)	CoV: <2%	Good
			Very high (>19.8 $km \cdot h^{-1}$)	CoV: <2%	Good

Table 2.11 Intra-operator reliability of SAIR tracking systems for measuring TMA variables during competitive matches

TMA System	Manufacturer (If applicable)	Study	Movement velocity	Reliability statistics	Interpretation of reliability
SAIR	ProZone	Bradley et al. (2009)	Overall	CoV: <2%	Good
			Walking	CoV: <2%	Good
			Jogging	CoV: <2%	Good
			Sprinting	CoV: <3%	Good
			High (>14.4 $km \cdot h^{-1}$)	CoV: <2%	Good
			Very high (>19.8 $km \cdot h^{-1}$)	CoV: <2%	Good
		Di Salvo et al. (2009)	Intermittent	CoV: 1.9-4.5%	Good
		Bradley et al. (2010)	Overall	CoV: 1.0%	Good
			Walking	CoV: 0.9%	Good
			Sprinting	CoV: 2.4%	Good
			High (>14.4 $km \cdot h^{-1}$)	CoV: 1.1%	Good
			Very high (>19.8 $km \cdot h^{-1}$)	CoV: 1.8%	Good

2.2 Movement demands of prolonged multiple sprint team sports

2.2.1 Total distance covered

Classification of movements based on players' running gait retrospectively from video footage has estimated that rugby league players cover between 8,458 and 9,929 m during a competitive match depending on playing position (Meir et al., 2001a). However, a limitation to this early TMA study is that their data were generated from subjective analysis of gait, with arbitrary velocities used to estimate distances from time spent in locomotive categories (Krustrup and Bangsbo, 2001). Therefore, the accuracy is highly reliant on the ability of the observer to correctly classify the movement (Di Salvo et al., 2006) and assumes that all players move at the same constant velocity within that movement. Notwithstanding this limitation and subsequent rule changes in 2001, Sirotic et al. (2009) reported a similar TD covered (8,517 m on the basis of players playing the entire match at 106 $m \cdot min^{-1}$) to that of Meir et al. (2001a) using a scaled drawing tablet. However, no attempt was made to explore positional differences and all players were from the same National rugby league (NRL) team restricting the heterogeneity of the data. More recently, McLellan et al. (2011a, 2011c) has used a commercially available NdGPS (SPI Pro, GPSports, Canberra, Australia) sampling at 5 Hz to monitor the movement demands of rugby league matches. Similar results were reported for both studies, with mean distances reported to range from 4,774-4,982 for forwards and 5,573-5,747 m for backs, which is noticeably lower than previously reported. However, data was collected from players from the same team and therefore the data may not be representative of all teams. Furthermore, due to the low sample size (*n*=17 during one match, McLellan et al., 2011a; *n*=15 across 5 matches, McLellan et al., 2011c), in-depth positional analyses were not conducted. Finally, involvement in contact was not reported and therefore distance travelled in low intensity activity and recovery between high intensity efforts may be overestimated. Using a comparable methodology (1 Hz NdGPS; SPI Elite, GPSports, Canberra, Australia), Cunniffe et al. (2009) reported rugby union players to cover slightly greater distances (6,680-7,227 m, depending on position) during competitive matches. Similarly, Roberts et al. (2008) reported mean TD covered in rugby union matches to be 5,581 ± 692 m for forwards (*n*=14) and 6,127 ± 724 m for backs (*n*=15) by manually digitising frames in a calibrated area.

Whilst female hockey players have been reported to cover 6,154-6,931 m (depending on position; Gabbett, 2010), male hockey players have been reported to cover 6,833 ± 823 m (Petersen et al., 2004). Therefore, based on NdGPS measurements, hockey players are reported to cover slightly greater distances than rugby league players (McLellan et al., 2010, 2011a, 2011c) during competitive matches, regardless of sex. However, through using NdGPS it has also been observed that Australian rules football players cover substantially greater overall distance during matches (12,939 m, Coutts et al., 2010; 12,734 m, Aughey, 2010; 11,705 m, Brewer et al., 2010; 11,700-12,300 m: Wisbey et al., 2010) than hockey, rugby union or rugby league players, which may in part due to the greater duration of games which have been reported to range from 118-126 min (Dawson et al., 2004). Nevertheless, relative to playing time, TD covered is substantially greater in elite Australian rules football (128 $m \cdot min^{-1}$, Brewer et al., 2010; 127 $m \cdot min^{-1}$, Aughey, 2010) than in elite rugby league (106 $m \cdot min^{-1}$, Sirotic et al., 2009). This may be a consequence of Australian rules football players working at higher intensities when on the field due to teams being permitted an unlimited number of substitutions which yields around 100 interchanges per team per match (Aughey, 2010).

An early TMA study using pitch markings to track the trajectory of elite soccer players during competitive matches would suggest that the TD covered in soccer matches (8,680 ± 1,011 m; Reilly and Thomas, 1976) was similar to rugby league matches. However, this study appears to grossly underestimate the current TD covered compared to subsequent estimations from gait analysis (10,860 m; Mohr et al., 2003; 11,527 m; Withers et al., 1982), manual digitisation of players' trajectories on a scaled drawing tablet (8,800-10,100 m: Burgess et al., 2006) and SAIR systems (10,714 ± 991 m: Bradley et al., 2009; 10,841 ± 950 m: Bradley et al., 2010; 10,613-10,786 m: Bradley et al., 2011; 10,494-10,949 m: Carling and Dupont, 2011; 11,393 ± 1,016 m: Di Salvo et al., 2007; 9,710-12,750 m: Rampinini et al., 2007a; 9,995-11,748 m: Rampinini et al., 2007b; 11,647-12,190 m: Rampinini et al., 2009; 10,794 ± 374 m: Weston et al., 2011). It is likely that the substantial variability between the values reported by Reilly and Thomas (1976) and those reported more recently are a consequence of the differences in TMA systems used and improvements in players' fitness levels over time.

The disparity between the overall distances covered during PMSTS may in part be due to the time that the ball is typically in play, as TD covered is largely accumulated when the ball is in play (Duthie et al., 2003). For example, the ball is reported to be in play for ~55 min in rugby league matches (Eaves et al., 2008), compared to 70 min in soccer (Withers et al., 1982). Accordingly, even though the overall exercise volume is greater in Australian rules football and soccer than in rugby union, rugby league or hockey, it is unclear whether the intensity of actual match play is that dissimilar between sports. Table 2.12 provides a summary of the overall distances covered during competitive PMSTS matches using various TMA systems.

2.2.2 Work-to-rest ratios

The overall demands of matches can be reported in terms of the WRR, which depict the average recovery time between every 1 s of work. The advantage of this approach in relation to contact sports such as rugby league is that players' involvement in static exertion, which contributes to the overall demands of match play, can be accounted for. Based on gait analysis, position specific WRRs for rugby league players were reported to be 1:10 for hookers, 1:7 for props, 1:12 for scrum halves and 1:28 for wingers (Meir et al., 2001a). However, these figures were based on the analysis of just four players from two professional clubs. Moreover, the study of Meir et al. (2001a) was conducted prior to the introduction of the limited interchange rule in 2001, which is believed to have led to changes in the physiological demands of rugby league matches (Orchard et al., 2003). Analysis post-2001 by King et al. (2009) yielded WRR of 1:6 for outside backs, 1:6 for hit-up forwards (back row and props) and 1:5 for pivots, which is markedly different to the pattern previously observed. In addition, unlike the findings of Meir et al. (2001a), King and colleagues (2009) reported relatively little positional variation in the observed WRRs (1:5-1:6 cf. 1:7-1:28). Positional grouping differences between studies and small sample sizes may account for some of these differences. Moreover, the data of King et al. (2009) were gathered from a small sample size (*n*=3) across three matches which has the limitation of being less representative of normative values than analysing the performances of multiple players from different teams (Wells et al., 2004).

In comparison, using a SAIR tracking system (ProZone 3, ProZone®, Leeds, England), senior elite rugby union players were reported to have WRRs of 1:7.5 to 1:14.6 (Eaton and George, 2006). These are similar to the WRR of 1:6.1 for forwards and 1:15.7 for backs based on gait analysis (Duthie et al., 2005) but lower than the 1:21.8 for backs reported by Deutsch et al. (2007). Based on the mean percentage of total time (%TT) spent in each locomotive category reported by Docherty et al. (1988), which equates to a WRR of 1:5.7, the analysis appears to suggest that the intensity of rugby union matches became less intense following the introduction of professionalism in rugby union in 1996. However, the reported changes in match intensity may be misleading as Docherty et al. (1988) confined their analysis to centres and props. Given that Deutsch et al. (2007) observed that centres and props performed more ‘work’ than other positions in their respective positional groups, the study by Docherty and colleagues (1988) may have overestimated the overall demands of rugby union prior to the introduction of professionalism. Furthermore, match demands (especially for backs) appear to have become more intense following the introduction of the Experiential Law Variations in the Southern Hemisphere in 2007-08 (Austin et al., 2011) and the Northern Hemisphere in 2008-09 (Cunniffe et al., 2009). Whilst Austin et al. (2011) reported WRRs of 1:4, 1:4, 1:5 and 1:6 for front and back row forwards, and inside and outside backs, respectively, Cunniffe et al.

(2009) reported WRRs of 1:5.7 for forwards and 1:5.8 for backs. Collectively, these studies would suggest a quicker distribution of the ball to the backs, due to shorter breakdowns and/or changes to their involvement during match-play following the introduction of the most recent rule changes. Consequently, on the basis of these findings there appears at present to be little diversity between the positional demands of rugby union players. However, it is worth noting that the latter study by Cunniffe et al. (2009) was measured solely using NdGPS (1 Hz; SPI Elite, GPSports, Canberra, Australia) and therefore, does not take into account time spent in contact, which in previous studies has been shown to be greater for forwards than backs (Docherty et al., 1988; Duthie et al., 2005; Roberts et al., 2008). Therefore, taking into account time spent in contact, the WRRs during elite competitive rugby union matches are likely to be even lower than that reported by Cunniffe and colleagues (2009), especially for forwards. Moreover, whilst MacLeod et al. (2007) reported WRRs during hockey of 1:17.2, 1:9.8 and 1:9.1 (based on gait analysis) for defenders (n=4), midfielders (n=4) and forwards (n=4), respectively, Peterson et al. (2004) reported mean WRRs of 1:10 using NdGPS. Collectively these findings suggest that hockey matches are less intense than rugby league matches.

Table 2.12 provides a summary of WRRs during competitive PMSTS matches using various TMA systems. Whilst WRRs may provide a useful indicator of the overall match demands and intermittent nature of the sport, they do not provide detailed enough information on the composition of locomotive movements and actions to successfully replicate match demands in training or in match simulation protocols.

Table 2.12 Overview of the TD covered and WRRs of PMSTS using various TMA systems

Sport	Study	TMA system	TD covered (m)	WRR
Rugby league	Meir et al. (2001a)	Gait analysis	8,458-9,929	1:7-1:28
	King et al. (2009)	Gait analysis	-	1:5-1:6
	Sirotic et al. (2009)	Drawing tablet	-	-
	McLellan et al. (2010, 2011a)	NdGPS (5 Hz)	4,774-5,747	-
	McLellan et al. (2011c)	NdGPS (5 Hz)	4,982-5,573	1:6-1:7
Rugby union	Docherty et al. (1988)	Gait analysis	-	-
	Duthie et al. (2005)	Gait analysis	-	1:6.1-1:15.7
	Eaton and George (2006)	SAIR	-	1:7.5-1:14.6
	Deutsch et al. (2007)	Gait analysis	-	1:7.3-1:14.6
	Roberts et al. (2008)	Manual digitisation	5,581-6,127	-
	Cunniffe et al. (2009)	NdGPS (1 Hz)	6,680-7,227	1:5.7-1:5.8
	Austin et al. (2011)	Gait analysis	4,662-6095	1:4-1:6

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Sport	Study	TMA system	TD covered (m)	WRR
Soccer (males)	Reilly and Thomas (1976)	Gait analysis	8,680	-
	Withers et al. (1982)	Gait analysis	11,527	-
	Mayhew and Wenger (1985)	Gait analysis	-	1:7
	Mohr et al. (2003)	Gait analysis	9,740-10,980	-
	Burgess et al. (2006)	Drawing tablet	8,800-10,100	-
	Rampinini et al. (2007a)	SAIR	9,710-12,750	-
	Rampinini et al. (2007b)	SAIR	9,995-11,748	-
	Di Salvo et al. (2007)	SAIR	11,393	-
	Di Salvo et al. (2009)	SAIR	-	-
	Rampinini et al. (2009)	SAIR	11,647-12,190	-
	Bradley et al. (2009)	SAIR	10,714	-
	Bradley et al. (2010)	SAIR	10,841	-
	Bradley et al. (2011)	SAIR	10,613-10,786	-
	Carling and Dupont (2011)	SAIR	10,494-10,795	-
	Weston et al. (2011)	SAIR	10,794	-

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Sport	Study	TMA system	TD covered (m)	WRR
Soccer (females)	Andersson et al. (2010a)	Gait analysis	9,700-9,900	-
Hockey (male)	Peterson et al. (2004)	NdGPS (1 Hz)	6,833	1:10
	MacLeod et al. (2007)	Gait analysis	-	1:9.1-1:17.2
Hockey (female)	Gabbett (2010)	NdGPS (1 Hz)	6,154-6,931	-
Australian rules	Coutts et al. (2010)	NdGPS (1 Hz)	12,939	-
football	Wisbey et al. (2010)	NdGPS (1 Hz)	12,200-12,500	-
	Brewer et al. (2010)	NdGPS (1 Hz)	11,705	-
	Aughey (2010)	NdGPS (5 Hz)	12,734	-

2.2.3 Percentage of total time in locomotive categories

The %TT spent in discrete locomotive categories yields detailed information on the composition of the movements to inform the development of sport-specific training practices (Gabbett, 2010) and/or the development of sport-specific match simulation protocols (e.g. Nicholas et al., 2000; Thatcher and Batterham, 2004) which look to replicate the activities and proportion of time spent in these activities during match play (Drust et al., 2007). However, disparities between the number of locomotive categories, definitions of categories, classification of movements depending on the TMA system used and inclusion of sport-specific movements (e.g. lunging in hockey; MacLeod et al., 2007 and static exertion in rugby union; Roberts et al., 2008) make comparisons of the %TT spent in locomotive actions between sports difficult. Nevertheless, Table 2.13 provides a summary of the %TT spent in locomotive categories across PMSTS. Whilst there are clear differences in the %TT spent in locomotive categories between sports, the majority of the time appears to be spent performing low intensity activity (walking and jogging), regardless of the sport. Therefore, sport-specific training and match simulation protocols should include periods of active and passive recovery in the proportions observed during matches in order to effectively replicate the movement and physiological demands of competitive games.

2.2.4 High and very high intensity running distances

More recently, distance covered in high (>14.4 $km \cdot h^{-1}$) and very high (>19.8 $km \cdot h^{-1}$) intensity running have been suggested as valuable indicators of physical match performance in soccer, the evidence for which is discussed in the subsequent section (2.2.5). Table 2.14 provides a summary of the high and very high intensity running distances reported in soccer matches using SAIR tracking systems.

Table 2.13 The %TT spent in locomotive categories during PMSTS

Sport	TMA System	Study	Locomotive action (%TT)								
			Stand	Walk	Jog	Low speed run	Stride/ cruise /run	HSR	Sprint	Utility	Static exertion
Soccer (male)	Gait analysis	Reilly and Thomas (1976)	-	24.8	36.8	-	20.5	-	11.2	6.7	-
	Gait analysis	Mayhew and Wenger (1985)	2.3	46.4	38.0	-	11.3	-	-	2.0	-
	Gait analysis	Mohr et al. (2003)	19.5	41.8	16.7	9.5	4.5	2.8	1.4	3.7	-
Soccer (female)	Gait analysis	Mohr et al. (2008)	19.4	42.8	-	27.7	-	6.0	1.2	3.9	-
Hockey	Gait analysis	McLeod et al. (2007)	11.4	45.1	35.6	-	5.1	-	1.5	1.3	-

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Sport	TMA System	Study	Locomotive action (%TT)								
			Stand	Walk	Jog	Low speed run	Stride/ cruise /run	HSR	Sprint	Utility	Static exertion
Rugby union	Gait analysis	Docherty et al. (1988)	37.7	31.0	16.4	-	3.8	-	2.0	-	9.1
	Gait analysis	Duthie et al. (2005)	41.0	27.0-38.0	16.0-20.0	-	1.7-2.1	-	0.5-1.5	-	1.5-10.0
	Gait analysis	Deutsch et al. (2007)	-	-	17.3-21.0	-	16.6-31.7	-	0.2-0.6	29.2-59.2	1.0-44.4

Table 2.14 Mean distances covered in high (>14.4 $km \cdot h^{-1}$) and very high (>19.8 $km \cdot h^{-1}$) intensity running during elite male competitive soccer matches based on analysis from SAIR tracking systems

Study	High intensity running distance (m)	Very high intensity running distance (m)
Rampinini et al. (2007a)	2,530	802
Rampinini et al. (2007b)	1,885-3,051	605-997
Bradley et al. (2009)	2,492	905
Bradley et al. (2010)	2,725	980
Gregson et al. (2010)	-	604-1,162
Weston et al. (2011)	-	703

2.2.5 Validity of movement parameters for monitoring fatigue toward the end of competitive prolonged multiple sprint team sports matches and as markers of physical performance

In soccer, the TD covered (Bangsbo et al., 1991), distance covered in high intensity running (Bangsbo et al., 1991; Ekblom, 1986; Mohr et al., 2003, 2008), distance covered sprinting (Mohr et al., 2003, 2008) and number of sprints (Bangsbo et al., 1991) have been shown to discriminate between playing standards. Similarly, overall and high intensity running locomotive rates during competitive Australian rules football matches have been shown to be higher in elite than sub-elite players (Brewer et al., 2010). Whilst some studies report TD covered per minute (Barbero-Álvarez et al., 2008) and TD covered (Bradley et al., 2009, 2010; Burgess et al., 2006; Carling and Dupont, 2011; Di Salvo et al., 2009; Drust et al., 1998; Rampinini et al., 2009; Reilly and Thomas, 1976) to be lower in the second half compared to the first, others report that overall distances in the second half relative to the first are dependent on playing standard (Mohr et al., 2008; Sirotic et al., 2009) or that there is no change between halves (Andersson et al., 2010a; Di Salvo et al., 2007; Krustrup and Bangsbo, 2001) due to reductions in high intensity running distance being offset by increases in distances covered in low intensity activity (<11 $km \cdot h^{-1}$: Di Salvo et al., 2007). Similarly, although a minority of studies in soccer (Burgess et al., 2006), rugby union (Roberts et al. (2008) and sub-elite rugby league (Sirotic et al., 2009) report no change in the distance covered in high intensity running throughout the match, distance covered running (11.1-19 $km \cdot h^{-1}$: Di Salvo et al., 2007) and in high (>14.4 $km \cdot h^{-1}$: Carling and Dupont, 2011; >18.0 $km \cdot h^{-1}$: Mohr et al., 2003; >14.0 $km \cdot h^{-1}$: Rampinini et al., 2009) and very high (>19.8 $km \cdot h^{-1}$: Di Salvo et al., 2009; >19.0 $km \cdot h^{-1}$: Rampinini et al., 2009) intensity running have generally been shown to be lower in the second half compared to the first ($P<0.05$) in elite soccer players. Similarly, a reduction in high intensity running in the second half has also been observed for soccer referees (D'Ottavio and Castagna, 2001; Krustrup and Bangsbo, 2001), elite hockey (MacLeod et al., 2007), female soccer (Andersson et al., 2010a; Mohr et al., 2008) and Australian rules football (Coutts et al., 2010; Brewer et al., 2010) players. Moreover, a reduction in high intensity running has been observed during the final 15 min of play compared to the first during competitive male (Bradley et al., 2009, 2010; Mohr et al., 2003) and female (Andersson et al., 2010a; Mohr et al., 2008) soccer matches irrespective of playing standard. However, although some studies suggest TD covered and distance covered in high intensity running are related (Mohr et al., 2003; Bangsbo and Lindquist, 1992), others argue that TD covered fails to reflect changes in technical performance which in soccer are observed in parallel with reductions in high intensity running distance (Rampinini et al., 2009) or the ability to execute actions which influence match outcome (such as breaking the defensive line; Roberts et al., 2008).

Whilst it is generally accepted that the reduction in exercise intensity during PMSTS is due to fatigue (Bradley et al., 2009; Carling et al., 2010; Coutts et al., 2010; Di Salvo et al., 2009; Mohr et al., 2008; Rampinini et al., 2009; Sirotic et al., 2009), the influence of external factors (such as team tactics and opponents' activity levels) cannot be discounted as potential influences (Rampinini et al., 2007b). That said, it has been observed that female (Krustrup et al., 2010) and youth (Rebelo et al., 1998) soccer players are unable to replicate pre-match repeated sprint and prolonged intermittent exercise performance following a competitive match. In addition, peak sprinting speed is 9% slower ($P<0.05$) during the final 15 min of elite soccer matches compared to the initial 15 min (Bangsbo and Mohr, 2005). Furthermore, observations that (i) the amount of high intensity running in the final 15 min of a soccer match is correlated with training status in females (Krustrup et al., 2005), (ii) high intensity running distance is sensitive to training interventions in soccer referees (Krustrup and Bangsbo, 2001), (iii) elite male soccer substitutes perform 25% more high intensity running in the final quarter of the game than players playing the entire game (Mohr et al., 2003) and (iv) the high speed running locomotive rate ($m \cdot min^{-1}$) of soccer midfield substitutes is greater than players who had started the game (Carling et al., 2010), lend support to the hypothesis that reductions in exercise intensity towards the end of competitive matches are, at least in part, due to fatigue.

Furthermore, Rampinini et al. (2007b) and Weston et al. (2007) demonstrated that when soccer players and referees, respectively, were required to carry out high levels of physical activity in the first half of games, overall, high and very high intensity running distance covered were all reduced in the second half. However, those players who 'paced' themselves between halves recorded lower overall, high and very high intensity running distances across the whole match than those players that did not but who exhibited signs of fatigue towards the end of the second half (Rampinini et al., 2007b). Therefore, whilst players should be encouraged to give their all-out effort in the first half, it must be accepted that this is likely to result in reductions in high intensity running in the second half. However, given that in soccer it has been observed that the majority of the actions that influence the outcome of a match occur in the final 15 min of each half (Abt et al., 1999) and that most goals are scored in the second half of games, specifically in the last 15 min of the match (Aramatas et al., 2007), lessening the rate of fatigue is likely to positively influence the match outcome.

There is also evidence to suggest a link between selected TMA parameters and technical performance. Specifically, Rampinini et al. (2009) observed a significant (*P*<0.01) decline in involvements with the ball, number of short passes and frequency of successful short passes between the first and second half in addition to observing a significant (*P*<0.01) decline in high and very high intensity running and TD covered. Similarly, Carling and Dupont (2011) observed a reduction in the number of skill-related involvements (passes, possession and duels) during the final 5 min of a soccer game compared to the first 5 min period. However, whilst passing success rate in relative terms was unaffected by the decline in high intensity running, reductions in skill-related indices paralleled the concomitant decline in HSR (>14.4 $km \cdot h^{-1}$) suggesting that the reduction in the number of skill-related involvements in PMSTS matches are largely due to a reduced involvement with play, rather than fatigue, leading to alterations in the execution of skills. However, if the decline in physical performance towards the end of competitive rugby league matches is indicative of fatigue then, speculatively, players may be more susceptible to contact injuries toward the end of matches as it has been observed that tackling technique is negatively affected by fatigue (Gabbett, 2008). Indeed, (Rahnama et al., 2002) observed that major injuries are more prominent in the final 15 min of soccer matches.

In the only study to-date investigating the changes in movement intensities in competitive rugby league matches, Sirotic et al. (2009) reported findings that were inconsistent and seemingly dependent on playing standard. Whilst the elite players showed a significant decrement in high intensity running (>13.1 $km \cdot h^{-1}$) locomotive rate (i.e. $m \cdot min^{-1}$) in the second half compared to the first (*P*<0.01), this decrement was not evident in the semi-elite players (*P*>0.01). Although this may be due to the higher levels of physical activity in the first half of elite matches, this disparity may also be due to the intra-reliability issues associated with classifying high intensity locomotive actions using drawing tablets (Sirotic et al., 2009). Furthermore, data reported by Sirotic et al. (2009) was collected from the same Australian rugby league club and may not be indicative of all senior elite teams.

2.2.6 Inter-match variability in overall, high and very high intensity running distances

Mohr et al. (2003) analysed eight soccer players in two consecutive games played within a 3-week period and observed a match-to-match variation in TD covered of 0.01 ± 0.08 km, with a CoV of 3.1%. In comparison, match-to-match variation in the distance covered in high intensity running was greater, with a CoV of 9.2% (Mohr et al., 2003). Similarly, Rampinini et al. (2007b) reported small (CoV=2.4%), moderate (CoV=6.8%), and large (CoV=14.4%) match-to-match variability for overall, high (>4 $m \cdot s^{-1}$) and very high (>5.5 $m \cdot s^{-1}$) intensity running distance, respectively. In agreement, Gregson et al., (2010) reported large match-to-match variability in distance covered in very high intensity running over the entire season (CoV=17.7%) and across an eight week period (CoV=23.5%). However, it has been observed that match-to-match variability of overall, high, and very high intensity running distance covered are lower when playing against the same opposition over repeated matches (Rampinini et al., 2007b), suggesting that the playing styles, fitness, tactics and ability of the opposition will also influence the variability in physical performance measures during competitive matches (Rampinini et al., 2007b). Using the nomogram developed by Batterham and Atkinson (2005) to observe a meaningful change of 10% it is estimated that 80 players would be required to make meaningful inferences about variables with a CoV of 20%. Consequently, the detection of any worthwhile changes due to an intervention would be difficult to detect in the field, with access typically restricted to players from one team (*n*=17).

A series of studies based on output from SAIR tracking systems have reported an effect of match outcome (Di Salvo et al., 2009) playing formation (Bradley et al., 2011) and the standard of the opposition (Rampinini et al., 2007b) on the movement demands of soccer matches. Moreover, Carling and Bloomfield (2010) observed that players covered a greater TD following the dismissal of a player early in the match than their normative profile. However, the increase in overall locomotive rate in the first half resulted in a reduction in the distance covered walking, jogging and sprinting in the second half compared to the first; a finding that was not observed in the absence of any dismissals in the normative profile. Additionally, it has been observed that players cover more high intensity running and TD against teams than finished higher in the league in comparison to when playing against lower standard opposition (Rampinini et al., 2007b). What is more, Rampinini et al. (2007b) reported significant moderate-strong correlations between teams for TD (r = 0.51, $P<0.001$) and distance covered in high (r = 0.72, $P<0.05$) and very high (r = 0.65, $P<0.001$) intensity running, indicating that players' activity levels during matches are related to the activity levels of the opposition. Finally, Bradley et al. (2011) demonstrated that defenders in a 4-4-2 formation covered a greater distance in high intensity running and overall than defenders in a 4-3-3 or 4-5-1 formation. In addition, the distance covered in very high intensity running whilst attacking was 32-39% greater in 4-3-3 and 4-4-2 formations than in a 4-5-1. In contrast, ~19% more distance was covered in very high intensity running whilst defending in a 4-5-1 versus 4-4-2 and 4-3-3 formations. Thus in soccer, physical performance is affected by ball retention and the playing formation resulting from the team tactics employed.

Given the numerous influences on high intensity running distance within a match, it is unsurprising that O'Donoghue (2004) reported the within-subject variation in time spent in high intensity running between matches often exceeded the level of between-subject variability. Whilst collectively these findings suggest TD covered is a more reliable movement parameter than high intensity running distance, TD covered may not be as representative of performance as the latter. Therefore, whilst the use of TMA data derived from matches might be considered the criterion measure for monitoring the effect of interventions on physical performance, this method of assessment is limited because of the low test-retest reliability resulting from the influences of the opposition, weather, team tactics and the match score (Sirotic and Coutts, 2008). Consequently, investigators would have to analyse performances over a large number of matches in order to negate this variability and detect real systematic changes resulting from interventions (Drust et al., 2007; Gregson et al., 2010; Weston et al., 2010). However, changes in fitness over this same time period may make it hard to isolate the cause of such changes. Given the aforementioned sources of variability in the movement demands observed during competitive matches, match simulation protocols based on representative match TMA data may provide a more reliable method for monitoring the effectiveness of interventions.

2.3 Physiological and metabolic responses to prolonged multiple sprint team sports

2.3.1 Heart rate and blood lactate

Players have been reported to produce mean heart rate (HR)s of 155 to 172 $b \cdot min^{-1}$(84-88 percent of maximum HR; %HR_{max}) during competitive PMSTS matches (Table 2.15). Based on HR-oxygen uptake ($\dot{V}O_2$) regression data, this would estimate players to be working at 70-85% of maximal aerobic capacity ($\dot{V}O_{2\,max}$). However, during matches the emotional stress, heat and static exertion that cause HR but not $\dot{V}O_2$ to rise, may result in this being an over-prediction of $\dot{V}O_2$ (Reilly, 1997). Nevertheless, the HR itself provides a useful index of overall physiological strain (Reilly and Thomas, 1979). Interestingly, although few studies report a significant difference in HR between halves (MacLeod et al., 2007), there is a trend for mean HR to be lower in the second half of male (Krustrup et al., 2006; Thatcher and Batterham, 2004) and female (Andersson et al., 2010a; Krustrup et al., 2010) soccer, semi-professional rugby league (Coutts et al., 2003) and professional rugby union (Cunniffe et al., 2009) matches (Table 2.15), which suggests a reduction in work rate in the second half of games.

Of the total time, Deutsch et al. (1998) calculated that rugby union forwards spent 72% of the match in high intensity HR zones (>85% HR_{max}), whilst backs spent the majority of the time in moderate (65-85% HR_{max}; 37%) and low (<65% HR_{max}; 18%) intensity HR zones. Similar to rugby union backs, semi-professional rugby league players have been reported to spend 15.9, 39.7 and 44.4% of their time in low (<70% HR_{max}), moderate (70-85% HR_{max}) and high (>85% HR_{max}) intensity HR zones, respectively (Coutts et al., 2003).

Observations on blood lactate responses to PMSTS matches are used as an indication of the energy demands from anaerobic glycolysis. Coutts et al. (2003) reported that mean blood lactate concentrations during a competitive rugby league match were 8.5 and 6.5 $mmol \cdot l^{-1}$ for semi-professional forwards and backs, respectively, which is slightly higher than those reported at half-time in elite female soccer players (5.1 ± 0.5 $mmol \cdot l^{-1}$; Krustrup et al., 2010). In comparison, mean blood lactate values taken during major stoppages in play (e.g. following tries or injuries) and at half-time and full-time were slightly lower in junior elite rugby union players, with forwards (6.6 $mmol \cdot l^{-1}$) demonstrating higher values than backs (5.1 $mmol \cdot l^{-1}$; Deutsch et al., 1998). However, during periods of low intensity activity, blood lactate is metabolised and therefore, blood lactate concentrations only represent a measure of the intensity of the most recent activity undertaken and not the overall demands of the game (McLean, 1992). Nevertheless, the moderate-high blood lactates and high HRs reported, suggest that players are exposed to high aerobic and anaerobic stimuli during PMSTS matches. Interestingly though, blood lactate has consistently been reported to be lower at the end of the first half than the second in junior elite male (Rebelo et al., 1998; Thatcher and Batterham, 2004) and senior female (Krustrup et al., 2010) soccer, and semi-professional rugby league (Coutts et al., 2003) players, suggesting that the number of high-intensity efforts are reduced during the second half of competitive PMSTS matches (Reilly, 1997).

Thus, the reduction in HR and blood lactate from the first to the second half of matches is in agreement with the aforementioned reductions in overall, high and very high intensity running distances.

Table 2.15 Mean HR responses during competitive PMSTS matches and per half‡

Sport	Level of Competition	Study	HR ($b \cdot min^{-1}$)	HR (% HR_{max})
Rugby league	Junior elite	Estell et al. (1996)	172 ± 10	86.7 ± 4.4
	Semi- professional	Coutts et al. (2003)	166 ± 10 (167 ± 9; 165 ± 11)	84.3 ± 4.8
	Professional (forwards)	McLellan et al. (2011c)	165 ± 15 (164 ± 13; 167 ± 13)	-
	Professional (backs)	McLellan et al. (2011c)	161 ± 11 (161 ± 9; 163 ± 10)	-
Rugby union	Professional	Cunniffe et al. (2009)	172 (173; 169)	88
Soccer (males)	Professional	Thatcher and Batterham (2004)	(170 ± 10; 163 ± 8)	(85; 81)
	Semi- professional	Krustrup et al. (2006)	156 ± 13 (157 ± 15; 155 ± 13)	-
Soccer (females)	Elite domestic	Mohr et al. (2005a)	164 ± 4	87 ± 1
	Elite domestic	Krustrup et al. (2010)	168 ± 1 (170 ± 1; 167 ± 2)	86 ± 1
	International	Andersson et al. (2010a)	162 ± 6 (164 ± 6; 162 ± 7)	85 ± 3 (86 ± 3; 85 ± 4)
Hockey (females)	Elite domestic	MacLeod et al. (2007)	172 ± 11(174 ± 12; 169 ± 11)	-

‡ Values inside the parenthesise are for first and second half, respectively.

2.3.2 Muscle adenosine triphosphate, inosine monophosphate and related by-products

During soccer matches muscle adenosine triphosphate (ATP) has only been shown to be moderately reduced during the game (~15%; Krustrup et al., 2006). Whilst some restoration of ATP may have occurred during the short (15-30 s) delay in taking muscle biopsies, the re-synthesis rate is relatively slow and therefore the observed ATP levels are likely to be a relatively good reflection of actual ATP levels during match play (Bangsbo et al., 2007). In parallel with this moderate reduction in ATP, there is a corresponding accumulation of inosine monophosphate (IMP) in the muscle (Krustrup et al., 2006) and rise in plasma ammonia (NH_3; Bangsbo, 1994; Krustrup et al., 2006), hypoxanthine (Bangsbo, 1994) and uric acid (UA; Andersson et al., 2008; Ascensão et al., 2008; Bangsbo et al., 1994; Magalhães et al., 2010) concentrations in the blood, suggesting a breakdown of IMP (Bangsbo et al., 2007). Nevertheless, given that muscle IMP concentrations were considerably lower than was observed during exhaustive exercise (Hellsten et al., 1999), and that ATP levels were only moderately reduced (Krustrup et al., 2006), it is unlikely that the reduction in overall, high and very high intensity running consistently reported towards the end of matches is due to either of these factors (Bangsbo et al., 2006, 2007; Krustrup et al., 2006).

2.3.3 Substrate utilisation

The fall in exercise intensity towards the end of a soccer game cannot be attributed to a fall in blood glucose, as blood glucose is actually slightly elevated during competitive (Bangsbo, 1994; Krustrup et al., 2006) and simulated (Morris et al., 1998, 2003; Nicholas et al., 2000) soccer games compared to rest. These findings suggest that the rate of glucose release from the liver is adequate to compensate for the use of blood glucose during matches. However, it has been observed that the concentration of free fatty acids (FFAs) in the blood increases throughout a soccer match, most markedly during the second half (Bangsbo, 1994; Krustrup et al., 2006). This may be a result of heightened adrenaline and suppressed insulin concentrations (Bangsbo, 1994) stimulating lipolysis and releasing FFA into the blood towards the end of competitive (Krustrup et al., 2006) and simulated (McGregor et al., 1999; Morris et al., 1998, 2003) soccer games. In addition, the higher FFA oxidation may occur to counteract the reduction in muscle glycogen levels whilst still maintaining normal blood glucose levels (Krustrup et al., 2006). Although some authors suggest that the lower lactate levels in the second half of games promote fat utilisation (Bangsbo et al., 2006; Krustrup et al., 2006,) it is equally plausible that the lower lactate concentrations are a consequence of the lowered exercise intensity resulting from utilising fat as the main energy substrate.

One possible explanation for the observed reductions in high and very high intensity running towards the end of PMSTS is the depletion of muscle glycogen levels which leads to an increased reliance of energy production from lipolysis (Bangsbo et al., 2007; Krustrup et al., 2006). Indeed, muscle glycogen levels have been reported to be significantly lower following competitive soccer matches compared to rest (63%, Jacobs et al., 1982; 42%, Krustrup et al., 2006) with approximately half of the individual muscle fibres completely or nearly completely glycogen depleted (Krustrup et al., 2006). In addition, a reduction in sprint performance immediately following a soccer game has been shown to parallel the depletion of muscle glycogen in individual muscle fibres (Krustrup et al., 2006). Moreover, it has been observed that ingestion of carbohydrate reduces glycogen depletion towards the end of prolonged intermittent running protocols (Balsom et al.,1999) and soccer matches (Leatt and Jacobs, 1989) and enables players to perform significantly more high intensity running (33%; Balsom et al.,1999), TD covered (Foster et al., 1986) and TD covered during the second half of games (Kirkendall et al., 1988). In addition, Saltin (1973) reported that players with low half-time muscle glycogen concentrations covered, on average, 1,800 m less overall distance in the second half compared with players with high muscle glycogen concentrations. The close relationship between muscle glycogen depletion and reductions in overall and high intensity running distance may be due to the shift in energy production from carbohydrate to fat metabolism observed progressively throughout soccer matches (Krustrup et al., 2006), which yields a lower rate of energy production (Newsholme and Leach, 1983).

2.3.4 Fluid consumption, sweat volume and changes in body mass

Another factor which mechanistically could be responsible for the reduction in exercise intensity towards the end of PMSTS games is dehydration, leading to hyperthermia (Reilly, 1997). Whilst the optimal rate of fluid replacement to attenuate hyperthermia is to replace as much fluid as is lost during the activity (Montain and Coyle, 1992), losses of 0.84 ± 0.52 kg (1.1 ± 0.6% of body mass; %BM), 0.1 ± 0.6 kg (0.2 ± 1.1 %BM) and 1.28 ± 0.70 kg (1.31 ± 0.66 %BM) are reported in competitive male soccer (Maughan et al., 2007), female hockey (MacLeod and Sunderland, 2009) and male rugby league (O'Hara et al., 2010), respectively. The much larger reductions during male rugby league and soccer matches compared to female hockey may be partly as a result of the lower sweat rates, which after correcting for fluid consumed and urinary loss equated to 1.17 ± 0.43 l in female hockey players (MacLeod and Sunderland, 2009) compared to 1.68 ± 0.40 l and 2.0 ± 0.17 l in male soccer (Maughan et al., 2007) and rugby league players (O'Hara et al., 2010), respectively. Moreover, the use of an unlimited number of substitutes in hockey means that players are regularly rotated, allowing fluids to be more easily replaced. This can clearly be evidenced by the much higher fluid intake in hockey (1.26 ± 0.39 l; MacLeod and Sunderland, 2009) compared to soccer (0.86 ± 0.47 l; Maughan et al., 2007) and rugby league (0.64 ± 0.50 l; O'Hara et al., 2010) players.

Dehydration equivalent to a 2% loss in body mass has been shown to significantly impair endurance performance (Armstrong et al., 1985). Traditionally, dehydration has been associated with an increase in cardiovascular strain resulting from a reduction in plasma and stroke volume and cardiac output (Costill and Fink, 1974). However, a reduction in body mass of 2.4% has been shown to result in deterioration of soccer-specific skill execution despite no change in plasma volume (McGregor et al., 1999).

Therefore, the mechanistic causes for deteriorations in skill appear more likely to be associated with reductions in muscle glycogen than dehydration *per se* (McGregor et al., 1999). Indeed, during endurance activities, fluid intake has been shown to increase fat oxidation resulting in glycogen sparing (Hargreaves et al., 1996; Fallowfield et al., 1996). In addition, increases in core temperatures may result in 'pacing' of effort due to reduced arousal of the central nervous system or intuitively to attenuate dehydration (Reilly et al., 2008). This is likely to result in an increased perception of effort for a set workload, as was observed in a soccer match simulation protocol following restricted fluid intake leading to dehydration (McGregor et al., 1999). Given that core temperatures exceeding 40^{o}C have been reported in competitive soccer matches (Ekblom, 1986), all of these mechanisms remain plausible.

Collectively, these findings may suggest that the dehydration observed through reductions in body mass during PMSTS matches may contribute to the reductions in overall, high and very high intensity running distances observed in the second half of matches, either through enhancing the rate of glycogen usage, voluntary reductions in exercise intensity or cardiovascular strain.

2.4 Recovery following competitive and simulated prolonged multiple sprint team sports matches

Whilst the majority of the intra-individual variability in high and very high intensity running distance between successive matches is likely to be due to the effect of the opposition (Rampinini et al., 2007b), weather and tactics (Sirotic and Coutts, 2008), it is unclear to what extent prior fatigue impacts upon performance. Although competitive domestic fixtures are generally 5 to 9 d apart, on occasions there can be as little as 3 d between matches and yet symptoms of exercise-induced muscle damage (EIMD) generally last 1 to 4 d depending on the mode of exercise performed (Byrne et al., 2004). Therefore, during these intense periods of competition subsequent performances and training may be compromised by inadequate recovery time.

2.4.1 Mechanisms of exercise induced muscle damage

Exercise-induced muscle damage is a well documented phenomenon following unaccustomed exercise resulting in muscle soreness and loss in muscle function in the days following exercise (Byrne et al., 2004). Furthermore, muscle soreness and damage may be the result of both mechanical and metabolic factors (Sherman et al., 1984; Ebbeling and Clarkson, 1989; Tee et al., 2007).

2.4.1.1 Mechanical

Exercise-induced muscle damage is often associated with eccentric exercise (Armstrong et al., 1991., Fridén and Lieber, 1992; Proske and Morgan, 2001; Vaile et al., 2008) which is thought to induce greater magnitudes of EIMD than concentric muscle actions. This may be a consequence of eccentric actions recruiting a lower number of muscle fibres to achieve the same force requirements than during concentric actions (Enoka, 1996; Kellis and Balzopoloulos, 1998) resulting in greater tension per active cross-sectional area (Armstrong, 1984). Electron microscopathy demonstrates disruption to sarcomeres in myofibrils, Z-line streaming and t-tubule damage immediately post-exercise (Close et al., 2005). The level of muscle damage is then amplified in the subsequent 1-3 d (Armstrong et al., 1991). Whilst previous studies have utilised downhill running (Eston et al., 1996; Chen et al., 2007) and high volume plyometric (Avela et al., 1999) and resistance (Vaile et al., 2007) damage protocols due to the high eccentric loads placed on the muscles, eccentric muscle actions are also a common occurrence in PMSTS (Osgnach et al., 2010), particularly when braking to change direction or decelerating (Fridén et al., 1988).

2.4.1.2 Oxidative Stress

Oxidative stress from reactive oxygen species (ROS) may increase muscle damage independently of the mechanical damage from eccentric muscle actions. Whilst ROS are produced as a bi-product of the purine nucleotide cycle under normal resting conditions, this is normally balanced by endogenous and dietary antioxidants (Andersson et al., 2010b). However, an imbalance in favour of ROS production over antioxidant availability may lead to oxidative damage, as characterised by a degradation of cellular lipids and proteins (Andersson et al., 2010b). Therefore, given that the purine nucleotide cycle is excited when energy demands are raised and that HR is elevated during PMSTS (Ascensão et al., 2008; Andersson et al., 2008, 2010a; Coutts et al., 2003; Cunniffe et al., 2009; Estell et al., 1996; Krustrup et al., 2006, 2010; MacLeod et al. 2007; Magalhães et al., 2010; McLellan et al., 2011c; Thatcher and Batterham, 2004), ROS production may be increased during and following competitive and simulated PMSTS matches. Indeed, during high intensity exercise the purine nucleotide cycle is extremely active (Ascensão et al., 2008) in order to meet the increased demands for intermediates in the Kreb's cycle. Briefly, adenosine monophosphate (AMP) deaminase catalyses AMP to IMP which then accumulates in the muscle following competitive soccer matches (Krustrup et al., 2006). Inosine monophosphate is then broken down into xanthanine and $NH_{3,}$ causing an observable increase in NH_3 in plasma following competitive (Bangsbo, 1994; Krustrup et al., 2006) and simulated (Morris et al., 1998, 2003) soccer matches. Xanthanine is then converted into UA and hypoxanthine by xanthine oxidase generating ROS in the process (Ascensão et al., 2008). This is supported by the observed increase in both UA (Andersson et al., 2008; Ascensão et al., 2008; Bangsbo, 1994; Magalhães et al., 2010) and hypoxanthine (Bangsbo, 1994) in plasma following competitive soccer matches. Furthermore, oxidative damage has been indirectly detected from the rise in lipid peroxidation by-products (such as malondaldehyde; MDA) following competitive (Ascensão et al., 2008) and simulated (Thompson et al., 2001; Magalhães et al., 2010) soccer matches.

2.4.2 Evidence of exercise-induced muscle damage following competitive and simulated prolonged multiple sprint team sports matches

2.4.2.1 Psychometric measures

2.4.2.1.1 Delayed onset muscle soreness

Muscle tenderness, pain and stiffness upon movement are characteristic symptoms of delayed onset muscle soreness (DOMS). Following EIMD there is an increase in cell membrane permeability (Smith, 1991) during which there is an influx of neutrophils and monocytes into the site of muscle damage. Given that neutrophils and monocytes are capable of muscle fibre necrosis (Weiss, 1989), the infiltration of the damaged area by leukocytes is likely to cause secondary muscle damage (Armstrong et al., 1991), postglandins synthesised during muscle necrosis sensitise type III and IV sensory neurons and membrane permeability results in an influx of fluid into the muscle which increases intramuscular pressure (Smith, 1991). Therefore, DOMS is hypothesised to be a result of the increase in compartmental pressure and hypersensitivity of sensory nerves and is exacerbated by muscular contractions and palpation due to increases in intra-muscular pressure (Newham et al., 1987). Despite the growing body of literature of DOMS, to-date DOMS and the associated decrements in muscle function remains one of the most commonly reported sport-related ‘injuries’ (Byrne et al., 2004). However, whilst the presence of DOMS provides strong evidence of muscular damage (Smart et al., 2008), the time course appears dependent on the mode of exercise and shows a poor correlation with measures of muscle function (Nosaka et al., 2002). Indeed, function is impaired prior to muscle soreness and may remain impaired even when soreness has returned to baseline. Whilst DOMS typically peaks between 1 and 3 d post-exercise (Cleak and Eston, 1992), returning to baseline by 7 d (Bailey et al., 2007; Ingram et al., 2009; Thompson et al, 2001), the peak reduction in muscle function is often reported immediately post-exercise and is often impaired for up to 4 d.

Several studies have reported an increase in general whole-body soreness following competitive (Ascensão et al., 2008) and simulated (Bailey et al., 2007; Thompson et al., 1999, 2001) soccer matches, with peak soreness reported immediately post-match (where measured), but remaining elevated for 2 (Ascensão et al., 2008; Bailey et al., 2007) to 3 d (Thompson et al., 1999, 2001). Furthermore, whilst an increase in perceived lower body muscle soreness has been reported for up to 3 d in males following both competitive (Magalhães et al., 2010) and simulated (Magalhães et al., 2010; Thompson et al., 1999, 2001) soccer matches, Andersson et al. (2008) reported an increase in lower body muscle soreness for just over 2 d (51 h) in females following a competitive soccer match. The more rapid return of perceived lower body soreness to baseline following soccer matches in females may be due to higher estrogen levels in females than males which help to maintain membrane integrity (Rogers et al., 1985; Rinard et al., 2000). In addition, soreness does not appear to be isolated to the lower body, with upper body soreness also reported for 2 (Thompson et al., 2001) to 3 d (Thompson et al., 1999) following simulated soccer matches.

2.4.2.1.2 Subjective feelings of 'well-being'

The profile of mood states (POMS) questionnaire is commonly used in sports science research to measure overall mood as it is quick and easy to administer (Bury et al., 1998; Raglin et al., 1991), non-fatiguing and cost-effective (McLean et al., 2010). This particular questionnaire measures six aspects of mood: tension, depression, anger, vigour, fatigue and confusion. Whilst depression and fatigue have been reported to be higher than baseline immediately following a competitive rugby union match in which participants won, there were no changes in any of the other factors and both depression and fatigue returned to baseline by 1 d (Suzuki et al., 2004). It is likely that following competitive matches the player's moods are mediated not only by the intensity of the exercise but also the result and their satisfaction with their own or team's performance (Suzuki et al., 2004).

An alternative approach is to ask individuals to rate themselves on a Likert scale. McLean et al. (2010) used a 5 point Likert scale with 0.5 increments whereby participants rated themselves against ‘anchors’ (e.g. ‘more tired than normal’) for fatigue, sleep quality, general muscle soreness, stress levels and mood. Overall well-being was then calculated by summing all five scores. McLean et al. (2010) observed that rugby league players had a reduction in overall well-being and increase in general muscle soreness and fatigue at 1 d following competitive matches regardless of the length of time between matches. However, overall well-being tended to remain lower and general muscle soreness and fatigue higher, at 2 d following matches when there were 7 and 9 d before the next match, but not when there was just 5 d between matches. This may indicate that in the competitive environment players may manipulate their responses in an attempt to influence the intensity of training or to affect their likelihood of match selection. Furthermore, although quantitative values are produced from both scales and questionnaires, inter-individual comparisons cannot be made due to the subjectivity of the responses.

2.4.2.1.3 Perception of effort

Increases in the sense of effort during exercise have been observed in the presence of EIMD, and have been suggested to impair functional performance. Several studies have shown that at 2 d following muscle damaging exercise rating of perceived exertion (RPE) for a given workload were higher than baseline (Twist and Eston, 2009; Davies et al., 2009; Scott et al., 2003). Moreover, during self-regulated exercise (i.e. time-trials), participants have been shown to cover less distance, combined with a lower metabolic cost and lower power output, despite RPE being similar to baseline values (Burt and Twist, 2011; Twist and Eston, 2009). The cues which mediate the perceptual response may arise from central or peripheral mechanisms that are altered as a result of symptoms of EIMD. Nevertheless, RPE appears to play a self-regulating role in mediating functional performance and may affect the intensity of training in the days following a rugby league match. Therefore, from a practical perspective, RPE may prove to be a simple, cost-effective and non-invasive marker of recovery when monitored during fixed-load training drills. However, as with well-being questionnaires and scales, RPE is subject to the same subjectivity, preventing inter-individual comparisons. Furthermore, in the competitive environment players may manipulate their RPE responses in an attempt to influence the intensity of training or to affect their likelihood of match selection if they believe these to be affected by the responses that they provide.

2.4.2.2 Creatine kinase and myoglobin

Creatine kinase is an intracellular enzyme responsible for maintaining adequate ATP levels during contraction. The appearance of CK in the blood is interpreted as an increased permeability of the muscle membrane (Fridén and Lieber, 2001). However, plasma CK concentration has a poor temporal relationship with muscle function (Fridén and Lieber, 2001), is poorly correlated with general soreness (Thompson et al., 1999) and has a high degree of inter-individual variation (Hortobágyi and Denahan, 1989; Thompson et al., 1999). Therefore, whilst serum CK concentration provides evidence of muscle damage, it may be a limited measure of functional recovery. Nevertheless, the initial increase in CK immediately (0-30 min) following simulated (Bailey et al., 2007; Kingsley et al., 2005; Magalhães et al., 2010; Thompson et al., 1999, 2001) and competitive soccer (Ascensão et al., 2008; Andersson et al., 2008; Magalhães et al., 2010), rugby union (Suzuki et al., 2004) and rugby league (McLellan et al., 2010, 2011a, 2011b) matches is attributed to mechanical damage (Thompson et al., 1999), ROS (Andersson et al., 2010b; Ascensão et al., 2008; Kinsley et al., 2005) and/or blunt trauma (Cunniffe et al., 2010; McLellan et al., 2010, 2011a, 2011b; Smart et al., 2008; Suzuki et al., 2004; Takarada, 2003). Creatine kinase concentrations are then observed to peak at 1 d following competitive soccer (Andersson et al., 2008; Ascensão et al., 2008), rugby union (Suzuki et al., 2004; Takarada, 2003), rugby league (McLellan et al., 2010, 2011a, 2011b) and simulated soccer (Bailey et al., 2007; Kingsley et al., 2005; Thompson et al., 1999, 2001) matches. This bi-phasic response is believed to be due to the phagocytic action of leukocytes leading to secondary muscle damage (Lapointe et al., 2002; MacIntyre et al., 1996; Smith, 1991). However, the rate of return to baseline CK values appears somewhat more unpredictable. Whilst some studies report plasma CK concentration to be elevated for just 1 (Bailey et al., 2007; Takarada, 2003) to 2 d (Kingsley et al., 2005; Thompson et al., 1999), others have reported CK to be elevated for up to 3 (Ascensão et al., 2008; Magalhães et al., 2010; Thompson et al., 2001) to 5 d (McLellan et al., 2010, 2011a, 2011b) following competitive or simulated PMSTS matches. Interestingly, CK concentrations following rugby union matches have been observed to be correlated with the frequency of contacts (i.e. involvements in tackles) in the match (Takarada, 2003; Cunniffe et al., 2010) which would suggest that that blunt trauma exacerbates muscle damage. Typically, peak values of 941 ± 392 $U{\cdot}l^{-1}$ (McLellan et al., 2011a, 2011b) to 889 ± 538 $U{\cdot}l^{-1}$ (McLellan et al., 2010) are reported 1 d following rugby league matches Although speculative, the disparity in the rate at which CK concentrations return to baseline may be due to the variability in the volume and magnitude of exercise completed in the days following the EIMD with some participants performing additional training throughout the monitoring process.

Similar to CK, Myoglobin (Mb) is an indirect indicator of muscle damage. However, unlike CK, Mb has been observed to peak immediately (0-60 min) post-exercise following simulated soccer (Ascensão et al., 2008; Kingsley et al., 2005; Magalhães et al., 2010; Thompson et al., 2001) and competitive rugby union (Takarada, 2003) and soccer (Magalhães et al., 2010) matches, but return to baseline by 1 d in simulated and competitive soccer matches (Ascensão et al., 2008; Kingsley et al., 2005; Magalhães et al., 2010; Thompson et al., 2001) but not following rugby union matches (Takarada, 2003). As per CK, a strong correlation has been observed between Mb and the number of tackles in a rugby union match (Takarada, 2003). However, Mb does not follow the same time-course as either DOMS or muscle function, possibly due to its smaller molecular size and therefore, quicker infiltration into the circulation (Warren et al., 1999).

2.4.2.3 Muscle function

Unlike the bi-phasic response of CK, and the delay in muscle soreness, muscle function is reported to occur immediately post-exercise with a gradual recovery in the following days (Byrne et al., 2004). This acute reduction in muscle function immediately following exercise is most likely related to glycogen depletion (Bangsbo et al., 2007; Krustrup et al., 2006), dehydration (Reilly, 1997) or a reduction in arousal (Reilly et al., 2008), rather than as a direct result of structural damage. Thereafter, losses in force are the result of disruption to the sarcomere leading to a loss of calcium homeostasis and excitation-contraction coupling dysfunction (Proske and Morgan, 2001).

2.4.2.3.1 Maximal isometric voluntary contractions

To date, just two studies have investigated whether a change in maximal isometric voluntary contraction (MIVC) is observed following PMSTS-specific exercise. Whilst both studies reported a reduction in MIVC for knee flexion for 2-3 d (Bailey et al., 2007; Thompson et al., 2001), Bailey et al. (2007) witnessed no change in the MIVC for knee extension. However, Thompson et al. (2001) did not monitor MIVC for the knee extension and therefore, the possibility that the knee flexors receive more EIMD damage than the knee extensors is as yet uncorroborated. Moreover, electrical stimulation must be superimposed on the muscle action to determine whether individuals can achieve the same level of activation before and after damage and identify the mechanisms responsible for strength loss (Newham et al., 1991; Westing et al., 1990). Given that isometric contractions of isolated muscles are rarely performed in PMSTS matches or in training, and that electrical stimulation was not imposed on the muscles, the practical relevance of these findings are unclear.

2.4.2.3.2 Peak torque at slow and quick angular velocities

Isokinetic peak torque at slow angular velocities (60-90 deg·s^{-1}) is reported to be lower than baseline for up to 3 d in the knee extensors following competitive (Ascensão et al., 2008; Magalhães et al., 2010) and simulated soccer matches (Magalhães et al., 2010). Similarly, knee flexor peak torque is reduced following competitive (Ascensão et al., 2008; Magalhães et al., 2010) and simulated (Thompson et al., 2001; Magalhães et al., 2010) soccer matches for up to 3 d, with the peak decrements observed at 1 d, regardless of the muscle action (Ascensao et al., 2008; Thompson et al., 2001). However, interestingly, recovery of muscle function in the knee flexors at a fast angular velocity (180 $deg \cdot s^{-1}$) appears dependent on limb dominance (Thompson et al., 2001). Whilst peak torque in the right leg had recovered by 2 d following a simulated soccer match, peak torque in the left limb was still impaired for a further day. This may be due to participants subconsciously turning in one direction in the simulation protocol or an enhanced protection in the dominant leg due to greater everyday use.

Given that type II muscle fibres comprise narrow Z-lines, which indicate a thin attachment of actin and myosin filaments (Fridén et al., 1983; Widrick et al., 1999) and that eccentric muscle actions preferentially recruit type II fibres (Enoka, 1996; Nardone et al., 1989; McHugh et al., 2000), it is unsurprising that there appears to be a selective damage of type II fibres following eccentric exercise (Brockett et al., 2002). Whilst several researchers have used this theory to explain the exacerbated relative loss in relative isokinetic torque they have observed at higher angular velocities following EIMD (Eston et al., 1996; Fridén et al., 1983), type II fibres are also known to be considerably active when working close to maximal force production regardless of the actual movement speed (Henneman et al., 1974; Sale, 1992). In addition, the slower angular velocities, which result in greater torques being produced, might be more negatively affected because of a voluntary reduction in the activation of higher threshold (type II muscle) motor units (Deschenes et al., 2000) in an attempt to prevent further damage to skeletal tissue (Westing et al., 1991). Therefore, it is unclear why selective type II fibre damage would cause a preferential drop in isokinetic peak torque at fast but not slow velocities, given that higher forces are observed in the latter (Fridén et al., 1983).

2.4.2.3.3 Vertical jumps

Vertical jumps can be classified based on the contribution of the stretch shortening cycle (SSC) to the movement. Squat jumps (SJ; without SSC) have been reported to be impaired greater than countermovement (CMJ; with SSC) or drop jumps (DJ; with high magnitude SSC) following resistance training (Byrne and Eston, 2002; Harrison and Gaffney, 2004) and endurance exercise (Chambers et al., 1998; Hortobágyi et al., 1991; Suzuki et al., 2006). Given that a pre-stretch produces a reduction in the duration of the eccentric phase and subsequently a greater force at the start of the concentric movement (Bobbert et al., 1996), it is proposed that less reliance may be placed on excitation of the fibres for cross-bridge formation (Byrne and Eston, 2002). Instead, jumps which accommodate a SSC predominantly utilise energy from the elastic stretch and whilst this may also be attenuated following EIMD due to central inhibition on landing (from a DJ or repeated CMJs; Horita et al., 1999) or through reduced proprioceptive reflexes (Komi, 2000), it appears that the SSC is better preserved than the body's ability to produce energy from excitation-contraction coupling (Byrne and Eston, 2002). Therefore, the relatively larger reduction in SJ than CMJ or DJ would suggest than SJs would be superior for monitoring recovery from PMSTS matches. However, CMJ jump height has been reported to be lower than baseline for up to ~3 d (69-72 h) following competitive (Andersson et al., 2008; Magalhães et al., 2010) and simulated soccer matches (Magalhães et al., 2010) and similarly, SJ height is impaired for at least 2 d (Bailey et al., 2007) following a simulated soccer match. Given that Bailey et al. (2007) did not obtain measurements beyond 2 d, it is unclear how the time taken for the SJ height to return to baseline compares with the recovery of CMJ height reported by Magalhães et al. (2010) following a similar soccer match simulation protocol. Therefore, at present it is unclear whether CMJ and SJ heights are affected in the same manner following PMSTS as they are following resistance and endurance training. Nevertheless, peak rate of force development (McLellan et al., 2011b), peak power (McLellan et a., 2011b), peak force (McLellan et al., 2011b) and flight time (McLean et al., 2010) during CMJs have been observed to be lower than baseline for 1 d following competitive rugby league matches. It is speculated that the faster recovery of

CMJ parameters following rugby league matches may be as a result of the recovery strategies (McLellan et a., 2011b) and recovery sessions (McLean et al., 2010; McLellan et a., 2011b) performed immediately and 1 d following matches, respectively, by the rugby league players. Similar to the findings in rugby league players, CMJ mean power, relative mean power and relative mean force were reported to be substantially lower at 1 d following an Australian rules football match, however, they had returned to pre-match levels by 3 d (Cormack et al., 2008). No testing was conducted at 2 d following the match owing to the fact that players were given this day as total rest. Therefore, it is unclear whether CMJ parameters would also have been reduced at 2 d following an Australian rules football match.

2.4.2.3.4 Single and repeated sprints

Single effort 20 m sprints have been shown to be slower immediately following simulated (Magalhães et al., 2010) and competitive (Andersson et al., 2008; Ascensão et al., 2008; Magalhães et al., 2010) soccer matches and remain slower than baseline for up to 3 d (Ascensão et al., 2008; Magalhães et al., 2010) in males but appear to return to baseline by 5 h following the match in females (Andersson et al., 2008). In addition, despite 20 m sprints being significantly slower for up to 3 d following a simulated soccer match compared to pre-match (Magalhães et al., 2010), no change in mean time over repeated sprints (11 x 15 m during performed during a 15 min block of the match simulation protocol) were reported 2 d following the same soccer match simulation protocol (Bailey et al., 2007). Noticeably, those participants that performed 20 m sprints during the simulation protocol observed slower sprint times (Magalhães et al., 2010) in the days following, whilst those that performed 15 m sprints did not (Bailey et al., 2007). No other differences were observed between the match simulation protocols owing to the fact that the mean 'individualised' movement velocities were similar between simulation protocols. Therefore, it is likely that the greater volume of overall distance, particularly high intensity sprint efforts, has had a negative effect on short (15-20 m) sprint performance.

2.4.3 The repeated bout effect

Following exposure to the same resistance training stimulus, symptoms of EIMD have been shown to be attenuated for up to six weeks (Howatson et al., 2007; Jones and Newham; 1985; McHugh, 2003) as a result of a phenomenon referred to as the 'repeated bout effect'. Several hypotheses exist to explain this phenomenon, which are broadly grouped into three theories.

Firstly, the cellular theory suggests that an adaptation occurs to make the cell membrane more robust to the insult of mechanical damage (Clarkson and Tremblay, 1988), or that the initial bout of exercise cause the removal of 'susceptible' fibres (Armstrong et al., 1983). Alternatively, in-line with the 'popping sarcomere' hypothesis (Morgan, 1990), sarcomeres are added in series following EIMD resulting in an acute shift in the optimum length of the muscle (Bowers et al., 2004; Brockett et al., 2001; Philippou et al., 2003; Prasartwurth et al., 2006). Thereafter, the muscle is more capable of coping with force at greater lengths due to less stretch on the sarcomeres. A second theory is that following the initial bout of exercise, connective tissue remodelling of damaged filaments takes place (Newham et al., 1987) resulting in greater resistance to future damage. Finally, the neural theory proposes that an adaptation in the motor unit recruitment patterns (e.g. increased motor unit activation and/or synchronisation; McHugh et al., 1999) occurs in response to the initial EIMD stimulus to deal with the demands more effectively in the future. For a more detailed review of the proposed mechanisms to explain the repeated bout effect, readers are directed to the review by McHugh (2003).

Therefore, whilst prior exposure to the exercise intensity and movement patterns may provide regular starting players with some degree of protection from EIMD during the season, early pre-season games and players 'stepping up' from lower standards of competition, returning from injuries or playing greater game time than they accustomed to, are all likely to experience EIMD. Despite these suggestions, EIMD and DOMS have been reported following in-season competitive (Magalhães et al., 2010) and simulated

(Magalhães et al., 2010) soccer matches by elite players. Furthermore, recent evidence suggests that even when matches and/or match simulation protocols are performed 7-15 d apart, EIMD and DOMS are similar following the second event as they are following the first (Kingsley et al., 2005; Magalhães et al., 2010). It is possible that the variability between match intensities, particularly with regard to high intensity efforts, and muscle damage resulting from oxidative stress, may explain the apparent lack of protection from subsequent PMSTS matches on EIMD and DOMS.

2.5 Match simulation protocols

2.5.1 Motorised treadmill simulation protocols

Drust et al. (2000) devised a motorised treadmill simulation based on the TMA data of Reilly and Thomas (1976). However, given the increase in fitness of elite soccer players over time, the analysis by Reilly and Thomas (1976) appears dated in comparison to that of more recent match analysis studies (Di Salvo et al., 2007; Rampinini et al., 2007a). The total duration of the protocol was 46 min 11 s which represented one half of a soccer match (Durst et al., 2000). Whilst the %TT spent in each of the locomotive category was similar to that described by Reilly and Thomas (1976), the durations of the different bouts of activity were much longer, with less frequent changes in activity than have been reported in matches (Mohr et al., 2008). Technical limitations owing to the use of a motorised treadmill will have prevented more rapid changes in treadmill speeds. Sprinting was set at a pre-selected speed of 21 $km \cdot h^{-1}$ and as a result maximal effort might not have been reached by all participants when sprinting. Furthermore, the absence of a quantifiable measure of performance prevents the use of the protocol for monitoring the effectiveness of interventions on game-related physical performance. In addition, the use of a motorised treadmill prevents the inclusion of utility (i.e. backward or sideways movements) or sport-specific movements (Drust et al., 2000). Given that Drust et al. (2000) have shown that there is a greater anaerobic energy provision during intermittent than continuous steady-state exercise, the low number of accelerations and decelerations is likely to have resulted in slightly lower energy demands than those observed in matches (Bangsbo, 1994). Nevertheless, the observed $\dot{V}O_2$ during the motorised simulation protocol (68% $\dot{V}O_{2\max}$; Drust et al., 2000) was only marginally lower than estimated during competitive soccer games using HR-$\dot{V}O_2$ regression lines determined via laboratory-based treadmill running (Reilly, 1990). Moreover, the observed loss of body mass during the motorised treadmill simulation protocol (1.0 ± 0.6 kg; 1.3 ± 0.7%BM) was similar to that reported following competitive soccer matches (0.84 ± 0.52 kg; 1.1 ± 0.6%BM: Maughan et al., 2007).

2.5.2 Non-motorised treadmill simulation protocols

Sirotic and Coutts (2008) developed a 30 min generic team sport simulation protocol (prolonged high intensity intermittent running simulation protocol; PHIR) using a non-motorised treadmill (NMT) based on the TMA of various team sports (Bangsbo, 1991; Duthie et al., 2003; Spencer et al., 2004). Although as a result of not basing the protocol directly on match data from any one sport and by making the protocol just 30 min in duration, the protocol lacks specificity to any particular PMSTS. The authors attempted to individualise the speeds at which locomotive categories were set by calculating velocities based on a percentage of maximal sprint speed. A speed chart displaying both target and current speed was placed at eye level and participants were instructed to match the target speed as closely as possible.

Similarly, Abt et al. (2003) designed a simulation protocol to replicate the activity profile of 'team sports'. Two 45 min periods were divided into six 15 min periods, with a 15 min interval separating the third and fourth period. Similar to Sirotic and Coutts (2008), locomotive activity speeds were based on percentages of maximal speeds. The TD covered in the simulation protocol was 10,196 ± 403 m, which is similar to that observed in soccer matches (Rampinini et al., 2007a; 9710-12,750 m; Mohr et al., 2003; 10,860 m). In total, the protocol involved 18 x 6 s sprints and 18 x 3 s sprints. As with the pattern of fatigue observed in soccer (Mohr et al., 2003), mean peak sprint speed decreased from the first to final 15 min period (7.9%).

Thatcher and Batterham (2004) created a Soccer Specific Exercise Protocol (SSEP) based on %TT in each locomotive category that they observed in senior elite soccer matches. The SSEP consisted of 2 bouts of activity each consisting of 9 x 5 min repeating cycles separated by a 15 min rest period to simulate half-time. Despite the authors rationalising the use of a NMT to enable rapid accelerations and decelerations, the average activity duration was still significantly greater than that observed in matches. Typically the activity duration in the SSEP was 10-20 s, resulting in far fewer changes in activity than in comparison to the ~1,350 changes in activity observed in a match, with an activity change every ~4 s (Mohr et al., 2008). Furthermore, due to sprints being performed at a set speed of 23 $km \cdot h^{-1}$, there was no measure of physical performance in the simulation protocol. Nevertheless, the protocol was directly validated against competitive match data with players covering a mean total of 9,942 and 10,274 m in the SSEP and matches, respectively. Furthermore, physiological responses were also similar to those observed during matches. Overall mean HR was reported to be 83% HR_{max} in the SSEP in comparison to 84.4-86.7% HR_{max} in matches (Thatcher and Batterham, 2004), which equated to an estimated $\dot{V}O_2$ of ~70%. In addition, lactate was 5.37 and 4.74 $mmol \cdot l^{-1}$ for first and 2nd half, respectively, compared to the match lactates of 5.1 $\pm$ 0.5 $mmol \cdot l^{-1}$ reported by Krustrup et al. (2010).

A distinct unavoidable disadvantage of NMT protocols is the inability to replicate utility or sport-specific movements. In addition, Highton et al. (2008) has shown a poor agreement between short (10-30 m) NMT and track sprint times, suggesting that it might not be possible to achieve maximal acceleration and peak velocity on a NMT. This is in accordance with Lakomy (1987) who showed that only approximately 80% of maximum velocity could be achieved on a NMT. Therefore, the validity of using NMTs to replicate the demands of matches is questionable. Nevertheless, NMT match simulation protocols have been shown to be highly reliable (Sirotc and Coutts, 2008) due to the high degree of control that is possible under laboratory conditions.

2.5.3 Field-based simulation protocols

Nicholas et al. (2000) designed an indoor running simulation protocol, the Loughborough Intermittent Shuttle Test (LIST), to simulate the demands of competitive male soccer matches. Briefly, the LIST requires participants to run between two 20 m cones at various locomotive speeds dictated by audio cues, for a total duration of 90 min. The simulation protocol consisted of a set pattern of intermittent running based on what is now considered to be the out-dated TMA match data of Reilly and Thomas (1976) and Withers et al. (1982). The paces of jogging and cruising components were individualised at 55 and 95% of the participant's individual speed at $\dot{V}O_{2\max}$ ($v\dot{V}O_{2\max}$). Therefore, assuming participants complete the protocol, those participants with a higher $v\dot{V}O_{2\max}$ will cover a greater overall distance than those with a lower $v\dot{V}O_{2\max}$ due to more cycles being completed in each 15 min block. The mean TD covered in the LIST has been reported to range from 6,971-11,100 m depending on ambient conditions, fluid availability and participants' $v\dot{V}O_{2\max}$ (Morris et al., 2003; Nicholas et al., 2000). The lower end of this range is somewhat lower than current estimations of the TD covered during elite soccer matches (11,393 m: Di Salvo et al., 2007; 9,710-12,750 m: Rampinini et al., 2007a). In addition, unlike motorised treadmill match simulation protocols where frequent changes in activities are difficult to achieve, participants actually perform more sprints (~55-60) during than the LIST than are reported during competitive matches (17-36 ; Di Salvo et al., 2010 : 31-33 ; O'Donoghue et al., 2005). Likewise, values for mean blood lactate concentrations (5.7-6.2 $mmol \cdot l^{-1}$, Nicholas et al., 2000) have been shown to replicate those obtained during soccer matches (Bangsbo et al., 1991) suggesting a similar anaerobic stress is imposed on participants during the LIST as that observed in matches.

Several authors have shown the fatiguing effect of the LIST on the performance of a soccer skill (McGregor et al., 1999) and in provoking muscle damage (Thompson et al., 1999, 2001). Furthermore, despite the structured protocol, and individualisation of activity speeds, a decrement in performance is still observed in mean sprint time from the first to final 15 min block (Morris et al., 1998, 2003; Thompson et al., 1999). However, given that the bias ± 95%LoA are -0.01 ± 0.13 s (TE=0.05 s) for 20 m sprints (calculated based on values from Nicholas et al., 2000), the 0.05-0.09 s mean change in mean 15 m sprint time between the first to last 15 min block (Morris et al., 2003; Thompson et al., 1999) must be interpreted with caution, as this level of change may not be meaningful with this amount of within-subject variability. In addition, because of the individualisation of jogging and cruising speeds, participants can only be studied one at a time or must be matched against someone with the same $v\dot{V}O_{2\max}$ which is not always possible. In an effort to allow more than one person to be run at once, Edwards et al. (2003) attempted to make the movement speeds of the LIST more generic by using the mean $v\dot{V}O_{2\max}$ achieved from a group of 23 male participants to produce generic running speeds. However, this adaptation of the LIST has yet to be validated with respect to the movement demands and physiological responses of matches.

Other authors have attempted to develop the LIST further by including movements with the ball (Bishop et al., 1999), multidirectional sprints (Kingsley et al., 2005) and utility movements, such as backward running (Bishop et al., 1999) or by making it specific to another sport (MacLaren and Close, 2000). For example, the soccer-specific simulation protocol (SSSP) designed by Bishop et al. (1999) differed from the LIST in that participants were required to perform 3 bouts of 14 min of exercise per half with 1.5 min rest between bouts (45 min per half). Each bout was subsequently divided into seven two minute circuits comprising: 50 m dribbling through cones placed 5 m apart, 50 m backward running, 25 m cruise running, 25 m maximal sprinting and 50 m walking. A TD of ~9,700 m was covered during the protocol which is somewhat lower than reported for elite soccer players in most positions (e.g. 9,710-12,750 m; Rampinini et al., 2007b). In addition, blood lactates at half-time (4.43 ± 0.83 $mmol \cdot l^{-1}$) and immediately following (4.76 ± 0.87 $mmol \cdot l^{-1}$) the SSSP (Bishop et al., 1999) suggest that the metabolic demands on the anaerobic system are slightly lower than during competitive matches (5.1 ± 0.5 $mmol \cdot l^{-1}$; Krustrup et al., 2010).

Subsequently, MacLaren and Close (2000) adapted the LIST to simulate the movement demands of rugby league referees based on time-motion observations from six matches. The simulation protocol consisted of an 8 min intermittent activity cycle followed by a 2 min static rest period. Four of these cycles were completed back-to-back followed by a 10 min break to replicate the half-time break. Three further cycles were then performed to replicate the first 30 min of the second half. However, the reason for this is unclear as it is normal for referees to officiate for the full 80 min. The TD covered by participants in the simulation protocol was 7,000 m with one 15 m sprint performed every 10 min cycle. Whilst, there was a trend for sprint times to increase after the half-time break in the placebo condition, this change was not significant (P>0.05). Given that just seven sprints were performed in total, it is possible that the low number of sprints and overall movement demand was not exhaustive enough to cause any fatigue. Furthermore, while reductions in high intensity activity are known to be most evident in the final 15 min of a match (Bradley et al., 2009, 2010; Mohr et al., 2003), the protocol used in the current study was 10 min shorter than the length of a match and might therefore, have been truncated before any fatigue was imposed on the participants.

More recently, Kingsley et al. (2005), adapted the LIST by including backward cruising (85% $v\dot{V}O_{2\max}$) and zig-zag sprinting. However, the exact arrangement of the protocol is unclear.

Notwithstanding the aforementioned concerns over the ecological validity of the LIST, it (along with its adapted versions) remains a popular research tool for replicating soccer matches. The popularity of the LIST probably owes to the fact that it is easy to administer, does not require a large amount of space (20 m in length) and is easy to follow due to the reciprocal nature of the test.

Cox et al. (2002) devised a soccer simulation protocol for assessing creatine supplementation on agility and short (20 m) sprint performance under game-related conditions in female soccer players. The protocol consisted of five 12 min exercise blocks (11 min of exercise and 1 min of recovery). Each 11 min exercise block consisted of 11 x 20 m sprints, two agility runs and one precision ball kicking drill separated by a standardised pattern of walking, jogging and running for active recovery. Interestingly, the protocol was just 60 min, which Cox et al. (2002) reasoned was necessary to improve participation as they felt that participants would be unlikely to comply with a lengthier protocol.

Similarly, Stuart et al. (2005) devised a match simulation protocol for assessing nutritional interventions, this time specific to rugby union match play. Briefly, the protocol consisted of 7 x 5.5 min circuits per half, with each circuit comprising 11 x 30 s stations. One novel aspect of the protocol was the inclusion of a bespoke dynamometer cart used to measure peak power during simulated rucks and tackle bags to simulate tackles. However, no comparison was made between the movement demands of the protocol and those observed during competitive matches. Although more recently, a match simulation protocol has been designed to replicate the demands of elite rugby union match-play in forwards (Roberts et al., 2010) based on the movements demands reported by Roberts et al. (2008) from manual digitisation of matches in a calibrated area. The Bath University Rugby Shuttle Test (BURST), comprised 16 x 315 s exercise periods grouped into 4 x 21 min quarters with 4 min break following quarters one and three and a 10 min break after quarter two to simulate half-time. Similar to the LIST and its adapted versions, the timings of the movements in the BURST were dictated by an audio CD with spoken commands to remind participants of the movements. Like the protocol of Stuart et al. (2005), the BURST included simulated contacts. Whilst a simulated ruck involved carrying a 20 kg tackle bag 5 m, a scrum involved pushing against a 120 kg one-man scrummaging machine and a maul involved 5 s grappling with an opponent to gain or retain possession of a ball. Despite the volitional intensity of the latter two of these activities, the CoV for mean HR, 15 m sprint time and time to complete an anaerobic game-specific agility test lasting ~17.75 s, were all ≤2.2% when the protocol was performed on a test-retest basis. However, test-retest reliability of blood lactate was not so favourable (CoV=14.4%) and was regarded as poor. A small drawback of both the BURST and the protocol by Stuart et al. (2005) is the specialist equipment that is required (e.g. 120 kg one-man scrummaging machine or bespoke dynamometer cart) which makes it difficult for others to replicate this protocol.

2.6 Conclusions

Reports that muscle function and perceived soreness are impaired 1 d following a competitive rugby league match (McLean et al., 2010; McLellan et al., 2011b) have obvious implications for the quality of training in the day following a match. It is likely that these signs of EIMD are the result of a combination of oxidative stress that is observed following similar PMSTS matches and match simulation protocols (Ascensão et al., 2008; Thompson et al., 2001; Magalhães et al., 2010) and mechanical damage from eccentric muscle actions during rapid accelerations and decelerations (Osgnach et al., 2010). Therefore, the assessment of recovery interventions to alleviate these symptoms is warranted. Yet, given the large variability in the movement demands observed during other PMSTS matches (Gregson et al., 2010; Mohr et al., 2003), it is likely that the rate and magnitude of recovery will be influenced by the match intensity. Therefore, the development of a match simulation protocol may be a useful research tool to remove these unavoidable issues.

In creating a match simulation protocol that is valid representation of a specific sport, it is necessary to recreate the activity of that sport as closely as possible (Wragg et al., 2000). Whilst protocols exist for replicating the match demands of soccer (Bishop et al., 1999; Drust et al., 2000; Kingsley et al., 2005; Nicholas et al., 2000; Thatcher and Batterham, 2004), rugby union

(Roberts et al., 2010; Stuart et al., 2005) and rugby league referees (MacLaren and Close, 2000), a sport-specific simulation protocol does not exist for rugby league players. Whilst both field-based and NMT protocols appear to allow sprinting intensity to be self-paced, the advantage of field-based protocols is that they incorporate sport-specific movements, such as turning, and offer a more ecologically valid solution than NMT protocols.

In order to devise a match simulation protocol an in-depth assessment of the overall demands of match-play is warranted. However, studies assessing the movement demands of competitive rugby league matches have (i) been conducted prior to the limited interchange rule in 2001 (Meir et al., 2001a); (ii) been generated from gait analysis and are therefore somewhat reliant on the ability of the observer (King et al., 2009; Meir et al., 2001a); (iii) were based on a small data set (McLellan et al., 2010, 2011a; Meir et al., 2001a); or (iv) were based on players from just one team (King et al., 2009; McLellan et al., 2010, 2011a, 2011c; Meir et al., 2001a; Sirotic et al., 2009). Moreover, despite initial findings that there may be differences in the exercise intensity when the ball is in play compared to stoppages (Doğramaci and Watsford, 2006), no study to date has performed such an in-depth analysis in rugby league.

Whilst both 5 Hz NdGPS and SAIR are accurate and reliable TMA methods for assessing the movement demand of match-play (Bradley et al., 2009, 2010; Coutts and Duffield, 2010; Di Salvo et al., 2006, 2009; Jennings et al., 2000; Petersen et al., 2009; Portas at al., 2010; Rampinini et al., 2009), SAIR tracking systems may be more appropriate given that they allow the movement demands of multiple players and permit the assessment of both teams during matches. In this way they provide a more normative profile of the demands of the game than relying on data from just one team.

In addition, high and very high intensity running distance and/or locomotive rates appear to be valid methods of distinguishing between different levels of ability (Bangsbo et al., 1991; Brewer et al., 2010; Ekblom, 1986; Mohr et al., 2003, 2008) and a reduction in these variables is observed towards the end of a number of PMSTS (Andersson et al., 2010a, Bradley et al., 2009, 2010; Carling and Dupont, 2011; Coutts et al., 2010; Di Salvo et al., 2007; MacLeod et al., 2007; Mohr et al., 2003, 2008). However, whether these reductions are also detectable in elite rugby leagues has yet to be elucidated.

CHAPTER 3

SEMI-AUTOMATED TIME-MOTION ANALYSIS OF SENIOR ELITE RUGBY LEAGUE

The contents of this chapter form the basis of the following publications and presentation:

Sykes, D., Twist, C., Hall, S., Nicholas, C., and Lamb, K. (2009). Semi-automated time-motion analysis of senior elite rugby league. *International Journal of Performance Analysis in Sport,* **9**, 47-59.

Sykes, D., Twist, C., Hall, S., Nicholas, C., and Lamb, K. (2008). Semi-automated time-motion analysis of senior elite rugby league. British Association of Sport and Exercise Sciences Annual Conference, University of Brunel, 2nd-4th September.

Sykes, D., Twist, C., Hall, S., Nicholas, C., and Lamb, K. (2008). Semi-automated time-motion analysis of senior elite rugby league [Abstract]. *Journal of Sports Sciences*, **26**, S124-125.

3.1 Abstract

The aim of this study was to examine the movement demands of senior elite rugby league with consideration of the impact of player position and match phase. A semi-automated image-recognition system (SAIR; ProZone 3, ProZone®, Leeds, England) was used to track 78 players during three senior elite matches. Players were categorised as outside backs (*n*=30), pivots (*n*=18), props (*n*=12) or back row (*n*=18). Total distance (TD) covered, work-to-rest ratio (WRR) and % total time (%TT) spent in each of seven selected locomotive categories were determined for defending, attacking, ball in play and stoppage phases. Analysis revealed that during the 86.8 min of match time, the mean TD covered was 8,503 ± 631 m, with pivots (8,800 ± 581 m) and outside backs (8,142 ± 630 m) covering the most and least distances, respectively. For pivots, props and back row players, defending resulted in a significantly lower WRR than when attacking (P<0.05). Outside backs had significantly higher WRRs for defending than all other positional groups (P<0.05). The time-motion data presented in this study provides position-specific benchmarks for assessing match performance.

3.2 Introduction

3.2.1 Time-motion analysis of rugby league

Estimates of the physical demands of rugby league on individual players have suggested they cover between 8,458 and 9,929 m during a competitive match, depending on playing position, and that WRRs are 1:10 for hookers, 1:7 for props, 1:12 for scrum halves and 1:28 for wingers (Meir et al., 2001a). Meir et al. (2001a) proposed that these WRRs equate to 4 s of high intensity activity followed by between 30 and 80 s of low intensity activity, depending on playing position. However, these figures were based on a small data set from only two professional clubs and reflected only four positions. Moreover, the study of Meir et al. (2001a) was conducted prior to the introduction of the ‘limited interchange’ rule in 2001, which is believed to have lead to changes in the physiological demands of rugby league matches (Orchard et al., 2003). Analysis post-2001 by King et al. (2009) yielded WRRs of 1:6 for outside backs, 1:6 for hit-up forwards (back row and props) and 1:5 for pivots, which is markedly different to the pattern previously observed. Unlike the findings of Meir et al. (2001), King et al. (2009) have reported relatively little positional variation (1:5-1:6 versus 1:7-1:28). Positional grouping differences between studies and small sample sizes may account for some of these differences. These inconsistencies notwithstanding, a limitation to the aforementioned studies is that their data were generated from subjective analysis of gait, with arbitrary velocities being associated with each locomotive category (Castagna et al., 2004). Therefore, the accuracy is highly reliant on the ability of the observer (Di Salvo et al., 2006). Recently, global positioning systems (GPS) have emerged as an objective method to analyse movement patterns in team sports, but concerns over their safety in contact sports have until lately, prevented their usage in official matches (Di Salvo et al., 2006). However, changes in the stance taken by national governing bodies on the use of GPS in competitive matches have subsequently resulted in the use of a commercially available, non-differential GPS (NdGPS) to monitor the movement demands of rugby league matches (McLellan et al., 2010, 2011a, 2011c). Similar results were reported for all studies, with mean distances reported to range from 4,774-4,982 for forwards and 5,573-5,747 m for backs, which is noticeably lower than previously reported in previous studies (Meir et al., 2001a., King et al., 2009; Sirotic et al., 2009). However, data are generated from just one team and therefore may not be representative of all teams. Furthermore, involvement in contact cannot be reported from GPS data without synchronisation with video footage, and therefore a true WRR cannot be reported.

However, developments in SAIR tracking systems have provided a valid (Di Salvo et al., 2006), reliable (Bradley et al., 2009, 2010; Di Salvo et al., 2009) and non-intrusive method for quantifying movement velocities and match involvements of multiple players from multiple teams during match play (Di Salvo et al., 2006) and has previously been used to report the movement demands of senior elite soccer (Bradley et al., 2009, 2010, 2011; Carling and Dupont, 2011, Di Salvo et al., 2007, 2009; Rampinini et al., 2007a; 2007b, 2009; Weston et al., 2011) and rugby union (Eaton and George, 2006) matches. Therefore the primary aim of this study is to use a SAIR tracking system to produce an accurate and up-to-date profile of the movement demands of elite rugby league matches. A secondary aim is to examine the impact of playing position, possession (attack versus defence) and match phase (ball in play versus stoppages) on these time-motion profiles.

3.3 Methods

3.3.1 Participants

All 78 participants were senior elite rugby league players representing professional clubs participating in either the English Engage Super League (*n*=52) or Australian National Rugby League (NRL; *n*=26). All competitive matches were played in England under fair weather conditions. The players were classified into playing positions as defined by Gabbett (2005), that is, props (*n*=12), back row (*n*=18), outside backs (*n*=30) and pivots (*n*=18). Approval for the study was obtained from the Faculty of Applied and Health Sciences Research Ethics Committee (Appendix 4).

3.3.2 Match analysis system

Video footage from a total of three senior elite competitive matches utilising six different teams was collected using a SAIR tracking system (ProZone 3, ProZone®, Leeds, England) and published with formal permission of the company (Appendix 1). This method used eight fixed colour cameras (ProZone, ProZone®, Leeds, England) installed along the roof of the stadia; two opposing corners of the stadia housing three cameras each and one camera situated in each of the other two corners. The fields of view of the cameras were positioned so that every area of the pitch was covered by a minimum of two cameras, as described by Di Salvo et al. (2006; Appendix 3), for increased accuracy and to reduce the occurrence of occlusions. The players' image co-ordinates were converted into pitch co-ordinates using a linear 4-point transformation calibration followed by a proprietary 50 point algorithm that eliminates vision distortion with respect to optical errors

(Hartley and Zisserman, 2002). The automated tracking was visually verified until the appearance of a tracking error, at which point the system operator was able to manually stop the tracking, move back to the frame of error and re-initialise the automatic tracking (Di Salvo et al., 2009).

On installation of the ProZone cameras, the pitches were calibrated and transformed into a two dimensional (2D) model to allow each player's position to be located as X and Y co-ordinates measured from the centre spot on the pitch. The ProZone 3 analysis system samples at a rate of 10 Hz by calculating the distance covered every 0.1 s as if moving in a straight line between co-ordinates, using Pythagoras' theorem. The average velocity across a 1 s period of time is then calculated by dividing the summated distance over the 10 frames by time. From this, players' movements are then classified into movement categories based upon specific velocity thresholds. The validity of this procedure has been evaluated previously by Di Salvo et al. (2006), who compared mean velocities from match-related activities obtained by the ProZone system to those obtained from timing gates. The mean coefficients of variation (CoV) obtained by the ProZone system compared to those obtained from the timing gates were 0.2, 0.3, 0.2 and 1.3% for a paced linear 60 m run, 50 m paced arced run, 15 m linear sprint and 20 m curved sprint, respectively. Subsequent analysis of the data set by Di Salvo et al. (2009) revealed no statistically significant differences between the mean velocity recorded via ProZone and the timing gates over a set distance. This was independent of the movement pattern (linear or multi-directional) or movement speed from (7.5-25.2 $km \cdot h^{-1}$). Furthermore, Di Salvo et al. (2009) assessed the inter-observer reliability of the system resulting from the manual correction by ProZone 'in-house' quality control personnel. Two quality control personnel observed the same footage from two outfield soccer players and the total time spent and distance covered in each of the discrete locomotive categories (based on calculating the velocity for each 0.1 s of the match) was analysed for each observer. No statistically significant differences (*P*<0.05) were observed between operators for time and distance, and the highest CoV for any of the comparisons was 6.5% for time spent sprinting (>25.2 $km \cdot h^{-1}$). Similarly, Bradley et al. (2009, 2010) reported inter- and intra-observer CoV for total distance covered in each of the locomotive categories to be <2%, with sprinting <3.5%, suggesting acceptable reliability (Stokes, 1985; Atkinson et al., 1999).

In the current study, the Prozone 3 analysis software (Prozone 3, ProZone®, Leeds, England) was used to classify movement into the following locomotive categories, as defined by Rampinini et al. (2007a):

- Standing (<0.7 $km \cdot h^{-1}$; <0.2 $m \cdot s^{-1}$)
- Walking (0.7-6.9 $km \cdot h^{-1}$; 0.2-1.9 $m \cdot s^{-1}$)
- Jogging (7.0-14.3 $km \cdot h^{-1}$; 2.0-3.9 $m \cdot s^{-1}$)
- Running (14.4-19.7 $km \cdot h^{-1}$; 4.0-5.4 $m \cdot s^{-1}$)
- High speed running (HSR; 19.8-25.2 $km \cdot h^{-1}$; 5.5-6.9 $m \cdot s^{-1}$)
- Sprinting (≥25.2 $km \cdot h^{-1}$; ≥7 $m \cdot s^{-1}$)

In addition, an analysis of the contact elements for players (hit-ups and tackles) was also performed. Contact was defined as the point of initial contact to the point at which the defender ceased contact with the attacker for defenders, and to the point at which the ball left the play the ball for attackers (Eaves et al., 2008). As a result of scrums being uncontested, physical exertion is likely to be minimal and hence they were not classified as 'work'. Instead, when players were involved in scrums, they were classified into a movement category based on their movement velocity.

3.3.3 Time-motion variables

The following time-motion outcome variables were calculated: TD covered (m); WRR, with 'work' defined as sprinting, HSR, running or involvement in a contact situation, and 'rest' defined as standing, walking or jogging. The %TT spent in each of the seven locomotive categories were calculated for each of four phases of play: attacking, defending, ball in play (summation of attacking and defending) and stoppages in play. When the ball was in play, teams were deemed to be either attacking or defending, based on which team was in possession of the ball. In the event that no team was in possession of the ball (e.g. immediately following a kick), the team having last made contact with the ball was still deemed to be attacking until the point in which either team regained possession. Stoppages were defined as commencing from the point of an infringement, when the ball passed out of the field of play or following a try, until the game was restarted. Hence, attacking, defending and ball in play all excluded stoppage data. The frequency and time of phases of play were recorded in each match along with total match time.

If a player was interchanged then his replacement was tracked to allow each position to be monitored for the entire match, enabling time-motion variables to be expressed per match per playing position.

3.3.4 Statistical analysis

Descriptive statistics for the time-motion variables were calculated as mean ± SD. Separate mixed between-within analysis of variance (ANOVAs) were used to compare the effect of possession (attacking vs. defending) and playing phase (ball in play vs. stoppage) with position (phase [2] x position [4]) on WRR and %TT in each locomotive category and where there was observed to be a main effect for position but no interaction Tukey HSD tests were used to identify positional differences. However, where there was found to be a phase by position interaction, separate one-way ANOVAs with Tukey HSD post-hoc tests were used to analyse the effect of position on the time-motion variable for each phase of play. Moreover, paired sample *t*-tests with Bonferroni adjustments were used to identify specific differences between phases for each position. In addition, separate one-way ANOVAs were used to analyse the effect of position on TD covered and overall WRR, and followed up, where appropriate, with Tukey HSD tests. Statistical significance was set at $P<0.05$.

3.4 Results

3.4.1 Descriptive match statistics

The ball was in play, on average, for 54.8 ± 0.4 min of the match which lasted 86.8 ± 1.6 min in total. Table 3.1 shows a breakdown of time and frequency measures in each phase of play.

Table 3.1 Descriptive match statistics (mean ± SD)

	Ball in play		Stoppages
	Attacking	Defending	
Total phase time (s)	1,642 ± 90	1,644 ± 92	1,922 ± 80
Frequency of phases (%)	34 ± 3	34 ± 3	33 ± 4
Mean phase time (s)	40 ± 6	40 ± 6	48 ± 4

3.4.2 Total distance covered and overall work-to-rest ratio

The mean TD covered for all players was 8,503 ± 631 m and the overall WRR was 1:10.9 ± 2.7. Table 3.2 indicates that there was a significant (P<0.05) main effect of position on distance covered and overall WRR, with the outside backs covering significantly less distance than pivots, props and back row players (P<0.05). In addition, whilst outside backs and pivots had a significantly (P<0.05) higher overall WRR than back row players, outside backs also had a significantly (P<0.05) higher overall WRR than props.

3.4.3 Ball in play and stoppage work-to-rest ratios

The mean WRRs (all players) were 1:6.9 ± 1.8 and 1:87.4 ± 75.2 for ball in play and stoppages, respectively. Independent of position, WRRs for ball in play were significantly lower (P<0.05) than WRR for stoppages (see Table 3.2). No positional differences were observed for ball in play or stoppage WRRs (P>0.05).

3.4.4 Attacking and defending work-to-rest ratios

The mean WRR (all players) was 1:7.8 ± 1.7 and 1:6.8 ± 3.2 for attacking and defending, respectively. The phase by position interaction was significant ($P<0.05$) with post-hoc analysis showing defending WRR to be significantly ($P<0.05$) lower than attacking WRR for pivots, props and back row (see Table 3.2). In contrast, for outside backs the attacking WRR was lower than the defending WRR, although this was not significant ($P>0.05$). In addition, defending WRR was significantly ($P<0.05$) higher for outside backs than all other positional groups. However, there was no effect of position on attacking WRR ($P>0.05$).

3.4.5 Percentage of total time spent in each locomotive category for ball in play and stoppage phases

The effect of position on %TT was significant ($P<0.05$) for ball in play only (Table 3.3), with outside backs spending significantly less time jogging, running and in contact, and more time walking than all other positional groups. Independent of position, players spent significantly ($P<0.05$) less time jogging, running, HSR, sprinting and in contact and with the exception of outside backs, more time walking during stoppages than ball in play phases. During ball in play phases, outside backs also spent more time in HSR than props and sprinting than pivots and props ($P<0.05$), whereas pivots spent significantly less time standing than outside backs and less time in contact than props and back row players ($P<0.05$). Furthermore, back row players spent significantly ($P<0.05$) more time in HSR than props.

3.4.6 Percentage of total time spent in each locomotive category when attacking and defending

Overall, players spent significantly ($P<0.05$) less time standing, walking, HSR and sprinting and more time jogging and running when defending, compared to attacking (Table 3.5). In addition, with the exception of outside backs, players spent significantly ($P<0.05$) more time in contact whilst defending than attacking.

Independent of possession, outside backs spent significantly (*P*<0.05) more time walking and less time jogging than all other positional groups. Moreover, outside backs spent significantly (*P*<0.05) less time running and in contact whilst defending than all other positional groups, but more time sprinting than pivots and props when both attacking and defending.

Furthermore, props and back row players spent significantly (*P*<0.05) more time than pivots in contact whilst both attacking and defending. In comparison to props and back row players, pivots spent significantly (*P*<0.05) more time walking when defending but more time jogging whilst attacking.

The only significant (*P*<0.05) differences between props and back row players were that when attacking props spent more time in contact, while back row players spent more time in HSR.

Table 3.2 TD covered and WRR by phase and position

	TD Covered (m)	Overall WRR	Ball in play WRR	Stoppage WRR	Attacking WRR	Defending WRR
All players	8,503 ± 631	1:10.9 ± 2.7	1:6.9 ± 1.8	1:87.4 ± 75.2	1:7.8 ± 1.7	1:6.8 ± 3.2
Outside backs (*n*=30)	8,142 ± 630	1:12.6 ± 2.7	1:8.2 ± 1.6	1:101.8 ± 114.5ǂ	1:7.9 ± 1.6	1:9.3 ± 3.4
Pivots (*n*=18)	8,800 ± 581†	1:10.9 ± 2.2	1:7.0 ± 1.6	1:73.9 ± 33.8ǂ	1:8.6 ± 2.4*	1:6.2 ± 1.9†
Props (*n*=12)	8,688 ± 405†	1:9.0 ± 1.6†	1:5.7 ± 1.0	1:83.3 ± 41.0ǂ	1:7.2 ± 1.3*	1:4.8 ± 1.2†
Back row (*n*=18)	8,685 ± 547†	1:8.9 ± 1.3†Ψ	1:5.5 ± 0.9	1:79.6 ± 20.2ǂ	1:7.2 ± 1.1*	1:4.5 ± 1.0†

† Significantly different ($P<0.05$) to outside backs. Ψ Significantly different ($P<0.05$) to pivots. * Significantly different ($P<0.05$) to defending.

ǂ Significantly different ($P<0.05$) to ball in play.

Table 3.3 The %TT spent in each locomotive category for ball in play and stoppage phases by position (mean ± SD)

	Standing	Walking	Jogging	Running	HSR	Sprinting	Contact
Ball in play							
All players	2.3 ± 1.1	53.9 ± 7.3	30.5 ± 5.4	6.7 ± 1.4	1.8 ± 0.5	0.4 ± 0.3	4.2 ± 1.9
Outside backs	2.6 ± 1.2	60.6 ± 4.7	25.7 ± 3.8	5.8 ± 1.1	2.0 ± 0.4	0.6 ± 0.4	2.7 ± 0.8
Pivots	1.7 ± 0.7[†]	50.5 ± 6.6[†]	34.9 ± 4.3[†]	7.1 ± 1.3[†]	1.7 ± 0.4	0.3 ± 0.2[†]	3.8 ± 1.5[†]
Props	2.5 ± 1.0	48.6 ± 5.1[†]	33.6 ± 3.9[†]	7.2 ± 1.7[†]	1.4 ± 0.3[†]	0.2 ± 0.1[†]	6.5 ± 0.9[†Ψ]
Back row	2.5 ± 1.0	49.8 ± 3.7[†]	32.1 ± 3.1[†]	7.6 ± 1.0[†]	1.9 ± 0.5[‡]	0.4 ± 0.3	5.8 ± 1.3[†Ψ]
Ball out of play							
All players	24.9 ± 7.0	63.4 ± 6.8	10.1 ± 1.6	1.4 ± 0.7	0.2 ± 0.2	0.0 ± 0.1	0.0 ± 0.0
Outside backs	23.7 ± 7.3[Ŧ]	64.8 ± 7.0	9.7 ± 1.6[Ŧ]	1.4 ± 0.9[Ŧ]	0.2 ± 0.3[Ŧ]	0.0 ± 0.1[Ŧ]	0.0 ± 0.0[Ŧ]
Pivots	22.2 ± 6.5[Ŧ]	65.3 ± 6.3[Ŧ]	10.8 ± 1.3[Ŧ]	1.5 ± 0.7[Ŧ]	0.2 ± 0.2[Ŧ]	0.0 ± 0.1[Ŧ]	0.0 ± 0.0[Ŧ]
Props	28.4 ± 5.6[Ŧ]	59.6 ± 5.7[Ŧ]	10.5 ± 1.3[Ŧ]	1.4 ± 0.8[Ŧ]	0.1 ± 0.1[Ŧ]	0.0 ± 0.0[Ŧ]	0.0 ± 0.0[Ŧ]
Back row	27.2 ± 6.7[Ŧ]	61.7 ± 6.3[Ŧ]	9.7 ± 1.9[Ŧ]	1.2 ± 0.3[Ŧ]	0.1 ± 0.1[Ŧ]	0.0 ± 0.0[Ŧ]	0.0 ± 0.0[Ŧ]

[†] Significantly different (P<0.05) to outside backs. [Ψ] Significantly different (P<0.05) to pivots. [‡] Significantly different (P<0.05) to props.
[Ŧ] Significantly different (P<0.05) to ball in play.

Table 3.4 Distance covered (m) in each locomotive category for ball in play and stoppage phases by position (mean ± SD)

	Standing and walking	Jogging	Running	HSR	Sprinting	Contact
Ball in play						
All players	2,111 ± 264	2,860 ± 554	1,012 ± 211	356 ± 94	109 ± 90	137 ± 58
Outside backs	2,321 ± 193	2,355 ± 346	878 ± 167	389 ± 84	157 ± 109	93 ± 38
Pivots	1,983 ± 275	3,253 ± 472	1,056 ± 186	326 ± 78	78 ± 55	119 ± 43
Props	1,966 ± 214	3,236 ± 395	1,083 ± 251	282 ± 64	51 ± 26	203 ± 18
Back row	1,987 ± 147	3,060 ± 321	1,145 ± 151	380 ± 110	97 ± 74	183 ± 37
Stoppages						
All players	1,227 ± 159	547 ± 89	120 ± 65	21 ± 22	4 ± 8	0 ± 0
Outside backs	1,271 ± 153	519 ± 87	123 ± 77	29 ± 28	7 ± 9	0 ± 0
Pivots	1,242 ± 162	591 ± 74	128 ± 67	20 ± 19	3 ± 8	0 ± 0
Props	1,163 ± 171	565 ± 62	122 ± 71	17 ± 14	1 ± 4	0 ± 0
Back row	1,178 ± 142	536 ± 104	104 ± 31	11 ± 9	4 ± 8	0 ± 0

Table 3.5 The %TT spent in each locomotive category when attacking and defending by position (mean ± SD)

	Standing	Walking	Jogging	Running	HSR	Sprinting	Contact
Attacking							
All players	3.1 ± 1.6	62.8 ± 5.5	22.3 ± 5.5	5.6 ± 1.2	2.1 ± 0.6	0.5 ± 0.6	3.5 ± 1.7
Outside backs	3.5 ± 1.8*	66.3 ± 4.5*	18.5 ± 3.3*	5.3 ± 1.1*	2.3 ± 0.6*	0.8 ± 0.8*	3.2 ± 1.2
Pivots	2.1 ± 1.1*†	57.6 ± 5.3*†	29.3 ± 4.7*†	6.4 ± 1.3*†	1.9 ± 0.6*	0.4 ± 0.4*†	2.2 ± 1.4*
Props	3.4 ± 1.7*	62.0 ± 4.1*†	22.1 ± 3.7$^{*\dagger\Psi}$	5.2 ± 1.1$^{*\Psi}$	1.6 ± 0.4*†	0.2 ± 0.2*†	5.5 ± 1.6$^{*\dagger\Psi}$
Back row	3.3 ± 1.5*	62.5 ± 3.5$^{*\dagger\Psi}$	21.8 ± 3.2$^{*\dagger\Psi}$	5.8 ± 0.8*	2.2 ± 0.6*‡	0.5 ± 0.4*	4.0 ± 1.3$^{*\Psi\ddagger}$
Defending							
All players	1.5 ± 0.9	45.1 ± 11.0	38.7 ± 7.0	7.9 ± 2.3	1.5 ± 0.5	0.3 ± 0.3	5.0 ± 3.0
Outside backs	1.7 ± 1.0	55.0 ± 7.7	32.7 ± 5.7	6.3 ± 1.7	1.6 ± 0.5	0.4 ± 0.3	2.3 ± 1.5
Pivots	1.2 ± 0.8†	43.4 ± 8.9†	40.6 ± 5.2†	7.9 ± 1.9†	1.4 ± 0.4	0.2 ± 0.2†	5.4 ± 2.6†
Props	1.6 ± 0.5	35.2 ± 6.0$^{\dagger\Psi}$	45.3 ± 4.5†	9.2 ± 2.6†	1.2 ± 0.4†	0.2 ± 0.1†	7.4 ± 1.3$^{\dagger\Psi}$
Back row	1.7 ± 0.9	37.0 ± 5.2$^{\dagger\Psi}$	42.5 ± 3.4†	9.5 ± 1.6$^{\dagger\Psi}$	1.6 ± 0.6	0.3 ± 0.4	7.5 ± 2.1$^{\dagger\Psi}$

† Significantly different (P<0.05) to outside backs. $^{\Psi}$ Significantly different (P<0.05) to pivots. ‡ Significantly different (P<0.05) to props.

* Significantly different (P<0.05) to defending.

Table 3.6 Distance covered (m) in each locomotive category when attacking and defending by position (mean ± SD)

	Standing and walking	Jogging	Running	HSR	Sprinting	Contact
Attacking						
All players	1,195 ± 147	1,027 ± 262	427 ± 92	211 ± 65	71 ± 80	54 ± 28
Outside backs	1,216 ± 155	840 ± 164	401 ± 91	232 ± 69	104 ± 107	49 ± 21
Pivots	1,104 ± 140	1,354 ± 246	477 ± 107	192 ± 57	57 ± 50	31 ± 22
Props	1,245 ± 140	1,024 ± 124	400 ± 85	166 ± 37	31 ± 20	86 ± 21
Back row	1,217 ± 111	1,011 ± 142	440 ± 59	226 ± 65	59 ± 57	64 ± 24
Defending						
All players	917 ± 204	1,834 ± 385	585 ± 171	145 ± 56	37 ± 42	82 ± 46
Outside backs	1,106 ± 127	1,514 ± 294	477 ± 131	158 ± 56	54 ± 49	43 ± 33
Pivots	879 ± 178	1,900 ± 277	580 ± 138	135 ± 42	22 ± 19	88 ± 36
Props	721 ± 103	2,212 ± 307	683 ± 199	116 ± 40	20 ± 18	117 ± 24
Back row	770 ± 94	2,048 ± 226	704 ± 126	155 ± 70	38 ± 51	119 ± 33

3.4.7 Movements per incidence in each locomotive category

In total there were 1,462 changes in locomotive activities (Table 3.7), 1,078 of which were during ball in play phases.

Table 3.7 Summary of movements (mean ± SD) per incidence in each locomotive category

	Per incidence			
	Time (s)	Distance (m)	Velocity ($m \cdot s^{-1}$)	Frequency
Standing	3.8 ± 1.3			149 ± 30
Walking	5.5 ± 0.9	6.2 ± 0.9	1.1 ± 0.0	546 ± 45
Jogging	2.3 ± 0.2	6.6 ± 0.8	2.9 ± 0.1	515 ± 62
Running	1.5 ± 0.1	7.0 ± 0.5	4.6 ± 0.0	163 ± 35
HSR	1.4 ± 0.1	8.6 ± 1.0	6.1 ± 0.2	44 ± 12
Sprinting	1.5 ± 0.5	11.7 ± 3.8	7.6 ± 0.2	9 ± 6
Contact	3.9 ± 0.5			36 ± 15

3.5 Discussion

In conducting the most comprehensive and precise analysis of the overall movement demands of senior elite rugby league players to date, the present study has quantified the TD covered, WRR, and %TT spent in discrete locomotive categories, and identified notable position- and phase-related differences in these time-motion variables.

3.5.1 Total distance covered and overall work-to-rest ratio

It was observed that outside backs covered markedly less distance across the three rugby league matches analysed than the three other positional groups in our study, the largest disparity (-658 m) existing with the pivots. Whilst not directly comparable, these figures show those reported by Meir et al. (2001a) to be overestimates of the TD covered by both the forwards (9,929 m) and the backs (8,458 m). This might simply reflect the inaccuracy in the analysis system used by Meir et al. (2001a), but may be also associated with rule changes occurring at about that time and the resulting tactical changes. A directly comparable analysis involving the same SAIR tracking system has shown senior elite soccer players to cover considerably larger distances (9,710-12,750 m) in a match (Rampinini et al., 2007a) than rugby league players. In addition, the overall WRRs (1:8.9 to 1:12.6) were comparable to those identified for senior elite rugby union players (1:7.5 to 1:14.6) measured using the same SAIR tracking system as the current study (Eaton and George, 2006). This would suggest that players are exposed to similar movement demands in both rugby codes, but that these demands are less than those observed in soccer match play.

3.5.2 Ball in play and stoppages phases

Independent of position, ball in play WRRs were significantly smaller than during stoppages. The only comparable data are those collected from Futsal (indoor 5-aside soccer) by Doğramaci and Watsford (2006), where ball in play WRR was reported to be significantly more intense (7.4:1) than for overall values (1:4.1). The results of this study support findings by Dogramaci and Watsford (2006), who suggested that stoppages in play consist largely of low intensity work whilst resetting into position or awaiting decisions. Hence, this might present an under-estimation of the WRR during active match play when averaged over the entirety of the match (Dogramaci and Watsford, 2006). Therefore, categorising of data into ball in play and stoppage phases, in addition to recording the frequency and length of stoppages, gives a more detailed analysis of the movement demands taking place. The mean time of ball in play (54.8 ± 0.4 min) was greater than that stated by Eaves et al.

(2008), who reported the ball was in play for 44.4 min during 12 professional games analysed between 2000 and 2002. More detailed analysis for matches analysed during this same period by Eaves et al. (2008), revealed a mean set time of 36 s, similar to the 40 s observed in the current study. Furthermore, mean match length was 86.8 $\pm$ 1.6 min, which was similar to the 86 min observed by Kay and Gill (2003) in a study of the movement demands of match officials during representative rugby league matches. In comparison, the ball has been shown to be out of play for an average of 16 min 24 s during a soccer match, resulting in ball in play time in excess of 70 min (Withers et al., 1982). This may, in part, explain differences in TD covered between soccer and rugby league matches as stoppages in play for injuries and kicks largely consist of prolonged rest periods (Duthie et al., 2003) and the majority of the TD covered is accumulated when the ball is in play.

On the basis of spending less time jogging, running and in contact, and more time walking, outside backs were found to be involved in less 'steady state' and static exertion work than all other positions. However, outside backs performed more HSR and sprinting than props, and more sprinting than pivots and props, suggesting that they had the most intermittent activity profile. In addition, props and back row players were involved in contact situations more so than pivots and outside backs. Typically, props and back row players are used to make the 'hard yards' close to the play-the-ball (O'Donoghue and Beck, 2004) and defensively they work to stop the forward progression of the attacking team by tackling the ball carrier (Meir et al., 2001b). As such, these positions are associated with a greater body mass compared to outside backs and pivots, which has been proposed to assist in the development of greater impact forces in collisions (Gabbett et al., 2008). These findings are also supported by those of Eaves and Broad (2007), who observed that in the defensive third of the field, hit-ups (carrying the ball into contact following a single pass from the play-the-ball) were the most common post play-the-ball activity, accounting for 44.6% of the total activities. Furthermore, in the transition zone (between the defensive and attacking thirds), hit-ups were again utilised 30.5% of the time following a play-the-ball

(Eaves and Broad, 2007). Hence, due to their effectiveness in collisions, props and back row players are heavily used in these activities and thus have an extremely high work rate in comparison to pivots and outside backs.

The results of this study show a similar positional trend to that reported by Meir et al. (2001a), in that props were most active and outside backs least, with WRRs between 1:10 and 1:12 for pivots and 1:7 for props and 1:28 for wingers (outside backs). Conversely, King et al. (2009) reported WRRs of 1:6 for outside backs and hit-up forwards (props, and back row) and 1:5 for pivots. In addition, King et al. (2009) also reported that there were no significant differences between positions for amount of time in high intensity exercise (defined as sprinting or tackling). In the current study players spent between 5.3 and 8.1% of the time in HSR, sprinting or contact whereas King et al. (2009) reported players spent between 15.9 and 17.0% in high intensity exercise. Based on the current findings, the study of King et al. (2009) appears to grossly overestimate the amount of high intensity work and fails to recognise positional differences. This may be due to the difficulties associated with the analysis of gait for classifying high intensity activity actions (Duthie et al., 2003). Moreover, the data of King et al. (2009) were gathered from a small sample size (n=3) across three matches. Indeed, Wells et al. (2004) have shown that data are more representative of normative values when analysing data from multiple players than analysing the same player over multiple matches. Therefore, match analysis should include measurement of players from different teams to establish a more normative profile. Furthermore, it is unclear whether these studies based their analysis on overall or ball in play only data. Based on our findings, there is a need to analyse and report both independently.

3.5.3 Attacking and defending

Our semi-automated TMA system has highlighted that with the exception of outside backs, attacking is significantly less physically demanding than defending, due to players having less recovery time during the defending phase.

Although not statistically significant, outside backs had a lower WRR when attacking and spent a greater proportion of time in HSR, sprinting and contact than when defending. This is possibly attributable to the positional role of outside backs which typically requires them to chase down and receive kicks and also make line breaks. Line breaks are more common on the fringes where defences are generally less compacted than close to the play-the-ball (Eaves and Evers, 2007), and may result in a higher frequency of line breaks in comparison to players active close to the play-the-ball due to lack of defensive cover in close proximity. Furthermore, outside backs often have to cover large amounts of ground to receive kicks, starting as they do from an on-side position behind the kicker. In the defensive line they spend much of their time following play on the pitch fringes and only largely come into play when required to chase down an opposing player or receive a kick (Meir et al., 2001b). However, in contrast to attacking, outside backs would drop back slowly from the defensive line in anticipation of receiving kicks and as a result would have to cover less distance to retrieve the ball than their attacking counterparts. Therefore, outside backs are required to cover greater distances and perform more work when attacking than defending.

It was also noticeable that whilst pivots performed less walking than back row players, and more jogging than props and back row players when attacking, they performed more walking than props and back row players when defending. Again, positional responsibilities imposed by coaching strategies probably explain these differences. When attacking, pivots play a key role in ball distribution and are therefore required to follow each play-the-ball (Meir et al., 2001a). They also play a role in 'probing' defences, taking the ball to the defensive line and reacting to and evading defending players (Gabbett, 2005). However, defensively there is a division in the roles of the pivots. Whilst hookers will defend in the centre of the field in anticipation of being required as a play-maker if the ball is turned over, scrum halves and stand-offs will generally defend toward the fringes (Gabbett, 2005), possibly because they are likely to be less effective in collisions due to their lower body masses and strength (Gabbett et al., 2008). Therefore, a possible limitation to the current study is the grouping of hookers as pivots, as this may have overestimated the defending and ball in play work rate for scrum halves and stand-offs. Nevertheless, pivots cover less distance overall than forwards in defence due to their high %TT spent walking, but are involved with more continuous running movements in attack due to their support role, as reflected by the large %TT spent jogging in comparison to props and back row. In addition, players spent less time walking and more time jogging during rest phases when defending, regardless of position. This is most likely as a result of the distances that attackers and defenders must retreat from the play-the-ball to stay on-side. Whilst attackers must only retire to the back foot of the player playing-the-ball, defenders must retreat 10 m and look to reset quickly to allow organisation of the defensive line with the inclusion of any defenders retreating from the tackle. To date, no other studies have investigated the movement demands of attacking versus defending.

A further limitation of the current study may be the decision to pool match data from Australian and English teams, given that Eaves and Broad (2007) have identified tactical differences in the Australian and English styles of match play. Nevertheless, the study does provide an overview of the mean movement demands representative of senior elite rugby league, independent of international differences in playing styles.

3.6 Conclusions

This TMA has identified that outside backs were notably the least active in that they covered the least TD, and had the highest overall and defending WRR. Conversely, props and back rows had the lowest overall WRR, as a consequence of spending less time walking whilst defending and more time in contact (both defending and attacking) than other positions. On the basis of these findings, it would be advisable for players to be divided into training groups based on their playing position so that training can be adapted to reflect the respective movement demands observed in matches. Regardless of position, WRRs for ball in play were significantly lower than during stoppages. For pivots, props and back row, defending resulted in a significantly higher WRR than when attacking.

The data presented in this study should be used to aid training prescription and provide position-specific performance benchmarks for future comparisons to other standards of play.

CHAPTER 4

CHANGES IN LOCOMOTIVE RATES DURING SENIOR ELITE RUGBY LEAGUE MATCHES

The contents of this chapter form the basis of the following publications and presentations:

Sykes, D., Twist, C., Nicholas, C., and Lamb, K. (2011). Changes in locomotive rates during senior elite rugby league matches. *Journal of Sports Sciences*, **29**, 1263-1271.

Sykes, D., Twist, C., Lamb, K., and Nicholas, C. (2009). Reduction in high intensity activity during senior elite rugby league matches. 14th Annual Conference of European College of Sports Sciences, 24th-27th June.

Sykes, D., Twist, C., Hall, S., and Lamb, K. (2009). Semi-automated time-motion analysis of senior elite rugby league. British Association of Sport and Exercise Sciences Annual Conference, Leeds Metropolitan University, 1st-3rd September.

Sykes, D., Twist, C., Hall, S., and Lamb, K. (2009). Semi-automated time-motion analysis of senior elite rugby league [Abstract]. *Journal of Sports Sciences*, **27**, S11.

4.1 Abstract

The aim of this study was to quantify the changes in locomotive rates across the duration of senior elite rugby league matches. A semi-automated image recognition system (SAIR; ProZone 3, ProZone®, Leeds, England) was used to track the movements of 59 players from six teams during three competitive matches. The players were classified into one of four positional groups: props (*n*=9), back row (*n*=9), pivots (*n*=14) or outside backs (*n*=27). Players' movements were classified as low, high or very high intensity running and reported as locomotive rates (distance covered per minute played) for successive quarters of each match. Analysis of variance revealed that only the outside backs experienced a significantly lower overall locomotive rate during the final quarter compared to the first ($P<0.05$). However, locomotive rates for high and very high intensity running during the final quarter were significantly lower ($P<0.05$) than the first quarter among outside backs, pivots and props despite no change in the rate of involvements in contact. On the basis of these findings, it is suggested that high and very high intensity running locomotive rates may be more effective methods of detecting fatigue during competitive matches than overall locomotive rate.

4.2 Introduction

Whilst Study One provides an up-to-date overview of the overall movement demands of competitive rugby league matches, it is unclear whether the exercise intensity changes throughout a rugby league match. Whilst a reduction in exercise intensity may result from the influence of external factors (such as team tactics and opponents activity levels; Rampinini et al., 2007b), it is generally accepted that a reduction in exercise intensity towards the end of prolonged multiple sprint team sports matches (PMSTS) is indicative of fatigue (Andersson et al., 2010a; Bradley et al., 2009; Carling et al., 2010; Coutts et al., 2010; Di Salvo et al., 2009; Duffield et al., 2009; Mohr et al., 2008; Rampinini et al., 2009; Sirotic et al., 2009). For example, Andersson et al. (2010a), Bradley et al. (2009, 2010) and Mohr et al. (2003, 2008) concluded that fatigue during competitive match play manifests itself as a reduction in the distance covered in high intensity running during the final 15 min of play. Alternatively, the players' degree of engagement in these locomotion categories has been expressed as a locomotive rate (Aughey, 2010; Barbero-Álvarez et al., 2008; Brewer et al., 2010), defined as the distance covered relative to the number of minutes they have played during the match (Barros et al., 2007). Moreover, these rates can be determined for discrete periods of a match and if indeed reductions in locomotive rates are indicative of fatigue, then real time analysis of locomotive rates during matches may be beneficial in informing substitutions based on a quantitative reduction in their physical performance rather than subjective measures of fatigue, such as body language. A further advantage of reporting locomotive rates over percentage of total time (%TT) in each of the locomotive categories is that they account for the intensity at which movements within each locomotive category are performed. For example, if during both the first and final 5 min of a match a player was to spend 40% of the time in high speed running (HSR; 14.4-19.8 $km \cdot h^{-1}$; Rampinini et al., 2007a), then it might be assumed that (based on the percentages being the same) there has been no change in running speed throughout the match. However, if during the first 5 min, running was performed (on average) at 19.8 $km \cdot h^{-1}$ (5.5 $m \cdot s^{-1}$) then the player would cover a distance of 1,200 m (330 $m \cdot min^{-1}$), whereas if during the final 5 min the movement was at 14.4 $km \cdot h^{-1}$ (4 $m \cdot s^{-1}$), a distance of just 1,440 m would be calculated (at a rate of 240 $m \cdot min^{-1}$) which is 27% lower than that calculated for the initial 5 min of the match. Therefore, a reliance on %TT in locomotive categories might mask distinct changes in movement intensities that are likely to be observed within matches. As in soccer, running performance is an easily quantifiable, yet important constituent of overall performance in rugby league and therefore warrants particular consideration. Furthermore, given that conditioning for team sports should aim to replicate the metabolic and physiological stresses typically experienced during competition (Gamble, 2007), locomotive rates could also provide a useful method of determining the required intensity of training drills.

In the only study to-date investigating the changes in locomotive variables during competitive rugby league matches, Sirotic et al. (2009) reported findings that were inconsistent and seemingly dependent on playing standard. Whilst their elite players showed a significant decrement in high intensity running activity in the second half compared to the first, this decrement was not evident in their semi-elite players. Although the authors speculated that the higher overall intensity of elite matches may have resulted in an earlier onset of fatigue in elite players, this disparity may also be due to the intra-reliability issues associated with classifying high intensity locomotive actions using drawing tablets (McLean, 1992). Furthermore, data reported by Sirotic et al. (2009) was collected from just one National Rugby League (NRL) club and might not be representative of senior elite teams.

Developments in SAIR tracking systems have provided a valid (Di Salvo et al., 2006), reliable (Bradley et al., 2009, 2010; Di Salvo et al., 2009) and non-intrusive (Di Salvo et al., 2006) method for quantifying movement velocities of multiple players during match play. Whilst this method has previously been used to measure changes in exercise intensity throughout competitive soccer matches (Bradley et al., 2009; Carling and Dupont, 2011; Di Salvo et al., 2009; Rampinini et al., 2009) and to measure the overall demands of senior elite soccer (Bradley et al., 2009, 2010; Di Salvo et al., 2007; Rampinini et al., 2007b), rugby union (Eaton and George, 2006) and rugby league (Sykes et al., 2009; Study One) matches, no study has, to date, used it to quantify changes in locomotive rates over the duration of senior elite rugby league matches. Such an analysis might be useful for monitoring any associated decrements in locomotive performance over the course of competitive games. Therefore, the aim of this study was to use a SAIR tracking system to investigate changes in locomotive rates, relative to playing position, during senior elite rugby league matches.

4.3 Methods

4.3.1 Participants

One hundred and two senior elite rugby league players representing professional clubs participating in either the English Engage Super League (n=68) or Australian NRL (n=34) during 2002-03 and 2003-04 seasons formed the initial sample for data analysis. The 102 players were classified into playing positions as defined by Gabbett (2005) as outside backs, pivots, props or back row. Typically, the outside backs spend the majority of their time following play on the pitch fringes and only largely come into play when required to chase down an opposing player, receive and return a kick or make a line break (Meir et al., 2001b). In contrast, props and back row players are generally positioned in the middle of the field and are used to carry the ball forward directly into contact close to the play-the-ball and stop the forward progression of the attacking team by tackling the ball carrier (Meir et al., 2001b). In attack, pivots play a key role in ball distribution and are therefore required to follow each play-the-ball (Meir et al., 2001a), take the ball to the defensive line and react to and evade defending players (Gabbett, 2005). However, defensively there is a division in the roles of the pivots. Whilst hookers will defend in the centre of the field in anticipation of being required as a play-maker if the ball is turned over, scrum halves and stand-offs will generally defend toward the fringes (Gabbett, 2005).

Players who played in more than one of the positional groups or who failed to participate for at least one minute during each quarter of the match were excluded from the analysis. This resulted in analysis being performed on 59 players: outside backs (n=27), pivots (n=14), props (n=9) and back row (n=9). All competitive matches were played in England under fair weather conditions. Approval for the study was obtained from the University of Chester's Faculty of Applied and Health Sciences Research Ethics Committee (Appendix 2). Data were supplied by ProZone® (Leeds, England) and published with formal permission of the company (Appendix 1).

4.3.2 Match analysis system

Video footage from six teams engaged in three senior elite competitive matches was analysed using a video-computerised, SAIR tracking system (ProZone 3, ProZone®, Leeds, England) as previously described in Study One.

In the current study, the Prozone 3 analysis software (Prozone 3, ProZone®, Leeds, England) was used to classify movement into the locomotive categories defined by Rampinini et al. (2007a): low (<14.4 $km \cdot h^{-1}$), high (>14.4$km \cdot h^{-1}$) and very high (>19.8 $km \cdot h^{-1}$) intensity running. The distance covered by each individual in each of these categories over the duration of a match was calculated, as was the overall total distance covered irrespective of running velocity. These distances were then expressed as locomotive rates by dividing an individual's distance covered in each locomotive category by the total amount of playing time per quarter. In addition, Excel (Microsoft Excel, Office 2003, Redmond, USA) was used to tabulate the frequency of contacts whilst watching the video footage on a second laptop, with contact scenarios classified as hit-ups or tackles using the following definitions:

- Hit-ups – a carry of the ball by an attacker into physical contact which resulted in a completed tackle
- Tackles – engagement in physical contact with an opponent while defending in an effort to stop the opponent from advancing the ball towards the player's goal line (Sirotic et al., 2009)

As per locomotive rates, the skill frequency counts were then expressed as rates by dividing an individual's frequency of tackles and hit-ups by the amount of playing time per quarter. In this way, relative measures of movement and involvement in contact were determined for each playing position for each quarter of the match. To prevent the effects of clock stoppages, only data obtained from the first 40 min of each half were used in these analyses.

4.3.3 Statistical analysis

For each positional group the locomotive indices (overall, low, high and very high intensity locomotive rate) and skill indices (tackle and hit-up rates) were checked for normality using the Shapiro-Wilk statistic, before the application of separate one-way analysis of variance (ANOVA)s with repeated measures to assess their variability over time (four quarters). In addition, a one-way

ANOVA with repeated measures was used to compare ball in play time between quarters. The Greenhouse-Geisser adjustment was employed if the assumptions of sphericity were violated. Where appropriate, paired sample *t*-tests with Bonferroni adjustments were used to identify specific differences. Finally, separate one-way ANOVAs with Tukey HSD post-hoc tests were used to assess the effect of position on total playing time, frequency of high intensity running bouts over discrete distances and maximal high intensity running bout distance. Statistical significance was set at $P<0.05$.

4.4 Results

4.4.1 Playing time

The total time on the pitch, excluding stoppage time, was 79.9 ± 0.5, 71.1 ± 11.6, 52.7 ± 7.4 and 72.2 ± 8.1 min for outside backs, pivots, props and back row players, respectively. The main effect for position was significant ($F=34.1$, $P<0.05$) and post-hoc analysis identified the differences between outside backs, pivots and back row players and between props and all other positional groups to be significant ($P<0.05$). Of the total match time, the ball was in play for similar amounts of time; 12.8 ± 2.1, 12.5 ± 0.7, 12.2 ± 1.1 and 13.1 ± 1.2 min for each consecutive quarter ($F=0.2$, $P>0.05$).

4.4.2 Discrete high intensity running bout distances

There was a significant effect of position on the frequency of high intensity running bouts performed over 10.1-20 m ($F=3.9$, $P<0.05$) and 20.1-30 m ($F=6.0$, $P<0.05$) distances, with post-hoc analysis revealing differences between outside backs and props for the frequency of 10.1-20 m high intensity running bouts and between outside backs and props and pivots for the frequency of 20.1-30 m high intensity running bouts (Figure 4.1). However, there was no significant difference in the maximum distance covered during discrete high intensity running bouts between positions ($F=0.8$, $P>0.05$), with mean values being 55.75 ± 14.84, 53.93 ± 9.21, 48.02

± 10.28 and 52.95 ± 15.07 m for outside backs, pivots, props and back row players, respectively (Figure 4.1).

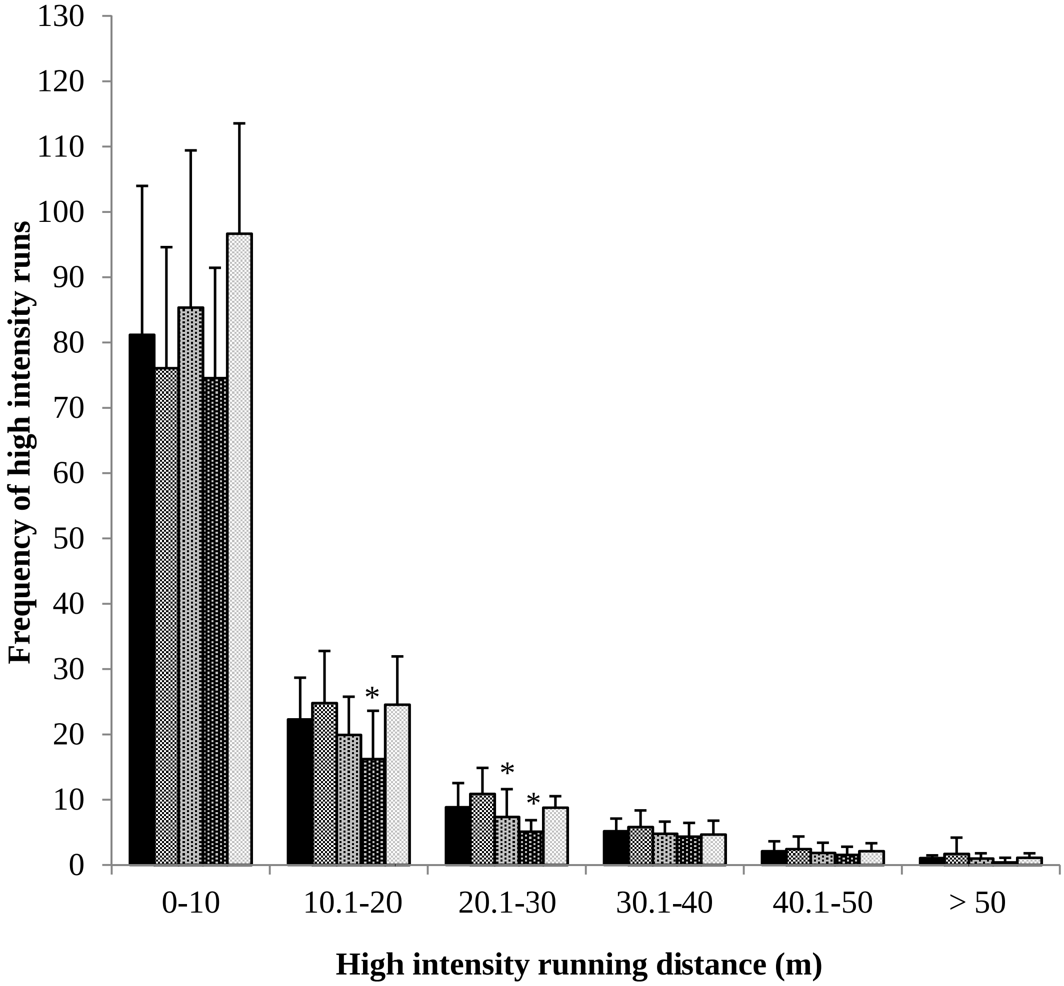

Figure 4.1 Mean (± SD) frequency distribution of high intensity running bouts over discrete distances for all players (■), outside backs (▩), pivots (▩), props (▩) and back row players (□).* Significantly different (P<0.05) to outside backs.

4.4.3 Tackle rates

There was no significant difference in tackle rates between time periods for all players (F=0.9, P>0.05) or any of the playing positions (outside backs: F=0.1, P>0.05; pivots: F=2.7, P>0.05; props: F=0.6, P>0.05; back row: F=2.1, P>0.05; Table 4.1).

4.4.4 Hit-up rates

There was no significant difference in hit-up rates between time periods for all players (F=0.3, *P*>0.05) and for pivots (F=0.4, *P*>0.05), props (F=1.8, *P*>0.05) or back row (F=0.7, *P*>0.05) players (Table 4.1). Whilst one-way ANOVA with repeated measures revealed a significant effect of time on hit-up rates in outside backs (F=3.8, *P*<0.05), post-hoc analysis revealed no difference between time periods (Table 4.1).

4.4.5 Overall locomotive rates

The effect of time period on overall locomotive rates for all players was significant (F=4.7, *P*<0.05), with mean values being 100.7 ± 8.1, 96.1 ± 12.0, 98.7 ± 10.0 and 95.5 ± 13.2 $m \cdot min^{-1}$ for successive quarters. Significant reductions (*P*<0.05) in overall locomotive rate for all players were observed in the final and second quarters compared to the first. However, when analysed by position, the effect of time (quarters) was only significant for outside backs (F=5.2, *P*<0.05), for whom a reduction in overall locomotive rate was evident in the final and second quarters compared to the first (Table 4.2).

4.5.6 Low intensity running locomotive rates

There was no significant difference in low intensity running locomotive rates between time periods for all players (F=0.7, *P*>0.05) or any of the playing positions (outside backs: F=0.4, *P*>0.05; pivots: F=0.3, *P*>0.05; props: F=1.4, *P*>0.05; back row: F=0.1, *P*>0.05; Table 4.3).

Table 4.1 Tackle and hit-up rates ($n \cdot min^{-1}$) by match quarter (mean ± SD)

	Match quarter							
	First		Second		Third		Fourth	
	Tackles ($n \cdot min^{-1}$)	Hit-Ups ($n \cdot min^{-1}$)	Tackles ($n \cdot min^{-1}$)	Hit-Ups ($n \cdot min^{-1}$)	Tackles ($n \cdot min^{-1}$)	Hit-Ups ($n \cdot min^{-1}$)	Tackles ($n \cdot min^{-1}$)	Hit-Ups ($n \cdot min^{-1}$)
All positions	0.28 ± 0.21	0.14 ± 0.10	0.28 ± 0.27	0.13 ± 0.12	0.26 ± 0.22	0.13 ± 0.10	0.32 ± 0.33	0.14 ± 0.09
Outside backs (*n*=27)	0.14 ± 0.11	0.13 ± 0.07	0.13 ± 0.14	0.11 ± 0.07	0.15 ± 0.11	0.11 ± 0.07	0.15 ± 0.12	0.16 ± 0.10
Pivots (*n*=14)	0.40 ± 0.24	0.08 ± 0.06	0.28 ± 0.14	0.09 ± 0.10	0.24 ± 0.18	0.10 ± 0.12	0.30 ± 0.15	0.07 ± 0.05
Props (*n*=9)	0.45 ± 0.14	0.22 ± 0.13	0.66 ± 0.41	0.30 ± 0.15	0.52 ± 0.27	0.23 ± 0.15	0.57 ± 0.41	0.18 ± 0.09
Back row (*n*=9)	0.34 ± 0.17	0.17 ± 0.11	0.33 ± 0.16	0.12 ± 0.12	0.38 ± 0.24	0.12 ± 0.05	0.63 ± 0.51	0.14 ± 0.07

Table 4.2 Overall locomotive rates ($m \cdot min^{-1}$) by match quarter and percentage changes (%Δ) relative to the first quarter (mean ± SD)

	Match quarter						
	First	Second		Third		Fourth	
	($m \cdot min^{-1}$)	($m \cdot min^{-1}$)	(% Δ)	($m \cdot min^{-1}$)	(% Δ)	($m \cdot min^{-1}$)	(% Δ)
All positions	100.7 ± 8.1	96.1 ± 12.0*	-4.5 ± 10.3	98.7 ± 10.0	-1.8 ± 8.9	95.5 ± 13.2*	-4.9 ± 12.2
Outside backs (*n*=27)	97.0 ± 9.0	90.4 ± 11.1*	-6.5 ± 10.4	94.8 ± 9.1	-2.0 ± 7.7	89.4 ± 11.0*	-7.4 ± 11.4
Pivots (*n*=14)	104.5 ± 4.9	100.6 ± 9.2	-3.6 ± 9.6	104.2 ± 12.0	0.0 ± 12.4	99.8 ± 7.9	-4.4 ± 8.5
Props (*n*=9)	104.9 ± 2.2	106.0 ± 13.5	0.9 ± 12.1	102.0 ± 6.4	-2.7 ± 6.5	106.6 ± 16.7	1.7 ± 16.6
Back row (*n*=9)	101.6 ± 8.8	96.2 ± 8.5	-5.0 ± 8.2	98.4 ± 8.1	-2.7 ± 9.3	96.2 ± 13.7	-4.8 ± 14.0

* Significantly different ($P<0.05$) to first quarter.

Table 4.3 Low intensity running locomotive rates ($m \cdot min^{-1}$) by match quarter and percentage changes (%Δ) relative to the first quarter (mean ± SD)

	Match quarter						
	First	Second		Third		Fourth	
	($m \cdot min^{-1}$)	($m \cdot min^{-1}$)	(% Δ)	($m \cdot min^{-1}$)	(% Δ)	($m \cdot min^{-1}$)	(% Δ)
All positions	78.5 ± 7.4	78.5 ± 9.9	0.4 ± 11.3	79.2 ± 10.6	1.5 ± 10.7	80.1 ± 10.6	2.8 ± 15.2
Outside backs (*n*=27)	74.8 ± 6.2	73.5 ± 7.7	-1.4 ± 10.9	75.4 ± 8.3	1.2 ± 8.8	74.6 ± 8.3	0.3 ± 12.9
Pivots (*n*=14)	83.3 ± 6.1	83.2 ± 5.0	0.5 ± 10.9	84.8 ± 5.7	2.6 ± 15.2	85.0 ± 5.7	2.8 ± 12.6
Props (*n*=9)	81.3 ± 6.8	87.3 ± 15.1	7.1 ± 13.3	85.5 ± 13.0	2.2 ± 10.9	90.6 ± 13.0	12.6 ± 22.1
Back row (*n*=9)	78.8 ± 8.6	77.2 ± 6.6	-1.4 ± 10.4	78.4 ± 9.5	0.1 ± 8.6	78.5 ± 9.5	0.7 ± 16.2

4.4.7 High intensity running locomotive rates

The effect of time period on high intensity running locomotive rate was significant for all players and for each positional group (all players, F=41.1, *P*<0.05; pivots, F=10.5, *P*<0.05; outside backs, F=24.1, *P*<0.05; back row, F=3.5, *P*<0.05; props, F=4.5, *P*<0.05), with significant reductions (*P*<0.05) evident in high intensity running locomotive rate between the final and first quarters among the outside backs, the pivots and the props, and between the third and first quarters among outside backs only. The high intensity running locomotive rates of the outside backs and back row players were also significantly lower (*P*<0.05) in the second quarter than in the first (Table 4.4).

4.4.8 Very high intensity running locomotive rates

The effect of time period on very high intensity running locomotive rate was significant for all players (F=34.7, *P*<0.05) and the outside backs (F=20.9, *P*<0.05), pivots (F=6.1, *P*<0.05) and props (F=6.7, *P*<0.05) owing to significant (*P*<0.05) reductions in very high intensity running locomotive rate occurring in the final quarter (compared to the first) among outside backs, pivots and props. Furthermore, there was a significant (*P*<0.05) difference in very high intensity running locomotive rate in the second quarter compared to the first and the third quarters among outside backs (Table 4.5).

Table 4.4 High intensity running locomotive rates ($m \cdot min^{-1}$) by match quarter and percentage changes (%Δ) relative to the first quarter (mean ± SD)

	Match quarter						
	First	Second		Third		Fourth	
	($m \cdot min^{-1}$)	($m \cdot min^{-1}$)	(% Δ)	($m \cdot min^{-1}$)	(% Δ)	($m \cdot min^{-1}$)	(% Δ)
All positions	22.3 ± 5.0	17.6 ± 5.4*†	-20.0 ± 21.4	19.5 ± 4.8*†	-10.7 ± 18.5	15.4 ± 5.5*	-30.5 ± 20.2
Outside backs (*n*=27)	22.2 ± 5.2	16.9 ± 4.9*	-23.2 ± 17.7	19.4 ± 5.7*†	-12.4 ± 17.7	14.8 ± 5.7*	-32.9 ± 22.6
Pivots (*n*=14)	21.2 ± 4.8	17.4 ± 6.8	-17.5 ± 26.9	19.4 ± 3.6†	-6.1 ± 16.3	14.7 ± 4.4*	-29.7 ± 16.3
Props (*n*=9)	23.6 ± 6.0	18.7 ± 5.7	-18.4 ± 30.1	19.5 ± 4.6	-13.6 ± 24.4	16.0 ± 6.2*	-33.1 ± 14.7
Back row (*n*=9)	22.8 ± 4.2	19.1 ± 4.4*	-16.1 ± 12.0	19.9 ± 4.0	-10.1 ± 21.7	17.8 ± 6.2	-21.8 ± 22.9

* Significantly different ($P<0.05$) to first quarter. † Significantly different ($P<0.05$) to fourth quarter.

Table 4.5 Very high intensity running locomotive rates ($m\cdot min^{-1}$) by match quarter and percentage changes (%Δ) relative to the first quarter (mean ± SD)

	Match quarter						
	First	Second		Third		Fourth	
	($m\cdot min^{-1}$)	($m\cdot min^{-1}$)	(% Δ)	($m\cdot min^{-1}$)	(% Δ)	($m\cdot min^{-1}$)	(% Δ)
All positions	7.8 ± 3.3	5.0 ± 2.9*†	-32.7 ± 41.6	6.2 ± 3.3*	-15.7 ± 35.6	4.0 ± 2.4*†	-46.8 ± 28.6
Outside backs (*n*=27)	9.2 ± 3.4	5.5 ± 2.9*	-37.6 ± 31.5	7.7 ± 3.5	-13.7 ± 31.9‡	4.9 ± 2.4*†	-44.6 ± 22.8
Pivots (*n*=14)	6.4 ± 2.6	4.5 ± 2.8	-22.7 ± 60.8	4.8 ± 1.3	-14.1 ± 34.3	3.3 ± 1.7*	-41.9 ± 32.7
Props (*n*=9)	6.8 ± 3.4	4.0 ± 2.9	-38.5 ± 42.5	4.4 ± 3.4	-24.2 ± 53.3	2.0 ± 1.9*	-75.8 ± 15.9
Back row (*n*=9)	6.8 ± 2.2	5.2 ± 3.3	-27.5 ± 34.7	5.8 ± 3.1	-15.8 ± 32.2	4.5 ± 2.6	-31.9 ± 31.8

***** Significantly different ($P<0.05$) to first quarter. ‡ Significantly different ($P<0.05$) to second quarter. † Significantly different ($P<0.05$) to third quarter.

4.5 Discussion

The main findings of this study were that whilst overall locomotive rate was only significantly lower in the second and final quarters compared to the first when all players were grouped collectively, high and very high intensity running locomotive rates were significantly lower in the final compared with the first quarter among the outside backs, the pivots and the props, and in the second quarter compared to the first in the outside backs and back row players. In addition, very high intensity running locomotive rates were significantly lower in outside backs in the second quarter compared to the first and the third quarters and high intensity running locomotive rates were significantly lower between the third and first quarters. Furthermore, outside backs performed a significantly greater frequency of discrete bouts of high intensity running of 10.1-20.0 m distance than props and 20.1-30.0 m distance than props and pivots. However, there was no significant difference ($P>0.05$) between positions in the maximum distance covered during discrete high intensity running bouts. The observations that outside backs played for virtually the entire match whilst the props, the pivots and the back row players played 52.7, 71.7 and 72.2 min, respectively, are similar to those recently reported by King et al. (2009). Given these observations, it is likely that the greater frequency of short high intensity running bouts performed by outside backs in comparison to props and pivots is partially as a result of the greater time that they are on the field of play.

Tackle (0.27 ± 0.13 $n \cdot min^{-1}$) and hit-up rates (0.17 ± 0.07 $n \cdot min^{-1}$) were similar to those described for Australian senior elite rugby league players (tackles: 0.25 ± 0.16; hit-ups: 0.12 ± 0.07 $n \cdot min^{-1}$) by Sirotic et al. (2009). However, overall (97.1 $m \cdot min^{-1}$), high (18.6 $m \cdot min^{-1}$) and very high intensity running (5.8 $m \cdot min^{-1}$) locomotive rates for all players in this study were lower than those described for Australian senior elite rugby league players by Sirotic et al. (2009), who reported values of 106.0 ± 9.3, 34.3 ± 7.9 and 13.1 ± 4.2 $m \cdot min^{-1}$ for overall, high and very high intensity running, respectively. These greater high and very intensity running locomotive rates are likely to reflect the lower velocity thresholds that Sirotic et al. (2009) used to define these locomotive categories (>13.1 $km \cdot h^{-1}$ and >18.6 $km \cdot h^{-1}$ for high and very high intensity running, respectively) compared to the current study (>14.4 $km \cdot h^{-1}$ and >19.8 $km \cdot h^{-1}$ for high and very high intensity running, respectively) which were selected in-line with previous research published using SAIR systems (Bradley et al., 2009, 2010; Rampinini et al., 2007a, 2007b).

Importantly, although the mean overall locomotive rate (all players) was only 4.9% lower in the final quarter compared to the first and despite no change in tackle or hit-up rates, mean high and very high intensity running locomotive rates were 30.5 and 46.8% lower, respectively. One possible explanation for this is that senior elite players are unable to maintain high and very high intensity running locomotive rates in the final quarter of matches. Whilst this is similar to findings in elite rugby league (Sirotic et al., 2009), Australian rules football (Aughey, 2010; Coutts et al., 2010) and soccer (Andersson et al., 2010a; Bradley et al., 2009, 2010; Mohr et al., 2003, 2008), it contrasts with those in elite rugby union (Roberts et al., 2008) where the amount of high-intensity activity performed during consecutive 10-min periods during match-play remained constant. In addition, our data reveal a mean increase of 2.8% in low intensity running locomotive rate (all players) in the final quarter compared to the first. This is similar to the findings observed in soccer players (Di Salvo et al., 2007) and soccer referees (Weston et al., 2007), whereby a significant reduction in the distance covered running (11.1-19 $km \cdot h^{-1}$) has been shown to be offset by an increase in walking and jogging, resulting in no difference between halves in the overall distance covered .

In the current study outside backs, pivots and props all showed a significant reduction in high and very high intensity running locomotive rates during the final quarter compared to the first. In addition, outside backs and back row players had a significantly lower high intensity running locomotive rate in the second quarter compared to the first. The trend for a reduction in high and very high intensity running locomotive rates between the second and final quarters suggests the occurrence of either a distinct change in tactics or the onset of fatigue. In soccer, the notion that a reduction in high intensity exercise toward the end of a match is indicative of fatigue has been supported by the evidence that substitutes perform more high intensity running during the final 15 minutes of a match than players who play the entire match (Mohr et al., 2003), suggesting that players exhaust their physical potential during the game (Mohr et al., 2005b). Whilst the outside backs, on average, played for virtually the entire match, the back row and props spent a greater proportion of time off the field of play and were therefore allowed time to recover between playing bouts.

Based upon previous observations in soccer (Carling and Dupont, 2011; Rampinini et al., 2009) and rugby league (Sirotic et al., 2009), the overall trend for a reduction in high and very high intensity running locomotive rates observed in this study may have an impact on technical performance and the style of play during a match. Whilst this may be in part due to a decreased involvement with play, acute fatigue has also been show to affect skill proficiency (Rampinini et al., 2008). Moreover, Sirotic et al. (2009) observed a positive correlation between high and very high intensity running intensities and the number of support runs performed. Hence, preventing the decline in high and very high intensity running locomotive rates is likely to improve attacking performance through providing greater support to the ball carrier and more decoy runners (Sirotic et al., 2009). Furthermore, while fatigue has been shown to compromise the quality of tackling technique (Gabbett, 2008), the implications of changes in high and very high intensity running for defending are yet to be established and warrant further investigation.

Given the findings of Sykes et al. (2009; Study One) that players spend greater time in HSR and sprinting when attacking, the amount of time in possession may have an impact on high and very high intensity running locomotive rates. Thus, where information on time in possession is not available, any changes observed in high and very high intensity running locomotive rates between quarters should be interpreted cautiously. Furthermore, Sykes et al. (2009; Study One) reported that players perform significantly more high intensity running when the ball is in play. Therefore, it is possible that the length and frequency of stoppages may affect high and very high intensity running locomotive rate per quarter. However, in the current study there was no significant difference for ball in play time between quarters and thus this cannot account for differences in locomotive patterns between quarters.

Since involvement in contact has previously been classified as high intensity work during rugby league matches (Sykes et al., 2009; Study One), it may be expected that in addition to the reductions in high and very high intensity running locomotive rates observed in the current study, players also exhibit signs of fatigue in contact situations however, the results of the current study show no change in the rate of tackles and hit-ups throughout the rugby league matches. Furthermore, whilst a recent study has used the tri-axial accelerometer in a commercially available NdGPS unit to quantify the intensity of contacts McLellan et al. (2011a), the data derived is the product of all players involved in the collision. Therefore, it would be difficult to quantify the contribution from each individual player. Thus, as present it is not possible to quantify the intensity of contacts during competition (Roberts et al., 2008).

4.6 Conclusion

There was no change in the relative overall distance travelled between quarters when players were grouped by position, but reductions in high and very high intensity running locomotive rates in the final quarter of an elite level rugby league match might be indicative of the occurrence of fatigue. This would suggest that the measurement of high and very high intensity running locomotive rates may be more effective strategies for detecting fatigue than the measurement of overall locomotive rate during competitive rugby league games. Therefore, real-time measurement of high and very high intensity running locomotive rates may be beneficial in informing substitutions during matches and would also provide a useful method of comparing the intensity of training drills to matches without the need for drills to be of the same duration. Furthermore, in order for training drills to replicate match demands more closely, the majority of high intensity running bouts during training should be less than 10 m in distance, but a small frequency of high intensity running bouts of up to 55 m in distance should also be incorporated to replicate the maximal distances observed during matches. Additionally, the indications for greater fatigue occurring among outside backs might have implications for the interchange strategies utilised by coaches.

CHAPTER 5

AN ASSESSMENT OF THE EXTERNAL VALIDITY AND RELIABILITY OF A NOVEL RUGBY LEAGUE MATCH SIMULATION PROTOCOL

5.1 Abstract

The primary aim of this study was to assess the external validity of a novel rugby league match simulation protocol (RLMSP) designed to replicate the physical and movement demands of a senior elite rugby league match using data obtained from the first and second studies of this thesis. A secondary aim was to examine the reliability of the movement and physiological responses elicited by the RLMSP over repeated trials. Following ethical approval, sixteen male non-elite, active sportsmen (age 22.4 ± 7.1 y, stature 1.77 ± 0.06 m, body mass; BM 81.4 ± 11.6 kg) performed the multi-stage fitness test (MSFT) and two cycles of the RLMSP to familiarise them with the movement speeds of the protocol. Participants then completed the RLMSP on two occasions 10 to 14 d apart whilst wearing a non-differential global positioning system (NdGPS; SPI Pro, GPSports, Canberra, Australia) and integrated heart rate (HR) monitor (Polar Electro, Oy, Finland). Briefly, the RLMSP is an intermittent protocol, which lasts 86.8 min in total with a 10 min interval to simulate half time after 43.4 min. The RLMSP comprises forty identical cycles of 2 min 10 s which each contain two parts; one part is designed to replicate the movement demands of when the ball is in play (cumulative total time of 53.9 min) and a second to replicate the movement demands during stoppage time. The locomotive speeds during each activity were dictated by an audio CD (based upon the movement demands reported in Study One). During the RLMSP participants covered a total distance (TD) of 8,444 ± 212 in comparison to 8,503 ± 631 m during competitive matches by elite players (Study One). Although the RLMSP appears to result in a greater very high intensity running locomotive rate than during competitive matches (Study One), the reduction in very high (-22.4%) and high (-8.6%) intensity running locomotive rates and increase in low intensity running locomotive rate (1.6%) from quarter one to quarter four are still apparent, albeit to a lesser extent, as was observed in competitive matches (Study Two). Furthermore, a comparison of data between trials revealed coefficient of variation (CoV) values of 1.1, 4.2 and 10.6% for overall, high and very high intensity running locomotive rates, respectively, and values of 2.1 and 5.0% for mean or summated peak sprint velocity and mean HR, respectively.

Therefore, the RLMSP provides an ecologically valid and repeatable simulation of rugby league matches.

5.2 Introduction

The emergent practice of performance analysts to analyse the actions of players in competitive team sports is deemed to be worthwhile on the basis that it can yield objective data on the movement and physiological demands of such activity. However, given the large inter-match variability in overall, high and very high intensity distance covered (Gregson, et al., 2010; Rampinini et al., 2007b) investigators would have to analyse performances over a large number of matches in order to negate this variability and detect real systematic changes resulting from interventions (Drust et al., 2007; Gregson et al., 2010; Weston et al., 2010). Moreover, changes in fitness over this same time period may make it hard to isolate the cause of such changes. Consequently, there is a case for utilising 'typical' match demands to produce match simulation protocols which reflect the movement and physiological demands observed during competitive matches. Developing a match simulation protocol with an acceptable level of reliability would provide an effective means of investigating the effectiveness of various interventions on physical match performance.

Indoor running (Bishop et al., 1999; Nicholas et al., 2000) and motorised (Drust et al., 2000) simulation protocols were the first developed for replicating the demands of soccer match-play. Early protocols were based on what is now considered to be the out-dated time-motion analysis (TMA) match data of Reilly and Thomas (1976) which appears to markedly underestimate the TD covered by players (8,680 ± 1,011 m) in comparison to the more recent TMA studies of Rampinini et al. (2007a; 9,710-12,750 m) Mohr et al. (2003; 10,860 m) and Di Salvo et al. (2007; 11,393 ± 1,016 m). It is likely that the substantial variability between values is a result of the improvements in players' fitness levels over time. Additionally, a limitation of the treadmill simulation protocols is that they are unable to replicate the rapid changes in speeds or multidirectional movements that are observed in match-play. Moreover, the simulation protocols performed on both motorised and non-motorised treadmills have restricted the speeds at which sprinting is performed (Drust et al., 2000; Thatcher and Batterham, 2004), which prevents the detection of changes in locomotive rates throughout the protocol. Importantly, these protocols were based upon TMA of a small number of players (n=12; Thatcher and Batterham, 2004) or not based upon any specific match data (Sirotic and Coutts, 2008) and are therefore unlikely to be representative of typical match-play. Furthermore, the game of rugby league is distinctive from soccer, not only by the inherent contact element, but in its movement demands and the duration of its matches. The match itself is played over two forty minute halves (excluding stoppage/injury time) during which players have been reported to cover, on average, between 8,142 and 8,800 m, depending on their playing position (Sykes et al., 2009; Study One). Of this, players cover 490 m in very high intensity running and 1,622 m in high intensity running (Sykes et al., 2011; Study Two). In comparison, soccer players are reported to cover substantially greater distance in high (2,530 m: Rampinini et al., 2007a) and very high intensity running (908 m: Di Salvo et al., 2009; 802 m: Rampinini et al., 2007a).

Currently, there are no published reports of a match simulation protocol for rugby league. Accordingly, the data collected via a semi-automated image recognition (SAIR) tracking system (ProZone 3, ProZone®, Leeds, England) reported in the first two studies of this thesis (Sykes et al., 2009; Sykes et al., 2011) have been utilised for this purpose.

The utility of the RLMSP has yet to be explored and the study that follows represents the first attempt to describe its development and evaluate its application amongst an independent sample of participants in a 'real-world' setting, far removed from the unique environment of the performance analysis laboratory. In this way, the primary purpose of the study was to assess the external validity of the RLMSP among non-elite, active sportsmen. Furthermore, from the perspective of employing 'good science', the validity of such a simulation protocol should not be undermined by an inability to produce movement and physiological responses that are repeatable when administered on a test-retest basis, rendering it improbable that the protocol could detect ‘real’ changes in physical performance that are independent of technological and biological error (Atkinson and Nevill, 1998). Therefore, a secondary aim of this study was to examine the reproducibility (reliability) of the movement and physiological responses elicited by the RLMSP over repeated trials.

5.3 Methods

5.3.1 Rugby league match simulation protocol design

An attempt was made to design a protocol that was easy to follow, could be performed in a small area and that would not be limited by equipment availability if other researchers subsequently wished to replicate the procedures. A series of pilot tests were undertaken in order to establish how closely the movement demands of the protocol replicated those observed during matches and decide the sequence in which to place the locomotive movements.

In order to reduce the number of sequences that the participants were required to learn and hence reduce the likely length of familiarisation required, a decision was reached fairly early in the protocol development not to differentiate between attacking and defending in the RLMSP. Moreover, in order to make subsequent findings applicable to a greater number of players and given that there were no positional differences between ball in play and stoppage WRRs or %TT spent in each of the locomotive categories during stoppages for any of the positional groups, the simulation protocol was designed to be generic to all rugby league positions. However, given that there were significant differences between %TT spent in each of the locomotive categories during ball in play and stoppage phases for all positions and that stoppages account for ~33% of the overall match time in senior elite rugby league matches (average of 48 s per stoppage; Sykes et al., 2009; Study One), the RLMSP was designed to differentiate between stoppages and when the ball is in play, and the movement demands associated with these contrasting phases. Therefore, the RLMSP was based on the mean time (as a percentage, relative to total time, %TT) during ball in play and stoppage phases averaged across three matches for all 78 players. Hence the RLMSP was divided into two components, Part A to replicate the mean %TT spent in each of the locomotive categories when the ball is in play during matches which was 2.3, 53.9, 30.5, 6.7, 1.8, 0.4, and 4.2% for standing, walking, jogging, running, HSR, sprinting and contact, respectively; and Part B to simulate the %TT spent standing, walking, jogging, running, HSR, sprinting and in contact during stoppages in the match (24.9, 63.4, 10.1, 1.4, 0.2, 0.0 and 0.0, respectively).

In order to replicate the %TT spent in contact during ball in play phases during matches a simulated contact element was also included in the RLMSP. However, in order to control the intensity of contact, reduce the need for specialist equipment (such as the one man scrummaging machine used by Roberts et al., 2010) and minimise the risk of injuries, it was decided that participants would replicate contact in a manner similar to Holloway et al. (2008) whereby during a repeated anaerobic rugby league test participants had to hit the floor on their front, roll onto their back, roll back to their front and regain their feet. Although, in order to maintain a cyclical pattern to the RLMSP and divide the %TT spent in contact across all ball in play cycles of the RLMSP, the roll onto their back was removed so that participants just had to hit the floor on their front and then regain their feet. Therefore, it must be accepted that this is more representative of a ‘passive’ tackle or an attacker ‘finding their front’ for a quick play-the-ball (PTB).

As it was observed in Chapter 4 that the majority of sprints were <10 m during competitive matches, initially an attempt was made to include a greater number of shorter (10 m) sprints. However, the high variability observed with 0-10 m sprints on grass measured using both infra-red photocells (Brower Wireless Sprint System, Brower Timing Systems, Utah, USA) and NdGPS (SPI Pro, GPSports, Canberra, Australia) made it unlikely that real systematic changes would be observed throughout the protocol. Therefore, the protocol was adapted to incorporate 0-20 m sprints as a compromise between maintaining a high frequency of short sprints and increasing the likelihood that systematic changes in sprint velocity would be observed throughout the protocol. Moreover, following pilot testing the order of two locomotive movements in the protocol were switched to allow participants to have more time to set themselves for the 20 m sprint and hence improve the reliability of this component of the protocol.

5.3.2 Participants

Sixteen male participants (age 22.4 ± 7.1 y, stature 1.77 ± 0.06 m, BM: 81.4 ± 11.6 kg) provided written informed consent (Appendix 6) to participate in the study, which was approved by the Research Ethics Committee of the Faculty of Applied and Health Sciences at the University of Chester (Appendix 4). All participants were non-elite, active sportsmen with estimated maximal aerobic capacity ($\dot{V}O_{2\max}$) values of 52.1 ± 4.5 $ml \cdot kg^{-1} \cdot min^{-1}$.

5.3.3 Experimental design

This was a single group repeated measures design in which the participants performed the RLMSP on two occasions on an outdoor grass pitch, 10-14 d apart. To avoid any diurnal variation, both trials were carried out at the same time of day (± 1 h). Three to four days prior to undertaking the first full RLMSP protocol (see 5.3.7 for details), stretch stature and BM were recorded in the Human Performance Laboratory using a wall-mounted Harpenden stadiometer (Holtain Ltd., Crymmych, Wales) and a balance beam scale (Seca, Hamburg, Germany) whilst wearing shorts and t-shirt. Thereafter, participants performed a 20 m MSFT (Ramsbottom et al., 1988) and familiarisation to the RLMSP. Participants were advised to engage in their normal physical activities between the two RLMSP trials, until 3 d prior to the second RLMSP.

5.3.4 Preliminary Measurements

The MSFT required participants to run at incremental speeds between two lines 20 m apart until volitional exhaustion. Heart rate was recorded continuously throughout the protocol via telemetry (s810i, Polar Electro, Finland) and later downloaded using Polar Precision Performance software (Polar Electro, Finland). The participants were required to perform the MSFT to assess whether they met the inclusion criterion of having an estimated $\dot{V}O_{2\max}$ ≥45 ml·kg^{-1}·min^{-1} on the basis of mean values of 48.6 to 56.4 ml·kg^{-1}·min^{-1} for senior elite rugby league players (O'Connor, 1996; Brewer et al., 1994). The $\dot{V}O_{2\max}$ of each participant was estimated from the final running speed achieved in the MSFT using the regression equation provided by Léger et al. (1988). In addition, maximum HR was determined for each individual as the highest HR recorded during the test. Following a period of recovery, participants then performed two cycles of the RLMSP to familiarise themselves with the movement speeds and technique of simulated contact in the simulated protocol.

5.3.5 Procedures

On the day of the first RLMSP, participants performed a standardised 10 min warm-up consisting of jogging, dynamic stretching and HSR parallel to the course laid out for the RLMSP. Thereafter, the RLMSP was conducted outdoors on a grass surface adjacent to the University's rugby pitch. Participants were fitted with a NdGPS (SPI Pro, GPSports, Canberra, Australia) for monitoring of distances relative to time, which was positioned between the scapulae, and integrated HR (Polar Electro, Oy, Finland). The ambient conditions were recorded at the start of the protocol and following every quarter using a portable temperature and humidity monitor (THG810, Oregon Scientific Ltd., Berkshire, UK). During the RLMSP participants were allowed to ingest water from individually labelled water bottles *ad libitum*. However, this was limited to consumption during low intensity periods of activity in order to replicate the stoppages that occur in senior elite matches. The water bottles were weighed on portable scales (Salter Arc Electronic

Scales, HoMedics Group Ltd, Kent, UK) to the nearest 1 g both prior to the start and immediately following the RLMSP and the amount of fluid consumed was recorded to the nearest ml. On completion of the RLMSP, participants towelled themselves to remove sweat and body mass was re-measured as described above. Sweat volume was calculated as:

Pre- to post- change in body mass (kg) + fluid intake (l)

Participants were asked to abstain from all exercise and nutritional supplements for 2 d prior to each session. In addition, they were asked to record a food diary for 2 d prior to the first RLMSP and to then consume the same food in the 2 d prior to the second in order to standardise their nutritional intake between trials.

5.3.6 Movement and physiological measurements

The NdGPS and HR data were downloaded to Team AMS software (Version 2.1, GPSports, Canberra, Australia) and then exported to Excel (Office 2007, Microsoft Excel, Redmond, USA) for classifying movements into standing (<0.2 $m \cdot s^{-1}$), walking (0.2-1.9 $m \cdot s^{-1}$), jogging (2.0-3.9 $m \cdot s^{-1}$), running (4.0-5.4 $m \cdot s^{-1}$), HSR (5.5-6.9 $m \cdot s^{-1}$) and sprinting (>7.0 $m \cdot s^{-1}$) in the manner described by Rampinini et al. (2007a) with the addition of contact. Furthermore, mean overall HR and time spent in each HR zone (low: <85%; moderate: 85-89%; and high: ≥90% HR_{max}) was summated for the entire RLMSP.

5.3.7 Performance variables

Given that in soccer high (Bangsbo et al., 1991; Ekblom, 1986; Mohr et al., 2008) and very high (Bangsbo et al., 1991; Mohr et al., 2003, 2008) intensity running distance have been shown to discriminate between playing standards, movements were also grouped broadly as low (<4.0 $m \cdot s^{-1}$), high (≥4.0 $m \cdot s^{-1}$) and very high (≥5.5 $m \cdot s^{-1}$) intensity running as described by Rampinini et al. (2007b). The distance covered by each individual in each of these categories over the duration of each quarter of the RLMSP was downloaded from the NdGPS, as was the overall TD covered irrespective of movement velocity. These distances were then expressed as locomotive rates by dividing an individual's distance covered in each locomotive category by the time of each quarter of the RLMSP (Barros et al., 2007) to determine relative measures of movement intensity for each quarter of the RLMSP.

In addition, peak running velocity was recorded from the NdGPS for each 20 m sprint (intra-unit reliability: CoV=1.9%; accuracy: 95% limits of agreement; 95%LoA = -2.19 ± 3.34 $km \cdot h^{-1}$; Waldron et al., under review). The summated and mean peak sprint velocities were then calculated for each quarter of the RLMSP as was described by Barbero-Álvarez et al. (2010).

5.3.8 Rugby league match simulation protocol

Following the initial pilot testing, the resulting RLMSP is an intermittent protocol which lasts 86.8 min in total with a 10 min interval to simulate half-time after 43.4 min. The RLMSP comprises forty identical cycles lasting 2 min 10 s, each containing two distinct components; Part A, designed to replicate the players' typical movement patterns when the ball is in play (a 40.4 s cycle performed twice) and Part B, designed to replicate the movement patterns during stoppages (lasting 49.3 s). The specific movements are as follows:

Part A

• 10.5 m jog (2.9 $m \cdot s^{-1}$) from yellow to red cones followed by 180º turn;
• 10.5 m walk (1.1 $m \cdot s^{-1}$) from red to yellow cones followed by 180º turn;
• 20.5 m maximal effort sprint from yellow to blue cones;
• 8 m deceleration to white cone followed by 1.70 s simulated contact (down and up off the ground);
• 13 m jog (2.9 $m \cdot s^{-1}$) from white to green cones;
• 15.5 m walk (1.1 $m \cdot s^{-1}$) from green to yellow cones.

Part B

• 10.5 m walk (1.1 $m \cdot s^{-1}$) from yellow to red cones followed by 180º turn;

• 10.5 m walk (1.1 $m \cdot s^{-1}$) from red to yellow cones followed by 180º turn;

• 6.00 s passive rest at yellow cone;

• 15.5 m jog (2.9 $m \cdot s^{-1}$) from yellow to green cone followed by 180º turn;

• 15.5 m walk (1.1 $m \cdot s^{-1}$) from green to yellow cones;

• 4.75 s passive rest at yellow cone.

Participants move between a series of cones positioned on a 28.5 m linear course (Figure 5.2) at locomotive speeds determined from the analysis of activity patterns in senior elite rugby league matches (see Study One). The locomotive speeds are dictated by an audio CD, with changes being signalled by a “beep” and an instructive voice command, such as, “Jog to red” (cone).

Whilst direct physical contact with a fellow participant was not included in the protocol due to an inability to control the intensity of the collision or subsequent ‘wrestle’, participants were required to lie prone on the floor with their waist level with the white cones and chest on the floor and then regain their feet as rapidly as possible following the rapid deceleration from each sprint. This technique required practise during the familiarisation trials and was accompanied by verbal instruction from the experimenter during the RLMSP. This movement was included in an attempt to replicate the physical exertion of contacts yet still control the reproducibility of the protocol and although participants performed this movement more frequently than contacts in the competitive match, %TT spent performing this movement was approximated to be that observed in contact during the match. In addition, in an effort to improve the ease to which participants became familiar with the protocol, the %TT in contact was distributed across every cycle of Part A allowing the cyclical pattern to be maintained throughout.

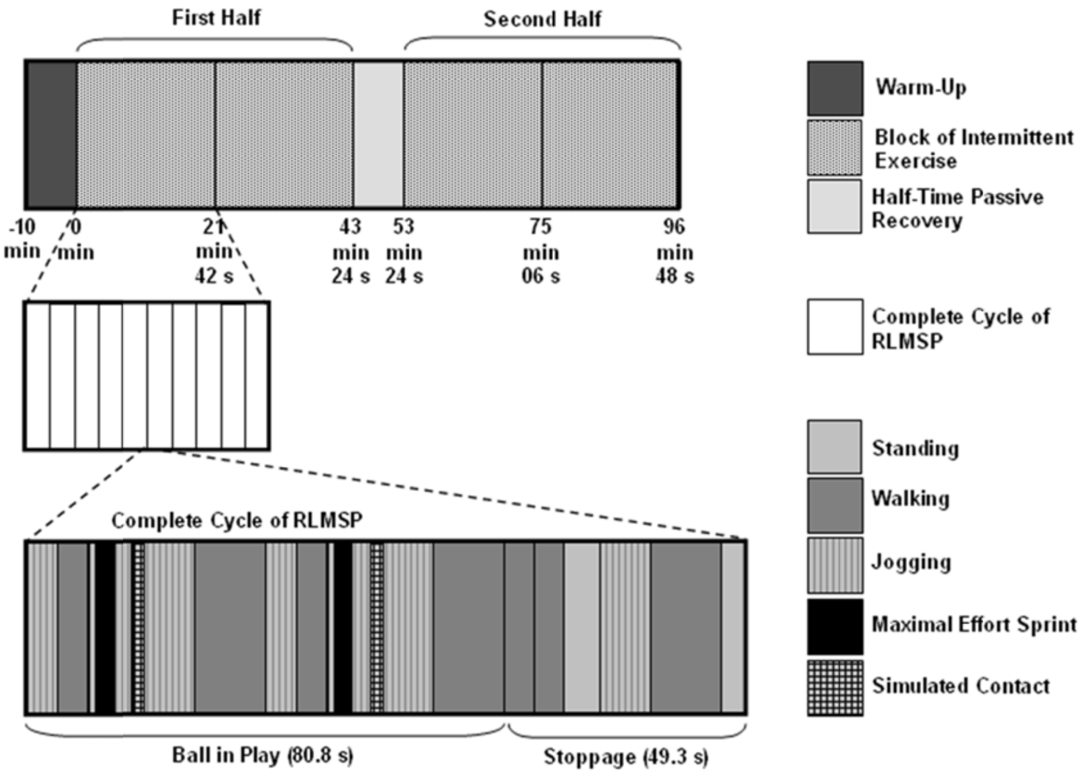

Figure 5.1 A schematic representation of the exercise pattern of the RLMSP

In order to add a competitive element to the protocol, participants performed the RLMSP in pairs (using lanes laid out side-by-side; Figure 5.2). Furthermore, verbal encouragement was provided throughout each trial, particularly during the 20.5 m sprints.

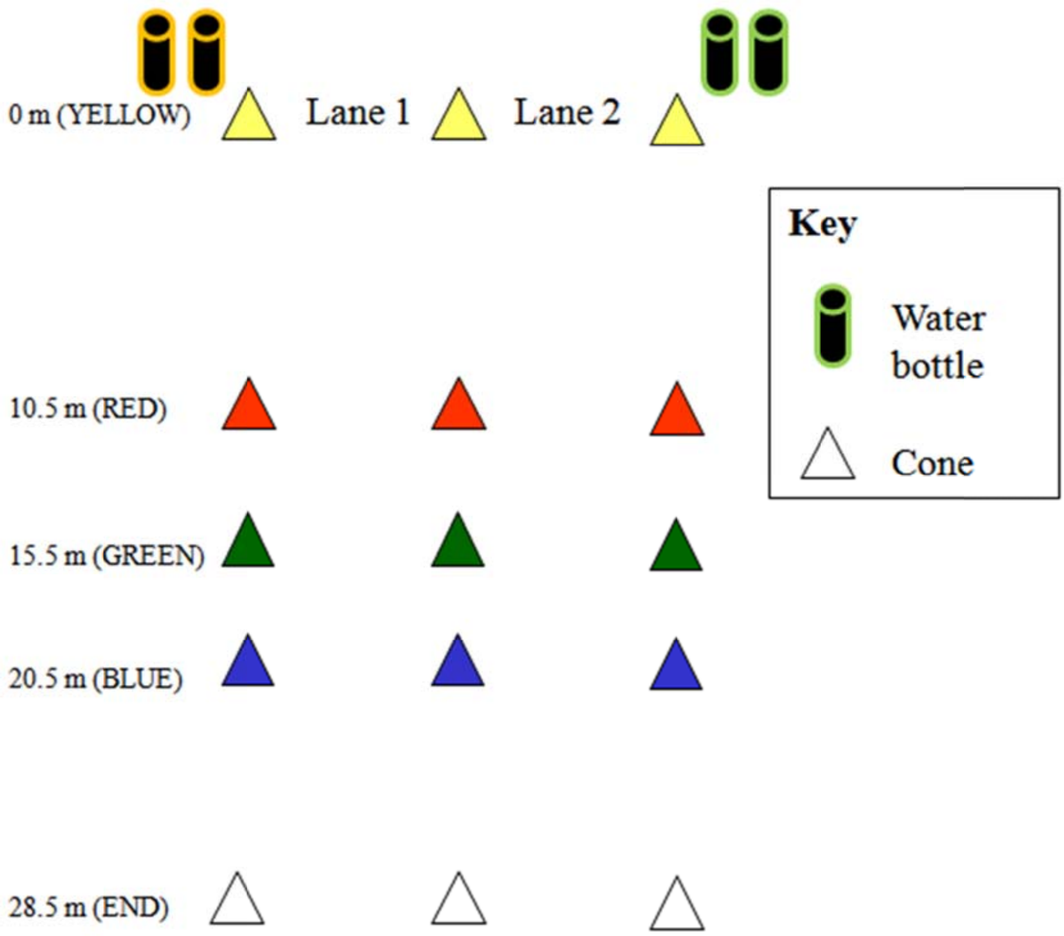

Figure 5.2 A schematic representation of the layout of the testing area used for the RLMSP

5.3.9 Statistical analysis

Data for each of the locomotive indices (overall, low, high and very high intensity running locomotive rate) and peak sprint velocity (mean and summated) during trials one and two were independently checked for normality using the Shapiro-Wilk statistic, before the application of a two-way analysis of variance (ANOVA) with repeated measures (quarter [4] x trial [2]) to assess their variability over time and between trials. The Greenhouse-Geisser adjustment was employed if the assumptions of sphericity were violated. Where appropriate, paired sample *t*-tests with Bonferroni adjustments were used as a post-hoc procedure to identify specific differences.

The principle technique adopted for assessing the reliability of the movement and physiological variables over the two trials was Bland and Altman's (1986) LoA, though owing to their popularity in other related research, the intraclass correlation (ICC), CoV and typical error (TE; Hopkins, 2000) were also calculated. Prior to performing LoA, checks were made for the absence of significant test-retest mean differences (via paired samples *t*-tests), normal distribution and homoscedastic errors (Lamb, 1998; Atkinson and Nevill, 1998). If the latter two conditions were violated, the relevant raw data were log transformed and re-checked in order to facilitate the calculation of ratio LoA (Atkinson and Nevill, 1998).

Comparisons (of summary statistics) were made between the original match data upon which the RLMSP was based (Studies One and Two) and the current RLMSP data. Given their independence, no attempt was made to employ hypothesis tests.

Statistical significance was set at $P<0.05$. Analyses were performed using SPSS (Version 17.0, Chicago, USA) and Excel (Office 2007, Microsoft Excel, Redmond, USA).

5.4 Results

5.4.1 Environmental conditions

The mean ambient temperature and humidity were 18.5 ± 7.6 °C and 58 ± 17% during trial one and 16.3 ± 3.8 °C and 75 ± 17% during trial two, respectively. While temperature remained unchanged ($P>0.05$), the between-trial difference in mean humidity was significant ($P<0.05$).

5.4.2 Consistency of changes in body mass, fluid consumption and sweat loss

Similar reductions in body mass were observed between trials one (0.61 ± 0.75 kg; -0.7 ± 0.9%) and two (0.68 ± 0.75 kg; -0.9 ± 0.9%) with 0.89 ± 0.58 and 1.09 ± 0.38 l of fluid consumed during trials one and two, respectively. This equated to a sweat volume of 1.49 ± 0.82 l for trial 1 and 1.67 ± 0.77 l for trial 2. None of these changes were significant between trials ($P>0.05$).

5.4.3 Validation of movement demands

During the RLMSP, 53.9 ± 0.0 min of the 86.8 min simulation protocol was spent simulating the movement demands of when the ball is in play, compared to 54.8 ± 0.4 min during actual match play (Study One). In addition, on the basis of running, HSR, sprinting and contact being classified as 'work', mean work-to-rest ratios (WRR) during the RLMSP were 1:5.7 for Part A (Table 5.1) and 1:104.8 for Part B (Table 5.2). Overall, participants covered 8,444 ± 212 m during the RLMSP compared to 8,503 ± 631 m during senior elite rugby league matches.

Table 5.1 The %TT spent in activity categories during senior elite rugby league matches whilst the ball was in play and Part A of the RLMSP

Activity	Time (%)	
	Senior elite matches*	RLMSP
Standing (<0.2 $m \cdot s^{-1}$)	2.3 ± 1.1	6.0 ± 2.2
Walking (0.2-1.9 $m \cdot s^{-1}$)	53.9 ± 7.3	63.5 ± 2.4
Jogging (2.0-3.9 $m \cdot s^{-1}$)	30.5 ± 5.4	16.0 ± 1.7
Running (4.0-5.4 $m \cdot s^{-1}$)	6.7 ± 1.4	4.4 ± 1.5
HSR (5.5-6.9 $m \cdot s^{-1}$)	1.8 ± 0.5	5.3 ± 0.9
Sprinting (≥7 $m \cdot s^{-1}$)	0.4 ± 0.3	0.6 ± 0.9
Contact	4.2 ± 1.9	4.5 ± 0.1

* Data are repeated from Study One

Table 5.2 The %TT spent in activity categories during senior elite rugby league matches during stoppages and Part B of the RLMSP

Activity	Time (%)	
	Senior elite match*	RLMSP
Standing	24.9 ± 7.0	14.3 ± 3.8
Walking	63.4 ± 6.8	74.5 ± 4.6
Jogging	10.1 ± 1.6	11.0 ± 2.1
Running	1.4 ± 0.7	0.9 ± 0.9
HSR	0.2 ± 0.2	0.1 ± 0.4
Sprinting	0.0 ± 0.1	0.0 ± 0.0
Contact	0.0 ± 0.0	0.0 ± 0.0

* Data are repeated from Study One

Whilst there were no significant effect of trials for any of the variables ($P>0.05$) there was a significant effect of quarter on overall ($F=5.8$, $P<0.05$), low (F=9.5, $P<0.05$), high (F=19.1, $P<0.05$), and very high (F=20.6, $P<0.05$) intensity running locomotive rates and mean (F=0.1, $P<0.05$) and summated (F=23.1, $P<0.05$), peak sprint velocity. Post-hoc tests revealed a significant reduction ($P<0.05$) in mean (Table 5.3) and summated (Table 5.4) peak sprint velocity and high (Table 5.7) and very high (Table 5.8) intensity running locomotive rates in all quarters compared to the first. Moreover, these variables, together with overall locomotive rate (Table 5.5) were significantly ($P<0.05$) lower in the final quarter compared to second and third quarters of the RLMSP. In addition, there was a significant interaction of quarter and trial for low (F=4.6, $P<0.05$) intensity running locomotive rates. Post-hoc tests revealed that low intensity running locomotive rate was significantly lower in the first quarter compared to all other quarters of the RLMSP for trial one only ($P<0.05$; Table 5.6).

Table 5.3 Mean peak sprint velocity ($m \cdot s^{-1}$) per quarter during trials of the RLMSP

RLMSP trial	Mean peak sprint velocity ($m \cdot s^{-1}$) per quarter			
	First	Second	Third	Fourth
One	6.83 ± 0.52	6.62 ± 0.54*†	6.51 ± 0.67*†	6.41 ± 0.63*
Two	6.79 ± 0.50	6.64 ± 0.51*†	6.61 ± 0.50*†	6.35 ± 0.56*

* Significantly different ($P<0.05$) to first quarter. † Significantly different ($P<0.05$) to fourth quarter.

Table 5.4 Summated peak sprint velocity ($m \cdot s^{-1}$) per quarter during trials of the RLMSP

RLMSP trial	Summated peak sprint velocity ($m \cdot s^{-1}$) per quarter			
	First	Second	Third	Fourth
One	136.6 ± 10.3	132.3 ± 10.8*†	130.1 ± 13.5*†	128.2 ± 12.7*
Two	135.9 ± 10.0	132.8 ± 10.1*†	132.2 ± 10.0*†	126.9 ± 11.2*

* Significantly different (*P*<0.05) to first quarter. † Significantly different (*P*<0.05) to fourth quarter.

Table 5.5 Overall locomotive rate ($m \cdot min^{-1}$) per quarter during trials of the RLMSP

RLMSP trial	Overall locomotive rate ($m \cdot min^{-1}$) per quarter			
	First	Second	Third	Fourth
One	97.7 ± 2.7	97.6 ± 2.6†	97.6 ± 2.2†	97.1 ± 2.0
Two	97.5 ± 2.8	97.3 ± 2.5†	97.0 ± 3.1†	96.5 ± 2.7

† Significantly different (*P*<0.05) to fourth quarter.

Table 5.6 Low intensity running locomotive rate ($m \cdot min^{-1}$) per quarter during trials of the RLMSP

RLMSP trial	Low intensity running locomotive rate ($m \cdot min^{-1}$) per quarter			
	First	Second	Third	Fourth
One	73.4 ± 2.7	74.9 ± 2.3*	75.3 ± 2.0*	75.2 ± 1.8*
Two	74.3 ± 2.3	74.7 ± 2.1	74.2 ± 2.6	74.9 ± 2.4

*Significantly different (*P*<0.05) to first quarter.

Table 5.7 High intensity running locomotive rate ($m \cdot min^{-1}$) per quarter during trials of the RLMSP

RLMSP trial	High intensity running locomotive rate ($m \cdot min^{-1}$) per quarter			
	First	Second	Third	Fourth
One	24.3 ± 2.9	22.7 ± 1.7*†	22.2 ± 1.1*†	21.9 ± 1.5*
Two	23.2 ± 1.7	22.6 ± 1.6*†	22.8 ± 2.1*†	21.6 ± 2.1*

*Significantly different (P<0.05) to first quarter. † Significantly different (P<0.05) to fourth quarter.

Table 5.8 Very high intensity running locomotive rate ($m \cdot min^{-1}$) per quarter during trials of the RLMSP

RLMSP trial	Very high intensity running locomotive rate ($m \cdot min^{-1}$) per quarter			
	First	Second	Third	Fourth
One	15.2 ± 2.3	13.8 ± 3.8*†	13.4 ± 4.0*†	12.8 ± 4.0*
Two	15.2 ± 2.4	14.0 ± 3.1*†	14.0 ± 3.1*†	11.2 ± 5.1*

*Significantly different (P<0.05) to first quarter. † Significantly different (P<0.05) to fourth quarter.

Tables 5.9-5.12 (below) show descriptive data only for overall, low, high and very high intensity running locomotive rates for successive quarters of the RLMSP in comparison to those reported in Study One.

Table 5.9 Comparison of overall locomotive rate ($m \cdot min^{-1}$) per quarter during a senior elite rugby league match (Study One) and during the RLMSP

	Overall locomotive rate ($m \cdot min^{-1}$) per quarter			
	First	Second	Third	Fourth
Match	100.7 ± 8.1	96.1 ± 12.0	98.7 ± 10.0	95.5 ± 13.2
RLMSP	97.6 ± 2.7	97.5 ± 2.5	97.3 ± 2.7	96.8 ± 2.3

Table 5.10 Comparison of low intensity running locomotive rate ($m \cdot min^{-1}$) per quarter during a senior elite rugby league match (Study One) and during the RLMSP

	Low intensity running locomotive rate ($m \cdot min^{-1}$) per quarter			
	First	Second	Third	Fourth
Match	78.5 ± 7.4	78.5 ± 9.9	79.2 ± 10.6	80.1 ± 2.8
RLMSP	73.9 ± 2.5	74.8 ± 2.2*	74.8 ± 2.4	75.0 ± 2.1*

*Significantly different (*P*<0.05) to first quarter.

Table 5.11 Comparison of high intensity running locomotive rate ($m \cdot min^{-1}$) per quarter during a senior elite rugby league match (Study One) and during the RLMSP

	High intensity running locomotive rate ($m \cdot min^{-1}$) per quarter			
	First	Second	Third	Fourth
Match	22.3 ± 5.0	17.6 ± 5.4*†	19.5 ± 4.8*†	15.4 ± 5.5*
RLMSP	23.8 ± 2.4	22.7 ± 1.6*†	22.5 ± 1.7*†	21.8 ± 1.8*

*Significantly different (*P*<0.05) to first quarter. † Significantly different (*P*<0.05) to fourth quarter.

Table 5.12 Comparison of very high intensity running locomotive rate ($m \cdot min^{-1}$) per quarter during a senior elite rugby league match (Study One) and during the RLMSP

	Very high intensity running locomotive rate ($m \cdot min^{-1}$) per quarter			
	First	Second	Third	Fourth
Match	7.8 ± 3.3	5.0 ± 2.9*‡	6.2 ± 3.3*	4.0 ± 2.4*‡
RLMSP	15.2 ± 2.3	13.9 ± 3.4*†	13.7 ± 3.5*†	12.0 ± 4.6*

* Significantly different (P<0.05) to first quarter. † Significantly different (P<0.05) to fourth quarter. ‡ Significantly different (P<0.05) to third quarter.

5.4.4 Reliability of movement variables

The mean difference (bias) in %TT standing, walking, jogging, running, HSR or sprinting between trials was not significant (P>0.05) (Table 5.13).

Table 5.13 Measures of reliability for movement variables during the RLMSP

Movement variables	CoV (%)	TE	ICC	95%LoA
Standing (%TT)	12.4	1.5	0.607	-0.6 ± 4.0
Walking (%TT)	1.8	1.5	0.642	0.6 ± 4.1
Jogging (%TT)	2.3	0.4	0.708	0.1 ± 1.2
Running (%TT)	13.5	0.5	0.679	0.0 ± 1.5
HSR (%TT)	9.6	0.4	0.547	0.1 ± 1.0
Sprinting (%TT)	45.9	0.2	0.869	-0.1 ± 0.6

CoV = ∑ (SD/mean) × 100; TE = (SD of di ÷ √2); 95%LoA = Mean di ± 1.96 × SD di. Where di = the difference between trials one and two.

5.4.5 Reliability of heart rates elicited

The mean HRs for trials one (82.4 ± 5.3% HR_{max}) and two (78.9 ± 4.1% HR_{max}) were not significantly different (*P*>0.05). Table 5.14 shows the reliability statistics for mean HR and time in HR zones.

Table 5.14 Measures of reliability for mean HR and time in HR zones during the RLMSP

HR variables	CoV (%)	TE	ICC	Ratio LoA
Mean HR (% HR_{max})	5.0	4.7	0.007	0.96 ×/÷ 1.18
Time in low HR zone (min)	35.3	19.3	-0.017	1.53 ×/÷ 3.63
Time in moderate HR zone (min)	63.8	10.6	0.207	0.34 ×/÷ 19.32
Time in high HR zone (min)	104.7	11.1	-0.081	0.22 ×/÷ 146.73

CoV = ∑ (SD/mean) × 100; TE = (SD of di ÷ √2‡); 95%LoA = Mean di ± 1.96 × SD di. Where di = the difference between trials one and two.

5.4.6 Reliability of performance variables

Mean overall, high and very high intensity running locomotive rates for the RLMSP were not significantly different (*P*>0.05) between trials (97.5 ± 2.3, 22.8 ± 1.6 and 13.8 ± 3.4 and $m \cdot min^{-1}$ for trial one and 97.1 ± 2.6, 22.5 ± 1.7 and 13.6 ± 3.2 $m \cdot min^{-1}$ for trial two, respectively). Likewise, summated and mean peak sprint velocity were not significantly different (*P*>0.05) between trials one (528.3 ± 43.7 and 6.60 ± 0.54 $m \cdot s^{-1}$) and two (520.0 ± 40.4 and 6.50 ± 0.50 $m \cdot s^{-1}$). Table 5.15 shows the CoV, TE and 95%LoA for performance measures during the RLMSP.

Table 5.15 Measures of reliability for performance variables during the RLMSP

Performance variable	CoV (%)	TE	ICC	95%LoA
Overall locomotive rate ($m \cdot min^{-1}$)	1.1	1.5	0.660	-0.4 ± 4.0
High intensity running locomotive rate ($m \cdot min^{-1}$)	4.2	1.3	0.404	-0.3 ± 3.6
Very high intensity running locomotive rate ($m \cdot min^{-1}$)	10.6	1.6	0.779	-0.2 ± 4.4
Mean peak sprint velocity ($m \cdot s^{-1}$)	2.1	0.15	0.906	-0.10 ± 0.42
Summated peak sprint velocity ($m \cdot s^{-1}$)	2.1	11.9	0.904	-8.4 ± 33.1

CoV = ∑ (SD/mean) × 100; TE = (SD of di ÷ √2); 95%LoA = Mean di ± 1.96 × SD di. Where di = the difference between trials one and two.

5.5 Discussion

This is the first study to attempt to evaluate the movement demands of a field-based simulation protocol in comparison to senior elite rugby league match data and the first match simulation protocol to distinguish between and replicate the different movement demands when the ball is in play and during stoppages. Unlike earlier studies which evaluate the movement demands of their simulation protocols based on mean velocities over each of the set distances (e.g. Nicholas et al., 2000), the current study evaluates the movement demands of a simulation protocol using TMA at a sampling rate of 5 Hz. However, on the basis of the NdGPS evaluation, the RLMSP appears to generate a greater very high intensity running locomotive rate than during matches (Study One). Moreover, the reductions in very high (-22.4%) and high (-8.6%) intensity running locomotive rates and increase in low intensity running locomotive rate (1.6%) from quarter one to quarter four are consistent with, albeit to a lesser extent, those observed in competitive matches in Study Two. Some of the differences between the movement demands of senior elite matches and the RLMSP are likely to be due to differences between the NdGPS and semi-automated image recognition (SAIR) tracking systems used to quantify the movement demands of the simulation protocol and match, respectively (Randers et al., 2010). In comparing a 5 (Minimax X, Catapult, Melbourne, Australia) and 1 Hz (SPI Elite, GPSports, Canberra, Australia) NdGPS and a 25 Hz SAIR tracking system (Amisco Pro®, version 1.0.2, Nice, France) Randers et al. (2010) reported that both the 5 and 1 Hz NdGPS units systematically underestimated HSR and sprinting (24-39%) in comparison to the SAIR tracking system. However, the accuracy of NdGPS units are dependent on sampling frequency (Duffield et al., 2010; Jennings et al., 2010; Portas et al., 2010) and manufacturer (Petersen et al., 2010). Likewise, it is probable that there are disparities between SAIR tracking systems from different companies, especially those that sample at different frequencies. Therefore, as neither of the systems used in the current thesis were compared by Randers et al. (2010) it is hard to extrapolate their findings to those observed here.

Furthermore, despite attempts through pilot testing to develop the RLMSP closer to the values observed in Study One, it proved difficult to estimate the instantaneous velocities at which participants would move between cones with large variation between individuals in their rate of acceleration and deceleration over varying velocities and distances. Based on the %TT spent in each of the locomotive categories, the higher very high intensity locomotive rate observed in the RLMSP compared to that in matches (Study One) appears to be largely as a result of participants performing more HSR during Part A of the protocol. This was offset by less time being spent jogging which may reflect participants covering the distance in the specified time by rapidly accelerating at the start of each discrete movement and having to spend less time at a constant moderate intensity velocity, possibly even walking in the last 1-2 steps on approach to the cones in order to stick to the verbal commands on the CD. This may also explain the slightly higher %TT recorded as walking during Part A of the protocol than was dictated by the average velocities on the CD.

Nevertheless, during the RLMSP participants covered a TD of 8,444 ± 212 m which was similar to the 8,503 ± 631 m covered during competitive matches by elite players. Mean HR during the RLMSP was 80.6 ± 5.0% HR_{max} which is slightly lower than the 84.3% HR_{max} reported by Coutts et al. (2003) in semi-professional rugby league players during competitive matches. However, it is not uncommon for HR during match simulation protocols to be lower for the same given workload as is performed in competitive games (Kingsley et al., 2005; Roberts et al., 2010) as it is likely that HR during competitive matches is elevated as a result of emotional stress (Reilly, 1997).

Mean reduction in BM during the protocol (0.63 kg, -0.9% BM) was also lower than that reported in professional players during competitive rugby league matches (1.28 kg, -1.31% BM; O'Hara et al., 2010), probably owing to the slightly higher fluid intake in the current RLMSP (0.99 l) than in the competitive matches (0.64 l; O'Hara et al., 2010). Though fluid consumption was limited to Part B of the RLMSP (designed to replicate the stoppages in play when water bottles can be bought onto the pitch during a competitive match) it is likely that the proximity to the water bottle during the RLMSP allowed more fluid to be consumed than would be possible during a competitive match in which more time is required to get the water bottles from the side line to areas of the pitch where players are located.

The reduction in high and very high intensity running locomotive rate and mean or summated peak sprint velocity between the first and final quarter was consistent across trials. In addition, the low systematic bias and lack of significant bias between trials for mean and summated peak sprint velocities, high and very high intensity running locomotive rates and mean HR demonstrates that the short familiarisation process (~4 min) was adequate. This is likely to be a consequence of designing a cyclical activity pattern with instructions that were simple and clear to follow. Whilst performing the RLMSP outdoors increases the external validity of the protocol and allowed

NdGPS data to be collected, the protocol is designed to fit into a sports hall with standard dimensions of 32 x 15 m (to accommodate a full sized basketball court) and performing the protocol indoors is likely to have improved the reliability of the RLMSP by reducing the impact of environmental conditions. Furthermore, given recent findings by Coutts and Duffield (2010) that the inter-unit reliability of 1 Hz NdGPS is poor at higher velocities and that a 1 Hz NdGPS is generally more reliable than a 5 Hz unit (Duffield et al., 2010), a large proportion of the variability observed between trials (especially in high and very high intensity running locomotive rates) is likely to have been due to instrument error as no attempt was made to assign the same NdGPS unit to participants on consecutive trials.

Even so, the current data demonstrate that the RLMSP provides a reliable tool for measuring physical performance during simulated rugby league matches, with all performance variables except very high intensity running locomotive rate yielding CoVs of <10%, a value recommended as a criterion for acceptable reliability by Stokes (1985) and Atkinson et al. (1999). Furthermore, the variability of overall, high and very high intensity running locomotive rate were lower than reported in soccer matches from SAIR tracking systems using the same velocity thresholds (Gregson et al., 2010; Rampinini et al., 2007b). In addition, the CoVs for mean and summated peak sprint velocities during the RLMSP were 2.1%, which is comparable to those reported for multiple 20 m sprints measured using timing gates (2.3%; Paton et al., 2001) and 3 and 6 s (1.7 and 1.3%, respectively) sprints on a non-motorised treadmill (NMT) during a generic team sport simulation protocol (Sirotic and Coutts, 2008). Furthermore, mean and summated peak sprint velocity show moderate to high reliability based on ICC scores >0.8 (Vincent, 1999).

However, perhaps more important is the ability of the measures to detect change in individuals. Therefore, as the ability to perform high and very high intensity running are vital to performance, changes in these locomotive rates throughout match simulation protocols may be a useful marker of physical performance. However, given that the TE for high and very high intensity running locomotive rates during the RLMSP have been calculated as 1.3 and 1.6 $m \cdot min^{-1}$, respectively, a change of greater magnitude than this would have to be detected in order to be confident that a meaningful change has occurred. On the basis of these TE values, the mean reduction from the first to last quarter of the RLMSP in high (2.0 $m \cdot min^{-1}$) and very high (3.2 $m \cdot min^{-1}$) intensity running locomotive rates suggest that a 'real' change is present across the duration of the match.

Furthermore, based on the nomogram designed by Batterham and Atkinson (2005; Appendix 8) and using the CoV, it can be estimated that a sample size of ~15 is required to detect a 5 and 10% change in high intensity locomotive rate. Moreover, ~5 and 10 participants are required to detect a 5% change in overall locomotive rate and mean or summated peak sprint velocity, respectively. However, based on the same nomogram (Batterham and Atkinson et al., 2005; Appendix 8), but using the ratio LoA, more than 200 participants would be required to detect a change in the time spent in each of the HR zones. On the basis of these findings, it is suggested that high intensity running locomotive rate or mean or summated peak sprint velocity should be used to assess physical performance when trying to detect small (<10%) performance changes. Indeed, high intensity activity appears to be closely related to other key aspects of performance, such as the number of line breaks, involvements with the ball (Rampinini et al., 2009) or support runs (Sirotic et al., 2009) and is therefore, a key performance indicator worth measuring.

A limitation to the current study was the method in which contact was simulated. Whilst the simulated contact was selected in order to minimise the risk of injuries associated with physical collisions and to control the intensity at which contact was performed, it is acknowledged that the lack of collision during simulated contact may not be as physically demanding as during actual match play. However, as getting up from the floor following a tackle is anecdotally reported to be an extremely physically taxing component of match play, the high frequency of simulated contacts in the RLMSP compared to matches may in part offset the lower demands per action. In addition, although the length of time in contact per incidence is lower than during actual match play, the overall time in contact was similar (4.5 vs. 4.1%).

5.6 Conclusions

The RLMSP provides a reliable measure of match-related physical performance which reflects similar movement demands during and physiological responses to professional rugby league matches when performed by male non-elite, active sportsmen. Based on the test-retest repeatability and consistent trial-by-trial changes throughout the protocol, high intensity running locomotive rate and mean or summated peak sprint velocity should be used to assess physical performance when trying to detect small performance changes using the RLMSP. Furthermore, the variability of high and very high intensity running locomotive rate was substantially lower than reported in soccer matches from SAIR tracking systems using the same velocity thresholds (Gregson et al., 2010; Rampinini et al., 2007b). Finally, following recent changes in the national governing body regulations on the use of NdGPS during competitive rugby league matches, future studies should look to directly compare the movement demands and physiological responses of senior elite rugby league players during matches and the RLMSP using NdGPS as is advised by Drust et al. (2007) in order to directly validate the ecological validity of match simulation protocols. However, to date just one study has used this approach to directly validate their match simulation protocol (Thatcher and Batterham, 2004). In addition, it would be useful to assess whether the performance variables in the RLMSP differentiate between players of different abilities and positions. However, to the knowledge of this author, at present no such assessment has been made in any match simulation protocol.

CHAPTER 6

THE RUGBY LEAGUE MATCH SIMULATION PROTOCOL: A STIMULUS FOR EXERCISED-INDUCED MUSCLE DAMAGE?

The contents of this chapter form the basis of the following presentation:

Sykes, D., Twist, C., Nicholas, C., and Lamb, K. (2010). Assessment of the affects of a rugby league match simulation protocol on perceived muscle soreness, muscle function and perceived exertion. Postgraduate Research Conference, University of Chester, 20th May.

6.1 Abstract

Following recent observations that players exhibit symptoms of exercise-induced muscle damage (EIMD) for up to 5 d following a competitive rugby league match (McLellan et al., 2010, 2011a, 2011b), the need has arisen for identifying and manipulating modes of recovery in a controlled environment. Accordingly, the aim of this study was to determine the efficacy of the rugby league match simulation protocol (RLMSP) for inducing EIMD to an extent similar to that observed following competitive matches. Following ethical approval, 10 male participants (age 22.7 ± 3.0 y, stature 1.76 ± 0.05 m, body mass; BM 78.9 ± 4.5 kg) provided baseline measurements of isokinetic peak torque in the knee extensors and flexors at 60 and 240 deg·s^{-1}, countermovement and squat jumps (CMJ and SJ, respectively), whole blood creatine kinase (CK) concentrations, perceived muscle soreness (in the hamstrings and quadriceps), and ratings of perceived exertion (RPE) and heart rates (HR) during a 4 min intermittent shuttle run. Participants then performed the RLMSP and returned to the laboratory at 1, 2, 3 and 7 d later to repeat the baseline measurements. Perceived muscle soreness in the quadriceps and hamstring muscle groups was significantly (P<0.05) elevated for up to 2 d following the RLMSP. The RLMSP resulted in a peak increase in circulating CK at 1 d following the RLMSP which remained significantly elevated for 2 d (P<0.05). The lower CK concentrations observed in the current study compared to those reported in competitive matches suggests that tissue damage measured after a competitive rugby league match might be exacerbated by physical contact. Furthermore, both SJ and CMJ jump heights were significantly reduced (P<0.05) at 1 d following the RLMSP and isokinetic peak torque at 60 deg·s^{-1} was reduced at 1 and 2 d in the knee flexors and at 2 d in the knee extensors. Moreover, whilst there was no effect of time on HR during the intermittent shuttle run, mean RPE was significantly (P<0.05) higher at 1, 2 and 3 d following the RLMSP, suggesting an altered sense of effort during intermittent exercise when experiencing the symptoms of EIMD. Notwithstanding the lower peak CK concentrations, these findings suggest that symptoms of EIMD evoked by the RLMSP follow a similar time course to those observed following competitive matches. Therefore, given the repeatability of the movement demands and physiological responses

from the RLMSP (Study Three), it could be used as a research tool to monitor the effectiveness of different recovery interventions on perceived muscle soreness and muscle function following rugby league game-related exercise.

6.2 Introduction

Competitive rugby league matches are generally 5 to 9 d apart, and it is expected that players will return to training in the days following a game. However, during this time a player's training output may be compromised as a result of EIMD and prolonged fatigue incurred as a result of the game (Tee et al., 2007). EIMD is a well-documented phenomenon following unaccustomed and eccentric-biased exercise (Byrne et al., 2004; Vaile et al., 2008) and typically results in common symptoms such as: delayed onset muscle soreness (DOMS; Cleak and Eston, 1992; Thompson et al., 1999), increases in intracellular proteins, (e.g. CK: Vaile et al., 2008; Byrne and Eston, 2002), muscle stiffness (Cleak and Eston, 1992), reductions in muscle strength and power (Thompson et al., 1999; Cleak and Eston, 1992; Byrne and Eston, 2002; Twist and Eston, 2005, 2007), and impaired sprint and agility performance (Twist and Eston, 2005; Highton et al., 2009). Whilst previous studies have utilised downhill running (Eston et al., 1996; Chen et al., 2007), high volume plyometric (Avela et al., 1999; Twist and Eston, 2005; 2007) and resistance exercise (Byrne and Eston, 2002; Vaile et al., 2007), few have investigated EIMD following sport-specific activities (Falvo and Bloomer, 2006).

Though EIMD might be the result of metabolic stress imposed during prolonged exercise (Tee et al., 2007) eccentric muscle actions (i.e. mechanical stress) are also a common occurrence in intermittent team sports as a consequence of the high number of accelerations and decelerations performed in such activities (Osgnach et al., 2010). Studies that have addressed the impact of intermittent team sports on symptoms of EIMD have focused on the use of soccer-based protocols such as the Loughborough

Intermittent Shuttle test (LIST; Nicholas et al., 2000). These studies report perceived muscle soreness and CK to be increased for up to 3 d following soccer-specific match simulation protocols (Bailey et al., 2007; Thompson et al, 2001; Ingram et al., 2009; Magalhães et al., 2010). Furthermore, isometric and isokinetic muscle force capabilities of the knee extensors and flexors (Bailey et al., 2007; Thompson et al., 2001; Ingram et al., 2009; Magalhães et al., 2010) and vertical jump performance (Bailey et al., 2007; Magalhães et al., 2010) are reported to be significantly lower than baseline values at 1 and 2 d following such protocols.

More recently, McLellan et al. (2010, 2011a, 2011b) and McLean et al. (2010) have reported symptoms of EIMD following actual rugby league matches in professional players. Peak rate of force development, peak power, peak force and flight time (McLean et al., 2010) during CMJs were significantly reduced for 1 d following competitive rugby league matches. In addition, plasma CK concentrations were elevated for at least 5 d (peaking 1 d post-match; McLellan et al., 2010, 2011a, 2011b). In addition, whilst general muscle soreness has been reported to peak at 1 d post-match, this remains elevated for up to 2 d during a 7 d microcycle (McLean et al., 2010).

Furthermore, whilst isokinetic muscle function data might provide indications of a player's force generating capability and susceptibility to muscle injury in the days following a match, to date, the effect of competitive rugby league matches on isokinetic muscle function has yet to be investigated. Of the measures afforded by isokinetic dynamometry, the hamstring-quadricep (H:Q) ratio may provide indications of an individual's injury potential in the hamstring muscle group if it is lowered by a greater magnitude than that of the knee extensors in the days following a match (Orchard et al., 1997). It has also been suggested that the angle of peak torque during isokinetic knee flexion provides a valid measure of hamstring injury susceptibility (Brockett et al., 2004). These authors observed that in those individuals with a previous history of hamstring injury, the angle of peak torque in the knee flexors of the previously injured limb was at a significantly shorter length (12^{o} on average) than the uninjured limb. Based upon the known characteristics of skeletal muscle during active lengthening (Morgan, 1990), Brockett and colleagues (2004) proposed that in individuals with a shorter optimal muscle length, a greater proportion of the muscle's functioning range would occur on the descending limb of the length-tension relationship. Therefore, according to the 'popping sarcomere' hypothesis (Morgan, 1990), where sarcomeres are activated beyond their optimum length, those at greatest stretch will be the weakest and thus more susceptible to damage (Morgan and Proske, 2004). An acute shift in the optimum length of the muscle, as observed in elbow flexors (Philippou et al., 2003: 16.7^o; Prasartwurth et al., 2006; 18.0^o), knee extensors (Bowers et al., 2004; 15.4^o) and knee flexors (Brockett et al., 2001; 7.7^o) following eccentric exercise bouts, may suggest the presence of muscle injury.

Increases in the sense of effort (perceived exertion) during exercise have been observed in the presence of EIMD, and have been suggested to impair functional performance. Following muscle damaging exercise (resulting in muscle soreness and reduced muscle force), several studies have shown that at 2 d participants reporting signs of EIMD report higher RPE than at baseline for a given workload (Scott et al., 2003; Twist and Eston, 2009; Davies et al., 2009; Burt and Twist, in press). Moreover, during self-regulated exercise (i.e. time-trials), participants have been shown to cover less distance, combined with a lower metabolic cost and lower power output, whilst their RPE remained similar to baseline values (Twist and Eston, 2009; Burt and Twist, 2011). The cues that mediate the perceptual response may arise from central or peripheral mechanisms that are altered as a result of symptoms of EIMD. Nevertheless, RPE appears to play a self-regulating role in mediating functional performance and may alter the intensity of training a player is willing to tolerate in the days following a rugby league match. Therefore, from a practical perspective, RPE responses may act as a simple, cost-effective and non-invasive marker of the state of recovery when monitored during exercise sessions following a competitive game.

Given suggestions by Batterham and Atkinson (2005) that a repeated measures cross-over design has greater statistical power than different treatment groups, a study to monitor recovery from ecologically valid exercise protocols on two or more occasions using the same population of participants is warranted. However, the rate and magnitude of recovery following actual match play is likely to be highly erratic due to the level of EIMD and fatigue reflecting the movement demands of the match which, are themselves highly variable (Gregson et al., 2010; Mohr et al., 2003; Rampinini et al., 2007b). Therefore, monitoring recovery from separate matches is inappropriate for comparing different recovery interventions. However, given the low variability reported for the movement demands of the RLMSP (Study Three), the RLMSP has the potential to provide an alternative and more scientifically sound method of monitoring recovery from game-related exercise via a repeated measures cross-over design.

Indeed, anecdotal reports from participants following piloting of the RLMSP suggest that the close replication of match movement demands performed in the RLMSP may result in similar symptoms of EIMD to those observed following competitive rugby league matches (e.g. McLean et al., 2010; McLellan et al., 2010, 2011b). Therefore, the purpose of this study was to evaluate the efficacy of the RLMSP for inducing EIMD compared with that observed following competitive matches (e.g. McLean et al., 2010; McLellan et al., 2010, 2011a, 2011b). Additionally, the study sought to investigate the changes in muscle function and exercise performance that followed the simulated rugby league match play.

6.3 Methods

6.3.1 Participants

Ten male participants (age 22.7 ± 3.0 y, stature 1.76 ± 0.05 m, BM 78.9 ± 4.5 kg, estimated maximal aerobic capacity; $\dot{V}O_{2\max}$ 50.24 ± 3.30 $ml \cdot kg^{-1} \cdot min^{-1}$) provided written informed consent (Appendix 6) to participate in the study, which was approved by the Research Ethics Committee of the Faculty of Applied and Health Sciences at the University of Chester (Appendix 4). All participants were intermittent team sports players (five rugby union, four soccer and one hockey) and on the basis that senior elite rugby league players have mean values in the range 48.6-56.4 $ml \cdot kg^{-1} \cdot min^{-1}$ (O'Connor, 1996; Brewer et al., 1994) they were required to have a minimum estimated $\dot{V}O_{2\max}$ ≥45 $ml \cdot kg^{-1} \cdot min^{-1}$.

6.3.2 Experimental design

This was a repeated measures design in which participants initially attended the laboratory for familiarisation with the procedures and baseline testing, and on four further occasions in the days (1, 2, 3 and 7) following their completion of the RLMSP, to monitor their recovery. On each visit to the laboratory, participants' perceived muscle soreness, whole blood CK concentration, isokinetic torque, vertical jump height and RPE and HR during intermittent running were assessed using the procedures outlined below.

Participants were asked to abstain from exercise, nutritional supplements, non-steroidal anti-inflammatory drugs, therapeutic modalities and hydrotherapies for 3 d prior to session one until completion of the study. Figure 6.1 provides a schematic of the experimental design.

6.3.3 Preliminary measurements

The participants were required to perform the multi-stage fitness test (MSFT; Ramsbottom et al., 1988) to assess whether they met the inclusion criterion of having an estimated $\dot{V}O_{2\max}$ ≥45 $ml \cdot kg^{-1} \cdot min^{-1}$. The MSFT required participants to run at incremental speeds between two lines 20 m apart until volitional exhaustion. Heart rate was recorded continuously throughout the protocol via telemetry (s810i, Polar Electro, Finland) and later downloaded using Polar Precision Performance software (Polar Electro, Finland). The $\dot{V}O_{2\max}$ of each participant was estimated from the final running speed achieved in the MSFT using the regression equation provided by Léger et al. (1988). In addition, maximum HR was determined for each individual as the highest HR recorded during the test. Following a period of recovery, participants then performed two cycles of the RLMSP to familiarise themselves with the movement speeds and technique of simulated contact in the simulated protocol.

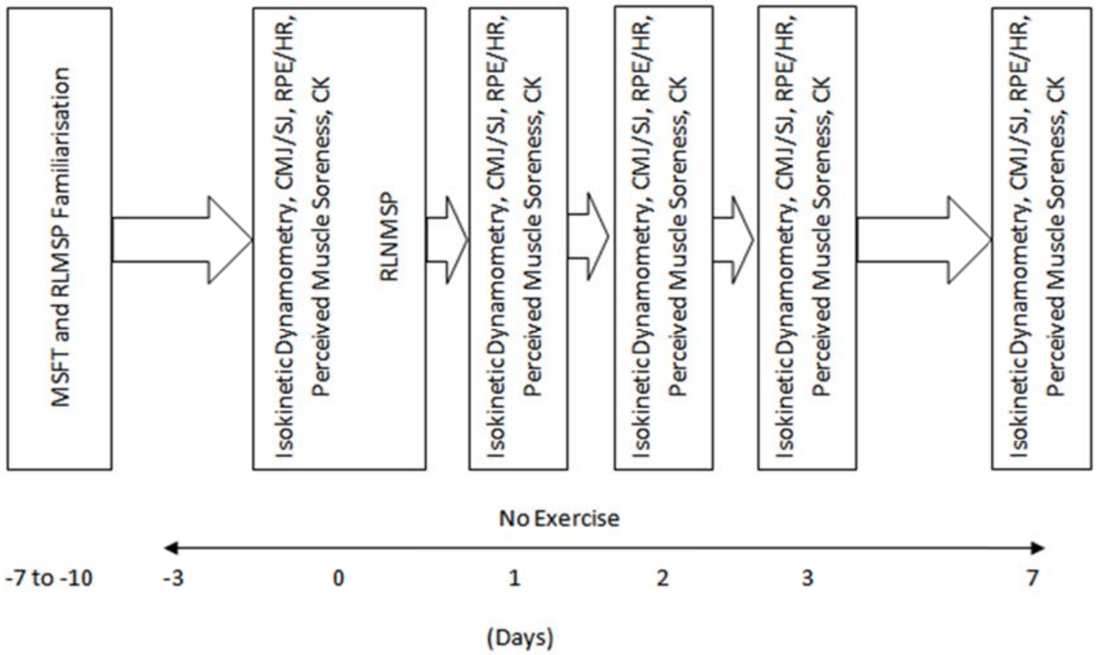

Figure 6.1 Schematic of the experimental design

6.3.4 The rugby league match simulation protocol

Upon arrival, participants removed heavy outer clothing and BM was measured wearing shorts and t-shirts via a portable digital scale (Seca 813 Robusta, Seca gmbh, Hamburg, Germany). Participants then performed a standardised 10 min warm-up consisting of jogging, dynamic stretching and high speed running (HSR), before undertaking the RLMSP (as described in Chapter Five) on an outdoor grass surface. Each participant wore a non-differential global positioning system (NdGPS; SPI Pro, GPSports, Canberra, Australia) and integrated HR monitor (Polar Electro, Oy, Finland) for the entirety of the protocol. The NdGPS and HR data were later downloaded using Team AMS (GPSports, Canberra Australia) software and exported to

Excel (Office 2007, Microsoft Excel, Redmond, USA) for further analysis whereby movements were classified into standing, walking, jogging, running, HSR, sprinting and contact, as defined in Study One. The NdGPS unit was worn in a purpose-made sleeveless vest (GPSports, Canberra, Australia) with the unit positioned in the rear of the vest in the centre of the upper back at the approximate height of thoracic vertebrae two. Briefly, the RLMSP is an intermittent protocol designed to replicate the physiological and movement demands of senior elite rugby league matches. In order to add a competitive element to the protocol, participants performed the protocol in pairs using lanes laid out parallel to one another. Every effort was made to provide a consistent level of verbal encouragement to the participants throughout each trial. During the RLMSP participants were allowed to ingest water from individually labelled water bottles *ad libitum*. However, this was limited to consumption during low intensity periods of activity in order to replicate the stoppages that occur in senior elite matches. The water bottles were weighed on portable scales (Salter Arc Electronic Scales, HoMedics Group Ltd, Kent, UK) to the nearest 1 g both prior to the start and immediately following the RLMSP and the amount of fluid consumed was recorded to the nearest ml. On completion of the RLMSP, participants towelled themselves to remove sweat and BM was re-measured as described above. Sweat volume was calculated as:

Pre- to post- change in BM (kg) + fluid intake (l)

Ambient temperature and humidity were recorded at the start, half-time and at the end of the protocol using a portable temperature and humidity monitor (THG810, Oregon Scientific Ltd., Berkshire, UK).

6.3.5 Indirect markers of muscle damage

6.3.5.1 Assessment of perceived muscle soreness

With hands on hips, feet shoulder-width apart and heels in contact with the floor, participants were asked to flex at the ankle, knees and hips to a knee angle of approximately 90^{o} and indicate the level of perceived muscle soreness of the knee extensors and flexors using a visual analogue scale. The scale is numbered from 0 to 10 on the reverse side of the sliding scale, with 0 indicating no soreness and 10 indicating the muscles are too sore to move. Such procedures have been shown to be both reliable and valid measures of perceived muscle soreness (Price et al., 1983) and have been used successfully in previous studies (e.g. Twist and Eston, 2005).

6.3.5.2 Assessment of creatine kinase

Creatine kinase concentrations were determined from fingertip blood capillary samples with the participant in a seated position. The participant's hand was pre-warmed in warm water (approximately 38-42^{o}C) and then the fingertip cleaned using an alcohol swab and then left to dry. A capillary puncture was made in the finger using a lancet (Softclix Pro, Roche Diagnostics, Mannhein, Germany) and a 30 microlitre sample of whole blood collected into a capillary tube. The capillary tube sample was then immediately pipetted onto a test strip and analysed for CK using a colorimetric assay procedure (Reflotron, Type 4, Boehringerm Mannhein, Germany).

6.3.6 Assessment of muscle function

6.3.6.1 Isokinetic torque

Isokinetic peak torque and the angle of peak torque at 60 and 240 deg·s^{-1} were measured in the knee extensors and flexors of the dominant leg using an isokinetic dynamometer (Biodex, Biodex Medical, New York, USA). Participants were tested in the seated position with the lateral femoral epicondyle aligned to the dynamometer’s axis of rotation. The upper body and active limb were secured with restraining straps to prevent extraneous movement (Baltzopoulos and Gleeson, 2001), and the participant was asked to maintain the arms positioned across the chest. The pad of the dynamometer lever arm was positioned at the distal point on the tibia above the malleoli. The dynamometer lever arm length and the vertical, horizontal and seat positions were recorded for each participant in order to replicate the exact position at each time interval. The range of motion for the dynamic contraction was set manually prior to testing for each individual and limb mass was assessed to allow gravity correction of all torque values (Gleeson and Mercer, 1996). During testing, participants performed five maximal repetitions at each angular velocity with a 2 min passive recovery between each set and the highest peak torque achieved for both flexion and extension was recorded for analysis. From these trials, the angle at which peak torque was achieved during knee extension and knee flexion was recorded and the H:Q ratio was calculated for each velocity as knee flexor/knee extensor peak torque. Participants performed the slower of the two angular velocities first as this has been shown to enhance the reproducibility of results (Wilhite et al., 1992). Visual feedback was used to encourage maximal efforts, with participants instructed to exceed torque values achieved in previous repetitions (Gleeson and Mercer, 1996). In-house reliability data for the dynamometer has established coefficient of variation (CoV) values for knee extension of 4.9% (60 $deg \cdot s^{-1}$) and 4.2% (240 $deg \cdot s^{-1}$) and knee flexion of 6.1% (60 $deg \cdot s^{-1}$) and 6.8% (240 $deg \cdot s^{-1}$).

6.3.6.2 Vertical jump height

Participants performed vertical jumps with (CMJ) and without (SJ) activation of the stretch-shortening cycle (SSC). For the SJ, participants were required to adopt a knee joint angle of approximately 90°, hold this position for 3 s and then perform a maximal jump vertically. For the CMJ, participants started from a standing position after which they were required to rapidly flex their knees to approximately 90° before performing a maximal vertical jump. For both the SJ and CMJ, flight times were recorded using the Optojump (Microgate S.r.I., Bolzano, Italy) infrared timing system interfaced to a laptop computer. The timing system assumes the participant's position is the same at take-off and landing (Byrne and Eston, 2002). Therefore, upon landing, the knees were fully extended and the ankle plantar-flexed. Jump height was calculated according to the method by Komi and Bosco (1978) as follows:

Jump height = $v^2/2g$

Where g is the acceleration due to gravity (9.81 $m \cdot s^{-2}$) and v is vertical velocity at take-off, calculated as:

$v = 0.5\ (F_{time} \times g)$

Where F_{time} is flight time.

The jumps were performed in the order of CMJ followed by SJ, with ~2 min recovery provided between each trial. The best height attained from three trials of each jump was used for analysis.

6.3.7 Assessment of ratings of perceived exertion and heart rate during intermittent running

Participants were required to perform a 4 min intermittent running protocol over a 20 m course. One cycle of the protocol consisted of a 20 m walk (1.25 $m \cdot s^{-1}$), followed by a 20 m run (4.55 $m \cdot s^{-1}$) and then a 40 m jog (2 x 20 m at 2.88 $m \cdot s^{-1}$), which was repeated seven times. The locomotive speeds during each activity were dictated by an audio CD and were based upon the approximate mean locomotive speeds per incidence and the work-to-rest ratio (WRR) during the ball in play phase of senior elite rugby league matches (Study One). Changes in locomotive activity during the intermittent run were signalled by a "beep" followed by a voice command to instruct participants of the locomotive activity. For example, a verbal instruction following the "beep" was as follows, "Jog". Heart rate (Polar, Polar Electro, Oy, Finland) was recorded continuously at a rate of 5 Hz throughout the exercise protocol and later downloaded using Polar Precision Performance software (Polar Electro, Finland) and RPE (Borg, 1982) was recorded during the final walking period of each cycle. Participants had been familiarised to the RPE scale using the standardised instructions from Borg (1982) prior to performing the intermittent running during the baseline testing.

6.3.8 Statistical analysis

The variability of the isokinetic peak torques and angle of peak torques of knee extensor to flexor peak torques and H:Q ratio at both 60 and 240 $deg \cdot s^{-1}$ were assessed using separate two-way (angular velocity [2] x time [5]) repeated measures analysis of variance (ANOVA). Likewise, vertical jump height (jump type [2] x time [5]) and perceived muscle soreness (location of soreness [2] x time [5]) were assessed via two-way repeated measures ANOVAs. The variability of CK concentration, RPE, and HR during the intermittent running protocol were analysed using separate one-way ANOVAs with repeated measures. The assumption of sphericity was assessed for each ANOVA using the Mauchly test, with any violations adjusted using the Greenhouse-Geisser correction. Significant effects were followed up with paired samples *t*-tests (with Bonferroni adjustments to the alpha level). In addition, a paired samples *t*-test was performed on BM immediately before and after the RLMSP. Statistical significance was set at $P \leq 0.05$.

6.4 Results

6.4.1 Environmental conditions

Ambient temperature and humidity were 11.6 ± 4.2 °C; 59 ± 9%, 11.1 ± 4.4 °C; 60 ± 11%, and 11.7 ± 4.4 °C; 62 ± 12% at the start, half-time and at the end of the RLMSP, respectively.

6.4.2 Change in body mass, fluid consumption and sweat volume

Despite 0.77 ± 0.39 l of fluid being consumed during the RLMSP, participants lost 0.58 ± 0.76 kg (-0.8 ± 1.0%) in BM which equated to a sweat volume of 1.35 ± 0.51 l. Body mass following the RLMSP was significantly (t (9), $P<0.05$) lower than before the start of the RLMSP

6.4.3 Physical and movement demands of the rugby league match simulation protocol

The mean HR during the RLMSP was 83.9 ± 4.5 percent of maximum HR (% HR_{max}) with participants covering 8,363 ± 245 m. Table 6.1 shows cumulative %TT spent standing, walking, jogging, running, HSR, sprinting and in contact during Part A (simulated ball in play) and Part B (simulated stoppages) phases of the RLMSP, respectively. The mean WRR ratio was 1:6.0 for Part A and 1:49.4 for Part B.

Table 6.1 The %TT spent in activity categories during the RLMSP

Activity	Time (%)	
	Part A	Part B
Standing	8.9 ± 4.1	15.4 ± 4.4
Walking	61.0 ± 5.4	71.1 ± 5.3
Jogging	15.9 ± 1.8	11.6 ± 1.8
Running	3.9 ± 0.9	1.5 ± 0.9
HSR	5.5 ± 0.7	0.5 ± 1.0
Sprinting	0.4 ± 0.4	0.0 ± 0.1
Contact	4.4 ± 0.0	0.0 ± 0.0

6.4.4 Markers of exercise-induced muscle damage following the rugby league match simulation protocol

There were no significant differences (P>0.05) between baseline and 7 d following the RLMSP for any of the markers of EIMD (Tables 6.2-6.3 and Figures 6.2-6.7), suggesting that all variables had returned to baseline by 7 d following the simulation protocol.

6.4.4.1 Perceived muscle soreness

There was a main effect of time on perceived muscle soreness (F=13.32, *P*<0.05) with values for both hamstrings and quadriceps significantly higher than baseline (Figure 6.2). The interaction of time and location on muscle soreness was not significant (F=0.67, *P*>0.05), reflecting a pattern of recovery in muscle soreness that was similar between quadriceps and hamstrings.

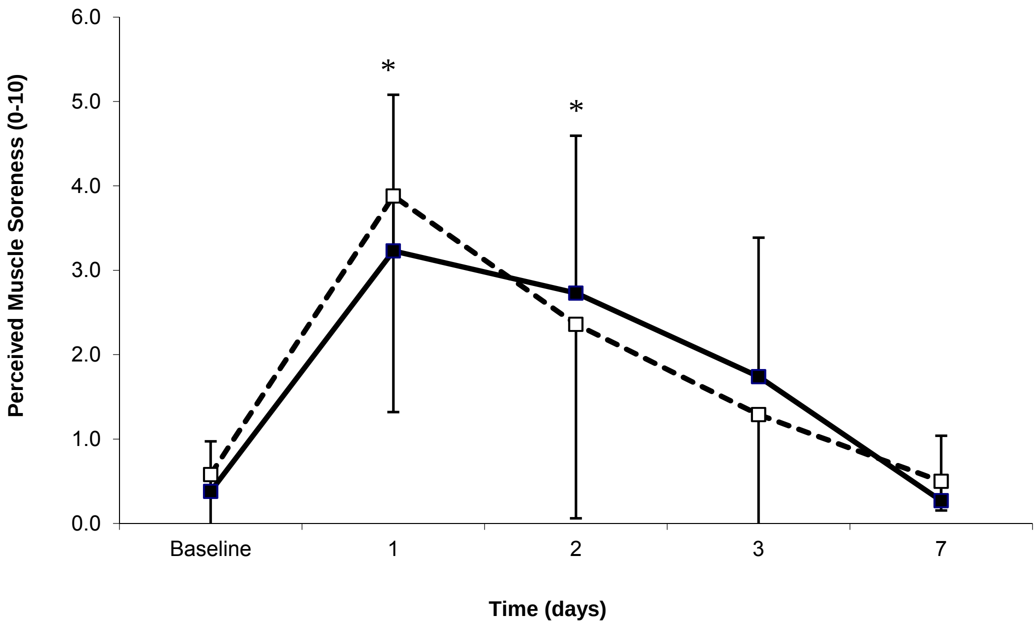

Figure 6.2 Perceived muscle soreness for hamstrings (□) and quadriceps (■) before and after the RLMSP. * indicates soreness is significantly different from baseline (*P*<0.05).

6.4.4.2 Whole blood creatine kinase concentration

Whole blood CK concentrations were 576 ± 792, 374 ± 657, 219 ± 413 and 208 ± 599% higher than baseline at 1, 2, 3 and 7 d following the RLMSP, respectively. There was a main effect of time on CK concentration (F=19.76, *P*<0.05) with values at 1 d following the RLMSP significantly higher than all other time points and values at 2 d following the RLMSP significantly higher than baseline (Figure 6.3).

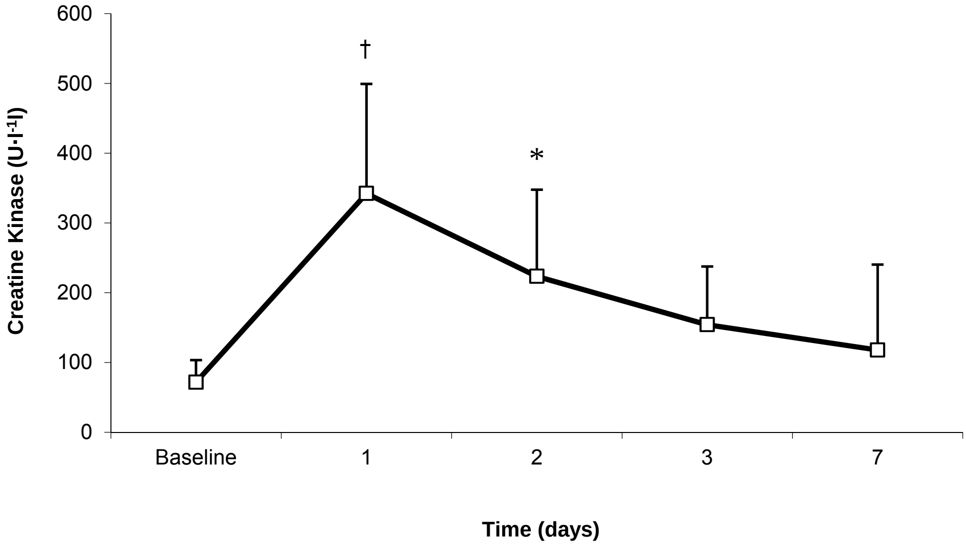

Figure 6.3 CK concentration (U·l^{-1}) before and after the RLMSP. * indicates significantly different from baseline (*P*<0.05). † indicates significantly different from all other time points (*P*<0.05).

6.4.4.3 Isokinetic peak torque, hamstring: quadricep ratio and angle of peak torque

There was a main effect of time on isokinetic peak torque in the knee extensors (F=8.24, *P*<0.05) (Figure 6.4) and flexors (F=9.47, *P*<0.05) (Figure 6.5). Post-hoc tests revealed that peak torque in the knee extensors and flexors were significantly lower (*P*<0.05) at 1 and 2 d following the RLMSP than at 7 d. However, the interaction of time and angular velocity on peak torque was also significant in both the knee extensors (F=5.10, *P*<0.05) and flexors (F=3.97, *P*<0.05). Post-hoc tests revealed that in comparison to 7 d following the RLMSP, isokinetic peak torque values at 60 deg·s^{-1} were significantly lower at 2 d following the RLMSP in the knee extensors and at 1 and 2 d following the RLMSP in the knee flexors. In contrast, no changes were observed in isokinetic peak torque at 240 deg·s^{-1} in the knee flexors or extensors over time.

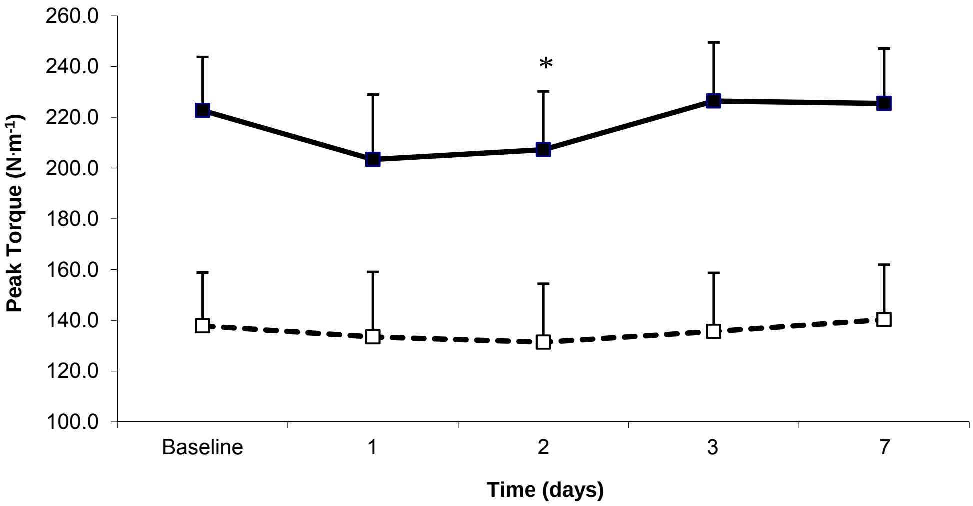

Figure 6.4 Isokinetic peak torque during knee extension at 60 (■) and 240 (□) deg·s^{-1}. * indicates significantly different from baseline at 60 deg·s^{-1}.

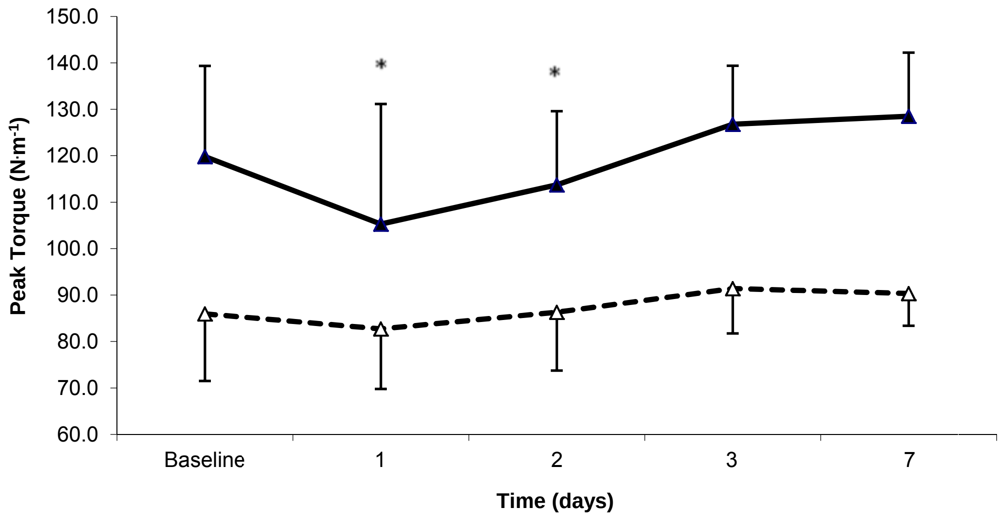

Figure 6.5 Isokinetic peak torque during knee flexion at 60 (▲) and 240 (Δ) deg·s^{-1}. * indicates significantly (P<0.05) different from baseline at 60 deg·s^{-1}.

There were no changes in the H:Q ratio over time (F=1.83, P>0.05) and no interaction effect of time and angular velocity on H:Q ratio (F=1.28, P>0.05) (Figure 6.6). Similarly, the angle of peak torque remained unchanged over time at both 60 and 240 deg·s^{-1} for both flexion (F=0.68, P>0.05) and extension (F=1.29 P>0.05) with no time and angular velocity interaction for either flexion (F=0.51, P>0.05) or extension (F=0.41, P>0.05) (Table 6.2).

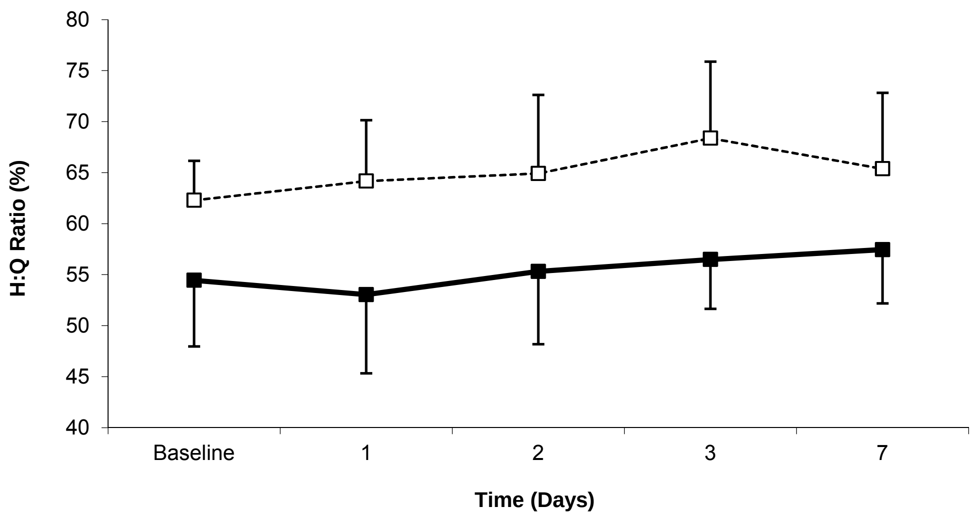

Figure 6.6 H:Q ratio (%) at 60 (■) and 240 (□) deg·s^{-1}.

Table 6.2 Angle of isokinetic peak torque at 60 and 240 deg·s^{-1} during flexion and extension.

	Baseline	1 d	2 d	3 d	7 d
Knee extension angle (°)					
60 deg·s^{-1}	71.9 ± 9.0	74.3 ± 4.7	74.9 ± 7.2	73.3 ± 5.4	73.3 ± 5.5
240 deg·s^{-1}	68.6 ± 6.5	72.6 ± 7.3	69.1 ± 6.4	70.7 ± 7.4	69.7 ± 4.8
Knee flexion angle (°)					
60 deg·s^{-1}	40.4 ± 4.7	42.9 ± 12.6	38.5 ± 5.9	39.7 ± 7.3	39.0 ± 9.2
240 deg·s^{-1}	40.5 ± 12.9	46.2 ± 10.8	44.7 ± 10.9	44.3 ± 10.5	44.5 ± 9.3

6.4.4.4 Vertical jump height

There was a main effect for time on vertical jump height (F=8.47, P<0.05), with the vertical jump height significantly (P<0.05) lower than baseline at 1 d following the RLMSP (Figure 6.7). However, the effect of jump type (F=1.22, P>0.05) and the interaction of time and jump type on jump height (F=1.23, P>0.05) were not significant and suggested that the recovery of SJ and CMJ performances were not different.

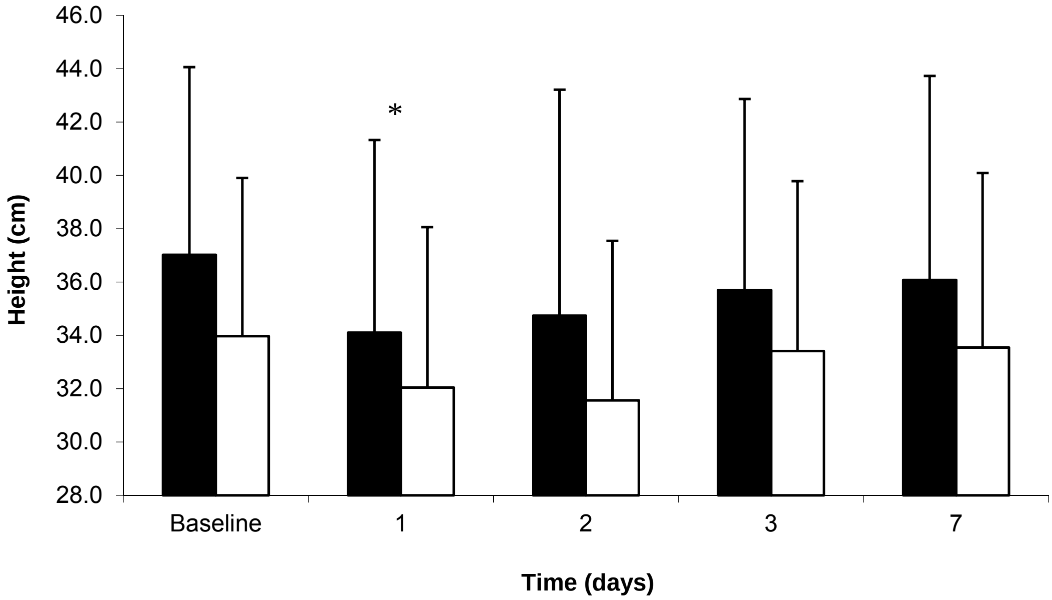

Figure 6.7 CMJ (■) and SJ (□) height (cm) before and after the RLMSP.
* indicates SJ and CMJ height significantly different from baseline (P<0.05).

6.4.4.5 Ratings of perceived exertion and heart rate during the intermittent running protocol

Whilst there was a main effect of time on RPE during the intermittent run (F=7.76, P<0.05) with RPE significantly higher than baseline at 1, 2 and 3 d following the RLMSP, HR remained unchanged from baseline at all time points (F=1.27, P>0.05) (Table 6.3).

Table 6.3 Mean RPE and % HR_{max} during a 4 min intermittent run performed before and after the RLMSP

	Baseline	1 d	2 d	3 d	7 d
RPE	11.5 ± 1.6	13.2 ± 1.6*	12.9 ± 1.5*	12.1 ± 1.2*	11.2 ± 1.2
% HR_{max}	80.4 ± 8.1	77.9 ± 4.0	77.9 ± 5.4	78.7 ± 4.6	78.1 ± 5.3

* indicates significantly different from baseline (P<0.05).

6.5 Discussion

The significant increase in CK concentrations at 1 and 2 d following the RLMSP suggests that tissue damage was induced by the RLMSP. Furthermore, peak CK concentration was observed at 1 d following the RLMSP, which is similar to that reported following competitive rugby league (McLellan et al., 2010, 2011a, 2011b), rugby union (Suzuki et al., 2004; Takarada, 2003), soccer (Andersson et al., 2008; Ascensão et al., 2008), and simulated soccer (Bailey et al., 2007; Kingsley et al., 2005; Thompson et al., 1999, 2001) matches. However, in the current study CK remained elevated for only 2 d, which whilst similar to that reported following simulated soccer matches (Kingsley et al., 2005; Thompson et al., 1999), is different to the time course of 5 d reported following competitive rugby league matches (McLellan et al., 2010, 2011a, 2011b). Furthermore, despite participants in the current study presenting greater relative increases in CK compared to baseline than in elite rugby league players (McLellan et al., 2010, 2011a, 2011b), peak absolute CK concentrations in the current study are lower in magnitude than those reported following a competitive rugby league match (McLellan et al., 2010, 2011a; 941 ± 392 $U \cdot l^{-1}$). Similarly, the values reported here are also lower than those reported following competitive rugby union matches (Cunniffe et al., 2010; Takarada, 2003).

The lower values and faster recovery of CK observed in this study compared to those in competitive rugby league and union games are possibly due to the absence of a true contact situation in the simulation protocol, which does not accurately replicate the physical collisions experienced by players during a competitive game. Indeed, both Takarada (2003) and Cunniffe et al. (2010) identified a positive correlation between CK increase and the number of collisions a player experienced during the game. However, interestingly McLellan et al. (2011a) reported a correlation between the number of hit-ups (i.e. carrying the ball into contact) and CK 1-3 d following a competitive match but not tackles made. Furthermore, Zuliani et al. (1985) reported that a competitive boxing fight resulted in a large increase in plasma CK concentrations, whereas shadow boxing (involving no contacts) for the same duration and intensity did not, suggesting that CK concentrations may also reflect blunt trauma from physical impacts as well as EIMD from eccentric muscle actions.

The findings suggest that while movement demands of rugby league *per se* impose some tissue damage (as evidenced by an increase in circulating CK), this is probably exacerbated by the incidence of physical collisions during a game, and coaches might be advised to take account of this when prescribing recovery in the days following competition. However, it should also be noted that participants in the present study possessed much lower baseline CK values than those reported for players prior to rugby union (Cunniffe et al., 2010; Takarada, 2003) and rugby league (McLellan et al., 2010; 2011a, 2011b) games. This is likely to be as a consequence of cumulative muscle damage from repetitive matches or acute muscle damage from training leading up to the matches. In contrast, participants in the current study performed baseline measurements after at least 3 d of complete rest. Therefore, tissue damage from prior exercise may in-part explain the higher CK concentrations reported following competitive matches compared to following the RLMSP. In addition, the elevated plasma CK levels reported for up to 5 d following a competitive match by McLellan et al. (2010, 2011a, 2011b) may also have been due to the resistance training and speed and agility field sessions undertaken at 2 and 3 d post-match, respectively. It should also be noted that differences in the blood measurement procedures adopted might account for some of the variance in CK values between the present study and those observed previously. Whilst Knoblauch et al. (2010) reported a correlation of 0.997 between CK in capillary and venous whole-blood samples, no comparisons have yet been made between CK measurements from venous plasma samples (as were used in the studies by McLellan et al., 2010, 2011a, 2011b) and CK from capillary whole-blood samples, as measured in this study.

Observations that isokinetic peak torque at 60 deg·s^{-1} was significantly reduced at 1 and 2 d in the knee flexors and at 2 d in the knee extensors compared to baseline provide the strongest evidence that skeletal muscle damage was present in both knee flexors and extensors following the

RLMSP (Warren et al., 1999). The decrements in muscle force are of a similar magnitude to those reported in previous studies with well-trained soccer players following simulated and competitive soccer performance (Anderson et al., 2008; Magalhães et al., 2010; Thompson et al., 2001). The results of this study also support previous observations that strength loss following eccentric exercise is greater at lower angular velocities of movement (Deschences et al., 2000; Michaut et al., 2002). Slower movement velocities, which demonstrate a greater capacity to generate force, might be impaired following EIMD because of a reduction in volitional activation (Deschenes et al., 2000) or as a result of neural inhibition, in an attempt to prevent further damage to skeletal tissue (Westing et al., 1991). Consequently, the finding that force generation is impaired at slower angular velocities for up to 2 d has implications for players engaging in strength training in the days following a game, particularly where the focus is on heavy load, slow velocity training. Accordingly, these data provide tentative evidence to suggest that coaches should limit resistance training that emphasises maximal strength development in the 2 d following a game.

No shift in the angle of peak torque was observed in either the quadriceps or hamstring muscle groups, suggesting that the RLMSP may not have been severe enough to cause sufficient structural damage for a change in the angle of peak torque to be detected. Indeed previous studies that have reported a shift in the angle of peak torque have tended to use high intensity eccentric exercise protocols (Brockett et al., 2001; Byrne et al., 2001) that have resulted in greater losses in force and much higher CK responses than observed in this study. Furthermore, although it was not possible to utilise elite level players in this study due to the reluctance of such populations to deviate from their normal training regimes, the participants utilised herein were regularly participating in exercise that required repeated eccentric actions whilst decelerating, sprinting, kicking and lunging. Therefore, it is possible that the familiarity of the participants to the movement patterns of exercise in the current study resulted in them being less susceptible to damage because of the protective effect associated with being accustomed to performing prior bouts of the mode of exercise (Nosaka and Clarkson, 1995; McHugh, 2003).

Both CMJ and SJ were reduced for 1 d following the RLMSP which is similar to the observed reductions in peak rate of force development (McLellan et al., 2011b), peak power (McLellan et al., 2011b), peak force (McLellan et al., 2011b) and flight time (McLean et al., 2010) during CMJs for 1 d following competitive rugby league matches. In contrast to the findings in this study, CMJ jump height has been reported to be lower than baseline for up to ~3 d (69-72 h) following competitive (Andersson et al., 2008; Magalhães et al., 2010) and simulated soccer matches (Magalhães et al., 2010) and similarly, SJ height is impaired for at least 2 d (Bailey et al., 2007) following a simulated soccer match. It is likely that the greater overall, high and very high intensity running distances covered in soccer compared to the RLMSP and rugby league matches result in a slower rate of recovery following competitive and simulated soccer matches. Interestingly, in the current study there were no differences observed in the time course of recovery between SJ and CMJ. These observations are in contrast to observations that SJ are impaired to a greater degree than CMJ following resistance training (Byrne and Eston, 2002; Harrison and Gaffney, 2004). It is possible that the reduction in muscle function in the current study following a more ecologically valid exercise stimulus has less of an effect on the excitation contraction coupling mechanism than high volume resistance training.

The collective reductions in neuromuscular performance following the RLMSP are consistent with the characteristics of low-frequency fatigue (LFF; Jones, 1996; Nielson et al., 2005) caused by tissue damage evoked by active lengthening of skeletal muscle during high intensity activity (i.e. accelerating and decelerating). LFF is caused by a reduction in calcium release per action potential leading to impairment of excitation-contraction coupling, and has been shown to be involved in reducing vertical jump performance 1 d following muscle-damaging exercise (Skurvydas et al., 2000). Alternatively, a reduced motor output at 1 d after the RLMSP might also be explained by an impaired central drive, stimulated by the increases in muscle soreness and perceived fatigue (see below). Indeed, Prasartwuth et al. (2005) identified that the effects of muscle soreness on central drive were significant for up to 1 d following muscle-damaging exercise, and thereafter any reduction in voluntary activation was a consequence of disruption to calcium homeostasis and impaired excitation-contraction coupling.

The observations in the current study that muscle soreness in the hamstrings and quadriceps were increased for up to 2 d following the RLMSP is similar to findings in lower body soreness following female competitive soccer (Andersson et al., 2008) and rugby league (McLean et al., 2010) matches, but not as prolonged (3 d) as following male competitive (Magalhães et al., 2010) and simulated (Magalhães et al., 2010; Thompson et al., 1999, 2001) soccer matches.

Although participants in the current study only reported muscle soreness to be significantly higher in the hamstrings and quadriceps for 2 d following the RLMSP, the perception of effort during the intermittent running protocol was increased at 1, 2 and 3 d following the RLMSP despite no change in HR. These findings are similar to those of Twist and Eston (2009) and Davies et al. (2009) who, in the presence of increased muscle soreness, reported an increase in perceived effort without any alterations in the physiological responses during fixed intensity exercise. Whilst it is likely that the perception of effort during the intermittent run is in part moderated by the muscle soreness of the quadriceps and hamstrings, the disparity in the time course of recovery between RPE and perceived muscle soreness provides further evidence that muscle soreness following the RLMSP may not be confined to these muscle groups. Given that a soccer-specific simulation protocol has been reported to induce whole-body muscle soreness (Thompson et al., 1999) and that the RLMSP incorporates a greater degree of upper body muscle actions as a result of performing the simulated contact, it is not surprising that muscle soreness may not be confined to the hamstring and quadriceps muscle groups. From an applied perspective, an increase in perceived intensity of exercise in the 3 d following a rugby league match might have implications for the quality of the training performed by players and their limit of exercise tolerance (Marcora, 2008), particularly when asking them to self regulate their training intensity. However, given that there is no evidence from the findings of the current study to suggest that players are at an increased risk of hamstring or quadricep injury in the days following the RLMSP, it would be interesting to investigate whether despite higher perceived effort, players are capable of performing high intensity metabolic training when performing running at a specified velocity. In addition, the type of metabolic training may also determine players' perceptions of effort. Nevertheless, the use of RPE during standardised warm-ups or during fixed load recovery sessions incorporating intermittent running may provide a useful marker of EIMD and the state of recovery following competition.

6.6 Conclusions

Peak decrements in vertical jump height and increases in perceived muscle soreness and CK concentrations were observed 1 d following the RLMSP. Whilst the RLMSP resulted in a peak increase in circulating CK at 1 d following the RLMSP, values were lower and returned to baseline faster than those reported following competitive rugby league matches. The lower CK concentrations observed in the current study compared to those reported in competitive matches suggests that tissue damage measured after a competitive rugby league match might be exacerbated by physical contact.

The current study provides strong evidence of EIMD following the RLMSP and therefore, given the repeatability of the movement demands and physiological responses from the RLMSP (Study Three), it could be used as a research tool to monitor the effectiveness of different recovery interventions on perceived muscle soreness and muscle function following game-related exercise. Moreover, on the basis of the findings of this study, research should focus on monitoring the effectiveness of recovery interventions in the 2 d following the RLMSP.

A limitation to the current protocol is the fact that the RLSMP does not account for the variation in movement demands between positions and it might be that a player will recover differently following a game depending on the positional requirements imposed on them. However, while future studies should investigate the effects of positional demands on symptoms of EIMD, the findings of this study provide useful information on the recovery of players following participation in exercise that broadly replicates the movement demands of an entire rugby league game (Study Three).

CHAPTER 7

CONCLUSIONS

7.1 Synthesis of main findings

7.1.1 Position-specific movement demands and performance decrements during senior elite rugby league matches

Study One revealed that the mean match length was 86.8 ± 1.6 min, of which the outside backs played virtually the entire match (79.9 min) whilst the props, the pivots and the back row players played 52.7, 71.7 and 72.2 min, respectively (Study Two). These position-related participation levels corroborate those reported by King et al. (2009). Whilst the 54.8 min mean ball in play time observed in Study One exceeded that calculated by Eaves et al. (2008; 44.4 min), the 40 s mean set time was similar to theirs (36 s).

Independent of position, the results of Study One showed that ball in play (1:6.9 for all players) work-to-rest ratios (WRRs) were significantly higher than stoppage (1:87.4) WRRs. Whilst mean total distance (TD) covered over the duration of the match was 8,503 m, the overall ball in play locomotive rate equated to 120.7 $m \cdot min^{-1}$ (Study One). In addition, when in possession players displayed a more intermittent profile than when defending, with more time spent in high speed running (HSR) and sprinting but with a greater percentage of the recovery time spent standing and walking (as opposed to jogging) than when defending. Whilst outside backs performed more HSR and sprinting than props, and more sprinting than pivots and props, props and back row players were involved in contact situations more so than pivots and outside backs (Study One). Moreover, players performed 121 ± 27 high intensity running bouts (Study Two). Outside backs performed a significantly greater frequency of discrete bouts of high intensity running of 10.1-20.0 m distance than props and 20.1-30.0 m distance than props and pivots, possibly as a result of greater time on the pitch. However, there was no significant difference in the maximum distance covered during discrete high intensity running bouts between positions, with mean values being 56, 54, 48 and 53 m for outside backs, pivots, props and back row players, respectively. Furthermore, tackle (0.27 ± 0.13 $n \cdot min^{-1}$) and hit-up rates (0.17 ± 0.07 $n \cdot min^{-1}$) were similar to those described for Australian senior elite rugby league players (tackles: 0.25 ± 0.16; hit-ups: 0.12 ± 0.07 $n \cdot min^{-1}$) by Sirotic et al. (2009).

Although the mean overall locomotive rate (all players) was only 4.9% lower in the final quarter of a game compared to the first and there were no changes in tackle or hit-up rates, mean high and very high intensity running locomotive rates were 30.5 and 46.8% lower, respectively. In addition, the data from Study Two reveals a mean increase of 2.8% in low intensity running locomotive rate (all players) in the final quarter of competitive games when compared to the first. Outside backs, pivots and props all showed a significant reduction in high and very high intensity running locomotive rates during the final quarter compared to the first. In addition, outside backs and back row players had a significantly lower high intensity running locomotive rate in the second quarter compared to the first. The trend for a reduction in high and very high intensity running locomotive rates during the second and final quarters of a game compared to the first suggests the occurrence of either a distinct change in tactics or the onset of fatigue.

7.1.2 Development of an ecologically valid and reliable match simulation protocol

The rugby league match simulation protocol (RLMSP) described in Study Three is an intermittent protocol that contains two parts; Part A replicated the movement demands of when the ball is in play during competitive rugby league matches (cumulative total time of 53.9 min), and Part B replicated the movement demands during stoppages. Findings in Study Three indicated that total distance covered in the RLMSP was similar to that observed in competitive matches (Study One). Moreover, the percentage of total time (%TT) for standing, walking, jogging, running, high speed running (HSR), sprinting and contact in the RLMSP was similar to that spent in these locomotive categories during matches for both the ball in and out of play phases (Study One). The RLMSP appears to result in a greater very high intensity running locomotive rate and mean WRR during part A and B than during competitive matches (Study One). This is alongside the mean heart rate (HR) during the RLMSP being lower than that reported by Coutts et al. (2003) during competitive rugby league matches (80.6 vs. 84.3% HR_{max}), which might be attributed to emotional stress that is associated with competitive games. However, the reduction in very high and high intensity running locomotive rates and increase in low intensity running locomotive rate from quarter one to quarter four of the RLMSP are still apparent, albeit to a lesser extent than was observed in competitive matches (Study Two). Finally, the due to the greater proximity of fluids and higher fluid intakes, reductions in body mass (BM) reported immediately following the RLMSP were lower than those values reported following competitive rugby league matches (O'Hara et al., 2010).

Nevertheless, from the perspective of reliability, findings from Study Three revealed coefficient of variation (CoV) values of 4.2, 10.6 and 2.1% for high and very high intensity running locomotive rates and mean (or summated) peak sprint velocity, respectively. Furthermore, given the low typical error (TE) for high (1.3 $m \cdot min^{-1}$) and very high (1.6 $m \cdot min^{-1}$) intensity running locomotive rates and mean reduction from the first to last quarter of the RLMSP in high (2.0 $m \cdot min^{-1}$) and very high (3.2 $m \cdot min^{-1}$) intensity running locomotive rates, the RLMSP appears sensitive to changes in physical performance across the course of the protocol.

With the exception of creatine kinase (CK), which was lower and recovered faster following the RLMSP, the rate and magnitude of recovery from the RLMSP was similar to that observed following competitive games (McLean et al., 2010; McLellan et al. 2010; 2011a, 2011b). Indeed, the RLMSP resulted in similar decrements in countermovement jump (CMJ) height and increases in perceived muscle soreness as has been reported following competitive rugby league matches, with peak changes observed 1 d following both the RLMSP and competitive matches (McLean et al., 2010; McLellan et al. 2011b). In addition, isokinetic peak torque was observed to be lower than baseline at 1-2 d following the simulation protocol at a slow but not fast angular velocity. Whilst this reduction was similar in magnitude to that observed following competitive soccer matches, changes in muscle function using isokinetic dynamometry has yet to be studied following competitive rugby league matches.

7.2 Limitations and future directions

7.2.1 Participant training status

Based upon the findings of Studies One and Two, the RLMSP was designed to replicate the movement demands of senior elite rugby league matches. However, in developing and evaluating the protocol (Studies Three and Four) it was not possible to utilise elite level players due to the frequent changes in personnel within the professional sport club and the reluctance of professional players to change their routines. Consequently, the recovery observed from the RLMSP in this thesis may be more representative of the post-game recovery of players following an enforced break from competition, for example, during the early phase of the season or when a player returns following injury when players are less well conditioned.

Whilst the ideal would be to collect data using elite participants, I would advise researchers engaging in applied research to approach the situation with realistic expectations of the commitment that professional players are able to provide. That is not to say that applied research should be discouraged, but that the planning of such research requires substantial thought and the feasibility of collecting the research data must be rigorously assessed.

7.2.2 Contact during the rugby league match simulation protocol

The procedure adopted to simulate the contact situation during the RLMSP was selected to minimise the risk of injuries from physical collisions (Gabbett, 2004) and to control the intensity at which contact was performed. However, the lower CK values observed in the days following the RLMSP in Study Four compared to those in competitive rugby league (McLellan et al., 2010; 2011a, 2011b) and union (Takarada, 2003; Cunniffe et al., 2010) games indicates that the collision scenario during the RLMSP may not be as physically demanding as that experienced by players during actual match play. However, it is also likely that the higher CK values reported before and following competitive rugby league matches (McLellan et al., 2010, 2011a, 2011b) are as a result of cumulative muscle damage from training as well as matches. In order provide a truer contact situation during the RLMSP that more closely replicates the impact experienced during a competitive game, future studies should consider the introduction of actual contact apparatus within the protocol. Such actions might involve hitting and driving back a bespoke ‘contact sled’ (Figure 7.1) which is essentially a foam filled tackle pad attached to the front of a ‘push sled’, and have been used in other sports such as American Football to condition players in contact situations (Hoffman and Hamilton, 2002). This modification would also permit investigation of the suggestion that CK concentrations reflect the blunt trauma from physical impacts as well as EIMD from eccentric muscle actions to compare symptoms of EIMD following the RLMSP (Study Four). It is hypothesised that higher CK values, together with greater muscle soreness will be observed in the days following the adapted version of the RLMSP compared to performing the RLMSP without physical contact, despite no change in the movement demands.

Figure 7.1 The bespoke 'contact sled' designed for simulating contact

7.2.3 Use of semi-automated image recognition tracking systems in matches and non-differential global positioning system in the rugby league match simulation protocol

Whilst the initial proposal of the thesis was to collect data from senior elite players both during a competitive rugby league match and the RLMSP using NdGPS in order to validate the movement demands and physiological responses of the protocol, concerns by the national governing body over the safety of using NdGPS in matches prevented this from being possible. Therefore, some of the differences observed between the movement demands of senior elite matches (Study One) and the RLMSP (Study Three) are likely to be as a result of differences between the NdGPS and the SAIR tracking systems used to quantify the movement demands of the simulation protocol and match, respectively. Indeed, comparing the movement demands reported from a 25 Hz SAIR tracking system (Amisco Pro®, version 1.0.2, Nice, France) with those from a 5 (Minimax X, Catapult, Melbourne, Australia) and 1 Hz (SPI Elite, GPSports, Canberra, Australia) NdGPS, Randers et al. (2010) reported that both NdGPS units systematically underestimated HSR and sprinting (24-39%) in comparison to the SAIR tracking system. However, given that there are differences in the accuracy of NdGPS units from different companies (Petersen et al., 2010), that there are probable disparities between SAIR tracking systems from different companies, and that neither of the systems used in the current thesis were compared by Randers et al. (2010) it is not possible to quantify the level of agreement between the two time-motion analysis (TMA) systems used in this thesis.

Recently, the national governing body has given the go-ahead to use NdGPS in matches and as a consequence studies have reported using NdGPS in competitive rugby league matches (McLellan et al., 2010, 2011a, 2001c). Looking forward, it may be possible to revisit the initial proposal to validate the movement and physiological demands of the protocol with those observed during matches. In addition, it would be useful to assess whether the performance variables in the RLMSP differentiate between players of different abilities.

7.3 Applied applications

7.3.1 Training specificity

Collectively, the findings presented in Studies One and Two, provide information that can be extrapolated to an applied setting in order to inform players' conditioning programmes. Firstly, the findings suggest that basing training on the overall match demands might under-prepare players for the most intense periods of the match. Therefore, training designed to replicate the movement demands of competitive matches should look to simulate the ball in play movement demands as they represent the most intense periods of the match. Furthermore, sprint and high intensity interval training should be performed over distances of up to 57.5 m for outside backs, 55 m for pivots and back row players and 50 m for props in order to prepare them for the ‘worst case scenarios’ observed in competitive matches. The findings also suggest that player conditioning programmes should emphasise preventing the decline in high and very high intensity running locomotive rates as this is likely to improve attacking performance through providing greater support to the ball carrier and more decoy runners throughout a game. Furthermore, where coaches have access to NdGPS, locomotive rates may be a more effective means of comparing training activities to match demands.

7.3.2 Training prescription in the days following matches

The reduction in isokinetic peak torque of the knee flexors and extensors at a slow angular velocity following the RLMSP (Study Four) provides evidence that coaches should limit maximal strength training in the lower body for up to 2 d following a game. Moreover, an increase in perceived intensity of exercise for up to 3 d following the RLMSP might have implications for the quality of metabolic training performed by players and their limit of exercise tolerance (Marcora, 2008), particularly when asking them to self regulate their training intensity.

7.3.3 Match tactics

Given that with the exception of outside backs, defending was more demanding than attacking, retaining possession may be important to minimise fatigue during matches. Therefore, the number of set completions and forced repeat defensive sets may be important key performance indicators for coaches. Percentage of time in possession may also have implications for the way in which coaches use their interchanges, with more interchanges of outside backs when retaining possession for long periods of play.

7.3.4 Research tool for assessing the effectiveness of recovery interventions

Taking into account the effect that time in possession and stoppage lengths have on high and very high intensity running locomotive rates and time in contact, it is likely that the rate of recovery following matches is highly variable. In addition, it is difficult to isolate and study the effectiveness of recovery interventions in an applied context due to players' being unwilling to abstain from recovery strategies through fear that they will not adequately recover ahead of future training and fixtures. Therefore, monitoring the effectiveness of recovery interventions cannot effectively be researched following actual match play. Whilst previous research has investigated the effects of cryotherapy (Bailey et al., 2007), active recovery (Andersson et al., 2008) and nutritional supplements (Kingsley et al., 2005; Thompson et al., 2001) on recovery from simulated or competitive soccer matches, the game of rugby league (and thus the recovery also) is distinct from other PMSTS such as soccer. Therefore, the application of research from soccer-specific match simulation protocols may not be transferable to rugby league players as is evidenced by the quicker neuromuscular recovery following the RLMSP and competitive rugby league matches (McLean et al., 2010; McLellan et al., 2011b) compared to simulated (Magalhães et al., 2010; Thompson et al., 2001) and competitive (Ascnsão et al., 2008; Magalhães et al., 2010) soccer matches.

As the RLMSP is capable of inducing symptoms of EIMD similar to those observed following competitive rugby league matches (Study Four) and demonstrates reliable movement demands and physiological responses (Study Three), the protocol provides a controlled procedure for investigating the utility of commonly used recovery strategies (e.g. compression garments or nutritional supplements) on recovery following match-related exercise specific to rugby league.

7.4 Summary

Thus, the RLMSP was devised to replicate the overall movement demands and intra-match fatigue observed during senior elite rugby league matches. Not only was there a low level of variability in the movement demands during the RLMSP over consecutive trials, but with the exception of creatine kinase, the rate and magnitude of recovery following the RLMSP was similar to that that has been published following competitive matches. Therefore, the RLMSP devised in this thesis may be a more appropriate research tool for assessing the effectiveness of recovery interventions following match related exercise than following actual match play.

CHAPTER 8

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CHAPTER 9

APPENDICES

APPENDIX 1

AGREEMENT WITH PROZONE LTD

Mr Shayne Hall
ProZone Group Limited
3 Craven Court
Beeston
Leeds LS11 8BN

Mr Dave Sykes
Department of Sport and Exercise Sciences
University of Chester
Parkgate Road
Chester CH1 4BJ

Date: 17/07/07

Dear Shayne

I write in response to your letter dated 5 June and agree as follows in consideration of ProZone releasing the data referred to ('the Confidential Information') for use in my research project:

1. I shall keep the Confidential Information secret and confidential and shall not use or disclose the same except as envisaged below and for the purpose of obtaining supervision from employees or agents of the University of Chester in respect of my research project.

2. I may publish the Confidential Information in a thesis, dissertation, assignment or other work arising out of or based on my research project, and if so I undertake to ensure that any material relating to any named individual, sports team or other organisation is published in such form as not to identify that individual, sports team or other organisation. The material in the thesis, dissertation, assignment or other work may be disclosed in confidence to any examiner appointed by the University of Chester and may be deposited in a library or electronic storage repository of the University of Chester in accordance with the University's relevant procedures.

3. Before I publish or disclose the Confidential Information in accordance with the above, I shall seek ProZone's written consent to do so. ProZone agrees not unreasonably to withhold its consent to publication or disclosure and pending such consent I will maintain confidentiality. ProZone agrees to respond to a written request for consent within 30 days of receipt thereof.

Yours sincerely,

Dave Sykes
Postgraduate Researcher – University of Chester

If you agree the above, please sign and return the enclosed copy of this letter.

On behalf of ProZone Group Limited

Shayne Hall
Rugby Operations Manager

Contact: **Shayne Hall**
Email: shayne.hall@prozonesports.com
Tel: 0113 2135011
Mob: 0798 4423671

ProZone Group Ltd
3 Craven Court
Millshaw
Leeds
LS11 8BN
United Kingdom
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Tel: 0113 244 9296
Fax: 0113 243 4205

5 June 2007
Version 1

To whom it may concern

I am writing with reference to the data being released by ProZone for use in research project by Dave Sykes.

I can confirm that all data being released is 100% owned by ProZone and is not contracted to any other party. However to keep in line with our companies stringent policy on security and confidentiality, all player and team specific data will be desensitised.

As I'm sure you can appreciate the information being provided is of the up-most sensitivity and hence a player will only be defined by their position and team name by home or away.

Any further questions on this matter don't hesitate to contact me.

Yours faithfully
On behalf of ProZone Group Limited

Shayne Hall
Rugby Operations Manager

APPENDIX 2

ETHICAL APPROVAL

(Study One and Two)

University of Chester

Centre for Exercise and Nutrition Science

Reader and Research Co-ordinator
Dr Stephen Fallows
BSc, PhD
Direct Line 01244 513407
Fax 01244 511310
s.fallows@chester.ac.uk

Dave Sykes
PhD Student
Department of Sport & Exercise Sciences
Room COP001, Old Pavilion
University of Chester

16 October 2007

Dear Dave

Study title: **Time-motion analysis of elite rugby league**
FREC reference: **161/07/DS/SES**
Version number: **2**

Thank you for sending the above-named application to the Faculty of Applied and Health Sciences' Research Ethics Committee for review.

The application has been considered on behalf of the Committee by Mike Morris as Lead Reviewer and reported to the Faculty's Research Ethics Committee.

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form and supporting documentation.

This approval is given provided that you comply with the conditions set out in the attached document. You are advised to study the conditions carefully.

The final list of documents reviewed and approved by the Committee is as follows:

Document	Version	Date
Application Form	1	May 2007
Statement from ProZone Group Ltd	1	June 2007
Disclosure Agreement between ProZone and University of Chester	1	July 2007

With the Committee's best wishes for the success of this project.

Yours sincerely,

Dr. Stephen Fallows
Chair, Faculty Research Ethics Committee

Enclosures *Standard conditions of approval*

c.c. Supervisor
FREC Representative

APPENDIX 3

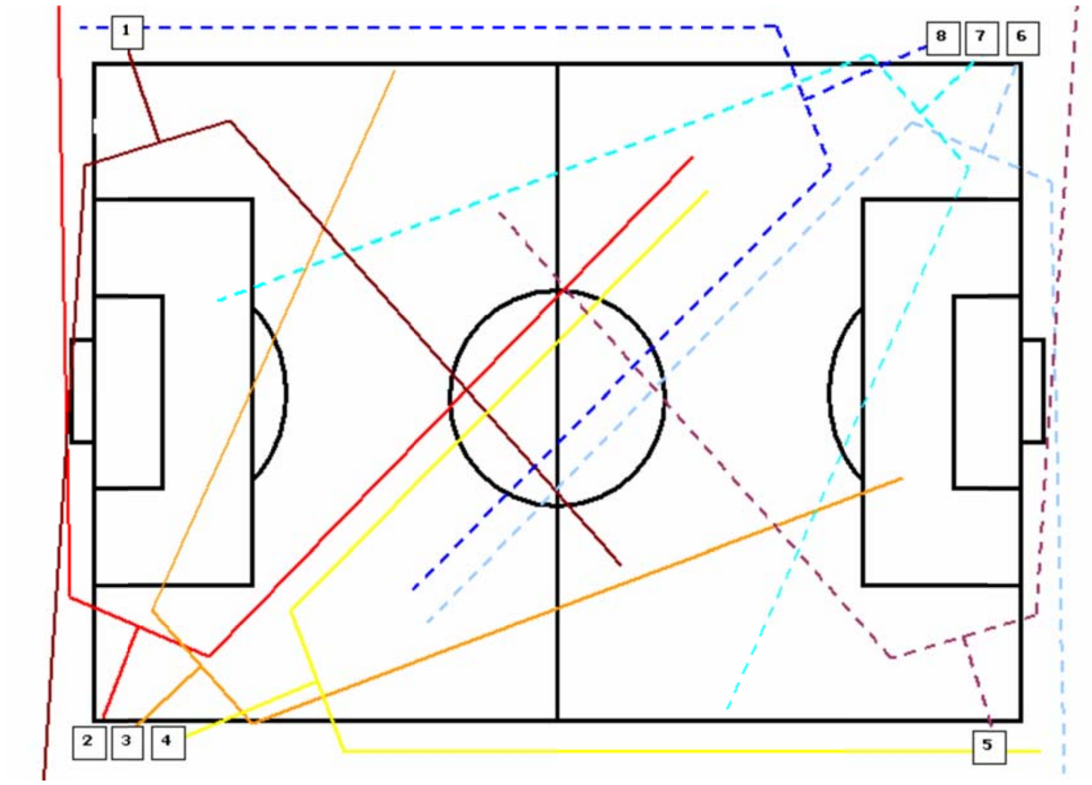

Figure from Di Salvo et al. (2006), p. 111

Figure depicting the placement and field of view of eight fixed cameras for collection of video footage from competitive matches using a semi-automated image recognition (SAIR) tracking system (ProZone 3, ProZone®, Leeds, England).

APPENDIX 4

ETHICAL APPROVAL

(Study Three and Four)

University of Chester

Faculty of Applied and Health Sciences

Research Ethics Committee

Direct Line 01244 511740
Fax 01244 511302
j.hitchcock@chester.ac.uk

Dave Sykes
Department of Sport and Exercise Sciences
5th Floor, Price Tower
University of Chester
Parkgate Road
Chester
CH1 4BJ

25th August 2009

Dear Dave,

Study title: Assessment of the reliability of a rugby league match simulation protocol and its effects on perceived muscle soreness, muscle function and perceived exertion.
FREC reference: 352/09/DS/SES
Version number: 1

Thank you for sending the above-named application to the Faculty of Applied and Health Sciences Research Ethics Committee for review.

The application has been considered by the Faculty Research Ethics Committee.

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form and supporting documentation.

The favourable opinion is given provided that you comply with the conditions set out in the attached document. You are advised to study the conditions carefully.

The final list of documents reviewed and approved by the Committee is as follows:

Document	Version	Date
Response to the Committee	1	August 2009
Consent Form	2	August 2009
Participant Information	2	August 2009

With the Committee's best wishes for the success of this project.

Yours sincerely,

pp.

Mohammed Saeed
Chair, Faculty Research Ethics Committee

Enclosures *Standard conditions of approval.*

c.c. Supervisor
FREC Representative

APPENDIX 5

PARTICIPANT INFORMATION SHEET
(Study Three and Four)

Assessment of the reliability of a rugby league match simulation protocol and its affects on perceived muscle soreness, muscle function and perceived exertion

You are being invited to take part in a research study. Before you decide whether or not to participate, it is important for you to understand why the research is being conducted and what it will involve. Please take the time to read the following information carefully and discuss it with others if you wish. If there is anything you are unsure about please ask for further clarification. Take time to decide whether or not you wish to participate.

Thank you for reading this.

What is the purpose of the study?

This study is being conducted as part of a PhD in Sport and Exercise Sciences which aims to examine the reliability of a rugby league match simulation protocol and to determine the effect of the protocol on the magnitude and rate of recovery of muscular function, perception of effort and perceived muscle soreness.

Why have I been chosen?

The study is seeking to investigate the above response in healthy, male competitive team sports players (18-30 years).

Do I have to take part?

It is entirely up to you to decide whether or not to take part. If you decide to take part you will be asked to sign a consent form giving your permission to participate. If you decide to take part you are still free to withdraw at any time without giving a reason.

What will taking part involve?

Four days prior to testing you will be asked to attend the laboratory to familiarise yourself with the procedures that will be used, these are described below.

Prior to commencing exercise you will be asked to have a capillary (finger prick) blood sample taken to measure your resting level of creatine kinase as a marker of muscle damage. Following this, your lower body strength and power will be measured by performing a squat and countermovement jump for maximal vertical height and using a specific piece of apparatus which will involve you performing maximal contractions of the quadricep and hamstring muscles at different speeds in a seated position. You will then be asked to indicate your perceived exertion in response to a fixed-load intermittent run of 4 minutes in duration. These measurements will provide a baseline against which to compare the effect of the match simulation protocol.

Following approximately a 15 min break, you will be required to carry out a multi-stage fitness test (i.e. bleep test) which involves running at incremental speeds between two lines 20 metres apart until exhaustion. This will provide a measure of your aerobic fitness. Finally, having been given time to recover from the bleep test you will be asked to perform 2 cycles of the rugby league match simulation protocol (~ 4 min) to familiarise you with the running speeds in the protocol.

On the day of the first main trial you will be asked to attend the laboratory at approximately 9 am in the morning. Following a 10 min warm-up you will then be asked to perform the rugby league match simulation protocol. The simulation protocol itself lasts 95 min 20 s in total inclusive of a 10 min rest interval after 42 min 20 s to simulate half-time. It comprises forty identical 2 min 8 s cycles which involve standing, walking, jogging and all-out sprinting in a manor designed to replicate the physiological and movement demands of a senior elite rugby league match.

After 24 hours rest you will be asked to return to the laboratory to re-measure your creatine kinase concentration, vertical jumps for maximal height, the strength of your upper-leg muscles, and your perception of effort in response to the 4 min fixed-load intermittent run. You will also be asked to provide a perceived rating of muscle soreness, measured by you bending at the knees and moving a pointer along a sliding scale to indicate discomfort. These procedures will then be repeated at 48, 72 and 168 hours (2, 3 and 7 days, respectively) after completing the simulation protocol.

Finally, following nine days recovery from the simulation protocol, you will be asked to return to the laboratory to perform the simulation protocol for a second time. The purpose of this is to establish the reproducibility of the physiological and movement demands of the simulation protocol.

You will be asked to abstain from exercise, nutritional supplements, non-steroidal anti-inflammatory drugs, therapeutic modalities (e.g. massages) and hydrotherapies (e.g. ice baths and Jacuzzis) for 3 days prior to the first session until completion of the study. Furthermore, on the 2 days prior to performing the simulation protocol for the first time and on the morning of the trial, you will be asked to complete a food diary detailing the type and amount of food and drink ingested. You will then be asked to replicate this diet in the two days prior to repeating the simulation protocol.

What are the possible disadvantages and risks of taking part?

It is likely that you may experience a short bout of muscle soreness, a decreased range of motion, swelling and stiffness in the upper leg muscles. This is likely to be most evident approximately two days following the simulation protocol, after which all symptoms will subside within approximately seven days with no lasting effects.

It is important that participants attend all laboratory and exercise sessions. This is a significant commitment for participants and will involve approximately 12 hours of your time in total.

What are the possible benefits of taking part?

By taking part, you will be enabling researchers to gain a greater understanding of the effects of a rugby league match on the rate and recovery of muscular function, perception of effort and perceived soreness. Subsequently, this will inform the manor in which training between games is constructed to optimise training adaptations, recovery and minimise injury susceptibility. Additionally, you will gain useful information about your physiological fitness, which may be useful for training purposes. A bout of muscle-damaging exercise will also provide a protective effect and reduce the occurrence of symptoms following a repeat of similar exercise in the future.

What if something goes wrong?

If you wish to complain or have any concerns about any aspect of the way you have been approached or treated during the course of this study, please contact Professor Sarah Andrew, Dean of the Faculty of Applied and Health Sciences, University of Chester, Parkgate Road, Chester, CH1 4BJ, 01244 513055.

If you are harmed by taking part in this project, there are no special compensation arrangements. If you are harmed due to someone's negligence (but not otherwise), then you may have grounds for legal action but you may have to pay for legal aid.

Will my taking part in the study be kept confidential?

All information that is collected about you during the course of this study will be kept strictly confidential so that only the researchers carrying out the research project will have access to such information. Furthermore, data used for publication purposes will be anonymised so that readers can not identify specific participants.

What will happen to the results of the research study?

Results of this project may be published but any data included will in no way be linked to any specific participant. You are, however, welcome to request a copy of your personal results should you wish. The data collected will be securely stored in such a way that only the researchers involved in the study will be able to gain access to it.

Who is organising and funding the research?

The Department of Sport and Exercise Sciences at the University of Chester along with Warrington Wolves Rugby League Football Club are responsibility for jointly organising and funding this study.

Who may I contact for further information?

If you have any questions about the project, either now or in the future, please feel free to contact Dave Sykes via the Department of Sports and Exercise Sciences, Tel:

Thank you for your interest in this research.

APPENDIX 6

CONSENT FORM
(Study Three and Four)

Assessment of the reliability of a rugby league match simulation protocol and its affects on perceived muscle soreness, muscle function and perceived exertion

I have read and understand the information pertaining to the above study. Furthermore, all my questions have been answered to my satisfaction and I understand that I am free to ask for further information at any stage.

I am aware that:

1. My participation in the above study is entirely voluntary
2. I am free to withdraw from the study at any stage without giving any reason and without any prejudice incurred
3. The results of this project may be published but my anonymity will be preserved
4. In the unlikely event of any grievances I understand that I may forward any complaints about the research process to Professor Sarah Andrew, Dean of the Faculty of Applied and Health Sciences, University of Chester, Parkgate Road, Chester, CH1 4BJ, 01244 513055.

I agree to take part in the above study.

……………………………..	**……………………………**	**…../…../……**
(Name of Participant)	**(Signature of Participant)**	**(Date)**
……………………………..	**……………………………**	**…../…../……**
(Name of Lead Researcher)	**(Signature of Lead Researcher)**	**(Date)**

APPENDIX 7

PRE-PARTICIPATION HEALTH QUESTIONNAIRE

(Study Three and Four)

(PLEASE NOTE THAT THIS INFORMATION WILL BE CONFIDENTIAL)

Name:……………………………. **DOB:**…………….. **Age:**…………

Research Study Title: Assessment of the reliability of a rugby league match simulation protocol

Please answer these questions truthfully and completely. The purpose of this questionnaire is to ensure that you are fit and healthy enough to participate in this laboratory practical/research project.

	Yes	**No**
1. Have you in the past suffered from a serious illness or accident. If Yes, please provide details	☐	☐

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……………………………………………………………………………………………
………

	Yes	**No**
2. Have you consulted your doctor the last 6 months If Yes, please provide details	☐	☐

……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………
………

3. Do you suffer, or have you suffered from:

	Yes	**No**
Asthma	☐	☐
Diabetes	☐	☐
Bronchitis	☐	☐
Epilepsy	☐	☐
High blood pressure	☐	☐

	Yes	**No**
4. Is there any history of heart disease in your family	☐	☐

	Yes	**No**
5. Are you suffering from any infectious skin diseases, sores, wounds, or blood infections i.e., Hepatitis B, HIV, etc.?	☐	☐

If Yes, please provide brief details

………………………………………………………………………………………………
………………………………………………………………………………………………
………………………………………………………………………………………………
………

		Yes	No
6.	Are you currently taking any medication If Yes, please provide details	☐	☐

………………………………………………………………………………………………
………………………………………………………………………………………………
………………………………………………………………………………………………
………

		Yes	No
7.	Are you suffering from a disease that inhibits the sweating process	☐	☐

		Yes	No
8.	Is there anything to your knowledge that may prevent you from participating in the testing that has been outlined to you? If Yes, please provide details	☐	☐

………………………………………………………………………………………………
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Persons will not be permitted to take part in any experimental testing if they:

- have a known history of medical disorders (i.e. hypertension, heart or lung disease)
- have a fever, suffer from fainting or dizzy spells
- are currently unable to train because of a joint or muscle injury
- have had any thermoregulatory disorder
- have a history of infectious diseases (i.e. HIV or Hepatitis B)

My responses to the above questions are true to the best of my knowledge and I am assured that they will be held in the strictest confidence.

Name: (Participant)………………………………………… Date:………………….

Signed: (Participant) ……………………………………….

Name: (Lead Investigator) Dave Sykes Date:………………….

Signed: (Lead Investigator) ………………………………

APPENDIX 8

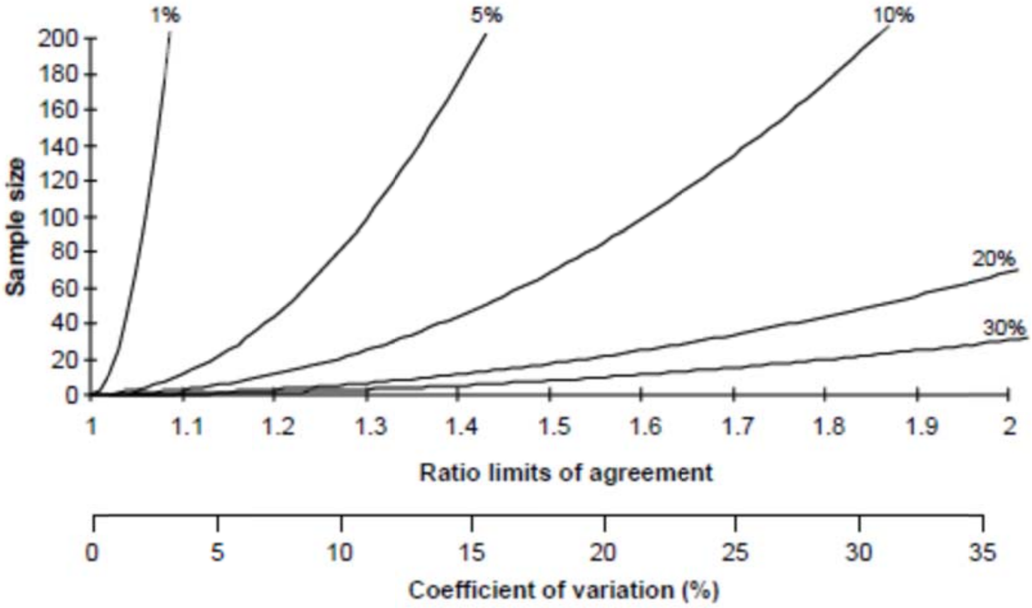

Figure from Batterham and Atkinson (2005), p. 157.

Figure used to estimate the effects of measurement reliability on whether the 'analytical goals' of the variable are attainable or not in research. Statistical power is 90%. The different lines represent different relative worthwhile changes (1, 5, 10, 20 and 30%) due to some hypothetical intervention. The measurement statistics which can be utilised in this nomogram are the ratio limits of agreement (LoA) and the coefficient of variation (CoV). For example, a variable which had a reported CoV of 10% (a typical cut-off for acceptable reliability, Atkinson et al., 199; Stokes, 1985) would require ~25 participants to allow detection of a 10% change.