SPRINT DECREMENT IN A SIMULATED RUGBY SEVENS TOURNAMENT IS MORE RELATED TO LACTATE THRESHOLD THAN AEROBIC CAPACITY

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ABSTRACT

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Rugby sevens is a sport with diverse physiological demands as aerobic fitness, sprint velocity and contact skills each have a significant impact on performance. Training for speed is an important part of physical preparation, but athletes often are unable to attain peak velocity during match play. Understanding the relationship between aerobic capacity and recovery between individual sprints and games may influence training practices. The purpose of the study was to examine the link between indicators of aerobic fitness and sprint decrements during a simulated rugby sevens tournament to guide training practices.

Eleven female members of the Finnish national rugby sevens team were recruited to the study and underwent aerobic capacity testing in the laboratory. Peak oxygen uptake (VO_{2peak}) and velocity at which lactate begins to accumulate (LT1) and at which lactate levels begin to rise exponentially (LT2) were measured. After two weeks, participants performed a series of maximal sprint tests followed by a simulated rugby sevens tournament over two days. Each game simulation included six sprints, which were recorded using a radar gun. Correlations were examined between VO_{2peak} / lactate thresholds and peak velocity decrements over the course of the tournament.

Velocity at LT2 was positively correlated with overall sprint decrement ($R = 0.763$, $p = <0.01$) and with sprint decrement between the two days of the tournament simulation ($R = 0.740$, $p = <0.01$). No correlations were found between VO_{2peak} and overall sprint decrement or sprint decrement between days of the tournament.

The main finding of the study was that sprint decrements during a simulated rugby sevens tournament are more closely related to LT2 than aerobic capacity. Whilst speed training is an important part of physical preparation, athletes and coaches should also focus on improving LT2. This will increase the likelihood that players can attain peak velocity during matches.

Key words: Rugby sevens, peak oxygen uptake, lactate thresholds, recovery, sprint, repeated sprint ability

ABBREVIATIONS

ATP	adenosine triphosphate
CK	creatine kinase
CMJ	countermovement jump
FAD	flavin adenine dinucleotide
GPS	global positioning system
HR	heart rate
NAD	nicotinamide adenine dinucleotide
LT1	first lactate threshold
LT2	second lactate threshold
PCr	phosphocreatine
RSA	repeated sprint ability
R7SP	rugby sevens simulation protocol
VO_2	volume of oxygen
VO_{2max}	maximum aerobic capacity
VO_{2peak}	peak aerobic capacity
vOBLA	velocity at the onset of blood lactate accumulation
VT2	second ventilatory threshold
vVO_{2max}	velocity at VO_{2max}

CONTENTS

1 INTRODUCTION

Building on the international success of the World Series, rugby sevens became an Olympic sport in 2016. With this recognition has come a flurry of scientific research into the physiological demands of the sport as practitioners seek optimal approaches for performance enhancement and player safety. Advances in wearable technology and video analysis have allowed researchers to quantify the demands of the sport in several categories. Movement data collected by global positioning systems have shown that rugby sevens is an intermittent sprint sport with athletes covering approximately 1 to 2 km in a 14-minute game, with the vast majority at low speeds such as walking or jogging (Ball et al. 2019, Sella et al. 2019). Play is punctuated however, with periods of high intensity running and sprinting as well as high intensity actions such as rucks, tackles and changes of direction. It has been shown that more tackles and carries into contact are performed per minute during rugby sevens than fifteen-a-side rugby Paul et al. (2022) contributing significantly to player load. Recovery between these actions and the ability to maintain maximal outputs over the course of a single rugby sevens game is extremely important in performance.

Rugby sevens follows a unique format as each event is played in a tournament structure with six games over two or three days. Recovery between games and days is therefore key to maintaining performance throughout a tournament weekend and into the final games. Intermittent high intensity actions must be repeated in all games as maximal velocity actions have been shown to be decisive in deciding game outcomes (Misseldine et al. 2021). There is some evidence for an increase in the running demands during games on the second day (Goodale et al. 2017), however there is no clear evidence that there is a physiological decrement in game performance as a tournament progresses. Despite this, creatine kinase (CK) levels have indicated signs of muscle damage in the days following tournament play (Clarke et al. 2019) and self-reported feelings of wellbeing and recovery have been shown to decrease during and after a tournament (Doeven et al. 2019). It is possible that physiological decrements do exist, but the nature of what they are is not yet clear.

The importance of maintaining running performance into the second day of a tournament is clear and therefore it is important to examine processes associated with recovery. Athletes must perform repeated high intensity efforts during each 14-minute game and repeat this several times in a weekend. A link between aerobic fitness and recovery from high intensity intermittent exercise has been proposed with several possible mechanisms identified that generally focus on either the removal of accumulated by-products of exercise or replenishment of substances necessary for energy production (Tomlin and Wenger, 2001). Several studies have explored the link between measures of aerobic fitness and tests of repeated sprint ability (RSA), but a consensus on a relationship remains elusive. Whilst some studies have identified a link between maximum aerobic capacity (VO_{2max}) and RSA (Stanula et al. 2014, Gharbi et al. 2015, Archiza et al. 2020, Jones et al. 2013), others have described a stronger correlation between RSA and lactate or ventilatory thresholds (Baldi et al. 2017, Lowery et al. 2018).

Identification of rugby sevens as a sport with a high aerobic demand (Malone et al. 2020) and the importance of sprint performance for success in games (Misseldine et al. 2021) demonstrates a need to understand the relationship between these variables in rugby sevens. Decrements in sprint performance during game play have been reported in field sports that are similar to rugby sevens (Massard et al. 2018, Al Haddad et al. 2015, Mendez-Villanueva et al. 2011, Misseldine et al. 2021) and coaches will benefit from identifying the source of these decrements to influence training practices.

2 PHYSICAL DEMANDS OF RUGBY SEVENS

Rugby sevens is played in tournament format over two or three days. Athletes compete on full-sized rugby pitches with fewer than half of the players that are in a traditional rugby union game. The larger amount of space available to players leads to higher running speeds and a higher density of game actions (Ross et al. 2013, Suarez-Arrones et al. 2013). Understanding the running demands of a single rugby sevens game enables coaches to plan training loads appropriately. Given the tournament structure of rugby sevens, it is also important to examine the cumulative player load over the course of a tournament and between tournaments. The understanding of game and tournament demands is also important in a research context so that physiological demands can be quantified and loading parameters standardised for study.

Rugby Sevens has a unique set of demands that combine high speeds and accelerations, with collisions and a high aerobic demand. In addition to physical qualities of players, Abe et al. (2020) showed that body composition may have a significant impact on sprint performance in female sprinters. Reductions in fat mass may have a greater impact on sprint performance than increases in muscle mass (Abe et al. 2020). Strength and muscle mass have been shown to play important roles in performance and injury prevention. For example, Gabbett (2016) demonstrated the importance of lower-body strength in protecting against fatigue-induced decrements in tackling performance of male rugby league athletes. Meanwhile, Sella et al. (2019) indicated the importance of momentum in rugby sevens, highlighting the importance of body mass for performance.

An international-level rugby sevens tournament is comprised of five to six matches over the course of two to three days. Tournaments commence with a pool stage of three matches, followed by a knockout phase of quarter-, semi- and finals. In theory, teams will be more evenly matched with their opponents as the tournament progresses, making for more demanding games on day two. Variations in the activity profiles of players have been shown to depend somewhat on the context of the game within the tournament. Players have been shown to run shorter total distances and lower high-speed metres during the second half of games (Goodale et al. 2017, Malone et al. 2020), although these findings have been contested in other studies (Suarez-Arrones et al. 2012). Activity profiles within games have also been found by Goodale et al. (2017) to reflect the outcomes of games, with losses resulting in higher total distances and high-speed running distances. However, tournament day, opponent rank, and margin of winning or losing were shown to only have a trivial impact on activity profiles of players (Goodale et al.2017).

2.1 Quantifying Match Demands in Rugby Sevens

Quantifying match demands in rugby sevens is difficult due to the dynamic nature of play and the range of variables that may impact performances. Determination of player load using global positioning systems (GPS) and heart rate (HR) tracking in match play allows researchers to quantify the exercise intensity and running demands for rugby sevens matches. Several studies (Malone et al. 2020, Suarez-Arrones et al. 2013, Ross et al. 2013) and subsequent meta-analyses (Sella et al. 2019, Ball et al. 2019) have been published, which present quantitative representations of the physiological demands of rugby sevens (Table 1).

The increase in popularity of rugby sevens has coincided with advances in readily available technology to provide real-time feedback from competitive performances. GPS has become a common data collection tool in field and repeated sprint sports, where the speed and frequency at which players travel is used in determining player load and performance (Sella et al. 2019, Ball et al. 2019). This allows researchers to observe distances covered and speeds at which players are travelling during games. Quantifying the actions of players using GPS may be useful in comparing performance variables between games or players. It may also help to examine interventions on match performance.

Heart rate (HR) monitoring has become a common feature in physical performance analysis at all levels of physical activity. Heart rate data can be easily measured and utilised as a tool for estimating exercise intensity in athletes. Field sports utilise these methods extensively at the elite level. Combining HR and GPS data has enabled researchers to model the match running demands of rugby sevens (Sella et al. 2019, Ball et al. 2019). The limitations in these models relate to the dynamic and contact nature of the sport, where high intensity actions are not limited to running. High intensity contact situations such as tackles, rucks and changes of direction contribute to extremely high physical demands (Malone et al. 2020).

TABLE 1: Summary of GPS match data of female rugby sevens athletes. (Sella et al. 2019).

Summary of GPS match data of female rugby sevens athletes.*†‡

	Total distance (m)	Relative distance ($m \cdot min^{-1}$)	Sprints, >5.5 $m \cdot s^{-1}$ (n)	Accelerations, >1.5 $m \cdot s^{-2}$ (n)	Max speed ($m \cdot s^{-1}$)	Distance covered per speed zone							
						<3.5 $m \cdot s^{-1}$	3.5–5.0 $m \cdot s^{-1}$	5.0–5.5 $m \cdot s^{-1}$	>5.5 $m \cdot s^{-1}$	<2.2 $m \cdot s^{-1}$	2.2–4.4 $m \cdot s^{-1}$	4.4–5.5 $m \cdot s^{-1}$	>5.5 $m \cdot s^{-1}$
Competition level													
International	1,623 ± 17	98 ± 12	3.9 ± 1.2	12.4 ± 1.5	7.3 ± 0.4 (741)	1,021 ± 32 m	439 ± 1 m	86 ± 22 m	116 ± 8 m	36 ± 2 $m \cdot min^{-1}$	36 ± 5 $m \cdot min^{-1}$	14 ± 0 $m \cdot min^{-1}$	7 ± 1 $m \cdot min^{-1}$
(no. files)	(296)	(845)	(296)	(279)		(46)	(46)	(46)	(296)	(134)	(134)	(384)	(190)
National	1,363 ± 222	94 ± 4 (192)	1.9 ± 1.4	10.5 ± 3.1 (21)	7.0 ± 0.5 (189)	961 ± 168 m	356 ± 94 m	46 ± 33 m	47 ± 39 m	39 ± 6 $m \cdot min^{-1}$	38 ± 12 $m \cdot min^{-1}$	10 ± 4 $m \cdot min^{-1}$	4 ± 3 $m \cdot min^{-1}$
(no. files)	(21)		(21)			(21)	(21)	(21)	(21)	(78)	(78)	(78)	(78)
ES	4.46^{X}	0.36^{S}	1.65^{L}	1.15^{M}	0.71^{M}	0.62^{M}	1.59^{L}	1.55^{L}	5.52^{X}	-0.76^{M}	-0.24^{S}	2.44^{V}	1.64^{L}
(95% CI)	(3.89 to 5.01)	(0.21 to 0.52)	(1.18 to 2.10)	(0.69 to 1.60)	(0.55 to 0.87)	(0.09 to 1.14)	(0.99 to 2.15)	(0.95 to 2.10)	(4.89 to 6.12)	(−1.04 to −0.47)	(−0.52 to 0.04)	(2.15 to 2.73)	(1.34 to 1.94)

	Total distance (m)	Relative distance ($m \cdot min^{-1}$)	Sprints, > 5.5 $m \cdot s^{-1}$ (n)	Accelerations, > 1.5 $m \cdot s^{-2}$ (n)	Max speed ($m \cdot s^{-1}$)	Distance covered per speed zones				
						4.4–5.5 $m \cdot s^{-1}$	≥5.5 $m \cdot s^{-1}$	<3.5 $m \cdot s^{-1}$	3.5–5.0 $m \cdot s^{-1}$	>5.0 $m \cdot s^{-1}$
Playing position (international level)										
Backs	1,728	88 ± 4	4.5	14.0	7.4 ± 0.3	223 m	133 m	61 ± 7 $m \cdot min^{-1}$	15 ± 5 $m \cdot min^{-1}$	10 ± 4 $m \cdot min^{-1}$
(no. files)	(131)	(122)	(131)	(131)	(253)	(131)	(131)	(103)	(103)	(103)
Forwards	1,422	88 ± 3	2.5	11.0	7.1 ± 0.4	174 m	102 m	61 ± 8 $m \cdot min^{-1}$	18 ± 6 $m \cdot min^{-1}$	9 ± 4 $m \cdot min^{-1}$
(no. files)	(119)	(100)	(119)	(119)	(219)	(119)	(119)	(88)	(88)	(88)
ES (95% CI)	NA	0.00 (−0.26 to 0.26)	NA	NA	0.86^{M} (0.67 to 1.04)	NA	NA	0.00 (−0.28 to 0.28)	-0.55^{S} (−0.83 to −0.26)	0.25^{S} (−0.04 to 0.53)

*GPS = global positioning system; CI = confidence interval; ES = effect size; Max = maximal; NA = data not available.
†Data are presented as mean or mean ± *SD*. Pooled based on number of GPS files analyzed.
‡^{T} = trivial; ^{S} = small; ^{M} = moderate; ^{L} = large; ^{V} = very large; ^{X} = extremely large.

2.1.1 Running Demands

Several studies have reported on the running demands in rugby sevens for both male and female players (Malone et al. 2020, Sella et al. 2019, Ball et al. 2019, Clarke et al. 2015). Further comparisons have been drawn between levels of play, different positions, halves of play, tournament stage and margin of victory (Murray et al. 2015, Goodale et al. 2017, Malone et al. 2020). At international level, Ball et al. (2019), found no significant differences between male and female players in mean total distances covered (1,413m and 1,216m respectively, p= 0.3486) (Ball et al. 2019). This is considerably lower than those found by Sella et al. (2019) for elite female players (1,623m ± 17). The range of total distances covered in games studied for both men and women was 916m - 2,486m, with the highest total distance for female players almost doubling the mean value (2,343m) (Ball et al. 2019). It is of note that none of the studies that examined elite senior international players passed the external validity quality assessments set by the researchers.

Rugby sevens is a repeated sprint sport that requires players to perform several accelerations and changes of direction in a single game. Misseldine et al. (2021) demonstrated the importance of maximum velocity sprints to performance in rugby sevens games and so higher numbers of sprints and accelerations are related to game outcome. Malone et al. (2020) described the importance of high intensity efforts including high intensity running to performance in rugby sevens. One challenge that researchers face is the definition of boundaries used to define running intensity. Several 'zones' are identified in most studies that examine GPS data (Malone et al. 2020, Cunniffe et al. 2009, Sella et al. 2019, Ball et al. 2019), yet no consensus exists on the appropriate definitions of each zone. Cummins et al. (2013) demonstrated the range of different speeds used to define distinct zones both within and between different sports. Further issues arise in relation to the terminology used to identify running intensity. Several studies use terms including 'striding', 'cruising' and 'high speed running' to indicate comparable speed zones.

Common categorisations of running zones for rugby union in research are based on those proposed by Cunniffe et al. (2009) (Figure 1). Sella et al. (2019) found elite female athletes to perform a higher number of sprints and accelerations (3.9 ± 1.2 and 12.4 ± 1.5) per game compared to national level players (1.9 ± 1.4 and 10.5 ± 3.1). Portillo et al. (2014) found similar differences between the number of accelerations and sprints performed by international and national level players, although with higher mean values (Accelerations: International, 24.8 and National, 17.0; Sprints: International, 6.5 and National, 1.6).

Standing and walking: 0–6 $km \cdot h^{-1}$
Jogging: 6–12 $km \cdot h^{-1}$
Cruising: 12–14 $km \cdot h^{-1}$
Striding: 14–18 $km \cdot h^{-1}$
High-intensity running: 18–20 $km \cdot h^{-1}$
Sprinting: >20 $km \cdot h^{-1}$

No. of accelerations over 1.5 $m \cdot s^{-1}$ in 1 s
No. of accelerations over 2.0 $m \cdot s^{-1}$ in 1 s
No. of accelerations over 2.5 $m \cdot s^{-1}$ in 1 s
No. of accelerations over 2.75 $m \cdot s^{-1}$ in 1 s

FIGURE 1. Speed zone categorization used in rugby sevens research (Cunniffe et al. 2009)

The threshold for high intensity running in rugby union of 18 $km \cdot h^{-1}$ (5 $m \cdot s^{-1}$) is widely used as the threshold for both male and female rugby sevens players, although it may not be a valid figure (Cummins et al. 2013). Clarke et al. (2015) challenged the use of 5 $m \cdot s^{-1}$ as an arbitrary threshold in women's rugby sevens as it may not accurately reflect the point at which female athletes commence high-intensity exercise. The use of individualised thresholds is recommended by several authors (Clarke et al. 2015, Abt et al. 2009). The velocity at which the second lactate threshold (LT2) occurs is proposed as a good guide for the commencement of high intensity running (Abt et al. 2009). This provides an impractical solution for application in the field however, and an arbitrary value is required. Clarke et al. (2015) proposed a value of 3.5 $m \cdot s^{-1}$ as a more appropriate threshold for women's rugby sevens.

In field sports it has been found that the number of accelerations is lower than the number of decelerations performed during a match. Only in American football were the number of accelerations found to be higher than the number of decelerations (Harper et al. 2019). The number of decelerations in rugby sevens therefore, may be higher than the number of accelerations presented in elite athletes by Sella et al. (2019) (12.4 ± 1.5). It has been found in soccer players that the effort for decelerations is 65% higher than the mean player load for all match actions, compared to 28% higher for accelerations (Dalen et al. 2016). This indicates that a high amount of player load may be attributed to accelerating and decelerating during games.

2.1.2 Heart Rate and Intensity

Several studies have reported the HR profiles of rugby sevens players and shown that time spent over 80% of maximum HR accounts for over 75% of a match (Suarez-Arronez et al. 2012, Malone et al. 2020, Portillo et al. 2014, Vescovi et al. 2015). Despite completing most of each game at over 80% of maximum HR, players spend a relatively small amount of the game at high intensity running speeds (10.6%, Ball et al. 2019, 6.8 - 12.4% Sella et al. 2019). National level players spend more time at HR > 90% of their maximum (54.6% ± 14.2), compared to international players (36.0% ± 15.2) (Sella et al. 2019). The intermittent high intensity efforts and high HR within games represent a high dependence on both the aerobic and anaerobic systems for performance.

Determining the intensity of activity in rugby sevens presents further challenges when the dynamic nature of play is considered. Malone et al. (2020) describe the data from their study of World Series players as indicative of a game that involves a range of movement patterns beyond linear running and sprinting. Lateral movement, change of direction, tackling and rucking all contribute to high physiological demands in the sport and to elevated HR. A major component of rugby sevens is the contact nature of the sport, which can require high levels of exertion and contribute to the intensity of exercise. Clarke et al. (2015) found that international players are subject to 7300 impacts (±2200) in a 2-day tournament, with 29 ± 11 impacts of greater than 10g. Paul et al. (2022) found that more tackles and carries into contact are performed per minute during rugby sevens than fifteen-a-side rugby. Body composition and strength and power qualities may also have a significant impact on performance within a game.

The dynamic nature of play and the range of high intensity actions that are performed during a rugby sevens game make it challenging to interpret HR data in terms of high-speed running during match play. Several factors other than running intensity impact HR and so it can only be used as an independent measure of overall match intensity rather than specifically related to running demands.

3 ENERGY SYSTEMS AND RECOVERY IN RUGBY SEVENS

The intensity and density of both inter- and intra- tournament structures in rugby sevens places a high premium on the athletes' ability to recover. Intermittent repeated high intensity actions across the course of a 2-day tournament requires players to maintain physical capacity to repeat these actions. Recovery may be sub-divided into three categories. Firstly, the ability to restore the capacity for high intensity outputs within a game (Bishop and Edge, 2006). Secondly, the ability to restore the capacity for high intensity outputs between games and overnight between tournament days (Clarke et al. 2015). Finally, athletes should be able to recover to baseline levels within 5 days when playing tournaments on consecutive weekends (West et al. 2013).

Several factors may impact the ability to recover. The demands of rugby sevens demonstrate that high neuromuscular outputs are required intermittently to execute a range of movement patterns including sprints, accelerations, decelerations, and impacts. In neural terms, parasympathetic activity may contribute to recovery (Flatt et al. 2019). In metabolic terms, repeated replenishment of anaerobic systems capable of delivering high ATP yields over short periods is necessary to ensure sufficient energy is available to drive muscle contractions (Gastin, 2001).

3.1 Recovery In Rugby Sevens Tournaments

Recovery for rugby sevens players must be considered within games, between games and between days. Despite no significant reductions in countermovement jump (CMJ) scores, players have been shown to have increased creatine kinase (CK) levels following days 1 and 2 of a rugby sevens tournament, indicating muscle damage sustained in games (Clarke et al. 2015). There is no evidence however, that physical performance determinants are reduced over the course of a Rugby Sevens tournament.

Several studies have noted high degrees of muscle damage measured by CK levels following rugby sevens matches. Takashi et al. (2007) found serum CK levels in males of 18% from baseline after a rugby sevens match. Following a second match, CK levels rose to 42% above baseline. Clarke et al. (2015) found increases in CK levels of female rugby players following the first day of a tournament, with further increases following day 2. These increases were found to be higher than female soccer players and was attributed to muscle damage caused by repeated collisions experienced in rugby sevens. Despite these increases in CK levels, no difference in CMJ was found over the course of the 2-day tournament in both elite and sub-elite players. These findings were repeated by Doeven et al. (2019) who found no decrease in CMJ over the course of a 2-day tournament and up to 2 days following the tournament.

Although no reduction in neuromuscular performance between tournament days and games has been observed, there is evidence for a reduction in on-field movement patterns on day 2 of a tournament. Players at both national and international level have shown reductions in relative distance covered and % distance covered at > 5 $m \cdot s^{-1}$ on day 2 (Clarke et al. 2015). Nevertheless, further studies have found trivial increases in total distance covered by players on day 2 of a tournament and attributed the change to the importance of knockout matches on day 2 (Goodale et al. 2017).

Decreases in perceived wellbeing scores have also been linked to rugby sevens tournament play and recovery. Doeven et al. (2019) recorded the perceived wellbeing scores for players during a World Series tournament. Scores for general muscle soreness, fatigue, stress, mood and total quality of recovery were all significantly impaired after day 1 of a tournament. The scores remained low after day 2 of the tournament and did not return to baseline up to 2 days after the tournament. Moderate associations were found between high intensity running metres (>3.5 $m \cdot s^{-1}$) and fatigue, and number of physical contacts and muscle soreness.

3.2 Energy Systems

The aerobic energy system refers to the use of oxygen in the breaking down of fats and carbohydrates to provide energy (McArdle et al. 2015). It has commonly been linked to recovery, as it is the predominant energy system in use during low intensity activity and at rest. The aerobic system has a large capacity relative to anaerobic systems but is limited in the rate at which it can provide large amounts of energy (Stackhouse et al. 2001). Aerobic capacity is quantifiable by measuring the largest amount of oxygen that the body can consume and utilise during a minute, relative to body mass. This is known as VO_{2max} or VO_{2peak} (McArdle et al. 2015).

The role of the aerobic and anaerobic energy systems is to resynthesise adenosine triphosphate (ATP) so that it may be metabolised, and the energy released may drive muscle contractions necessary for movement. These reactions take place within the muscle cells themselves and the limited supply of stored ATP means that replenishment is an ongoing process. The anaerobic phosphagen (ATP-PC) and glycolytic systems are both capable of resynthesizing ATP quickly and without oxygen and are thus particularly useful during relatively short bouts of intense exercise (Gastin, 2001). These pathways have relatively small capacities and therefore can only be used for a limited time before recovery is needed. Aerobic pathways can produce a larger yield of ATP than anaerobic systems, but at a far slower rate (Gastin, 2001). Theoretically the aerobic pathways are limitless.

3.2.1 Anaerobic Systems

There are two anaerobic systems for energy production. The ATP-PC system can deliver a short-term high yield of ATP and thus it is essential in performing short activities beyond steady state (Gastin, 2001). These actions are not necessarily high intensity but do require an instant supply of energy. The breakdown of phosphocreatine (PC) by creatine kinase releases the energy required for ATPase to drive resynthesis of ATP from ATP and inorganic phosphate (McArdle et al. 2015). The ATP-PC system provides only a short-term solution for ATP resynthesis as PC levels can become almost completely depleted and ATP supplies can decrease by up to 40% (Gastin, 2001).

Sustained high energy outputs that demand higher rates of ATP resynthesis require high rates of ATP resynthesis through anaerobic glycolysis. This series of reactions uses energy from the breakdown of ATP to metabolise stored glycogen and produce a net gain of 2 ATP (McArdle et al. 2015). Maintaining a high rate of ATP resynthesis through glycolysis indefinitely is, however, impossible as its by-products cause fatigue (Kemp, 2005). Chief amongst these are hydrogen protons (H^+) that, if not utilised in mitochondrial respiration will accumulate within the muscle cell and cause acidosis (Kemp, 2005).

3.2.2 The Aerobic System

Adenosine triphoshate (ATP) is resynthesized in the aerobic system through the oxidation of carbohydrates and fats in the mitochondria of muscle cells. Anaerobic glycolysis is a precursor to aerobic metabolism of glycogen that results in the production of pyruvate and 2 molecules of ATP. If insufficient oxygen is available, then lactate is produced by combining pyruvate with excess hydrogen atoms (McArdle et al. 2015). The available pyruvate is converted to acetyl coenzyme A (acetyl-CoA) and enters the citric acid cycle (Stackhouse et al. 2001). Through a series of enzyme-driven reactions, carbon dioxide and hydrogen atoms are removed, and 2 molecules of ATP are produced. Carbon dioxide is carried in the blood and expired through respiration. Carrier coenzymes nicotinamide adenine dinucleotide (NAD) and flavin adenine dinucleotide (FAD) collect the hydrogen atoms and transport them to the inner membrane of the mitochondrion as NADH and FADH (McArdle et al. 2015). Prevailing theories of lactate metabolism have been challenged in recent years by proposals such as lactate shuttles where lactate is transported for energy production both within cells and in other cells (Kane, 2014).

The oxidation of hydrogen atoms from NADH and FADH occurs in a series of reactions called the electron transport chain. Oxidative phosphorylation describes the process by which electrons are transferred from NADH and FADH to oxygen and ATP is resynthesized (Tomlin and Wenger, 2001). Due to the large amount of NADH and FADH that results from the citric acid cycle, the yield of ATP is comparatively high in oxidative phosphorylation.

Aerobic metabolism of fat also provides a large yield of ATP. Mobilisation of fatty acids through lipolysis converts triglycerides to glycerol and 3 fatty acids. Whilst the glycerol will undergo glycolytic processes, the fatty acids are transported to the muscle cells where they are converted to fatty acyl-CoA and then transported to the mitochondrion (Tomlin and Wenger, 2001). Beta oxidation describes the process by which acyl-CoA is converted to acetyl-CoA so that it may enter the citric acid cycle, and hydrogen atoms are removed and transported to the electron transport chain as NADH and FADH (McArdle et al. 2015).

3.2.3 Physiological Explanation of Peak Oxygen Uptake

Peak oxygen uptake (VO_{2peak}) denotes the maximum amount of oxygen that an individual can consume and use in one minute. It is an indicator of an individual’s capacity for resynthesis of ATP using aerobic mechanisms (McArdle et al. 2015). Absolute values of VO_2 are calculated as millilitres of oxygen per minute ($ml \cdot min^{-1}$), however values are generally presented as relative to bodyweight ($ml \cdot kg \cdot min^{-1}$). It has been suggested that values relative to fat-free mass may be a more accurate indicator of aerobic capacity (Ahn et al. 2013, Tarnopolsky, 2008, Carter et al. 2001).

Peak oxygen uptake is commonly measured using incremental tests on a treadmill or cycle ergometer. A mask is placed over the participant's mouth and nose so that the amount of oxygen and carbon dioxide that is inspired and expired can be measured. There are several protocols for incremental tests, but most of them involve increasing the intensity of exercise via speed or incline increases every 1-4 minutes. When the volume of oxygen being inspired and utilised by the body reaches a plateau, this is recorded as the participant's VO_{2max}. If the test ends prior to a plateau being reached, then the value is recorded as VO_{2peak}.

There are several contributing and limiting factors to VO_{2peak}. Intake of oxygen is impacted by factors governing pulmonary ventilation, whilst its delivery to the mitochondria is impacted by haemoglobin concentration, blood volume, cardiac output, and peripheral blood flow (Lundby et al. 2017). These factors can be related to several other variables such as age, gender, stature, and training status. Cardiac output is calculated from heart rate (in beats per minute) and stroke volume (the volume of blood pumped out of the left ventricle with each contraction). During exercise, cardiac output increases and a relationship exists between VO_{2max} and maximum cardiac output (Lundby et al. 2017).

Although maximal oxygen consumption is considered the gold standard as the best measure of aerobic fitness, there are also several studies that highlight the importance of velocity at VO_{2max}. McLaughlin et al. (2010) describe the velocity at VO_{2max} as the best predictor of running performance in endurance athletes as it combines maximal aerobic power with running economy. This was consistent with the findings of Morgan et al. (1989) which showed a correlation between vVO_{2max} and 10 km running time in a homogenous population with similar VO_{2max}. This correlation was explained by differences in running economy.

Velocity at VO_{2max} is also described as maximal aerobic speed (MAS) and several methods exist for testing in field sports. No consensus exists over the most reliable method of measuring vVO_{2max} in the field and a range of different tests are used, so comparison between studies is difficult. Correlations have been found between vVO_{2max} and distance covered in rugby union matches (Swaby et al. 2016). Similarly, correlations have been found between vVO_{2max} and high intensity running distance during soccer matches (Krustrup et al. 2003). Specifically, this study found that both VO_{2max} and MAS correlated with total distance covered, whilst only vVO_{2max} correlated with high intensity running distance ($>15 km \cdot h^{-1}$). This may indicate that vVO_{2max} is a good indicator of running performance in field sports such as rugby and football.

The common practice of expressing aerobic capacity relative to body mass has been challenged in studies examining female subjects (Welshman et al. 1996, Heil 1997.) Several studies have found significant differences between genders when assessing VO_2 relative to body mass versus fat-free mass (Landgraff et al. 2021, Lambert et al. 2013). Duke (2017) describes differences in stature as the primary cause of lower ventilation for women during high intensity exercise. At rest these differences disappear when scaled for body surface area (BSA) but not at high intensities.

Ahn et al. (2013) recommended the use of VO_{2peak} relative to fat-free mass (FFM) to remove the confounding influence of adiposity as a method for examining insulin resistance in children. It has been proposed that expressing VO_2 relative to FFM eliminates the differences between gender that account for the 5-8% higher fat mass in women (Tarnopolsky, 2008, Carter et al. 2001).

3.2.4 Aerobic and Anaerobic Thresholds

Through incremental tests it is common to identify exercise intensity thresholds at which the contribution of different energy systems alters. Both thresholds occur below VO_{2peak} and can be identified using ventilatory data or accumulation of lactate in the blood (Vesterinen et al. 2016). The imbalance caused by the change in the NAD+/NADH ratio causes H+ to bind to pyruvate and create lactate. As this process occurs at a faster rate than the body can utilise lactate, it accumulates in the blood, indicating that the body is relying more heavily on anaerobic metabolism (McArdle et al. 2015).

The aerobic threshold or first lactate threshold (LT1) represents the point at which anaerobic systems begin to make a significant contribution to energy production. This point can be identified by an increase of blood lactate of 0.3 $mmol{\cdot}L^{-1}$ from the lowest recorded level (Vesterinen et al. 2016). The anaerobic threshold, or second lactate threshold (LT2) can be identified at intensities where blood lactate begins to accumulate as the rate of production significantly surpasses the rate at which it is metabolised. There are several methods used for the identification of LT2, but the use of a linear model from LT1 to the next lactate point and the line between points after a rise of 0·8 $mmol.L^{-1}$ is commonly used (Vesterinen et al. 2016). LT2 is distinct from the onset of blood lactate accumulation (OBLA), which occurs at 4 $mmol{\cdot}L^{-1}$ of blood lactate (McArdle et al. 2015).

3.2.5 Normative Data on VO_{2peak} in International Rugby Players

Maximum aerobic capacity scores for international rugby players are relatively rare in scientific literature, perhaps due to the impracticalities of incremental treadmill testing. Studies tend to use field-based tests such as the Yo-yo intermittent recovery test 1 to estimate aerobic capacity as these are easier to conduct in team sports settings. There is, however, some data available. Clarke et al. (2013) measured VO_{2max} in 22 female international level rugby sevens players (mean value: 46.5 ± 5.2 ml.kg.min^{-1}). Suarez-Arrones et al. (2012) measured 12 international players with mean VO_{2max} of 51.1 ± 3.6 ml.kg.min^{-1}. Clarke et al. (2015) also measured 7 international level players with VO_{2max} of 51 ± 4 ml.kg.min^{-1} and vVO_{2max} of 4.1 ± 0.6 m·s^{-1} (14.76 ± 2.16 km·h^{-1}).

3.3 Aerobic Capacity, Lactate Thresholds and Recovery

Rugby sevens requires players to have highly developed aerobic systems (Malone et al. 2020). Mean values in the Yoyo Intermittent Recovery Test 1 (Yoyo IR1) for elite female players are 350m higher than non-elite athletes indicating that aerobic capacity is an important factor in high performance (Sella et al. 2019). A perceived link exists between aerobic capacity and recovery, despite equivocal evidence in scientific research. Research into the link between aerobic variables and recovery in team sports has focused largely on repeated sprint ability (RSA). The aerobic system can resynthesize a large amount of ATP relative to the anaerobic systems and must contribute to the repeatability of physical outputs (Gastin 2001). Although RSA is a good indicator of repeated high intensity efforts in a short time such as within a game, it does not give indication of recovery over the course of a day or a weekend. Tomlin and Wenger (2001) proposed dividing recovery into two distinct components. A fast component lasts up to a few minutes and is characterised by the replenishment of PCr and ATP stores as well as tissue oxygen. A slow component is associated with removal of accumulated metabolic by-products such as lactate and H+ ions. Both components involve a retained post-exercise elevation of certain physiological functions such as heart rate and body temperature as the body's metabolism returns to a resting state (Tomlin and Wenger, 2001).

3.3.1 Repeated Sprint Ability

Repeated sprint ability is a commonly described feature of team sprint sports such as rugby, football, and basketball. It is the ability to perform short sprint activities (<10s) with incomplete recovery periods (<30s) (Bishop and Edge, 2006). The research into the link between RSA and aerobic capacity is equivocal, with methodological issues causing some problems in achieving consensus. Ice hockey players have shown a correlation between fatigue index during an RSA test and VO_{2max} (Stanula et al. 2014). Gharbi et al. (2015) also found that VO_{2max} was strongly correlated with RSA fatigue index. Aerobic capacity, particularly the peripheral component, was also found to be a significant factor in recovery during intermittent exercise in male rugby players (McMahon and Wenger, 1998). Several studies have demonstrated correlations between VO_{2max} and RSA in football players (Archiza et al. 2020, Jones et al. 2013).

Aziz et al. (2000) concluded that an increase in aerobic capacity would have only marginal impact on RSA in team sport athletes. Similarly, it has been demonstrated that professional football players had significantly better RSA than amateur players, despite similar VO_{2max} (Rampinini et al. 2009), suggesting that other factors may contribute to RSA. These findings are supported by those of Cooke et al. (1997) who also suggest that differences between the recovery rates for individuals with similar VO_{2max} could be attributed to other factors. Edge et al. (2005) found that untrained individuals made larger improvements in RSA performance following 5 weeks of high intensity training (HIT) compared to moderate intensity training (MIT), despite both groups showing similar improvements in both VO_{2peak} and LT2. The authors attributed the RSA performance improvements to a greater ability to perform a high amount of work in the latter sprints of the protocol as there were no significant differences between groups in measures of metabolites associated with exercise.

Several studies have explored a possible link between RSA and lactate or ventilatory thresholds. Baldi et al. (2017) examined the relationship between RSA decrement and lactate accumulation in male soccer players. The authors found significant correlations between sprint decrements and both velocity at the onset of blood lactate accumulation (vOBLA), and peak blood lactate. Lowery et al. (2018) found that the second ventilatory threshold (VT2) to be a significant factor in RSA performance amongst male ice-hockey players. Importantly, the authors found that VT2 was more closely associated with RSA than VO_{2peak}.

There are several possible mechanisms proposed that may link RSA to aerobic performance markers such as $VO2_{peak}$ and LT2. It is possible that a higher aerobic capacity results in an increased aerobic contribution to each sprint during the RSA activity, therefore reducing the contribution required from anaerobic systems. This may particularly apply in the latter sprints of the RSA activity (Bishop and Edge, 2006). Smaller anaerobic contributions to exercise will result in lower levels of fatigue associated with anaerobic exercise such as accumulation of metabolic by-products such as inorganic phosphates and hydrogen ions (H+) and, changes in blood pH (Gharbi et al. 2015). A large aerobic capacity has been linked to the ability to tolerate, buffer, and remove H+ from working muscles (Gharbi et al. 2015).

Repeated sprint ability has also been linked to a faster ability to resynthesise Phosphocreatine (PCr) stores between sprints (Girard et al. 2012). It has been proposed by Bishop and Edge (2006) that the higher VO_2 attained during each sprint of a repeated sprint activity will result in a higher VO_2 at the cessation of each sprint. This higher level of oxygen delivery at the start of recovery may accelerate PCr resynthesis and thus allow for more sustained repeated usage of the ATP-PC system. Higher VO_{2peak} and LT2 have both been linked to a greater ability to rapidly recover PCr stores following depletion through exercise (McMahon and Jenkins, 2002).

Many studies have also linked initial sprint performance to repeated sprint performance (Hamilton et al. 1991, Bogdanis et al. 1996, Wadley and Le Rossignol, 1998). Faster sprinters may therefore experience lower sprint decrements than slower sprinters. Non-elite athletes matched for initial sprint performance have been shown to experience smaller RSA decrements with higher VO_{2max} (Bishop and Edge, 2006).

3.3.2 Recovery

There is a consensus that acute post-exercise recovery measured by blood lactate clearance is enhanced through active recovery (Baldari et al. 2005, Greenwood et al. 2008, Hinojosa et al. 2021, Devlin et al. 2014). It has been shown that recovery to pre-exercise blood lactate levels is dependent on several factors including exercise intensity, training status and intensity of active recovery, but that blood lactate will normally return to pre-exercise levels in around 30 minutes (Hinojosa et al. 2021). Yet Tomlin and Wenger (2001) suggest that recovery of lactate and blood pH may take up to an hour or more. There is sufficient time between games in a rugby sevens tournament and reduces the likelihood of lactate accumulation and acidosis as direct contributing factors to fatigue in between games. Furthermore, it has been demonstrated that lactate removal may be a factor in post-exercise recovery, but no correlation was found between lactate recovery and subsequent exercise performance (Weltman et al. 1977).

Studies into short-term recovery of neuromuscular function over 24h of rugby sevens tournaments have not shown reductions in performance despite CK levels showing muscle damage (Clarke et al. 2015). No consensus exists on the role of aerobic metabolism in the recovery of neuromuscular function and ATP production over multi-day events such as a rugby sevens tournament. Restoration of lost water and glycogen through consumption of carbohydrate and protein appears to remain the most important aspect of recovery over longer time periods (Alghannam et al. 2018).

4 STANDARDISING TOURNAMENT DEMANDS TO STUDY RUGBY SEVENS IN A RESEARCH SETTING

Advances in technology have allowed for data collection on team sports to extend to match-play. GPS, accelerometer and HR devices and non-invasive blood sampling allow researchers to examine the physiological impact of real match play on athletes. Although this presents excellent opportunities for researchers exploring the demands of team sports, it is impractical for examining correlations or the impact of interventions on performance. Several factors influence the individual activity profiles of rugby sevens games including position, score, opponents, substitutions, and game half (Murray et al. 2015, Goodale et al. 2017, Malone et al. 2020). Total distances covered in games studied for both men and women has ranged from 916m - 2,486m, with the highest total distance for female players almost doubling the mean value (2,343m) (Ball et al. 2019). This variation in match demands makes research into performance during games difficult to quantify.

The need exists for a standardised model that replicates the demands of rugby sevens games so that practitioners can explore the effects of independent variables on rugby sevens performance. A simulated game protocol has been used to examine the effect of heart rate variability in male rugby sevens players (Douglas et al. 2016). This protocol included a repeated sprint activity during the first 2 minutes consisting of 6 x 30m sprints with a 180-degree turn. The remainder of the match simulation consisted of shuttle running and arm-ergometer exercise designed to mimic the metabolic and running demands of a game. A standardised total distance of 1480m was consistent with the findings of Ball et al. (2019) from real match GPS data. Time spent in each speed zone was based on findings of Ross et al. (2013) and included sprinting (>6 $m{\cdot}s^{-1}$) 12.1%, high-intensity running (5–6 $m{\cdot}s^{-1}$) 4.8%, striding (3.5–5 $m{\cdot}s^{-1}$) 19.1%, jogging/cruising (2–3.5 $m{\cdot}s^{-1}$) 21.4%, standing/walking (0–2 $m{\cdot}s^{-1}$) 33.1%, and grappling (0 $m{\cdot}s^{-1}$) 9.5% (Douglas et al. 2016). No differences were found in repeated sprint performance over a simulated tournament weekend using this protocol, possibly due to the measurements taking place only at the beginning of each game. This would not account for the fatigue accumulated during games that may hinder sprint performance late in the game. Furthermore, although some grappling activities were included in the simulation, it fails to account for the large number of impacts sustained during rucks and tackles in rugby sevens games (Ross et al. 2013, Suarez-Arrones et al. 2013, Ball et al. 2019).

4.1 The Rugby Sevens Simulation Protocol

Furlan et al. (2016) proposed that the Rugby Sevens Simulation Protocol (R7SP) is a reliable protocol for testing selected variables in a research environment, independent of position specific variation. It was developed based on the match analysis conducted by Furlan et al. (2015) and Higham et al (2012). The protocol involves two halves of alternating high and low intensity periods of work, including high intensity running and sprinting, shuttle running, deceleration and simulated contact situations. There are 6 x 30m sprints followed by a rapid deceleration of 6m, spread throughout the course of the simulation. This does not qualify the R7SP as an RSA test as defined by Bishop and Edge (2006) as the rest periods exceed 30 seconds between each sprint. It does, however, simulate the fluctuations in running intensity experienced in rugby sevens matches, with the most intense periods of work reflecting the those found in match play by Furlan et al. (2015). Also included in the R7SP are 12 contact activities designed to simulate rucks and tackles, adding to the ecological validity of the protocol (Furlan et al. 2016).

4.1.1 Running Demands Comparisons

The total distance covered in the R7SP is 1745 ± 68 m measured by GPS (Furlan et al. 2016). This is somewhat higher than the mean values reported elsewhere for both male and female players (Male: 1,413m and Female: 1,216m, Ball et al. 2019. Female:1,623m ± 17, Sella et al. 2019). Furthermore, the 6 x 30m sprints in the protocol is higher than the 3.9 ± 1.2 sprints per game previously identified for elite female players, as is the number of accelerations (12.4 ± 1.5) (Sella et al. 2019). High intensity running meters (27 m/minute) was also higher than that reported for real match play (21 $m.min^{-1}$). The thresholds used for high-speed running were slightly lower in the R7SP analysis than in real match play meta-analysis (>4.21 $m{\cdot}s^{-1}$ vs >4.4 $m{\cdot}s^{-1}$) (Sella et al. 2019).

4.1.2 Heart Rate Demands

The 10 male participants who completed the R7SP on two occasions had HR values above 90% of their maximum HR for 45.4% ± 27.1% of the simulation. This is considerably higher than the 36.0% ± 15.2% found during match play for elite female players. It is, however, lower than the figure given for national level players of 54.6% ± 14.2% (Sella et al. 2019). Mean HR % in the R7SP were similar to those in female match play (87.6% vs 90%) (Malone et al. 2020, Sella et al. 2019).

Despite differences between the physiological and running demands in the R7SP and meta-analyses of match play, the R7SP appears to have ecological validity in standardising match-like conditions for research purposes. The inclusion of a contact element help to give a more realistic simulation of rugby games than those that only focus on running and metabolic demands. The contact aspect of rugby sevens has been shown to be a significant part of match fatigue (Takashi et al. 2007., Clarke et al. 2015., Doeven et al. 2019).

5 RESEARCH QUESTIONS AND HYPOTHESES

The purpose of this study is to explore the relationship between aerobic capacity, lactate thresholds, and decrements in sprint performance over the course of a simulated rugby sevens tournament. The physiological demands of rugby sevens have been documented through real-match measurement, but links between aerobic capacity, sprint performance, and recovery have not been fully established. Whilst the significance of speed is clear in games, practitioners may benefit from understanding which aerobic and anaerobic fitness variables contribute to maintenance of sprint performance during a tournament. Aerobic capacity and lactate thresholds were measured in female international rugby players in a laboratory setting three weeks prior to a simulated rugby sevens tournament set over two days. 6 sprint measurements were recorded using a radar gun during each of six games to observe sprint decrements during performances.

Research Question 1: Does aerobic capacity correlate with sprint decrement during a simulated rugby sevens tournament?

Hypothesis 1.1: Rugby players with a higher VO_{2peak} will experience smaller sprint decrements between days of a rugby sevens tournament.

No difference has been found in measures of neuromuscular performance through CMJ scores between days 1 and 2 of a rugby sevens tournament (Clarke et al. 2015, Doeven et al. 2019). However, CK levels have been shown to increase after games (Takashi et al. 2007) and between days 1 and 2 (Clarke et al. 2015). Changes in the running demands between days 1 and 2 have been observed (Goodale et al. 2017). Decrements in peak sprint performance during games have been observed by Misseldine et al. (2021). These decrements may increase between games, and this may be related to aerobic capacity.

Hypothesis 1.2: Rugby players with a higher VO_{2Peak} will sprint at higher % of peak velocity during a rugby sevens match.

Several authors have described overall sprint decrements during field-based sports (Misseldine et al. 2021, Kyprianou et al. 2019). A higher aerobic capacity may lead to less reliance on anaerobic systems for high intensity efforts during each game (Bishop and Edge, 2006). A higher level of oxygen delivery at the start of recovery after each high intensity effort may accelerate PCr resynthesis and thus allow for more sustained repeat usage of the ATP-PC system (Bishop and Edge, 2006). Fatigue and acidosis caused by build-up of excess H+ ions may also be reduced, allowing for sustained maximal performances (Gharbi et al. 2015).

Research Question 2: Does the second lactate threshold have a stronger relationship than aerobic capacity with sprint decrements during a simulated rugby sevens tournament?

Hypothesis 2.1: The % of peak velocity achieved during a simulated rugby sevens match will be more closely associated with velocity at second lactate threshold than VO_{2peak} or velocity at VO_{2peak}.

Sprint decrement in RSA has been shown to be more closely related to the second ventilatory threshold than VO_{2peak} in male ice-hockey players (Lowery et al. 2018). Peripheral fatigue leading to sprint decrement may be more closely related to LT2 than aerobic capacity.

Hypothesis 2.2: The reduction in sprint performance between days of a simulated rugby sevens match will be more closely associated with velocity at second lactate threshold than VO_{2peak} or velocity at VO_{2peak}.

Any sprint decrement observed between games will be more closely related to LT2 than $VO_{2peak.}$ The observed contributions to peripheral fatigue on day 2 of a tournament (Clarke et al. 2015, Doeven et al. 2019, Takashi et al. 2007) will contribute to a similar sprint decrement as that observed by Lowery et al. (2018).

Research Question 3: Does peak sprint velocity have a more significant correlation than aerobic capacity with sprint decrements during a simulated rugby sevens tournament?

Hypothesis 3.1: Decrements in sprinting speed will be more closely associated with peak velocity than VO_{2Peak} or velocity at VO_{2Peak}.

Initial sprint performance will be a better indicator of sprint decrements than aerobic variables. This will confirm the relationship between aerobic capacity and repeated sprint performance that has been observed in several studies. (Hamilton et al. 1991, Bogdanis et al. 1996, Wadley and Le Rossignol, 1998).

6 METHODS

6.1 Subjects

This study was part of a larger project into relative energy deficiency in sport (REDS) that included long term monitoring of female athletes from a range of sports over several years. The NOREDS project is led by Dr. Johanna Ihalainen, Senior Lecturer at the University of Jyväskylä. Twelve female members of the Finland rugby sevens national team volunteered to take part in the study. One subject completed the laboratory testing but was forced to withdraw from the study during the rugby sevens simulation due to injury sustained outside of the study. The remaining eleven subjects were included in all analyses (age 28.7 ± 3.5 years, height 167.0 ± 4.4 cm, body mass 68.1 ± 9.7 kg, VO_{2peak} 45 ± 2.8 $ml \cdot kg \cdot min^{-1}$). All subjects had a history of physical training for their sport and had represented Finland in international rugby competitions. The study was approved by the Ethical Committee at the University of Jyväskylä (Statement ID: 514/13.00.04.00/2021) and the measurements were completed in accordance with the declaration of Helsinki.

6.2 Experimental Design

All subjects completed an incremental treadmill test at the University of Jyväskylä in October 2021 at the beginning of the off-season for rugby in Finland. After a period of two weeks, participants completed a series of field tests outdoors on artificial turf in Tampere and Helsinki. Following initial sprint measurements, subjects completed three rugby sevens simulations on two consecutive days following the protocol in the R7SP (Furlan et al. 2016). Each game in the protocol included 6 x 30m sprints with a 6m deceleration. Peak velocity for each of these sprints was recorded using a radar gun for a total of 6 sprints per game and 36 sprints for the entire tournament simulation.

6.3 Laboratory Testing

Laboratory testing was conducted at the University of Jyväskylä. Participants first completed a 10-minute dynamic stretching warm up of their own choosing to prepare for the strength and power tests. They completed 3 CMJ and 3 isometric leg press tests, followed by an incremental treadmill test to determine $VO2_{peak}$ (Figure 2). The results of the CMJ and leg press are included only as descriptive statistics of the sample.

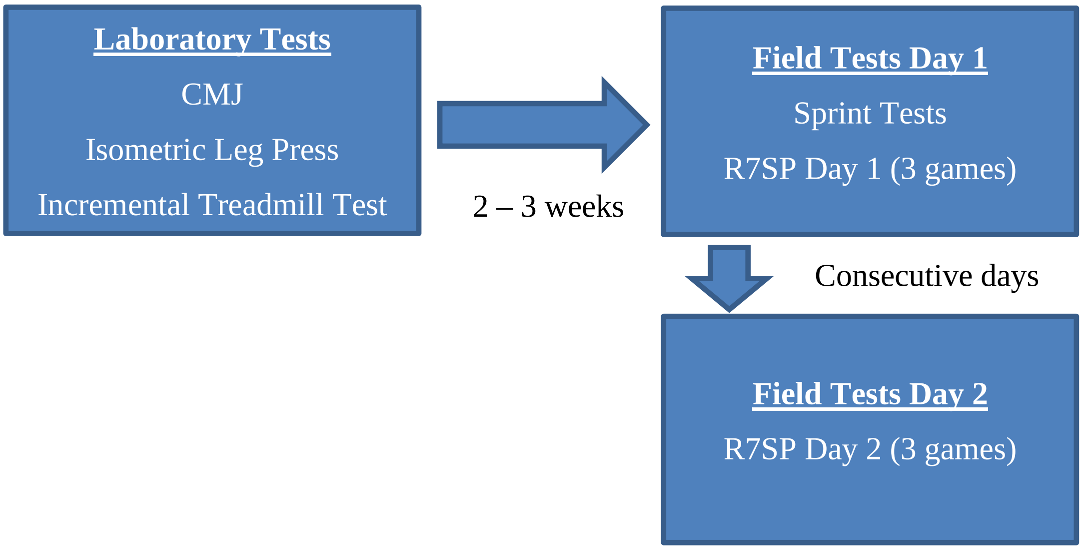

FIGURE 2: Procedure for the testing period

In preparation for the incremental treadmill test, a resting blood lactate measure was taken. This was obtained as a blood sample taken from the middle fingertip of the left hand (20 µL). All blood analysis were conducted with a Biosen C-line lactate analyser (EKF Diagnostic, Magdeburg, Germany). This was followed by a 5-minute warm up on the treadmill at 7 $km{\cdot}h^{-1}$ (OKJ-1 treadmill, Telineyhtymä Kotka, Kotka, Finland). During this warm-up, test procedures and safety information was discussed. Participants were then fitted with a mask and connected to the Vyntus CPX metabolic cart gas analyser (Jaeger-CareFusion, Hoechberg, Germany) for breath-by-breath analysis during the test. Polar V800 (Polar Electro, Kempele, Finland) sensors were used to measure HR.

The treadmill test started at 7 $km{\cdot}h^{-1}$and the speed was increased by 1 $km{\cdot}h^{-1}$ after every 3 minutes, stopping briefly in between levels for a blood lactate measurement. The treadmill was set to a 0.5 degree incline for the entirety of the test. The break between levels never exceeded 30 seconds so there was no need to add extra time for any of the test levels. The test continued until the participant reached exhaustion and terminated the test using a pre-determined signal. Average VO_2 was recorded during the final 60 seconds of each level. HR was recorded using the average during the last 30 seconds of each phase. At the end of each level, participants were asked their rating of perceived exertion (RPE) on Borg's scale from 6-20. Lactate thresholds were determined using the methods identified by Vesterinen et al (2016). A rise of 0.3 $mmol·L^{-1}$ above the lowest lactate value marked LT1. The intersection of linear models from LT1 to the next lactate point and following a rise of 0.8$mmol·L^{-1}$ marked LT2 (Vesterinen et al. 2016). A final lactate measurement was taken 1 minute following termination of the test.

6.4 Sprint Testing

After a period of 2 weeks, participants completed the field-based portion of the study. Following a standardised 10-minute warm up consisting of a short jog, dynamic stretching, and some short sprint drills, players completed 3 maximal 30m sprints followed by a 6m deceleration and a 3-minute rest in between each sprint. These sprints were recorded using an ATS Stalker II radar gun (Applied concepts, Dallas, TX, USA). The radar device was held 10 m behind the subject at a height of 1m (Figure 3). Peak velocity was established using the manufacturer's software for ATS Stalker II (STALKER ATS version 5.0.3.0). A medium filter was applied in accordance with manufacturer's instructions.

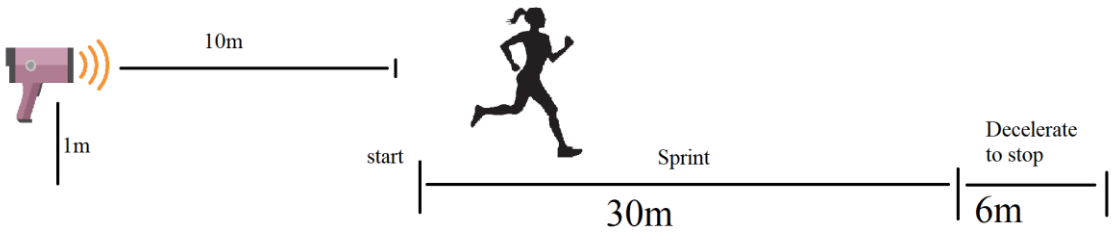

FIGURE 3: Setup for the sprint testing. This was used both in pre-sprints and as part of the R7SP.

6.5 Rugby Sevens Simulation Protocol

Following the sprint testing, participants completed the R7SP three times on two consecutive days to simulate a full rugby sevens tournament (Furlan et al. 2016). Each simulation (excluding the first) was immediately preceded by the same standardised 10-minute warm up and followed by a full 90-minute rest period. Participants were familiarised fully with the protocol before the first trial. The protocol is designed to replicate the physical demands of a rugby sevens game for use in a research setting. It consists of two, seven-minute halves of alternating 'High intensity' (HI) and 'Low intensity' (LI) blocks. Each half is separated by a 1-minute rest period or 'half time' (Figure 4).

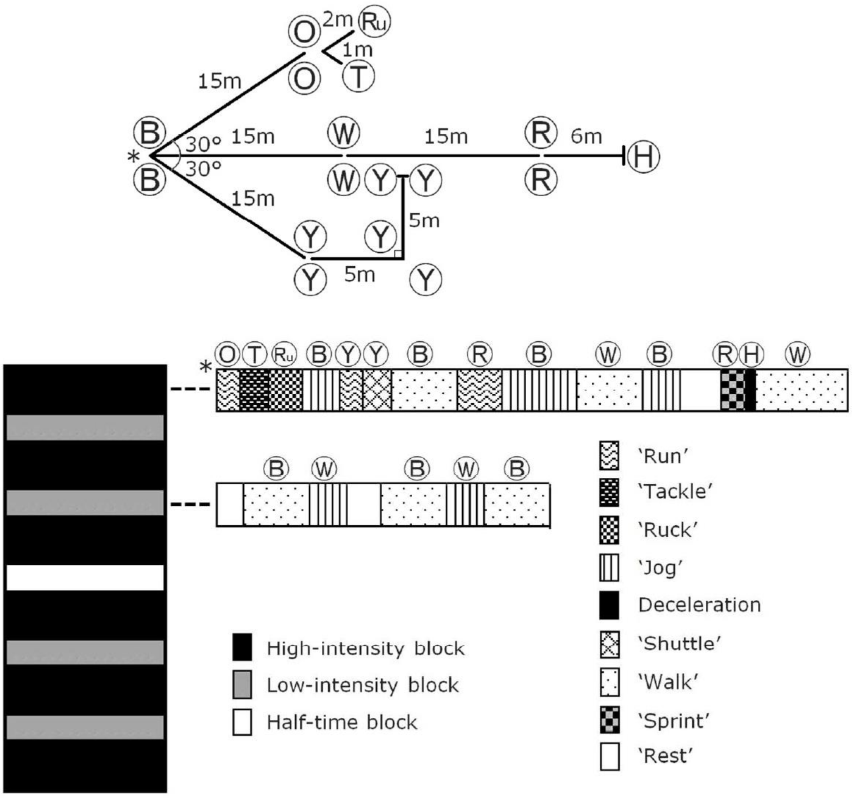

FIGURE 4. Schematic diagram of the R7SP. * = starting point B = blue cone; W = white cone; R = red cone; O = orange cone; Y = yellow cone; H = hurdle; T = tackle area; Ru = Ruck area (tyre). b) Schematic representation of the R7SP exercise pattern (time weighted) (Furlan et al. 2016)

TABLE 2: Chronological sequence of movements and cues in the R7SP (d = distance in metres, t = time in seconds) (Furlan et al. 2016)

	Instruction	Direction	d(m)	t(s)
High-intensity Period	Run	Orange	15	3.95
	Tackle	Tackle bag	4	5.00
	Ruck	Tyre	4	6.00
	Jog	Blue	15	6.52
	Run	Yellow	15	3.95
	Shuttle	Yellow	20	5.13
	Walk	Blue	15	11.54
	Run	Red	30	7.89
	Jog	Blue	30	13.04
	Walk	White	15	11.54
	Jog	Blue	15	6.52
	Rest			7.00
	Sprint	Red	30	4.29
	Stop (not cued)	Hurdle	6	1.50
	Walk	White	21	16.15
Low-intensity Period	Rest		0	5.00
	Walk	Blue	15	11.54
	Jog	White	15	6.52
	Rest			6.00
	Walk	Blue	15	11.54
	Jog	White	15	6.52
	Walk	Blue	15	11.54

Participants were instructed to follow a set of audible commands around a course of coloured cones that included ‘walk, jog, run, tackle, ruck, shuttle, and sprint’. These were described in accordance with the protocol described by Furlan et al. (2016). ‘Walk’ and ‘jog’ were described as low intensity activities. ‘Run’ was described as ‘cruise-type events that do not require a maximal acceleration’. ‘Sprint’ was described as ‘a maximal acceleration in attempt to reach and maintain peak speed’. ‘Tackle’ involved hitting a tackle bag with force and dropping to the floor before immediately returning to their feet. For the ‘Ruck’, participants hit a tackle bag and completed a sustained drive of 2 seconds. ‘Shuttle’ involved a 5m L-shaped shuttle sprint. All activities were ‘full speed’ and ‘maximum intensity’ other than ‘Walk’, ‘Jog’ and ‘Run’. Prior to each ‘Sprint’, subjects were given the instruction to ‘rest and ready for sprint’, requiring them to place 1 hand on the floor and ready themselves for the sprint. Each HI block culminated in a single 30m sprint with a 6m deceleration. These were measured using the same method as the pre-tournament sprints and the ATS Stalker II radar gun.

6.6 Sprint Analysis

A total of 429 sprint files were collected and analysed. The files were uploaded to the STALKER ATS version 5.0.3.0 programme and displayed as shown in figure 5. Points that followed the acceleration curve were selected for inclusion in the analysis, whilst those that deviated significantly from the path were excluded. All sprint files were of high quality and therefore included in the analysis.

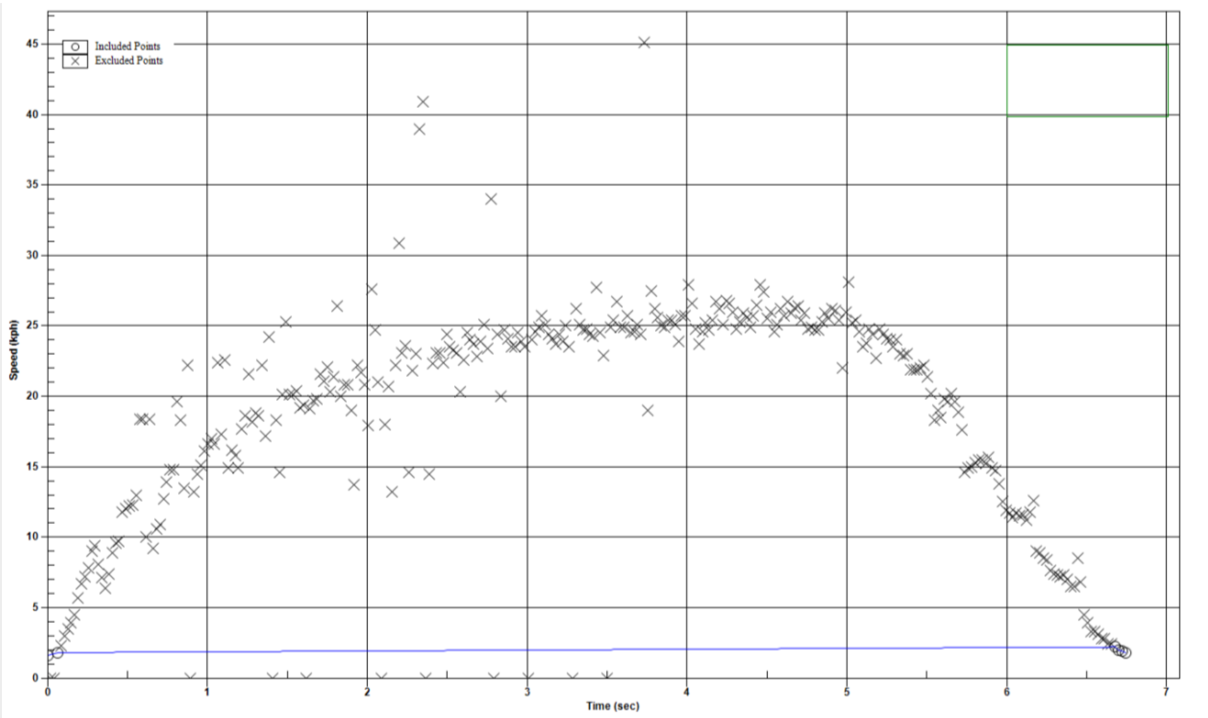

FIGURE 5: Example raw data from the sprint files captured by the ATS Stalker II radar gun

Following the manufacturer's instructions for processing sprint files, the 'acceleration run' file type was selected, and a medium digital filter was applied to each of the files (Figure 6). The statistics menu in the software was used to identify the peak velocity of each sprint.

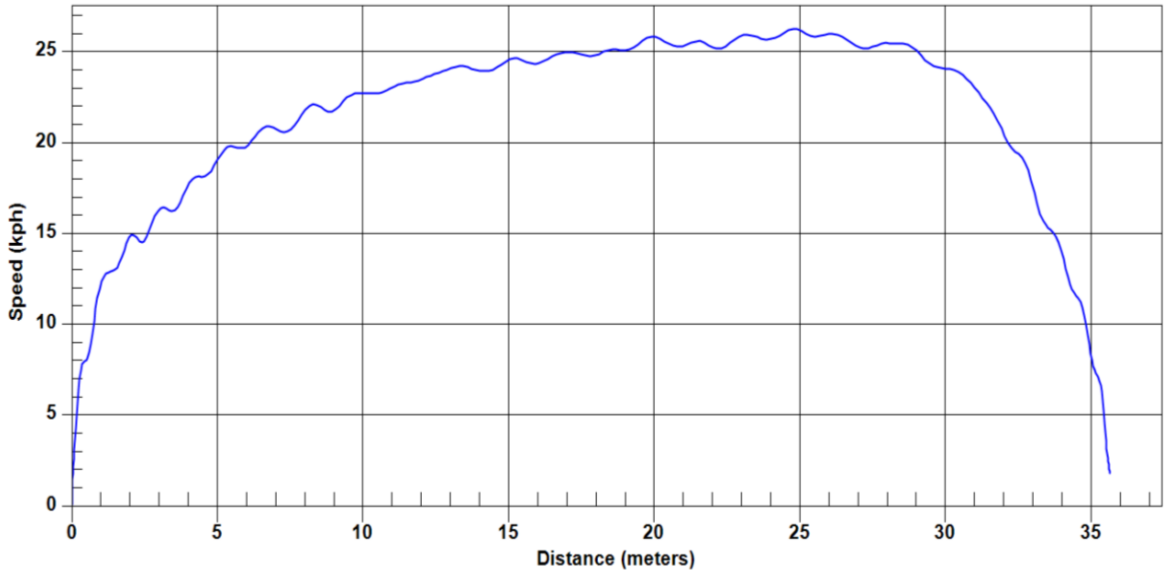

FIGURE 6: Individual sprint file following application of a medium digital filter as recommended in the manufacturer's instructions using the Stalker ATS 5.0 programme.

6.7 Statistical Analysis

Interpretation of the data and statistical analysis was performed with SPSS software (IBM Corporation, Armonk, NY, USA) and Microsoft Excel for Microsoft 365 software (Microsoft Corporation, Redmond, WA, USA). All results are presented as mean ± standard deviation. Due to a relatively small sample size (n=11), non-parametric tests were used in analysis. Comparisons were made between aerobic fitness variables obtained in the treadmill test and sprint variables obtained during the field tests to examine correlations. Peak sprint velocities were both averaged and summed for each day. Summed peak velocity was used to measure between day differences as recommended by the author of the protocol. Average peak velocity was used to assess sprint decrements from peak velocity measured in the sprint tests. Wilcoxon Signed Rank Test was used to determine differences between the sprint values of different days. Spearman's rank-order correlation was used to examine the relationship between aerobic and velocity variables. With the relatively small sample size, only correlations ≥0.6 were rated as significant and correlations were not given any ranking based on their strength. Using a larger sample size and parametric tests would have allowed for ranking of the strength of the correlations. Statistical significance was determined using p-values of ≤0.05 and ≤0.01.

7 RESULTS

7.1 Physical Performance characteristics

Physical performance characteristics of the participants are recorded in Table 3. All data presented as mean ± standard deviation.

TABLE 3. Physical performance characteristics of participants (n=11)

	Mean
VO_{2peak} (ml·kg·min^{-1})	45 ± 2.8
vVO_{2peak} (km·h^{-1})	13.7 ± 1.0
LT1 (km·h^{-1})	9.1 ± 0.8
LT2 (km·h^{-1})	11.2 ± 0.9
VO_{2peak} / FFM (ml·kg·min^{-1})	59.4 ± 3.9
La_{peak} (mmol·L^{-1})	11.2 ± 1.9
CMJ (cm)	34.6 ± 5.7
ILP (N)	347.2 ± 70.5
vPeak (km·h^{-1})	26.5 ± 1.7

VO_{2peak} = peak oxygen uptake, vVO_{2peak} = speed at which VO_{2peak} occurred, LT1 = speed at the first lactate threshold, LT2 = speed at the second lactate threshold, VO_{2peak} / FFM = maximal oxygen uptake expressed per kilo of fat-free mass, La_{peak} = peak lactate value recorded, CMJ = countermovement jump, ILP = isometric leg press, vPeak = peak sprint velocity.

7.2 Sprint Performance Decrements

All players experienced significant sprint decrements compared to pre-tested peak velocity during the R7SP (Figure 7). The average pre-testing velocity was 26.5 ± 1.7 $km \cdot h^{-1}$. On day 1, the average sprint velocity during games was 24.8 ± 1.9 $km \cdot h^{-1}$ and on day 2 it was 24.7 ± 2.1 $km \cdot h^{-1}$. There was an average decrement between day 1 and 2 of only 0.1 $km \cdot h^{-1}$ that was not statistically significant ($p = 0.508$).

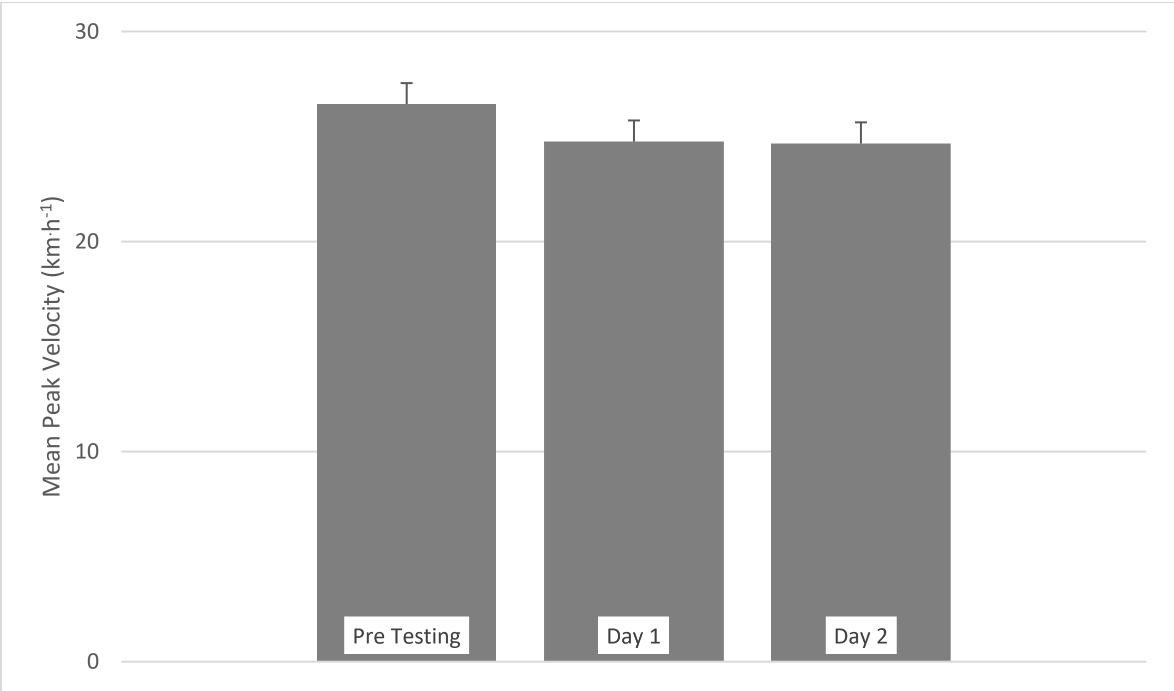

FIGURE 7: Average peak velocity per day (Pre = 26.5 ± 1.7, Day 1 = 24.8 ± 1.9, Day 2 = 24.7 ± 2.1)

Velocity at LT2 showed a statistically significant correlation with average overall sprint decrement (Figure 8) ($R = 0.763$, $p = <0.01$). To ensure correct analysis of the data, the outlying datapoint at -4km·h^{-1} was temporarily excluded, and correlations were repeated. This brought similar results and thus confirmed that a statistically significant correlation exists ($n = 10$, $R = 0.779$, $p = <0.01$).

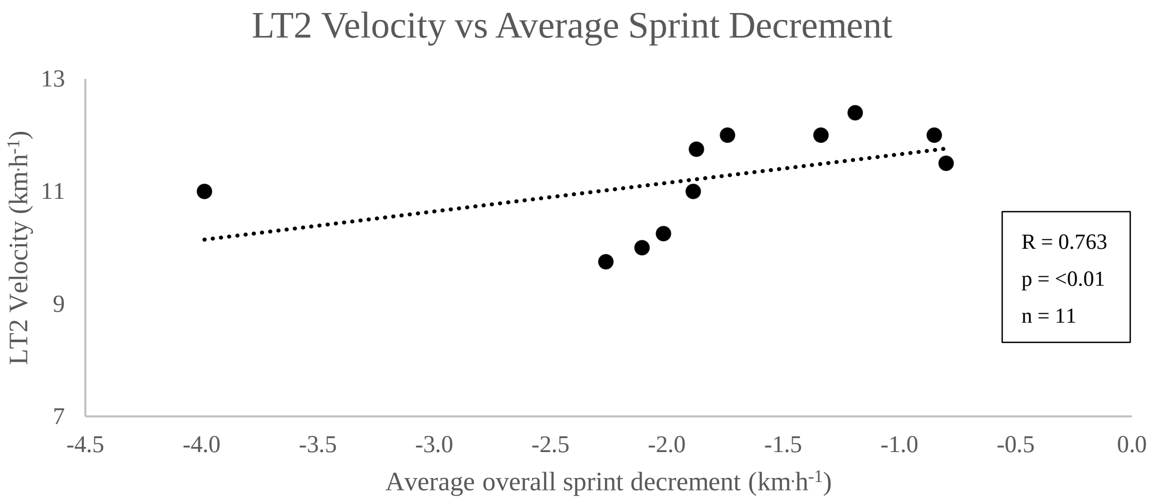

FIGURE 8: Relationship between velocity at LT2 and average overall sprint decrement during both days of the tournament simulation.

VO_{2peak} did not correlate with average overall sprint decrement (Figure 9). Analysis was again conducted with the datapoint at -4km·h^{-1} excluded, and no correlation was observed.

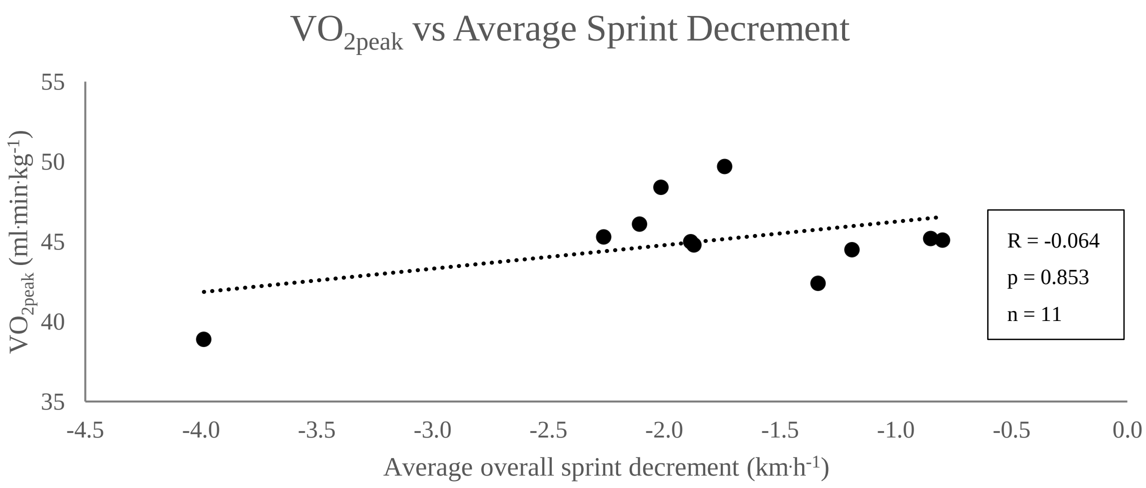

FIGURE 9: Relationship between VO_{2peak} and average overall sprint decrement during both days of the tournament simulation.

7.3 Day 1 to Day 2 Decrements

There was a significant correlation between velocity at LT2 and sprint decrement between days (Figure 10) ($R = 0.740$, $p = <0.01$). The outlying datapoint at -0.9 $km.h^{-1}$ was temporarily excluded from the analysis and the correlation was re-examined with similar results ($n = 10$, $R = 0.702$, $p = 0.02$).

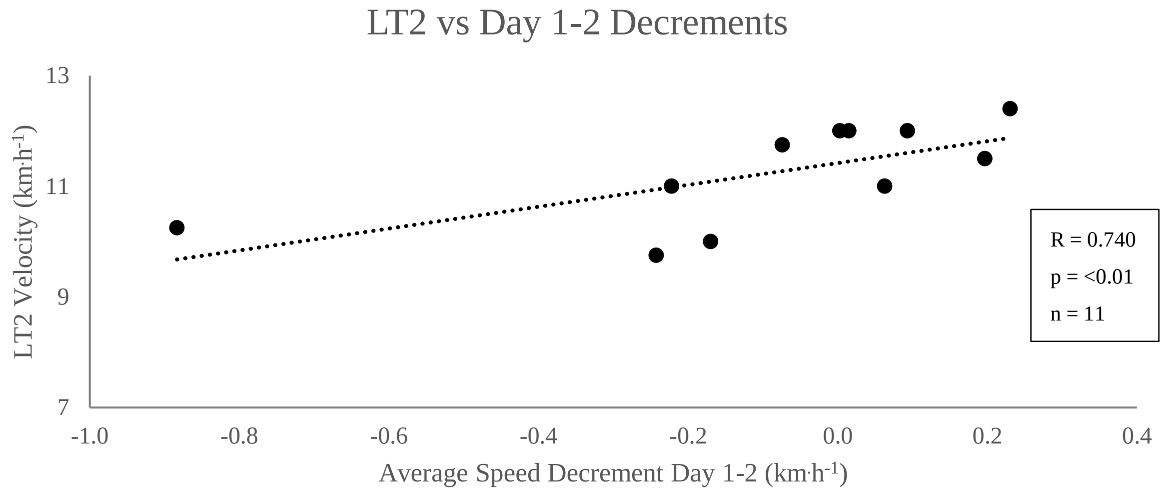

FIGURE 10: Relationship between velocity at LT2 and average sprint decrement between days 1 and 2 of the tournament simulation.

Sprint decrements between tournament days did not correlate with VO_{2peak} (Figure 11). With the datapoint at -0.9 $km{\cdot}h^{-1}$ excluded, no correlation was observed.

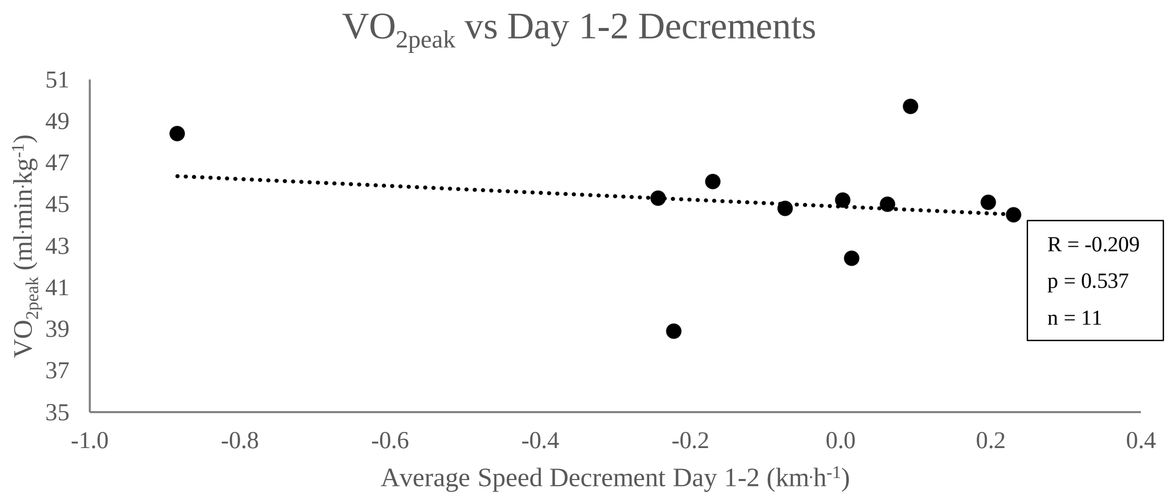

FIGURE 11: Relationship between VO_{2peak} and average sprint decrement between days 1 and 2 of the tournament simulation.

7.4 Peak Velocity

There was evidence of a correlation between peak velocity measured in pre-testing and decrement between days, although this was not statistically significant (Figure 12) ($R = 0.600$, $p = 0.051$). Temporary removal of the datapoint at -0.9 km·h^{-1} weakened the correlation considerably ($n = 10$, $R = 0.479$, $p = 0.162$).

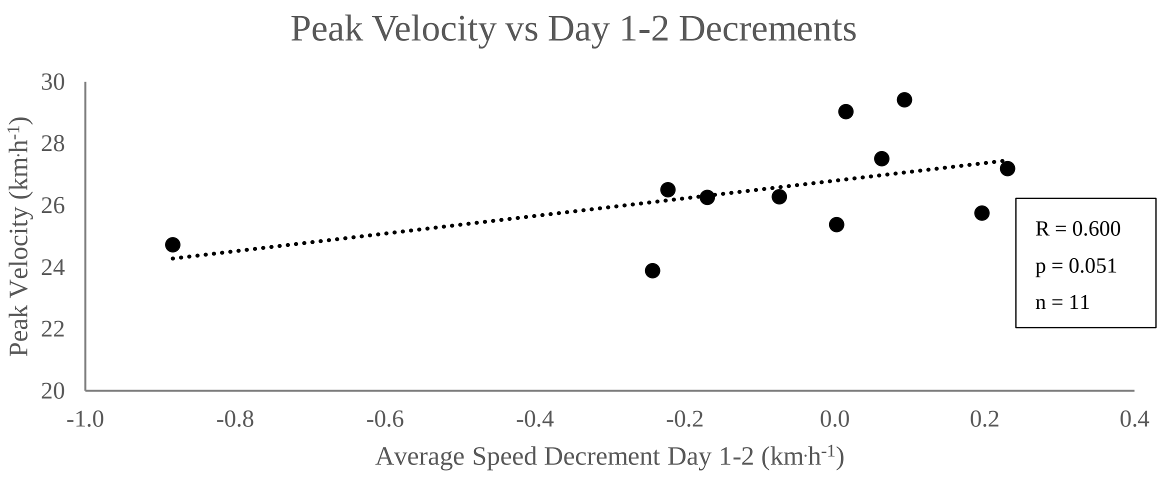

FIGURE 12: Relationship between peak velocity and average sprint decrement between days 1 and 2 of the tournament simulation.

There was no relationship between peak velocity and overall velocity decrement (Figure 13). With the datapoint at -4 km·h^{-1} excluded, no correlation was observed.

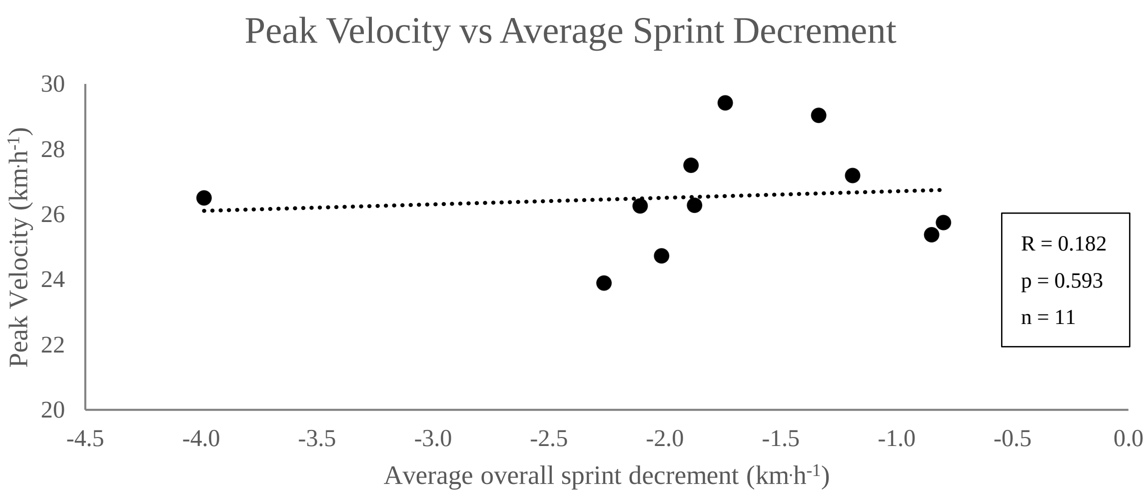

FIGURE 13: Relationship between peak velocity and average overall sprint decrement during both days of the tournament simulation.

8 DISCUSSION

The results of this study showed that international female rugby sevens athletes attain an average of 90-95% of their peak velocities during 30m sprints in a rugby sevens tournament simulation. It appears that velocity at LT2 was a good predictor of overall sprint decrement and sprint decrement between days 1 and 2 of a tournament simulation. It also showed lactate thresholds to be more strongly related to sprint decrements than VO_{2peak}. Finally, the study revealed that there was no significant relationship between initial sprint performance and sprint decrements over the course of a rugby sevens simulation.

8.1 Overall sprint decrements

Of particular interest in this study were that players experienced a sprint velocity decrement during the game simulations compared to their pre-tested peak velocities. Players sprinted on average 94% (Day 1) and 93% (Day 2) of their pre-tested peak velocities during games and only 2 players reached 98% of their pre-tested velocities during any games. The range of average sprint decrements were -0.8 $km \cdot h^{-1}$ to -4 $km \cdot h^{-1}$. The difference between pre-tested peak velocity and average velocity on day 1 and day 2 was statistically significant. This has implications for performance during a rugby sevens tournament if players are not able to reach maximum velocity at any point and if there is a physiological factor that can be trained to ensure higher % of peak velocity in match play.

Several studies have reported that peak velocities achieved during games do not match those measured in pre-testing. Misseldine et al. (2021) has demonstrated that elite female rugby sevens players achieve average peak velocities of 90-95% of their maximum during match play but that some players can reach up to 100%. Kyprianou et al. (2019) found that young male soccer players recorded higher peak velocities in 40m sprint tests than during match play. This was confirmed in several studies, which found that male players reached average peak velocities of ~90% of their recorded maximum (Massard et al. 2018, Al Haddad et al. 2015, Mendez-Villanueva et al. 2011). Contrary to other studies however, Massard et al. (2018) found that the absolute peak velocity recorded by players came during match play rather than sprint testing.

There are several factors that may influence the overall sprint decrement seen during the tournament simulation. Firstly, the sprint in the R7SP is only 30m long and it has been shown that athletes may take up to 6 seconds for elite female sprinters to reach peak velocity (Slawinski et al. 2017). This would support Kyprianou et al.'s (2019) assertion that maximum velocity is not reached during match play because of the relative short distances sprinted during games. This concern is mitigated by the fact that peak velocity was tested under the exact same conditions as those in the R7SP, with a 30m sprint followed by a 6m rapid deceleration. This presents a potential limitation to the study in that the peak velocity measured during the pre-testing may also not be representative of the participant's best and was limited by the testing conditions.

Fatigue may have played a significant part in the inability of athletes to reach peak velocity. Prior to each sprint in the R7SP is 88 seconds of high-intensity actions (tackle, run, ruck and shuttle) interspersed with low-intensity actions (walk, jog, rest). It is possible that peripheral fatigue such as that caused by acidosis or reduced PCr stores accumulated during these actions would contribute to relatively low sprint performance. The correlation between LT2 and overall sprint decrement would support this idea as a strong link has been demonstrated between lactate thresholds (vOBLA) and neuromuscular performance in jumping tasks (Baldi et al. 2017).

8.2 Relationship between aerobic capacity and sprint decrements

Velocity at the second lactate threshold (LT2) has a more positive correlation with sprint decrements during a rugby sevens tournament than VO_{2peak}. This is consistent with previous studies that have found RSA sprint decrement to be related to velocity at the onset of blood lactate accumulation (vOBLA) in male soccer players (Baldi et al. 2017). These findings are consistent with previous studies that show RSA sprint decrement to correlate more strongly with the second ventilatory threshold (VT2) than VO_{2peak}, in male ice hockey players (Lowery et al. 2018). Relationships between VT2 and LT2 have been shown in several studies (Burke et al. 1994, Edwards et al. 2003, Beaver et al. 1986). It has been proposed that thresholds based on blood lactate accumulation (vOBLA) may represent peripheral aspects of aerobic fitness such as capillary density and the transportation of lactate and H+ ions (Baldi et al. 2017). These peripheral factors have been highlighted as large contributors to RSA performance (Girard et al. 2012).

Aerobic capacity expressed as VO_{2peak} did not correlate with overall sprint decrements or decrements between day 1 and 2 of the tournaments. It has been suggested that for female athletes, aerobic capacity may be expressed as VO_2 / FFM to account for the 5-8% higher fat mass in women compared to men (Tarnopolsky, 2008, Carter et al. 2001). This adjustment still produced no significant correlation with day 1-2 decrement or overall sprint decrement.

A correlation between vVO_{2peak} and overall sprint decrement was statistically significant. Earlier correlations with vVO_{2peak} have shown larger volumes of high-speed running during soccer matches (Krustrup et al. 2003) and total distance covered in rugby matches (Swaby et al. 2016). This may contribute to the evidence that vVO_{2peak} is a better evaluation tool for running performance in games than VO_{2peak}.

8.3 The effect of initial sprint performance

Despite several studies linking initial sprint performance to repeated sprint performance (Hamilton et al. 1991, Bogdanis et al. 1996, Wadley and Le Rossignol, 1998), there was limited evidence for such a link in this study. Initial sprint performance did not correlate with overall sprint decrement. There was some correlation between initial sprint performance and day 1-2 sprint decrement, but this was not statistically significant. This indicates that initial sprint performance is not necessarily related to sprint decrement during a tournament simulation.

Misseldine et al. (2021) used expert coaches to examine the importance of 35 game clips where female players reached >90% of maximum velocity. Over half of the maximum velocity efforts were considered highly influential to the game outcome. This highlights the importance of training to improve maximum velocity in rugby sevens as it can have a significant impact on game outcome. However, this study does not provide evidence that a higher maximum velocity has any impact on an athlete’s ability to sprint repeatedly at maximum velocity. Other factors must explain sprint decrement.

8.4 Sprint performance between days

Several players increased their average speed on day 2 of the tournament. This is consistent with previous findings that there are no differences in CMJ height over the course of a 2-day tournament as both CMJ and maximum velocity can be used to evaluate neuromuscular performance (Clarke et al. 2015, Doeven et al. 2019).

Players in this study with higher LT2 were also able to run faster on the second day of the tournament than on the first day. This may be important in the context of Doeven et al.'s (2019) finding of moderate associations between high intensity running metres (>3.5 $m \cdot s^{-1}$) and perceived fatigue after tournament days. It has been proposed that players run higher relative distances both overall and at high speeds on day 2 of a tournament, however these findings were only trivial and may lack practical significance (Goodale et al. 2017). The authors of that study suppose that the increase in running may be due to an increase in intensity of competition during the knockout stages of a tournament. The increase in mean sprint speed observed in some participants on day 2 of this study is clearly not related to these findings as there was no competitive element to the tournament simulation.

It is important to note that the mean difference in peak velocity from day 1 to day 2 was negligible and not statistically significant, with most athletes falling within a range of -0.2 to 0.2 $km \cdot h^{-1}$. Although a correlation between sprint decrement between days and LT2, it has little practical significance given the relatively small decrements and increases seen.

8.5 The second lactate threshold and high intensity running

Studies into the running demands of field sports have extensively used GPS to record time and distance running in set velocity zones. These zones vary between studies and sports, and the terminology used is inconsistent (Cummins et al. 2013). Clarke et al. (2015) recommended that individual ventilatory thresholds be set for measuring high intensity running in female rugby sevens athletes, or that the ~5 $m \cdot s^{-1}$ (18 $km \cdot h^{-1}$) figure used in men's rugby was not appropriate for female athletes. A speed of 3.5 $m \cdot s^{-1}$ (12.6 $km \cdot h^{-1}$) was proposed as more appropriate. This built upon work by Abt et al. (2009) who recommended that the second ventilatory threshold would be a better descriptor of high intensity running than an arbitrary figure used by the GPS manufacturer.

The mean velocity at LT2 of the participants in this study was slightly lower than the figure proposed by Clarke et al. (2015) as high intensity running, which was based on the mean VT2 of seven international rugby sevens players. This may be explained by the difference in level of the player groups and the distinction between international athletes in different countries. This supports the argument for the use of individualised thresholds based on LT2 or VT2 for high-speed running. The standardised protocol used in the R7SP means that athletes completed the same amount of work at approximately the same time during every simulated game. Athletes with a higher LT2 will have had a smaller reliance on the anaerobic glycolysis as the aerobic system is able to provide ample replenishment of ATP to a higher intensity of exercise. This will result in less peripheral fatigue caused by accumulation of H+ ions, improved buffering of lactate (Girard et al. 2012, Gharbi et al. 2015) and an increased ability to repeatedly perform tasks with a high neuromuscular demand (Baldi et al. 2017). Tomlin and Wenger (2001) assert that accumulated H+ ions reduce the efficiency of metabolic pathways and slow recovery. It can be concluded that athletes with a higher LT2 would have accumulated less H+ and therefore would recover faster during the simulated games.

Fatigue resulting in peak sprint velocity decrements as seen in this study can result from either limitation of energy supply or accumulation of metabolic by-products (Girard et al. 2012). Changes in blood pH that are related to the accumulation of lactate have been linked to a reduction in phosphofructokinase activity and ultimately a reduction in the rate at which ATP is resynthesized (Hinojosa et al. 2021). A diminished availability of ATP would impact the ability to repeatedly perform high intensity actions such as sprinting to maximum velocity. Da Silva et al. (2010) state that vOBLA reflects peripheral training adaptations including transportation of lactate and H+ ions and is thus a good indicator of repeated sprint performance. Associations have been found between H+ accumulation, PCr degradation and muscular fatigue in soccer players (Balsom et al. 1992) that support this theory. However, Stackhouse et al. (2001) argued that although changes in pH caused by accumulation of H+ may be a contributing factor to fatigue, it is not a major factor. They assert that accumulation of inorganic phosphate has a more significant role in decreasing muscle force at the cross-bridge level. It is likely that a combination of factors contribute to the reductions in sprint performance seen during field sports.

8.6 Strengths and limitations of the study

There are several limitations with this study that must be taken into consideration when interpreting the results for practical application. Firstly, the population sample was relatively small and homogenous which makes conclusions drawn from correlation difficult to justify.

While the range of VO_{2peak} for most of the group was between 42 and 50 ml·min·kg^{-1}, one athlete had a VO_{2peak} of 38.9 ml·min·kg^{-1}. This athlete also demonstrated larger overall sprint decrement than other athletes (-4 km·h^{-1}). It is possible that a testing a population with a larger range of VO_{2peak} values would demonstrate some correlation between aerobic capacity and overall sprint decrement.

A second limitation is that the 30m sprint distance and 6m deceleration may not allow some of the athletes to reach peak velocity. Although the pre-sprint tests were conducted under the same conditions, the impact of peripheral fatigue may confound the results during the R7SP as the ability to perform maximal neuromuscular tasks is impaired (Baldi et al. 2017). Deceleration has been shown to have a higher impact on player load than acceleration in field sports (Dalen et al. 2016) and as the deceleration area was standardised at 6m, the players may not have reached peak velocity to ensure that they decelerated in time.

This study failed to control some factors that are specific to rugby sevens and to female sport. Firstly, no control was made for the athletes' menstrual status, which may have some impact on aerobic performance. Ventilation, thermoregulation, and energy substrate selection appear to be impacted by progesterone levels, for example (Constantini et al. 2005). Secondly, the study took place in the autumn when the weather in Finland is relatively cool. Rugby sevens is often played during the summer months and the climate can have an impact on the physiological responses of female rugby sevens athletes (Henderson et al. 2022).

The benefit of using the R7SP over a standard RSA test is that it reflects the demands of the sport, including some level of impact and contact work. This adds to the ecological validity of the study. The inclusion of the standardised 6m deceleration phase may also contribute to the ecological validity of the peak velocity testing but may require other variables than peak velocity to be tested. Acceleration, deceleration, momentum, 36m start-and-stop time or sprint times at fixed shorter distances may be more appropriate measures when using this protocol to quantify fatigue and recovery between exertions.

The R7SP is an extremely useful tool for standardising the physiological demands of a rugby sevens game and tournament that has strong ecological validity for use in a research environment (Furlan et al. 2016). It is of course impossible to replicate the contact demands and dynamic nature of the game in a standardised setting, so this limitation is difficult to overcome. The ‘tackle’ and ‘ruck’ segments of the R7SP allow for some standardised contact but do not represent the impacts that have been shown in rugby sevens, which occur at a higher density than in other forms of rugby and form a significant portion of the demands of the sport (Paul et al. 2022).

8.7 Conclusions

This study has demonstrated that LT2 is more important than VO_{2peak} in limiting the sprint decrement experienced during a rugby sevens tournament. It supports previous research demonstrating that lactate and ventilatory thresholds are more important than maximum aerobic capacity in RSA activities (Lowery et al. 2018, Baldi et al. 2017, da Silva et al. 2010). Higher lactate thresholds equate to a higher aerobic contribution to exercise and a reduction in peripheral fatigue caused by accumulation of H+, inorganic phosphate and lactate. Repeated performance of tasks with a high neuromuscular demand that are affected by peripheral fatigue, such as sprinting, are therefore related to LT2.

8.8 Practical Applications

This research has valuable practical applications for coaches and athletes in rugby sevens. The importance of maximal sprint velocity in rugby sevens has been previously demonstrated (Misseldine et al. 2021). The ability to perform sprints at maximum velocity and to maintain repeated performances appears to be related to the lactate thresholds. Coaches could therefore combine sprinting with training specifically aimed at increasing the intensity at which the second lactate threshold occurs. This will help athletes to achieve the sprint performances that they are capable of during real match play.

REFERENCES

Abt, G., Lovell, R. (2009). The use of individualized speed and intensity thresholds for determining the distance run at high-intensity in professional soccer. J Sports Sci, 27(9):893–8.

Abe, T., Kawamoto, K., Dankel, S. J., Bell, Z. W., Spitz, R. W., Wong, V. & Loenneke, J. P. (2020). Longitudinal associations between changes in body composition and changes in sprint performance in elite female sprinters. European journal of sport science, 20(1), 100-105. https://doi.org/10.1080/17461391.2019.1612950

Ahn, B., McMurray, R., Harrell, J. (2013). Scaling of VO2max and its relationship with insulin resistance in children. Pediatr Exerc Sci.25(1):43-51. doi: 10.1123/pes.25.1.43. PMID: 23406706.

Alghannam, A. F., Gonzalez, J. T. & Betts, J. A. (2018). Restoration of Muscle Glycogen and Functional Capacity: Role of Post-Exercise Carbohydrate and Protein Co-Ingestion. *Nutrients, 10*(2), 253. https://doi.org/10.3390/nu10020253

Al Haddad, H., Simpson, B. M., Buchheit, M., Di Salvo, V. & Mendez-Villanueva, A. (2015). Peak match speed and maximal sprinting speed in young soccer players: Effect of age and playing position. *International journal of sports physiology and performance, 10*(7), 888-896. https://doi.org/10.1123/ijspp.2014-0539

Archiza, B., Andaku, D.K., Beltrame, T., Libardi, C.A. & Borghi-Silva, A. (2020). The Relationship Between Repeated - Sprint Ability, Aerobic Capacity, and Oxygen Uptake Recovery Kinetics in Female Soccer Athletes. Journal of Human Kinetics, 75 (1), 115-126. https://doi.org/10.2478/hukin-2020-0042

Aziz, A. R., Chia, M., & Teh, K. C. (2000). The relationship between maximal oxygen uptake and repeated sprint performance indices in field hockey and soccer players. Journal of Sports Medicine and Physical Fitness, 40(3), 195-200.

Baldari, C., Videira, M., Madeira, F., Sergio, J. & Guidetti, L. (2005). Lactate removal during active recovery related to the individual anaerobic and ventilatory thresholds in soccer players. *European journal of applied physiology, 94*(1), 220. https://doi.org/10.1007/s00421-005-1320-9

Baldi, M., DA Silva, J. F., Buzzachera, C. F., Castagna, C. & Guglielmo, L. G. (2017). Repeated sprint ability in soccer players: Associations with physiological and neuromuscular factors. *The Journal of sports medicine and physical fitness, 57*(1-2), 26. https://doi.org/10.23736/S0022-4707.16.05776-5

Ball, S., Halaki, M. & Orr, R. (2019). Movement Demands of Rugby Sevens in Men and Women: A Systematic Review and Meta-Analysis. Journal of Strength and Conditioning Research, 33(12), pp. 3475-3490.

Balsom, P. D., Seger, J. Y., Sjödin, B., & Ekblom, B. (1992). Maximal-intensity intermittent exercise: effect of recovery duration. *International journal of sports medicine*, *13*(7), 528–533. https://doi.org/10.1055/s-2007-1021311

Beaver, W. L., Wasserman, K. & Whipp, B. J. (1986). A new method for detecting anaerobic threshold by gas exchange. *Journal of Applied Physiology, 60*(6), 2020-2027. https://doi.org/10.1152/jappl.1986.60.6.2020

Bishop, D., Edge, J. (2006). Determinants of repeated-sprint ability in females matched for single-sprint performance. European Journal of Applied Physiology 97, 373–379 https://doi.org/10.1007/s00421-006-0182-0

Bogdanis, G.C., Nevill, M.E., Boobis, L.H. & Lakomy, H.K. (1996). Contribution of phosphocreatine and aerobic metabolism to energy supply during repeated sprint exercise. Journal of Applied Physiology, 80 (3), 876-884. https://doi.org/10.1152/jappl.1996.80.3.876

Burke, J., Thayer, R. & Belcamino, M. (1994). Comparison of effects of two interval-training programmes on lactate and ventilatory thresholds. *British journal of sports medicine, 28*(1), 18-21. https://doi.org/10.1136/bjsm.28.1.18

Carter, S., McKenzie, S., Mourtzakis, M., Mahoney, D.J., Tarnopolsky, M.A. (2001). Short-term 17beta-estradiol decreases glucose R(a) but not whole body metabolism during endurance exercise. J Appl Physiol, 90(1):139–46.

Clarke, A.C., Presland, J., Rattray, B. & Pyne, D.B. (2013). Critical velocity as a measure of aerobic fitness in Women's rugby Sevens. Journal of Science and Medicine in Sport, 17 (1), 144-148. https://doi.org/10.1016/j.jsams.2013.03.008

Clarke A, Anson J & Pyne D. (2015) Physiologically based GPS speed zones for evaluating running demands in Women’s Rugby Sevens, Journal of Sports Sciences, 33:11.

Clarke, A. C., Anson, J. M. & Pyne, D. B. (2015). Neuromuscular Fatigue and Muscle Damage After a Women's Rugby Sevens Tournament. *International journal of sports physiology and performance, 10*(6), 808-814. https://doi.org/10.1123/ijspp.2014-0590

Constantini, N. W., Dubnov, G. & Lebrun, C. M. (2005). The Menstrual Cycle and Sport Performance. *Clinics in sports medicine, 24*(2), pp. e51-e82. doi:10.1016/j.csm.2005.01.003

Cooke, S., Petersen, S. & Quinney, H. (1997). The influence of maximal aerobic power on recovery of skeletal muscle following anaerobic exercise. Eur J Appl Physiol 75, 512–519. https://doi.org/10.1007/s004210050197

Cummins, C., Orr, R., O'Connor, H. & West, C. (2013). Global positioning systems (GPS) and microtechnology sensors in team sports: A systematic review. Sports Medicine, 43, 1025–1042.

Cunniffe, B., Proctor, W., Baker, J. S., & Davies, B. (2009). An evaluation of the physiological demands of rugby union using global positioning system tracking software. Journal of Strength and Conditioning Research, 23(4), 1195-203

da Silva, J. F., Guglielmo, L. G. A. & Bishop, D. (2010). Relationship Between Different Measures of Aerobic Fitness and Repeated-Sprint Ability in Elite Soccer Players. *Journal of strength and conditioning research, 24*(8), 2115-2121. https://doi.org/10.1519/JSC.0b013e3181e34794

Dalen, T., Jørgen, I., Gertjan, E., Geir H.H., Ulrik, W. (2016). Player Load, Acceleration, and Deceleration During Forty-Five Competitive Matches of Elite Soccer, Journal of Strength and Conditioning Research. 30(2), 351-359. doi: 10.1519/JSC.0000000000001063

Devlin, J., Paton, B., Poole, L., Sun, W., Ferguson, C., Wilson, J. & Kemi, O. J. (2014). Blood lactate clearance after maximal exercise depends on active recovery intensity. *Journal of sports medicine and physical fitness, 54*(3), 271-278.

Doeven, S.H., Brink, M.S., Huijgen, B.C.H., de Jong, J. & Lemmink, K.A.P.M. (2019). High Match Load's Relation to Decreased Well-Being During an Elite Women's Rugby Sevens Tournament. International Journal of Sports Physiology and Performance, 14 (8), 1036-1042. https://doi.org/10.1123/ijspp.2018-0516

Douglas, J., Plews, D.J., Handcock, P.J. & Rehrer, N.J. (2016). The Beneficial Effect Of Parasympathetic Reactivation On Sympathetic Drive During Simulated Rugby Sevens. International Journal of Sports Physiology and Performance, 11 (4), 480-488. https://doi.org/10.1123/ijspp.2015-0317

Duke, J. (2017). Sex Hormones and Their Impact on the Ventilatory Responses to Exercise and the Environment . In Hackney, A. C. *Sex Hormones, Exercise and Women: Scientific and Clinical Aspects*. Springer International Publishing.

Edwards, A. M., Clark, N. & Macfadyen, A. M. (2003). Lactate and Ventilatory Thresholds Reflect the Training Status of Professional Soccer Players Where Maximum Aerobic Power is Unchanged. *Journal of sports science & medicine, 2*(1), 23-29.

Flatt, A. A., Howells, D. & Williams, S. (2019). Effects of consecutive domestic and international tournaments on heart rate variability in an elite rugby sevens team. *Journal of science and medicine in sport, 22*(5), 616-621. https://doi.org/10.1016/j.jsams.2018.11.022

Furlan, N., Waldron, M., Shorter, K., Gabbett, T. J., Mitchell, J., Fitzgerald, E., . . . Gray, A. J. (2015). Running-Intensity Fluctuations in Elite Rugby Sevens Performance. International journal of sports physiology and performance, 10(6), 802-807. https://doi.org/10.1123/ijspp.2014-0315

Furlan, N., Waldron, M., Osborne, M. & Gray, A. J. (2016). Ecological Validity and Reliability of the Rugby Sevens Simulation Protocol. International journal of sports physiology and performance, 11(6), 749-755. https://doi.org/10.1123/ijspp.2015-0487

Gabbett, T. J. (2016). Influence of Fatigue on Tackling Ability in Rugby League Players: Role of Muscular Strength, Endurance, and Aerobic Qualities. PloS one, 11(10), e0163161. https://doi.org/10.1371/journal.pone.0163161

Gastin, P. B. (2001). Energy System Interaction and Relative Contribution During Maximal Exercise. *Sports Medicine, 31*(10), 725-741. https://doi.org/10.2165/00007256-200131100-00003

Girard, O., Mendez-Villanueva, A. & Bishop, D. (2012). Repeated-Sprint Ability — Part I: Factors Contributing to Fatigue. *Sports medicine (Auckland), 41*(8), 673-694. https://doi.org/10.2165/11590550-000000000-00000

Gharbi, Z., Dardouri, W., Haj-Sassi, R., Chamari, K., & Souissi, N. (2015). Aerobic and anaerobic determinants of repeated sprint ability in team sports athletes. Biology of sport, 32(3), 207–212. https://doi.org/10.5604/20831862.1150302

Goodale, T.L., Gabbett, T.J., Tsai, M., Stellingwerff, T. & Sheppard, J. (2017). The Effect of Contextual Factors on Physiological and Activity Profiles in International Women's Rugby Sevens. International Journal of Sports Physiology and Performance, 12 (3), 370-376. https://doi.org/10.1123/ijspp.2015-0711

Greenwood, J. D., Moses, G. E., Bernardino, F. M., Gaesser, G. A. & Weltman, A. (2008). Intensity of exercise recovery, blood lactate disappearance, and subsequent swimming performance. *Journal of sports sciences, 26*(1), 29-34. https://doi.org/10.1080/02640410701287263

Hamilton, A., Nevill, M., Brooks, S. & Williams, C. (1991). Physiological Responses to maximal intermittent exercise: Differences between Endurance-trained Runners and games players. Journal of sports sciences, 9 (4), 371-382. https://doi.org/10.1080/02640419108729897

Harper, D. J., Carling, C. & Kiely, J. (2019). High-Intensity Acceleration and Deceleration Demands in Elite Team Sports Competitive Match Play: A Systematic Review and Meta-Analysis of Observational Studies. Sports medicine (Auckland), 49(12), 1923-1947. https://doi.org/10.1007/s40279-019-01170-1

Heil DP. (1997). Body mass scaling of peak oxygen uptake in 20- to 79-yr-old adults. Medicine and Science in Sports and Exercise. 29(12):1602-1608. DOI: 10.1097/00005768-199712000-00009. PMID: 9432093.

Henderson, M. J., Chrismas, B. C. R., Fransen, J., Coutts, A. J. & Taylor, L. (2022). Responses to a 5-Day Sport-Specific Heat Acclimatization Camp in Elite Female Rugby Sevens Athletes. *International journal of sports physiology and performance,* 1-10. https://doi.org/10.1123/ijspp.2021-0406

Higham D.G., Pyne D.B., Anson J.M. (2012). Movement patterns in rugby sevens: Effects of tournament level, fatigue and substitute players. J Sci Med Sport. 15(3):277-282

Hinojosa, J. N., Hearon, C. M. & Kowalsky, R. J. (2021). Blood lactate response to active recovery in athletes vs. non-athletes. *Sport sciences for health, 17*(3), 699-705. https://doi.org/10.1007/s11332-021-00735-w

Jones, R.M., Cook, C.C., Kilduff, L.P., Milanović, Z., James, N., Sporiš, G.,. . . Vučković, G. (2013). Relationship between Repeated Sprint Ability and Aerobic Capacity in Professional Soccer Players. The Scientific World, 2013 , 952350-5. https://doi.org/10.1155/2013/952350

Kane, D. A. (2014). Lactate oxidation at the mitochondria: A lactate-malate-aspartate shuttle at work. *Frontiers in neuroscience, 8*, 366. https://doi.org/10.3389/fnins.2014.00366

Kemp, G. (2005). Lactate accumulation, proton buffering, and pH change in ischemically exercising muscle. *American journal of physiology. Regulatory, integrative and comparative physiology, 289*(3), R895-R901. https://doi.org/10.1152/ajpregu.00641.2004

Keskinen, K., Häkkinen, K., Kallinen, M. (2018). Fyysisen kunnon mittaaminen – käsi- ja oppikirja kuntotestaajille. Helsinki: Liikuntatieteellinen Seura ry, 174.

Krustrup, P., Mohr, M., Amstrup, T., Rysgaard, T., Johansen, J., Steensberg, A., Bangsbo, J. (2003). The Yo-Yo intermittent recovery test: Physiological response, reliability, and validity. Medicine and science in sports and exercise, 35 (4), 697-705. https://doi.org/10.1249/01.MSS.0000058441.94520.32

Kyprianou, E., Di Salvo, V., Lolli, L., Al Haddad, H., Villanueva, A. M., Gregson, W. & Weston, M. (2019). To Measure Peak Velocity in Soccer, Let the Players Sprint. *Journal of strength and conditioning research, 36*(1), 273-276. https://doi.org/10.1519/JSC.0000000000003406

Lambert, C. P., Winchester, L., Jacks, D. A. & Nader, P. A. (2013). Sex differences in time to fatigue at 100% VO2 peak when normalized for fat free mass. Research in sports medicine, 21(1), 78-89. https://doi.org/10.1080/15438627.2012.697809

Landgraff, H. W., Riiser, A., Lihagen, M., Skei, M., Leirstein, S. & Hallén, J. (2021). Longitudinal changes in maximal oxygen uptake in adolescent girls and boys with different training backgrounds. Scandinavian journal of medicine & science in sports, 31(S1), 65-72. https://doi.org/10.1111/sms.13765

Lowery, M. R., Tomkinson, G. R., Peterson, B. J. & Fitzgerald, J. S. (2018). The relationship between ventilatory threshold and repeated-sprint ability in competitive male ice hockey players. *Journal of exercise science and fitness, 16*(1), 32-36. https://doi.org/10.1016/j.jesf.2018.03.003

Lundby, C., Montero, D. & Joyner, M. (2017). Biology of VO2max: Looking under the physiology lamp. *Acta Physiologica, 220*(2), 218-228. https://doi.org/10.1111/apha.12827

Malone S, Earls M, Shovlin A, Eddy A, Winkelman N. (2020). Match-Play Running Performance and Exercise Intensity in Elite International Women's Rugby Sevens. J Strength Cond Res. 34(6):1741-1749.

Massard, T., Eggers, T. & Lovell, R. (2018). Peak speed determination in football: Is sprint testing necessary? *Science and medicine in football, 2*(2), 123-126. https://doi.org/10.1080/24733938.2017.1398409

McArdle W., Katch F. & Katch V. (2015). Exercise physiology: Nutrition, energy, and human performance (8 painos). Baltimore, MD: Wolters Kluwer Health.

McLaughlin, J. E., Howley, E. T., Bassett, D. R., Jr, Thompson, D. L., & Fitzhugh, E. C. (2010). Test of the classic model for predicting endurance running performance. Medicine and science in sports and exercise, 42(5), 991–997. https://doi.org/10.1249/MSS.0b013e3181c0669d

McMahon, S. & Jenkins, D. (2002). Factors Affecting the Rate of Phosphocreatine Resynthesis Following Intense Exercise. *Sports Medicine, 32*(12), 761-784. https://doi.org/10.2165/00007256-200232120-00002

McMahon, S., & Wenger, H. A. (1998). The relationship between aerobic fitness and both power output and subsequent recovery during maximal intermittent exercise. Journal of science and medicine in sport, 1(4), 219–227. https://doi.org/10.1016/s1440-2440(09)60005-0

Mendez-Villanueva, A., Buchheit, M., Simpson, B., Peltola, E. & Bourdon, P. (2011). Does On-Field Sprinting Performance in Young Soccer Players Depend on How Fast They Can Run or How Fast They Do Run? *Journal of strength and conditioning research, 25*(9), 2634-2638. https://doi.org/10.1519/JSC.0b013e318201c281

Misseldine, N. D., Blagrove, R. C. & Goodwin, J. E. (2021). Speed Demands of Women's Rugby Sevens Match Play. *Journal of strength and conditioning research, 35*(1), 183-189. https://doi.org/10.1519/JSC.0000000000002638

Morgan, D. W., Baldini, F. D., Martin, P. E., & Kohrt, W. M. (1989). Ten kilometer performance and predicted velocity at VO2max among well-trained male runners. Medicine and science in sports and exercise, 21(1), 78–83. https://doi.org/10.1249/00005768-198902000-00014

Murray, A.M. and Varley, M.C. (2015). Activity Profile of International Rugby Sevens: Effect of Scoreline, Opponent and Substitutes. Int J Sports Physiol Perform. 10(6):791-802.

Paul, L., Naughton, M., Jones, B., Davidow, D., Patel, A., Lambert, M. & Hendricks, S. (2022). Quantifying Collision Frequency and Intensity in Rugby Union and Rugby Sevens: A Systematic Review. *Sports medicine - open, 8*(1), 12. https://doi.org/10.1186/s40798-021-00398-4

Portillo, J., González-Ravé, J.M., Juárez, D., García, J.M., Suárez-Arrones, L., Newton, R.U. (2014). Comparison of running characteristics and heart rate response of international and national female rugby sevens players during competitive matches. J Strength Cond Res. 28(8):2281-9.

Rampinini, E., Sassi, A., Morelli, A., Mazzoni, S., Fanchini, M. and Coutts, A.J. (2009). Repeated-sprint ability in professional and amateur soccer players. Applied Physiology, Nutrition, and Metabolism. 34(6): 1048-1054. https://doi.org/10.1139/H09-111

Ross, A., Gill, N. & Cronin, J. (2013). Match Analysis and Player Characteristics in Rugby Sevens. Sports medicine (Auckland), 44 (3), 357-367. https://doi.org/10.1007/s40279-013-0123-0

Ross, A., Gill, N., and Cronin, J. (2015) The match demands of international rugby sevens. J Sports Sci. 33(10):1035-1041.

Sella, S., Mcmaster, T., Beaven, M., Gill, D. & Hébert-Losier, D. (2019). Match Demands, Anthropometric Characteristics, and Physical Qualities of Female Rugby Sevens Athletes: A Systematic Review. Journal of Strength and Conditioning Research, 33(12), pp. 3463-3474.

Slawinski, J., Termoz, N., Rabita, G., Guilhem, G., Dorel, S., Morin, J. & Samozino, P. (2017). How 100-m event analyses improve our understanding of world-class men's and women's sprint performance. *Scandinavian journal of medicine & science in sports*, *27*(1), 45-54. https://doi.org/10.1111/sms.12627

Stackhouse, S. K., Reisman, D. S. & Binder-Macleod, S. A. (2001). Challenging the role of pH in skeletal muscle fatigue. *Physical therapy*, *81*(12), 1897-1903. https://doi.org/10.1093/ptj/81.12.1897

Stanula, A., Roczniok, R., Maszczyk, A., Pietraszewski, P., & Zając, A. (2014). The role of aerobic capacity in high-intensity intermittent efforts in ice-hockey. Biology of sport, 31(3), 193–199. https://doi.org/10.5604/20831862.1111437

Swaby, R., Jones, P.A. & Comfort, P. (2016). Relationship Between Maximum Aerobic Speed Performance and Distance Covered in Rugby Union Games. Journal of Strength and Conditioning Research, 30 (10), 2788-2793. https://doi.org/10.1519/JSC.0000000000001375

Suarez-Arrones L., Arenas C., Lopez, G. (2013). Positional Differences in Match Running Performance and Physical Collisions in Men Rugby Sevens. Int J Sports Physiol Perform. 9(2):316-23.

Suarez-Arrones, J., Nuñez, J., Portillo, J. & Mendez-Villanueva, J. (2012). Match Running Performance and Exercise Intensity in Elite Female Rugby Sevens. Journal of Strength and Conditioning Research, 26(7), 1858-1862.

Swanwick, E. & Matthews, M. (2018). Energy Systems: A New Look at Aerobic Metabolism in Stressful Exercise. MOJ Sports Medicine. 2. 10.15406/mojsm.2017.02.00039.

Takahashi, I., Umeda, T., Mashiko, T., Chinda, D., Oyama, T., Sugawara, K. & Nakaji, S. (2007). Effects of rugby sevens matches on human neutrophil-related non-specific immunity. British journal of sports medicine, 41(1), 13-18. https://doi.org/10.1136/bjsm.2006.027888

Tarnopolksy, M. A. (2008). Sex Differences in Exercise Metabolism and the Role of 17-Beta Estradiol. Medicine & Science in Sports & Exercise. 40(4), 648-654 doi: 10.1249/MSS.0b013e31816212ff

Tomlin, D. L. & Wenger, H. A. (2001). The Relationship Between Aerobic Fitness and Recovery from High Intensity Intermittent Exercise. *Sports medicine (Auckland), 31*(1), 1-11. https://doi.org/10.2165/00007256-200131010-00001

Vescovi J and Goodale T. (2015). Physical Demands of Women's Rugby Sevens Matches: Female Athletes in Motion (FAiM) Study International Journal of Sports Medicine. 36(11): 887 – 892

Vesterinen, V., Nummela, A., Heikura, I., Laine, T., Hynynen, E., Botella, J. & Häkkinen, K. (2016). Individual Endurance Training Prescription with Heart Rate Variability. *Medicine and science in sports and exercise, 48*(7), 1347-1354. https://doi.org/10.1249/MSS.0000000000000910

Wadley, G. & Le Rossignol, P. (1998). The relationship between repeated Sprint ability and the aerobic and anaerobic energy systems. Journal of Science and Medicine in Sport, 1 (2), 100-110. https://doi.org/10.1016/S1440-2440(98)80018-2

Welsman, J.R., Armstrong, N., Nevill, A.M., Winter, E.M., Kirby, B.J. (1996). Scaling peak VO2 for differences in body size. Medicine and Science in Sports and Exercise. 28(2):259-265. DOI: 10.1097/00005768-199602000-00016. PMID: 87751

Weltman A, Stamford BA, Moffatt RJ, Katch VL (1977) Exercise recovery, lactate removal, and subsequent high intensity exercise performance. Res Q 48(4):786–796

West, D. J., Cook, C. J., Stokes, K. A., Atkinson, P., Drawer, S., Bracken, R. M. & Kilduff, L. P. (2013). Profiling the time-course changes in neuromuscular function and muscle damage over two consecutive tournament stages in elite rugby sevens players. *Journal of science and medicine in sport, 17*(6), 688-692. https://doi.org/10.1016/j.jsams.2013.11.003