

**DEVELOPMENT OF A NON-MOTORISED TREADMILL
PROCEDURE TO ASSESS THE PERFORMANCE OF
REPEATED-SPRINT EXERCISE**

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LIST OF ABBREVIATIONS

ADP	- Adenosine diphosphate
AK	- Adenylate kinase
AMP	- Adenosine monophosphate
ATP	- Adenosine triphosphate
AvF	- Average of all average (6 s) forces achieved by a subject through an RSE test (N).
AvPO	- Average of all average (6 s) power outputs achieved by a subject through an RSE test (W).
AvSp	- Average of all average (6 s) velocities achieved by a subject through an RSE test ($\text{m}\cdot\text{s}^{-1}$).
Ca^{2+}	- Calcium ion
CHO	- Carbohydrates
CK	- Creatine kinase
Cr	- Creatine
H^+	- Hydrogen ion
HR	- Heart rate
HR max	- Maximal heart rate
[La]	- Blood lactate concentration
MxSp	- Average of all maximal 1-s velocities achieved by a subject through an RSE test ($\text{m}\cdot\text{s}^{-1}$).
NMT	- Non-motorised treadmill
PCr	- Phosphocreatine
P_i	- Inorganic phosphate
RSE	- Repeated sprint exercise
$\dot{\text{V}}\text{O}_2$	- Rate of oxygen consumption
$\dot{\text{V}}\text{O}_{2 \text{ max}}$	- Maximal rate of oxygen consumption

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ABSTRACT

The ability to perform repeated-sprint exercise is a requirement for competitors in many sports although no previous studies have sought to devise and validate a reliable test of repeated sprint performance using running as the activity mode. Therefore the aim of the studies in this thesis was to devise a repeated sprint performance test using non-motorised treadmill ergometry.

In study I, the reliability of a repeated sprint procedure was investigated and there was found to be no significant difference in any of the performance variables across the three trials of this study ($P>0.05$). Good reliability was observed for the measures of sprint velocity and power, especially when the mean of the mean 6 –s values were taken as the dependent variables.

In study II the time between successive sprints was manipulated in order to establish the most appropriate recovery duration for the repeated sprint test. By applying criteria that the repeated sprint procedure should elicit physiological responses similar to those observed in game-sports competition while also causing a fatigue in performance, a 10 x (6 –s sprint, on 40s) procedure was selected as the procedure for use in later studies.

In studies III, IV and V the validity and sensitivity of the procedure from study II were assessed. In study III, a group of game-sports competitors were monitored over seven weeks at the start of their competitive season. Their maximal rate of oxygen consumption and repeated-sprint performance both improved significantly, demonstrating sensitivity and construct validity of the repeated sprint test. In study IV, the validity of the repeated sprint test was further demonstrated when measures of velocity were compared between non-motorised treadmill and over-ground sprinting and observed to give related results. Other than training, few interventions have been shown to enhance repeated sprint performance. Frequently, however, creatine supplementation has been shown to do so although study V showed that the repeated sprint test performance was not affected by short-term creatine supplementation.

In conclusion these studies have shown that the present repeated-sprint test can be used to provide a valid and reliable assessment of the ability to perform repeated sprints. It is recommended that future studies in this area adopt standardised procedures, like those proposed in this study, for the assessment of repeated-sprint performance.

CHAPTER 1. INTRODUCTION

The ability to perform repeated bouts of high-intensity exercise is vital in the performance of many activities and sports (Balsom *et al.*, 1992b; Bangsbo, 2000; Tomlin and Wenger, 2001). The 'game-sports' (i.e., field games, racket sports and the court sports) generally require prolonged activity where the outcome is frequently determined by the ability to exercise repeatedly at a very high intensity for a short period of time (Ghosh *et al.*, 1990; Reilly, 1997; Christmass *et al.*, 1998; Deutsch *et al.*, 2007). Although it is difficult to generalise about the physiological requirements for this range of sports, it is generally accepted that short-term, high-intensity work, sustained throughout the duration of a match requires activation of both oxidative phosphorylation and substrate level phosphorylation (i.e., 'aerobic' and 'anaerobic' metabolic pathways, respectively; Balsom *et al.*, 1992b; McMahon and Wenger, 1998; Bangsbo, 2000).

The performance of a single bout of high-intensity exercise (i.e., a 'sprint') is based on a wide array of physiological abilities. For example, high strength, anaerobic power and anaerobic capacities will all impact on the performance of a single sprint (Ross and Leveritt, 2001). The intensity required for a sprint will necessitate near-maximal muscle fibre recruitment (Achten *et al.*, 1990) and a rapid activation of substrate-level phosphorylation (Harris *et al.*, 1976; Gaitanos *et al.*, 1993). A consequence of sprint performance is the rapid development of intramuscular fatigue, probably due to a loss of energy substrates, an accumulation of metabolic by-products and an increased acidity resulting from the heavy exercise (Cooke *et al.*, 1997a; Hargreaves *et al.*, 1998; McMahon and Jenkins, 2002; Westerblad *et al.*, 2002). When subsequent sprints are performed, there may be a delay before a maximal effort can be produced once again (Balsom *et al.*, 1992a; Glaister, 2005). It is unclear which mechanisms promote fatigue or recovery from a sprint but it is likely that factors related to oxygen availability (Balsom *et al.*, 1994a), oxidative capacity (Paganini *et al.*, 2000) and maximal rate of oxygen consumption ($\dot{V}O_2$ max; McMahon and Jenkins, 2002) help to promote recovery. The high energetic demands of sprint exercise, combined with the need to recover from those sprints supports the notion that repeated-sprint exercise requires an integrated response from the aerobic and anaerobic metabolic pathways.

The literature provides examples of established tests that attempt to evaluate the extent of ATP resynthesis which is possible from either aerobic or anaerobic processes in isolation (e.g., $\dot{V}O_2$ max, the Wingate anaerobic test, respectively). However, Dawson *et al.* (1991) have recommended that game-sports competitors should also be assessed

using repeated-sprint exercise (RSE) procedures that combine aerobic and anaerobic metabolic processes.

The most common approach to evaluate the repeated sprint performance of game-sports competitors has been to use performance tests that require subjects to perform repeated short-duration, high-intensity exercise bouts. For the purpose of the present thesis, these procedures have been termed repeated-sprint exercise tests ('RSE tests') (further defined in Appendix 1). The outcomes of typical RSE tests are usually a measure of fatigue in conjunction with the average or peak performance in the series of sprints (Dawson *et al.*, 1993; Wadley and LeRossignol, 1998; Glaister *et al.*, 2005). Modifications in each aspect of the RSE test procedures (i.e., sprint duration, number of sprints, rest duration, work:rest ratio, exercise mode) have been shown to have a significant impact on test performance (Dawson *et al.*, 1991; Balsom *et al.*, 1992a; Holmyard *et al.*, 1994; Ratel *et al.*, 2004) but the RSE tests that have already been used show a wide variation in all of these procedural variables. A summary of the many RSE tests that have been published (Appendix 1) shows that there is no standardisation in the procedures that are used by investigators, so by implication, there are no reference values for the performance of this type of activity.

The diversity of the RSE procedures currently in use also means that it is impossible to compare different studies for the results of physiological measurements made during RSE performance. In other areas of physiological assessment, for example, the assessment of endurance performance, an athlete may benefit from evaluations which are based on measuring their physiological responses to activity (e.g., exercise economy, $\dot{V}O_{2\max}$ or their blood lactate response). These tests give information that is additional to performance measures and they can help to optimise preparation for competition as well as helping to understand the athlete's physiological characteristics. In the assessment of repeated sprint performance, however, there appears to have been no attempt to investigate the use of physiological variables that may give additional feedback to the athlete's performance characteristics. The absence of physiological markers which can be used to assess the ability to perform repeated-sprint exercise may be surprising given the fact that previous authors have supplied some evidence that rapid adjustments in heart rate (Edwards *et al.*, 2003) and $\dot{V}O_2$ (Dupont *et al.*, 2005) could relate to the ability to recover during repeated-sprint exercise.

To date, there have been few attempts to validate RSE tests even though such procedures are becoming frequently reported in the literature (Spencer *et al.*, 2005). The only authors who have systematically set out to devise an RSE test have investigated its validity (Bishop *et al.*, 2001) and reliability (Fitzsimons *et al.*, 1993). However, their selection of cycling as the exercise mode has been criticised, even from within their own research group (Fitzsimons *et al.*, 1993; Spencer *et al.*, 2005), as cycling is an activity that is not specific for the assessment of performance in game-sport competitors. Although these procedures, first proposed by Dawson *et al.* (1993), have been shown to be valid and reliable, no other investigators have adopted their procedures even when using cycling as the mode of exercise for their RSE test (e.g., Balsom *et al.*, 1994b; Capriotti *et al.*, 1999; Heller and Psotta, 1999; Tomlin and Wenger, 2002). Therefore, the majority of the published studies of RSE performance have used procedures which have not been investigated for their reliability or validity, meaning that the testing of RSE performance is currently based on procedures that are not standardised and that may not be valid or reliable.

The current literature has examples of investigators who have used cycling (Dawson *et al.*, 1993; McMahon and Wenger, 1998), over-ground running (Aziz *et al.*, 2000; Dupont *et al.*, 2005) or non-motorised treadmill (NMT) running (Holmyard *et al.*, 1988; Hamilton *et al.*, 1991) as exercise modes for RSE testing. For competitors in most sports, over-ground running is more sport-specific than cycling but may lack some of the experimental control and precision which is possible using laboratory testing. The development of NMT systems (Lakomy, 1987) has allowed for laboratory-based assessment of sprinting and this apparatus has already been used for the assessment of performance in single (Cheetham *et al.*, 1986; Tong *et al.*, 2001) and repeated sprints (Holmyard *et al.*, 1988; Hamilton *et al.*, 1991). An additional advantage of the NMT is that it allows for the assessment of haematological, metabolic and respiratory variables which may be impractical in the field-based setting. This is especially important for the assessment of RSE, as there are currently no physiological correlates of RSE performance. Although the NMT has previously been used for RSE testing, no published work exists which documents the reliability or validity of the NMT as a piece of equipment for the evaluation of RSE performance.

Although there has been a recent proliferation of research into the physiology of repeated sprint performance, the procedures that are currently used for these

investigations lack standardisation and have not been shown to demonstrate reliability or validity.

Aims and objectives

The primary aim of these studies, therefore, was to investigate whether a valid, reliable and sensitive assessment of the ability to perform repeated sprints could be developed using non-motorised treadmill sprinting. Specifically, this aim was addressed using the following objectives:-

1. To establish a reliable repeated-sprint procedure.
2. To establish the appropriate post-sprint recovery duration that would approach the physiological demands of repeated-sprint sports performance while also causing fatigue in sprint performance.
3. To demonstrate the sensitivity and construct validity of the test procedure by use of short-term and long-term interventions which have previously been shown to enhance repeated-sprint performance (creatine supplementation and repeated sprint training, respectively).
4. To demonstrate the effects of performing the repeated-sprint test using a non-motorised treadmill in comparison with those achieved in over-ground sprinting.

The secondary aim of these studies was to investigate whether certain physiological measures could be used as indicators of the ability to perform repeated-sprint exercise. To achieve this aim, the effect of the manipulations listed above (objectives 2 and 3) on changes in the rate of oxygen consumption and heart rate recovery were monitored to establish whether these physiological variables were related to repeated-sprint performance.

CHAPTER 2. REVIEW OF LITERATURE

Background to the Physiology of Repeated-Sprint Exercise

The pioneering research into the physiology of repeated sprints established that the energetic requirements of intermittent exercise were different from those of continuous work. Rest periods between bouts of exercise were shown to allow more work to be done before fatigue in comparison to performing the same average intensity continuously (Åstrand *et al.*, 1960b). Even when exercise intensity and work:rest ratios were controlled for, variations in the exercise duration were found to have a major impact on the physiological responses to exercise (Åstrand *et al.*, 1960a). Clearly, the physiological response was not purely determined by the intensity of exercise but also by its duration and the work:rest ratio. Two studies (Åstrand *et al.*, 1960a; Margaria *et al.*, 1969) were conducted in which the overall amount of exercise performed was controlled for (work done in cycling or distance covered in running, respectively) to investigate the physiological differences between continuous and intermittent work. It was shown that, even for relatively high-intensity exercise, blood lactate concentration ([La]) could be maintained at low levels provided that exercise duration was kept fairly short and that the intervening rest period was relatively long. Margaria *et al.* (1969) stated that short-duration exercise could be maintained 'indefinitely' provided that an intervening period of sufficient length was used. However, with longer work periods, shorter rest periods or increased work:rest ratios, [La] rose and fatigue occurred far more rapidly. In contrast, cardiorespiratory measures (the rate of oxygen consumption - $\dot{V}O_2$ and heart rate) for a given overall amount of exercise performed, were relatively unaffected by alterations in these temporal factors (Åstrand *et al.*, 1960b). Additionally, substrate metabolism was observed to be altered when work was undertaken intermittently, with Christensen *et al.* (1960) noting a relatively high contribution from lipid metabolism with shorter periods of work.

The conclusion to be drawn from these studies was that the physiological responses to intermittent exercise should be considered as distinct to those from continuous activity. While the explanations for the findings of these early researchers are now more advanced, the principles of their findings remain true: that once exercise is followed by recovery and then repeated, many temporal factors and physiological mechanisms must be considered that are less important in the performance of continuous exercise (Essen and Kaijser, 1978; McCartney *et al.*, 1986).

Overview of repeated-sprint exercise metabolism

The mechanisms used to explain the findings of these early researchers centred around the apparent lack of anaerobic contribution to intermittent, high-intensity work which conflicted with the high blood lactate accumulation that resulted from continuous high-intensity work. It was proposed that myoglobin acted as an intramuscular store for limited amounts of oxygen which could be readily accessed to allow aerobic resynthesis of adenosine tri-phosphate (ATP), irrespective of exercise intensity (Åstrand *et al.*, 1960a). As these stores would be rapidly depleted and replenished, this aerobic contribution to intermittent exercise was consistent with the apparent lack of anaerobic metabolism seen with short work and short rest periods. More recently, the mechanisms which influence high-intensity, intermittent activity have been studied more thoroughly. While the role of myoglobin has not been dismissed (Dupont *et al.*, 2004b), enhanced knowledge of intracellular metabolism has provided more insight into the factors which differentiate intermittent, from continuous exercise.

The onset of high-intensity exercise leads to hydrolysis of intracellular ATP, which is rapidly compensated for by the hydrolysis of phosphocreatine (PCr), liberating energy and inorganic phosphate (P_i) to help reform ATP (Soderlund and Hultman, 1991; Gaitanos *et al.*, 1993). However, PCr stores are highly limited and the ATP resynthesis due to PCr, even in a 6 -s sprint, has been reported to be as low as 50 %, with an increasing influence of anaerobic glycolysis and the aerobic pathways as exercise duration increases (Cheetham *et al.*, 1986; Gaitanos *et al.*, 1993). The reduction of PCr is widely implicated as a cause of fatigue in high-intensity exercise (Balsom *et al.*, 1992b; Cooke *et al.*, 1997a; Hargreaves *et al.*, 1998) but its recovery is a fairly rapid process, with a half-time often quoted to be in the order of 30 s (Harris *et al.*, 1976; Gaitanos *et al.*, 1993; Cooke *et al.*, 1997a; McMahon and Jenkins, 2002). Re-formation of PCr requires aerobic resynthesis of ATP, reversing the reaction which occurs during activity. This PCr resynthesis is therefore oxygen-dependent and, consequently, the performance of RSE is usually considered to be related to oxidative processes (i.e., the use and delivery of oxygen in muscle; Jansson *et al.*, 1990; McMahon and Jenkins, 2002).

The repeated performance of high-intensity bouts, followed by relatively low-intensity periods of recovery is a characteristic of many 'game-sports' such as soccer, hockey, rugby, badminton, tennis, volleyball and basketball. Consequently, an understanding of the physiology of RSE is important for appreciating the requirements of these sports. Typically, these sports have a long duration, which further emphasises the aerobic requirements. Therefore, performers in these sports usually need to be powerful and fast but also need to demonstrate the ability to recover from sprint exercise by use of oxidative processes. Owing to the distinctions that exist between continuous and intermittent activity, performance tests have been designed to assess these types of exercise separately. While the assessment of purely aerobic or anaerobic activity is comparatively straight-forward, assessment of RSE performance is more complex.

The interaction of the factors already mentioned demonstrates that tests to evaluate the performance of RSE will be influenced by many procedural factors. For example, small changes in rest duration (Holmyard *et al.*, 1994; Glaister *et al.*, 2005) or sprint duration (Dawson *et al.*, 1991) have been shown to have a significant impact on subsequent exercise performance. Additionally, a wide range of physiological requirements are likely to impact on RSE. These include maximal strength (Wisloff *et al.*, 1998), anaerobic enzyme activity (Gaitanos *et al.*, 1993), muscle fibre type and anaerobic threshold (Bogdanis *et al.*, 1996b), maximal rate of oxygen consumption ($\dot{V}O_{2\text{ max}}$) (Reilly and Gilbourne, 2003), exercise economy (Helgerud *et al.*, 2001), prior nutrition (Balsom *et al.*, 1999) and acid-base balance (Bishop *et al.*, 2004b). With this range of procedural and physiological factors to consider, it is not surprising that little is known about the factors that limit or enhance RSE (Bishop *et al.*, 2004b; Glaister, 2005) and, similarly, in relation to the present thesis that little consensus exists on how to assess this component of physical performance. The complex nature of metabolism in repeated-sprint exercise suggests that the performance of continuous or single-bouts of activity will not represent valid tests for the ability to perform RSE.

Repeated-sprint exercise in sports

It is fundamental for any sport scientist to have an understanding of the activity profile of any sport being considered. The activity profile is usually an indication of how much time is spent performing given types or intensities of exercise throughout a competitive period. For most sports, the activity profile is fairly complex. Game-sports typically

require periods of high-intensity activity, interspersed with recovery periods. A wide range of factors (technical, environmental, level of competition, tactical, physical, positional) will influence an activity profile but, in general, the demands of sports can be described reasonably well in this way.

Many authors have classified the game-sports together due to their similar, intermittent, activity profile (Balsom *et al.*, 1992a; Bangsbo, 2000; Glaister, 2005). However, the activity profile does not necessarily inform the coach or scientist about the sport's physiological requirements. With more objective, physiological assessment of the consequences of activity, greater confidence can be placed in decisions regarding the assessment and enhancement of exercise performance.

In many cases an activity profile, in conjunction with physiological measures (such as heart rate - HR, [La] or $\dot{V}O_2$), will provide a good description of the competitive demands of a sport. There are many examples of such physiological measurements in the literature and typical values for some game-sports are summarised in Table 1.

The combination of descriptive and physiological measurements allows a far more valid characterisation of a sport's physical demands. For all of the sports noted above, their physiological demands appear to be broadly similar to those which would be expected in continuous, moderate-intensity, aerobic activity of a similar duration. However, the activity profiles clearly indicate that extremely high intensities are experienced within these games. These periods of heavy exercise are usually followed by periods of relative rest. The duration of work and rest periods is partially dependent on technical or tactical issues but physiological quantities (e.g., the players' $\dot{V}O_{2\max}$; Mohr *et al.*, 2003) have also been shown to have a significant impact on the activity profile of competitive performance.

Table 1. Physiological measurements from match situations (mean values unless otherwise stated) in a range of game-sports.

	Heart rate	Intensity	[La] (mmol.l ⁻¹)	Comments
Soccer				
Thatcher and Batterham (2004)	83 % HR max		NR	English Premier League, match play
Bangsbo <i>et al.</i> (1991)	-		4.4	Danish league, post-match
Bangsbo (1994)	~ 85 %HR max		3-9	Typical range of post-match values
Badminton				
Majumdar <i>et al.</i> (1997)	~ 85 % HR max		NR	National squad, singles matches
Liddle <i>et al.</i> (1996)	89 % HR max		NR	County or national singles
Liddle <i>et al.</i> (1996)	79 % HR max		NR	County or national doubles
Cabello-Manrique and Gonzalez - Badillo (2003)	173 beats.min ⁻¹		3.8	International players in matches. [La] represents highest measured
Rugby Union				
Deutsch <i>et al.</i> (1998)	~72% of time above 85 % HR max		6.6	Under 19 elite players (forwards)
McLean (1992)	NR		~ 6.0	Scottish first division players
Tennis				
Bergeron <i>et al.</i> (1991)	74 % HR max		2.3	US University, matches
Christmass <i>et al.</i> (1998)	83 % HR max		5.9	Australia state matches, [La] is mean of highest values
Field Hockey				
Lothian and Farrayly (1995)	170 beats.min ⁻¹		NR	Combined male, female match play
Netball				
Woolford and Angove (1992)	> 70 % of time above 85 %HR max		NR	Australia state players in matches
NR – no result given				

The nature of a sport dictates the ease with which activity profiles can be established. For example, the racket sports usually involve heavy exercise during rallies which are immediately followed by a period of relative rest. An activity profile is less easily established in team sports like hockey, soccer, basketball and rugby. Nevertheless, authors have classified different match activities and evaluated how long a player performs these activities for. For example, in youth soccer, sprint-running has been observed to occur with an average frequency of 19 times per game with each sprint lasting an average of less than 3 s (Bangsbo, 1994; Thatcher and Batterham, 2004). Soccer players spend typically around 8 % of their time in 'high-intensity' activity (Bangsbo *et al.*, 1991; Mohr *et al.*, 2003). More than half of a match is spent either standing or walking (Bangsbo *et al.*, 1991; Mohr *et al.*, 2003). In rugby union, elite forwards have been shown to perform work bouts lasting on average 5.1 s, followed by an average rest period of around 37 s (Deutsch *et al.*, 2007). In individual sports the demands on players are more constant. For example, mean rally time in badminton is around 5 s, with an average subsequent rest period of over 9 s (Majumdar *et al.*, 1997). Similar figures exist for squash and tennis. (Smekal *et al.*, 2001; Lees, 2003). In spite of these differences in the activity profiles of the game-sports, it is generally accepted that their physiological requirements are similar in that they all require the ability to sustain very high-intensity activity for short periods, followed by a recovery (Balsom *et al.*, 1992a; Bishop and Spencer, 2004; Glaister, 2005).

Given that the game-sports can be classed as requiring similar physiological characteristics, it is essential that the characteristics of RSE are reflected in the physical training and testing of game-sports competitors. With reference to training, the challenge is for coaches and sport scientists to ensure that an appropriate balance is given between the conflicting metabolic requirements of short-duration, high intensity activity and the need to maintain performance levels throughout the course of a prolonged match or training (Castagna *et al.*, 2002). Similarly, for testing performance, there is a need for procedures which use appropriate exercise mode to stress the relevant physiological systems, while taking into account the many procedural and physiological considerations that influence the performance of RSE.

Physiology of Repeated-Sprint Exercise

Metabolic responses to a single sprint

The metabolic responses to repeated sprints may be best understood by beginning from a context of the responses to a single sprint. The performance of a short bout of exercise at a maximal intensity will immediately disrupt the intracellular homeostasis, initially due to the hydrolysis of ATP and the consequent elevation of P_i and adenosine diphosphate (ADP).

The phosphocreatine reaction

The threat to ATP concentration is almost immediately buffered by the activation of creatine kinase (CK) which promotes the PCr-driven resynthesis of ATP (Greenhaff and Timmons, 1998; Dahlstedt *et al.*, 2000). The rate of PCr hydrolysis is thought to peak at around 2 s into a sprint (Greenhaff and Timmons, 1998). The capacity of muscle to store PCr is very limited, however, and even within 6 s the concentration of PCr ([PCr]) has been shown to be decreased to between 40 and 45 % of pre-exercise levels (Gaitanos *et al.*, 1993; Dawson *et al.*, 1997). With longer sprint duration (11 s), Hirvonen *et al.* (1987) found post-sprint [PCr] to be below 40 % of resting. Unsurprisingly, therefore, high-intensity exercise lasting for longer durations causes further PCr depletion. After single sprints lasting from 20 to 30 s, PCr concentration has been found to be reduced to between 30 and 15 % of resting levels (McCartney *et al.*, 1986; Bogdanis *et al.*, 1996b; Casey *et al.*, 1996b).

In addition to exercise duration and PCr depletion, other factors appear to impact on the rate of PCr hydrolysis. Hirvonen *et al.* (1987) found that the rate of PCr hydrolysis discriminated between sprint performance in elite runners, suggesting that the fastest times were found among those who could break down PCr most rapidly. This may, in turn, be associated with the observation that fast muscle has higher resting [PCr] than slow muscle (Tesch *et al.*, 1989; Soderlund and Hultman, 1991; Soderlund *et al.*, 1992). Given that the ATP-PCr reaction rapidly uses up its own substrate, higher [PCr] prior to exercise is likely to be advantageous to performance. However, it appears that CK activity does not increase with training (Simoneau *et al.*, 1986; Cadefau *et al.*, 1990;

Linossier *et al.*, 1997b), implying that CK activity may not be a key determining factor in the performance of short sprints (Cadefau *et al.*, 1990).

In spite of the large decreases in PCr levels that have been described, ATP concentrations are relatively well preserved even after prolonged sprint activity (McCartney *et al.*, 1986; Hirvonen *et al.*, 1987; Dawson *et al.*, 1997). This is achieved by a combination of other metabolic pathways which become increasingly important as exercise continues.

Anaerobic glycolysis

Activity-induced increases in P_i , ADP and adenosine monophosphate (AMP) serve to activate anaerobic glycolysis shortly after the commencement of high-intensity activity (Balsom *et al.*, 1992a; Gaitanos *et al.*, 1993; Crowther *et al.*, 2002). With increased sprint duration the glycolytic pathway contributes an increased proportion of the ATP resynthesis required for prolonged activity. The contribution to ATP resynthesis from glycolysis in sprint exercise rises from around 50 % at 6 s (Gaitanos *et al.*, 1993) to around 70 % after 30 s (Bogdanis *et al.*, 1996b). Muscle has a higher capacity for the storage of substrates for glycolytic ATP resynthesis (i.e., glucose or glycogen) than for the PCr, the substrate of CK-derived ATP resynthesis (Cheetham *et al.*, 1986). However, the maximal ATP resynthesis rate for the glycolytic pathway is lower than that for the ATP-PCr pathway (Bogdanis *et al.*, 1998). For this reason once the influence of the CK reaction decreases, a decrement in performance is likely to result. Additionally, glycolysis leads to accumulation of hydrogen ions from lactic acid and this rise has often been implicated as a potential cause of fatigue in high-intensity exercise (McMahon and Jenkins, 2002; Glaister, 2005). Therefore fatigue and the resultant accumulation of metabolic 'waste products' are inevitable consequences of the performance of high-intensity activity.

Other pathways.

There are two further metabolic pathways that can impact on the performance of short-duration, high-intensity activity, although their relative importance in terms of the rate of ATP resynthesis is less than for glycolysis or the CK reaction. Activity-induced ATP hydrolysis will result in ADP formation. Both glycolysis and the ATP-PCr pathway promote ATP resynthesis by providing phosphate groups to allow ATP resynthesis but

this outcome can also be achieved by the adenylate kinase (AK) or myokinase reaction. Adenylate kinase promotes the formation of ATP from two ADP molecules, resulting in the formation of AMP. Adenosine monophosphate is then further metabolised to inosine monophosphate (IMP), before being removed from the muscle as hypoxanthine (Balsom *et al.*, 1992a; Hellsten-Westing *et al.*, 1993). Finally, even the performance of very short-duration sprints can promote some contribution from aerobic metabolism (Ross and Leveritt, 2001). This contribution has been evaluated as less than 15 % of ATP resynthesis for sprints lasting up to 10 s, with increased contribution for longer sprint durations (Bogdanis *et al.*, 1998; Parolin *et al.*, 2000). A proportion of the oxygen for this aerobic contribution is likely to come from the oxygen bound to myoglobin within the muscle (Åstrand *et al.*, 1960a; Bangsbo *et al.*, 2000; Dupont *et al.*, 2004b).

Fatigue from high-intensity exercise

It is clear that the performance of all but the shortest duration, high-intensity exercise is associated with the onset of fatigue. However, the mechanisms which can explain the development of fatigue are not clearly established. The potential causes of fatigue are also dependent on the duration of the exercise that is performed.

There are clear associations between fatigue from high-intensity exercise and a reduction in intramuscular [PCr] (Bogdanis *et al.*, 1996b; Cooke *et al.*, 1997a; Bogdanis *et al.*, 1998). However, the reduction in [PCr] also leads to an accumulation of P_i which, in itself, is thought to be a potential cause of fatigue either through its inhibitory effect of calcium ion (Ca^{2+}) release from the sarcoplasmic reticulum (SR), by increasing Ca^{2+} leakage from the SR, or by reducing myofibrillar Ca^{2+} sensitivity (Westerblad *et al.*, 2002; Tupling, 2004). Single bouts of sprint exercise also cause rapid accumulation of hydrogen ions (H^+) due to lactic acid production. This acidosis has often been cited as a potential cause of fatigue, particularly in the older literature (Åstrand *et al.*, 1960a; Margaria *et al.*, 1969; Harris *et al.*, 1976), because of the potential for disruption of glycolytic enzyme activity, calcium-troponin binding and general calcium handling by the SR (Bangsbo, 2000). However, there is an increasing tendency to attribute fatigue to factors other than 'lactic acidosis' when referring to single, short-duration bouts of activity (Bangsbo *et al.*, 1996; Westerblad *et al.*, 2002; Tupling, 2004).

With the range of experimental models used to investigate fatigue it not possible to nominate any one factor as the primary 'fatigue agent' in high-intensity exercise. Even in the relatively simple situation of a single sprint, there are many metabolic factors that interact, leaving little consensus in the current literature as to the cause of fatigue. What is clear is that a range of physiological processes is involved and that the likely causes of fatigue from a sprint will differ according to procedural considerations, especially exercise duration. The issue is further complicated in RSE where high-intensity activity may be performed many times in succession, often with incomplete recovery.

Metabolic response to repeated-sprint exercise

Phosphocreatine metabolism

The metabolic responses to a single sprint that have been described also impact on the performance of subsequent sprints. The importance of the ATP-PCr reaction in resynthesising ATP at the start of a sprint has already been highlighted. The fast rate at which this reaction can reform ATP dictates that the performance of short sprints is likely to be highly influenced by the rates of hydrolysis and reformation of PCr. The hydrolysis of intramuscular PCr is closely related to force production, both in single sprints (Hitchcock, 1989; Soderlund *et al.*, 1992) and repeated sprints (Bogdanis *et al.*, 1996b; Hargreaves *et al.*, 1998). Therefore the capacity of skeletal muscle to break down and then recover its PCr stores is likely to be an essential component of RSE performance.

Hydrolysis of phosphocreatine in repeated sprints

The metabolic disturbance from a series of repeated sprints is significantly greater than that found from a single sprint (Dawson *et al.*, 1997). This disturbance is reflected in the higher loss of PCr observed from repeated sprints compared to single sprints (McCartney *et al.*, 1986; Jansson *et al.*, 1990; Gaitanos *et al.*, 1993). Dawson *et al.* (1997) concluded that this increased loss of PCr is due to incomplete PCr recovery as opposed to any change in the rate of depletion within sprints. These authors noted that while a single sprint caused a reduction in [PCr] to 55 % of its resting level, a series of five 6 -s sprints (each interspersed with 24 -s recovery) resulted in a fall to 27 % of resting [PCr]. Given that the CK reaction is the key process promoting ATP resynthesis for such short periods, these figures show that there was clearly some resynthesis of PCr

in the recovery periods but that 24 s in this case was insufficient to promote full recovery. The elevated rate of PCr depletion after repeated, compared to single sprints was also reflected in the metabolic recovery after exercise. Dawson *et al.* (1997) showed that a 3 -min recovery was enough to cause a return to resting [PCr] after a single 6 -s sprint. In contrast, when 5 bouts of 6 -s sprints were performed, interspersed by 24 -s rest, recovery of [PCr] was still incomplete 3 min into the recovery.

The rate of PCr depletion is also determined by the muscle fibre type being used in the activity. The faster ATP hydrolysis rates of fast muscle allow for a far more rapid depletion of PCr during activity (Casey *et al.*, 1996b). This fibre-type distinction is continued into the recovery period, as fast fibres are seen to resynthesise PCr at a slower rate (Soderlund and Hultman, 1991).

Recovery of phosphocreatine

The recovery of intramuscular [PCr] is promoted by oxidative resynthesis of ATP in the recovery period after an exercise bout. This observation was first made by Harris *et al.* (1976) and has been verified by many similar observations linking aerobic ATP provision with the recovery of PCr (Sahlin *et al.*, 1979; Sahlin and Ren, 1989; Achten *et al.*, 1990; Quistorff *et al.*, 1992). Due to the links between repeated-sprint performance and PCr recovery, the time course of PCr recovery is likely to be an important factor in determining performance. The recovery of PCr has been investigated in many studies using a range of experimental procedures (Harris *et al.*, 1976; McCann *et al.*, 1995; Takahashi *et al.*, 1995; McCreary *et al.*, 1996; Haseler *et al.*, 1999). The time course of PCr recovery is generally quantified by the half-time of the reaction or, given that the process is often modelled by an exponential equation, the time constant of the reaction (i.e., the time to recover 63 % of the PCr). The literature gives half-times for PCr resynthesis as low as 21 s (Harris *et al.*, 1976) to values as high as 69 s for this reaction's time constant (Takahashi *et al.*, 1995).

Other than the distinction that needs to be made between half-times and time constants, there are procedural differences that will influence the time course of recovery. It would appear that differences in the oxidative contribution to recovery relate to the speed of PCr resynthesis. Cross-sectional studies have shown that aerobically trained subjects have faster PCr kinetics than do controls (Takahashi *et al.*, 1995; McCreary *et al.*,

1996). Similarly, oxidative capacity has been shown to be closely related to PCr resynthesis (Paganini *et al.*, 2000; Thompson *et al.*, 1995) as has oxygen transport and availability (Balsom *et al.*, 1994a). Another factor which influences the resynthesis rate of PCr is the prior exercise intensity. The recovery of PCr is delayed when prior, high-intensity exercise has been performed (Bogdanis *et al.*, 1995; McCann *et al.*, 1995; Takahashi *et al.*, 1995). This protracted recovery time may be due to H⁺ ion accumulation resulting from anaerobic glycolytic metabolism (McCann *et al.*, 1995; Walter *et al.*, 1997). The issue of muscle fibre type and recovery of PCr has already been raised and is a further example of the associations between aerobic processes and PCr resynthesis: type I fibres show consistently faster PCr recovery rates than do type II fibres (Tesch *et al.*, 1989; Soderlund and Hultman, 1991).

Glycolytic response

Anaerobic glycolysis in repeated-sprint exercise

The emphasis so far in this section has been on PCr metabolism, but, as with the responses to a single sprint, other metabolic processes also play an important role in determining the responses seen in RSE. For a single sprint, it has already been shown that the influence of PCr is reduced with exercise duration and, conversely, the contribution from anaerobic glycolysis is increased. Given that the performance of a single sprint causes a lower metabolic stress than when a sprint of the same duration is repeated it would be expected that the influence of the glycolytic pathway increases as a series of sprints is performed. Repeated-sprint exercise is known to cause very high rates of [La], confirming that high rates of anaerobic glycolysis do occur in repeated-sprint work. Mean peak post-exercise [La] after repeated sprints are typically above 10 mmol.l⁻¹ (Cheatham *et al.*, 1986; Fitzsimons *et al.*, 1993; Bishop *et al.*, 2004b) and have been reported to be over 17 mmol⁻¹ (Balsom *et al.*, 1992b). However, it appears that the contribution to ATP resynthesis from glycolysis decreases in relative terms as sprint number increases. Illustrating this reduced rate of glycolysis, Gaitanos *et al.* (1993) showed from a single 6 -s sprint, that 44 % of the ATP resynthesis was from the glycolytic pathway, whereas this figure was less than 20 % for the last in a series of ten 6 -s sprints starting on 30 s. The ATP production rate from glycolysis was reduced from 6.6 to 0.9 mmol ATP .kg dry wt⁻¹.s⁻¹ from sprint 1 to 10 respectively. The equivalent figures for the PCr pathway were 7.4 to 4.2 mmol ATP.kg dry weight⁻¹.s⁻¹. These

authors concluded that the decline in performance in their repeated-sprint protocol was mainly attributed to a reduced glycolytic contribution to ATP resynthesis (Gaitanos *et al.*, 1993). A similar reduction of glycolytic rate has been observed in other studies, both in RSE (Spriet *et al.*, 1989) and in high-intensity (but below sprint-speed), intermittent activity (Essen and Kaijser, 1978). Whether this reduced glycolytic rate is a cause or an effect of fatigue is unclear. The causes of fatigue in RSE will be considered in more detail later in this review of literature.

Recovery from glycolytic activity

The time course of recovery from acidosis is known to be far more prolonged than the results quoted for PCr recovery (Cooke *et al.*, 1997a; Bogdanis *et al.*, 1998), with acidosis following a more linear recovery (with respect to time) compared to the exponential recovery of PCr (Radda, 1996). Given the associations between PCr recovery and RSE performance, this observation indicates that normal pH is not necessarily a requirement for high levels of repeated-sprint performance. For example, high [La] has been observed without a decline in repeated-sprint performance (Holmyard *et al.*, 1988; Balsom *et al.*, 1992b) provided that sprint duration is short and recovery duration is relatively long (in these studies at least ten times more than the sprint duration). However, low pH is a general factor that can impact on many other physiological processes. Various authors have speculated on the mechanisms by which low pH may affect RSE and these include inhibition of contractile function, inhibition of glycolytic enzymes (e.g., phosphofructokinase and glycogen phosphorylase), delayed resynthesis of PCr and impaired Ca²⁺ handling (Bangsbo, 2000; Glaister, 2005). As is the case for single bouts of activity, there is a lack of consensus on the links between acidosis and fatigue in RSE but the range of processes which may be affected and the protracted recovery of pH after RSE mean that acidosis is not likely to be a primary cause of fatigue in RSE.

Oxidative processes

The aerobic contribution to a single short sprint has been discussed and it has been shown to be relatively minor (Bogdanis *et al.*, 1998). The importance of aerobic processes in the recovery from sprint exercise has also been introduced, showing that oxidative processes promote recovery after exercise is performed. It is clear that there is a significant contribution of oxidative phosphorylation to the performance of RSE. The

extent of the oxidative response increases as the number of sprints increases (Spriet *et al.*, 1989; Hamilton *et al.*, 1991; Gaitanos *et al.*, 1993; Chamari *et al.*, 1995). Typical repeated-sprint procedures have elicited $\dot{V}O_2$ above 65 % $\dot{V}O_{2\max}$ (Hamilton *et al.*, 1991; Balsom *et al.*, 1999) and one study has shown that a 15 × (40 -m sprint, with 25 -s active recovery) procedure caused $\dot{V}O_{2\max}$ to be reached by all subjects (Dupont *et al.*, 2005).

The link between PCr and $\dot{V}O_2$ is one of the key aspects in the oxidative response to RSE but other issues such as the role of myoglobin, the oxidation of lactic acid and simply, the prolonged exercise durations that are inherent in RSE dictate that oxygen-dependent processes are an essential consideration for this type of exercise. The high rates of PCr use and replenishment from a sprint are likely to elevate $\dot{V}O_2$ very rapidly in the performance of a series of sprints due to the reciprocal PCr - $\dot{V}O_2$ relationship. Unless the recovery duration between sprints is prolonged, $\dot{V}O_2$ will be elevated prior to the performance of the next sprint and an ever-increasing aerobic contribution to repeated-sprint activity will result. Further evidence for the importance of oxidative processes in the performance of RSE comes from studies where oxygen transport has been enhanced due to administration of erythropoietin (EPO) (Balsom *et al.*, 1994a) or reduced, due to hypoxia (Balsom *et al.*, 1994b). These studies showed lower indices of fatigue with EPO and reduced performance in hypoxia.

Fatigue in repeated-sprint exercise

The development of fatigue in this type of exercise is a complex process where the interaction of the metabolic pathways must be considered in order to see the factors that influence fatigue. Fatigue is likely to be a consequence of the performance of repeated sprints unless the recovery period is excessively long or the accompanying work period, very short. Fatigue is certainly a characteristic of the game-sports and is evident in all of the repeated-sprint performance test procedures that have been published. All of the anaerobic pathways for ATP resynthesis induce fatigue through various mechanisms and even the process of ATP hydrolysis elevates intramuscular Pi, which is also considered a potential 'agent' of fatigue (Westerblad *et al.*, 2002; Tupling, 2004). Therefore, in the context of the present thesis, it is necessary that any RSE test which may be developed should elicit some degree of fatigue as a series of sprints is performed.

The subjects who achieve the highest levels of performance at the start of a test procedure tend to be those who experience most fatigue as a RSE test proceeds while those with high maximal rates of oxygen consumption tend to be the subjects who exhibit the lower fatigue rates and lower power outputs (Holmyard *et al.*, 1988; Hamilton *et al.*, 1991; Wadley and LeRossignol, 1998; Ratel *et al.*, 2002; Bishop and Spencer, 2004). Other authors have also confirmed these findings using intermittent exercise models which would not fit the definition of RSE tests used in this thesis (Jansson *et al.*, 1990; Bogdanis *et al.*, 1995; Takahashi *et al.*, 1995; Li *et al.*, 2002). It has been suggested that the most powerful subjects can activate their metabolic pathways most rapidly and are thus able to cause greater metabolic disturbance (e.g., breakdown of ATP and PCr) to their exercising muscles (Cheatham *et al.*, 1986; Hirvonen *et al.*, 1987; Ross and Leveritt, 2001). Additionally, there is evidence that type II fibres tend to store significantly more intracellular PCr (Tesch *et al.*, 1989; Soderlund and Hultman, 1991). Together, these factors indicate that, even after the first in a series of sprints, those subjects with the greatest power and speed will have performed more work and experienced more intracellular disruption than would a subject with a physiological profile that favours 'aerobic characteristics' such as high $\dot{V}O_{2\max}$ and a higher proportion of type I fibres.

Fibre types

Fibre type proportion is often considered to be an important issue in relation to the development of fatigue (Tomlin and Wenger, 2002). The higher PCr storage and higher CK concentrations of 'fast muscle' mean that greater PCr depletion will occur which, while removing the substrate for ATP resynthesis, will also elevate P_i levels (Dahlstedt *et al.*, 2000). This elevation of P_i has been associated with both, reduced calcium handling and lowered myofibrillar sensitivity to Ca^{2+} (Westerblad *et al.*, 2002) and could explain the greater susceptibility to fatigue and disrupted Ca^{2+} kinetics attributed to fast fibres by Li *et al.* (2002). In addition to these characteristics of fast fibres, their relative lack of 'slow fibre characteristics' will also predispose them to higher rates of fatigue. 'Slow muscle', in spite of its tendency to not produce high forces, does possess superior capillarisation, higher oxidative enzyme activity and improved lactate removal, and thus is associated with a greater resistance to fatigue.

Acidosis

The development of lactic acidosis as a consequence of activating the glycolytic pathway has historically been considered to be a primary reason for fatigue in many exercise contexts (Åstrand *et al.*, 2003). However, fatigue observed in RSE has been attributed to a reduction in glycolytic activity (Gaitanos *et al.*, 1993). It is unclear whether reduced glycolysis is self-limiting or whether other factors lower the ATP requirement, thus decreasing the glycolytic rate (Spriet *et al.*, 1989). It has been suggested that the muscle's acidosis inhibits contractile force production, possibly due to compromised Ca^{2+} handling by the SR, but various investigators have observed normal muscle force production characteristics even with low pH (Sahlin and Ren, 1989; Bogdanis *et al.*, 1995; Bogdanis *et al.*, 1998). On the other hand, studies of RSE have shown a reduced ability to sustain high force production within a sprint even when the maximal performance within a sprint may not have been reduced (Wootton and Williams, 1983; Holmyard *et al.*, 1988; Balsom *et al.*, 1992b; Bogdanis *et al.*, 1995). This finding has led to the suggestion that, although acidosis may not directly reduce force production *per se*, it may still reduce ATP resynthesis rates from glycolysis (Bangsbo, 2000; McMahon and Jenkins, 2002). Contrary arguments have been made that, within the normal physiological range of muscle acidosis, pH is unlikely to drop sufficiently to affect glycolytic rate (Spriet *et al.*, 1987) or, even if it did, that other by-products of energy metabolism (e.g., ADP, AMP, P_i) would give an additional stimulus for enhanced glycolytic activation that would compensate for the low pH (Spriet *et al.*, 1987; Greenhaff and Timmons, 1998). Finally, among the few studies that have attempted to induce alkalosis in RSE, there is no consensus as to whether bicarbonate administration benefits performance (Lavender and Bird, 1989; Price *et al.*, 2003; Bishop *et al.*, 2004b; Bishop and Spencer, 2004). These findings fail to provide convincing support for the contention that acidosis is key to the development of fatigue in RSE.

Further evidence on whether pH influences fatigue can be taken from the relationship between PCr and force production. The trends in the decline and recovery of PCr have been shown to match closely those of force production; however, the post-exercise recoveries of pH and PCr are considered to be fairly independent (Sahlin and Ren, 1989; Bogdanis *et al.*, 1995), especially in the short work and rest periods that are relevant to RSE (Walter *et al.*, 1997). Consequently, based on all of the mechanisms referred to here, it is increasingly being accepted that acidosis is not a primary cause of

fatigue in short-duration, high-intensity exercise (Bangsbo, 2000; Westerblad *et al.*, 2002).

Depletion of phosphocreatine

The relationship between force production and PCr means that changes in PCr are an important consideration in the fatigue from RSE (Harris *et al.*, 1976; Sargeant and Dolan, 1987; Balsom *et al.*, 1992b). Fatigue associated with the ATP-PCr reaction has been considered to be primarily due to either a depletion or an inadequate resynthesis of PCr when repeated sprints are performed (Gaitanos *et al.*, 1993; Dawson *et al.*, 1997; Hargreaves *et al.*, 1998). There is little doubt that low PCr is closely associated with the accumulation of fatigue in RSE. Evidence which has previously been discussed, relating to muscle fibre types and the aerobic recovery of PCr support this view. Further support is provided by the studies which have shown that enhancing muscular PCr stores through nutritional supplementation may enhance the performance of RSE (Balsom *et al.*, 1993a; Aaserud *et al.*, 1998). However, the ATP-PCr reaction also produces P_i which, in turn reduces SR function. Consequently, the performance effects often attributed to changes in PCr could also be attributed to P_i (Bogdanis *et al.*, 1995).

Accumulation of other metabolites

Historically, the incidence of fatigue has often been linked with the accumulation of metabolites (e.g., lactic acid) or depletion of substrates (e.g., PCr) directly related to energy metabolism. This approach tends to ignore some other metabolites which are known to impact on fatigue. For example, references to P_i being associated with fatigue have only appeared fairly recently in the RSE literature (e.g., Bogdanis *et al.*, 1995). Evidence suggests that increased intramuscular P_i leads to reduced Ca^{2+} release and increased Ca^{2+} leakage which would both result in decreased contractile force (Westerblad *et al.*, 2002; Tupling 2004). Another metabolite which is thought to relate to the development of fatigue is the potassium (K^+) ion whose intracellular concentrations in exercise seem to be related to a decline in performance (Bangsbo *et al.*, 1996; Hargreaves *et al.*, 1998) but this association has not been investigated in the context of RSE. The accumulation of hypoxanthine, due to the AK-derived formation of ATP from two ADP molecules, has also been associated with metabolic fatigue in RSE (Hellsten-Westling *et al.*, 1993; McCann *et al.*, 1995). This molecule has been mostly used as a marker of fatigue (Balsom *et al.*, 1992a; Spencer *et al.*, 2004) but the loss of

adenine nucleotides due to reduced hypoxanthine loss from the muscle, has been shown to be decreased after a period of training (Spencer *et al.*, 2004). This finding suggests that retention of adenine nucleotides may be related to fatigue.

In summary, there is no consensus in the literature for there being a single factor which 'causes' fatigue in RSE. More research is needed before the mechanisms of fatigue can be established. It is clear that there are many processes which could indicate fatigue and many associations can be made between fatigue and these physiological processes. Overall, the metabolic responses to RSE are relatively complex due to the reliance on so many systems and reactions. The interactions between these processes must be considered; the uniqueness of RSE metabolism and the significance of durations and intensities of recovery and exercise should all be considerations in the performance and assessment of RSE.

Physiological Factors Influencing Performance of Repeated-Sprint Exercise

An aim of the present thesis was to investigate the development of a test procedure to assess RSE performance. With this in mind, the previously-reviewed metabolic effects of RSE performance are important but in order to comment on the validity of a test procedure, it is essential to be able to investigate the influence of a range of factors that may affect RSE performance. Consequently, the effects of fitness status, creatine supplementation and $\dot{V}O_2$ kinetics on RSE performance are reviewed in this section. For the purposes of this thesis 'fitness' is defined as "A set of attributes that people have or achieve relating to their ability to perform physical activity" (United States Department of Health and Human Services, 2000). In the following sections the terms 'aerobic fitness' and 'anaerobic fitness' will be used to extend the preceding definition of fitness to apply to aerobic (i.e., the ability to perform prolonged activity which stresses the cardiovascular system and the oxidative metabolic processes) and anaerobic fitness (i.e., the ability to perform high-intensity exercise whose metabolic demands are met by substrate-level phosphorylation).

Fitness status

The complexity of RSE means that its performance could be affected by alterations or differences in a diverse range of physiological processes. Metabolically, it is clear that a balance of aerobic and anaerobic metabolic processes will be fundamental to successful

performance in repeated sprints and this is reinforced by the good all-round fitness levels that are seen in competitors from the game-sports (Åstrand *et al.*, 2003). However, there is no consensus as to the ideal physiological characteristics or training activities that optimise performance in game-sports (Dawson *et al.*, 1993). This situation is worsened by the lack of standardised repeated sprint test procedures and the consequent absence of standard scores or norm values (Spencer *et al.*, 2005).

The anaerobic metabolic processes contribute most to the force production in a series of sprints, but the consequence of high rates of anaerobic work is a higher rate of fatigue (Wadley and LeRossignol, 1998). Conversely, well developed oxidative processes seem to promote good recovery but, are associated with low rates of force production (Hamilton *et al.*, 1991). Therefore, the mixed demands of game-sports mean that players are likely to have sub-optimal development of both the aerobic and anaerobic systems. This seems to be the case for the aerobic fitness status of elite game-sports players. The typical $\dot{V}O_{2\max}$ result for male games sport competitors is around $60 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; a value that would be considered low for an athlete training exclusively for aerobic endurance activities at an equivalent level of competition (Maughan, 1997) (see Table 2). In the literature on well-trained game-sports competitors, it is rare to observe $\dot{V}O_{2\max}$ values for males in excess of $65 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, as shown by the data in Table 2. This homogeneity of the results in Table 2 is noteworthy as it has been suggested that a 'threshold' of aerobic fitness may exist for game-sports players, such that further improvements in $\dot{V}O_{2\max}$ beyond that level may not promote more rapid recovery between sprints (Tomlin and Wenger, 2002).

Table 2. Maximal rate of oxygen consumption ($\dot{V}O_{2 \max}$) for male competitors in a range of game-sports (all results are means).

Investigation	$\dot{V}O_{2 \max}$ (ml.kg ⁻¹ .min ⁻¹)	Subjects
Soccer		
Bangsbo <i>et al.</i> (1991)	60.6	Professional, Danish league (<i>n</i> =14) (aged 24 years)
Wisloff <i>et al.</i> (1998)	63.7	Highest league, Norwegian (<i>n</i> =29) (aged 24 years)
Chamari <i>et al.</i> (2004)	61.1	Top Tunisian junior players (<i>n</i> =34) (aged 18 years)
Badminton		
Faccini and Dal Monte (1996)	59.8	Italian 'national class' (<i>n</i> =7) (aged 21 years)
Majumdar <i>et al.</i> (1997)	55.7	Indian internationals (<i>n</i> =6) (aged 24 years)
Rugby Union		
McLean (1992)	53.4	Scottish national squad (age and <i>n</i> not given)
Mayes and Nuttall (1995)	55.6 *	Senior players (<i>n</i> =79) (no age given)
Tennis		
Bergeron <i>et al.</i> (1991)	58.5	US University Div. I players (<i>n</i> =10) (aged 20 years)
Christmass <i>et al.</i> (1998)	53.4	Australia state senior players (<i>n</i> =8) (aged 24 years)
Smekal <i>et al.</i> (2001)	57.3	Competitive Austrian domestic (<i>n</i> =20) (aged 26 years)
Field Hockey		
Boyle <i>et al.</i> (1994)	61.8	N. Ireland internationals (<i>n</i> =9) (aged 26 years)
Australian Rules Football		
Wadley and LeRossignol (1998)	59.0	Professional league players (<i>n</i> =17) (aged 21 years)
Pyne <i>et al.</i> (2006)	57.8 *	AIS training camps (<i>n</i> = 495) (no age given; part-longitudinal study)

* Predicted $\dot{V}O_{2 \max}$ from 20 -m multistage, shuttle-run performance.

Anaerobic fitness and repeated-sprint performance.

In order to investigate the impact of anaerobic processes on repeated-sprint performance, studies which evaluate both aspects separately should be considered. However, the lack of standardised and criterion measures for either RSE or anaerobic activity makes it difficult to conclude the extent of influence that anaerobic processes have over RSE performance. Of the few studies in this area, Dawson *et al.* (1993) showed that discrete anaerobic test performance (in vertical jump, 10 m, 40 m and 400 -m sprints) was strongly correlated with the time to perform 6 × 40 -m sprints, but not to the recovery characteristics between sprints. This finding lends further support to the notion that anaerobic processes enhance force production while recovery is more aerobically determined. Bishop *et al.* (2001) used hockey players to compare sprint performance in a controlled match-simulation with the decrement in performance (total work and peak power) through a 5 × 6 -s RSE test on a cycle ergometer. The decline in sprint times for the match simulation was only related to the decline in the performance of the RSE test when 15 -m sprints (as opposed to 5 or 10 -m) sprint times were considered. These authors also found that fastest sprint speeds (over 5, 10 and 15 m) were correlated significantly with both measures of performance decrement in the cycle RSE test, showing again the links between anaerobic power production and fatigue. A weakness of this study is that running was compared with cycling, meaning that as well as sprint duration, the mode of activity may have also affected the relationships between these variables. Later in this review, training studies that have used repeated sprints as an intervention or as a method of assessing fitness will be reviewed and their findings also contribute to this area, but the evidence presented here asserts that high anaerobic performance is associated with greater fatigue in RSE tests.

Aerobic fitness and repeated-sprint performance.

Many investigators have studied the impact that aerobic fitness has on the performance of RSE (Dawson *et al.*, 1993; Tomlin and Wenger, 2002; Bishop *et al.*, 2004a). The oxidative recovery of PCr after exercise is of great practical significance to the preparation of competitors in the sports which require repeated sprints. These sports have been shown to have a high aerobic component (see Table 1) and the oxygen-dependent PCr recovery is likely to be a significant part of that aerobic demand. As an example of the importance of aerobic processes in game-sports, Bangsbo (1993) has estimated that 90 % of the energy contribution to soccer play is derived aerobically. It is

not surprising, therefore, that the assessment of aerobic fitness is widespread in the game-sports literature and that a general belief exists that improved aerobic fitness will improve RSE performance through enhanced rate of recovery (Tomlin and Wenger, 2002). However, aerobic fitness is a term that encompasses cardiorespiratory, muscular and metabolic processes. The most widely used assessment of aerobic fitness is the $\dot{V}O_2_{\max}$ test as the limit of aerobic ATP resynthesis is quantified in this measure. However, this test is considered to relate most closely with the cardiovascular aspects of aerobic performance (i.e., oxygen delivery) in contrast to the peripheral aspects (i.e., oxygen extraction at the muscle) which are probably best indicated by evaluating the relationship between energy expenditure or the extent of anaerobic metabolism at a given intensity (exercise economy or the blood lactate response to exercise, respectively) (Coyle, 1995).

Table 3. Studies which have investigated the relationship between RSE test performance and $\dot{V}O_{2\text{ max}}$

	Exercise mode	Procedures	Work period (s)	Work : Rest ratio
<u>No correlation</u>				
Bangsbo <i>et al.</i> (1992)	Field sprint	40 × (15 -s high intensity: 10 -s low intensity)	15	3:2
Dawson <i>et al.</i> (1993)	Cycle	6 × (6 -s sprint, on 30 s)	6	1:4
Wadley & LeRossignol (1998)	Field sprint	12 × (20 -m sprint, on 20 s)	3 *	1:6 *
Ratel <i>et al.</i> (2002)	Cycle	10 × (10 -s sprint, on 70 s)	10	1:6
<u>Moderate correlation</u>				
Aziz <i>et al.</i> (2000)	Field sprint	8 × (40 -m sprint, 30 -s rest)	6 *	1:5 *
<u>Significant correlation</u>				
Chamari <i>et al.</i> (2005)	Field sprint	40 × (15 s high intensity, 10 s low intensity)	15	3:2
Ratel <i>et al.</i> (2002)	Cycle	10 × (10 -s sprint, on 40 s)	10	1:3
Bishop <i>et al.</i> (2004a)	Cycle	5 × (6-s sprint, on 36 s)	6	1:4
Dawson <i>et al.</i> (1993)	Field sprint	6 × (40 -m sprint, on 30 s)	6 *	1:4 *
Tomlin & Wenger (2002)	Cycle	10 × (6 -s sprint, on 36 s)	6	1:5
McMahon & Wenger (1998)	Cycle	6 × (15 -s sprint: 90-s active recovery)	15	1:6

* denotes approximate timing

The relationship between $\dot{V}O_{2\text{ max}}$ and repeated-sprint performance has been investigated by many authors (McMahon and Wenger, 1998; Aziz *et al.*, 2000; Bishop *et al.*, 2004a) and, although some have shown relationships (McMahon and Wenger, 1998; Ratel *et al.*, 2002; Bishop *et al.*, 2004a), others have not (Dawson *et al.*, 1993; Wadley and LeRossignol, 1998). Other studies, although not necessarily reporting correlations, have suggested that the relationship between $\dot{V}O_{2\text{ max}}$ and RSE performance is not of great importance (Aziz *et al.*, 2000; Bishop and Spencer, 2004). The absence of conclusiveness in this area may be partly attributed to differences in experimental procedures, as illustrated in Table 3. A conclusion from these reports would be that recovery duration may have to be within a certain range for the relationship between $\dot{V}O_{2\text{ max}}$ and RSE performance to be established. This is illustrated by comparison of findings from the studies by Wadley and LeRossignol (1998) and Ratel *et al.* (2002). Ratel *et al.* (2002) manipulated recovery duration and showed that only with short (30 s compared to 60 s) recovery duration was there a relationship between $\dot{V}O_{2\text{ max}}$ and RSE performance. The study of Wadley and LeRossignol (1998) was unusual in that the sprint duration was very short (half that of most repeated-sprint procedures), but perhaps more significantly, that this was accompanied by only 20 s recovery time (Wadley and LeRossignol, 1998). The short recovery time of this study was the one aspect that differentiated it from the other studies listed in Table 3 which all used a similar work: rest ratio. Given the assumption that oxidative processes promote recovery of performance, it would make sense that a short recovery period may not give enough time for an effect to be observed (Bishop *et al.*, 2004a). Equally, given that the half-time for PCr recovery is probably between 30 and 60 s, long recovery times may not be sufficiently affected by improved aerobic fitness status (Bishop *et al.*, 2004a). However, the area still remains inconclusive given that, even with the same procedures but different exercise modes, contrasting findings have been seen (Dawson *et al.*, 1993; see Table 3). With a different experimental approach, Edwards *et al.* (2003) and Bishop and Spencer (2004) used subject groups matched for $\dot{V}O_{2\text{ max}}$ but of contrasting training background, and concluded that $\dot{V}O_{2\text{ max}}$ could not be used to differentiate RSE performance.

Other studies, especially in soccer, have been performed that have described match performance, and correlated those results with $\dot{V}O_{2\text{ max}}$ (Bangsbo *et al.*, 1992; Wisloff *et*

al., 1998). The obvious limitation to this approach is that match performance is hard to define and that it is not necessarily limited by fitness alone. Bangsbo *et al.* (1992) showed that $\dot{V}O_{2\max}$ was correlated with distance covered in a match but not to the distance covered at 'high intensity'. Given that the time spent in high-intensity activity discriminates between players of different standards (Mohr *et al.*, 2003) and that crucial moments of competition are usually at high intensity, this relationship with total distance covered may not be so important for effectiveness in the game. In contrast, $\dot{V}O_{2\max}$ has been linked with the standard of play in Norwegian soccer players (Wisloff *et al.*, 1998). However, the higher-level players in this study also showed superior strength, suggesting that they had a higher general level of fitness. Additionally, Helgerud *et al.* (2001) showed that training to improve $\dot{V}O_{2\max}$ also improved match performance - most notably, the number of sprints, distance covered and the intensity of exercise sustained throughout competition. It should be pointed out, though, that the aerobic improvements found from their training programme also improved other measures of aerobic fitness, namely, the blood lactate response and running economy (Helgerud *et al.*, 2001).

The links between the other areas of aerobic fitness and RSE performance have been investigated less extensively. Bogdanis *et al.* (1996b) distinguished between $\dot{V}O_{2\max}$ and 'endurance fitness' (defined as the % $\dot{V}O_{2\max}$ at a [La] of 4 mM) and found that endurance fitness was correlated most closely to recovery of performance characteristics. They attributed these findings to peripheral aspects of aerobic fitness (capillarisation, fibre type proportion and oxidative capacity), rather than the central aspects of cardiovascular function which are more related to $\dot{V}O_{2\max}$. However, their findings were derived from procedures (2 × 30 -s sprint, 240 -s rest) that bore little resemblance to RSE (Bogdanis *et al.*, 1996b). Only Bishop *et al.* (2004a) have addressed this issue with an RSE model. They showed that RSE performance was related to endurance fitness but that the strength of the correlation was similar to that between performance and $\dot{V}O_{2\max}$. Additionally, their study used untrained female subjects with a high heterogeneity of aerobic fitness status (i.e., range of $\dot{V}O_{2\max}$ from 33.6 - 56.6 ml.kg⁻¹min⁻¹), thus raising the likelihood of finding correlations (Vincent, 1999). Data collected by Chamari *et al.* (2004) showed that RSE test performance was not related to $\dot{V}O_{2\max}$, but correlations were observed with the velocity at $\dot{V}O_{2\max}$ during their incremental test. This finding suggests that exercise economy, which is

known to be related to muscle fibre type (Mogensen *et al.*, 2006), may be relevant to RSE performance. Further research, using more standardised procedures are needed to establish which components of aerobic fitness are related most closely to RSE performance.

Another approach that can be used to investigate the fitness-related determinants of RSE performance is to examine the outcomes from training studies. For the purposes of this review, studies that have used repeated-sprint training as an intervention will be considered, as will those that have evaluated the impact of other kinds of training on the performance of repeated sprints.

Use of repeated-sprint exercise as training.

The mixed demands of RSE make it a potentially valuable way of improving many aspects of fitness (Gullstrand and Lawrence, 1987; Tabata *et al.*, 1996). For the purposes of this aspect of the review, RSE should be considered as all-out exercise bouts lasting less than or equal to 15 s followed by a subsequent rest period at least double that of the sprint duration, repeated between 5 to 20 times. The programmes summarised in Table 4 are made up of predominantly RSE training. All of these studies document increases in RSE performance after the training period (lasting as little as 2 weeks in duration; Rico-Sanz, 2000). The fact that these studies also show increases in a range of other outcomes from 40 -m sprint time (Dawson *et al.*, 1998; Dupont *et al.*, 2004a) to $\dot{V}O_{2\max}$ (Dawson *et al.*, 1998; Rico-Sanz, 2000) and aerobic enzyme concentrations (Rico-Sanz, 2000) confirms the likely diversity of the determinants of RSE. The conclusions from these studies are not always in agreement with those from other similar studies, however. Dawson *et al.* (1998), whose training study is the most comprehensive of those summarised here, observed decreases in citrate synthase activity and type I fibre proportions, findings which oppose those observed in many other training studies (MacDougall *et al.*, 1998; Ross and Leveritt, 2001; Barnett *et al.*, 2004). Equally, Rodas *et al.* (2000) showed increased CK activity after their training programme, a finding that is inconsistent with other studies of anaerobic training (Ross and Leveritt, 2001). Perhaps one of the most significant findings in these studies is concerned with sarcoplasmic reticulum function. Ortenblad *et al.* (2000) found their successful RSE training programme caused enhanced Ca^{2+} release. Given the increasing tendency to consider factors other than just the ATP resynthesis pathways as limiting

performance (Westerblad *et al.*, 2002), the calcium kinetics and their links with performance may become an increasingly important area of study in the future.

Training to improve repeated-sprint exercise performance.

In addition to the studies where a training programme was composed of predominantly RSE, other training programmes have also been used to enhance RSE performance (see Table 5). Three of these studies incorporated training programmes that used a range of intensity domains (Krustrup and Bangsbo, 2001; Spencer *et al.*, 2004) or a selection of anaerobic or 'explosive' activities (Siegler *et al.*, 2003). In contrast, Helgerud *et al.* (2001) used training which was designed to increase $\dot{V}O_{2\max}$ with sport-specific activity (4 sets of high-intensity dribbling; 4 -min work, 3 -min rest) in addition to the usual mixed training programme followed by the junior footballers in this study. In all of these studies improvements were made in either match-performance or in the results of an RSE test.

It would appear that RSE performance is trainable and that this effect can be achieved using a range of training techniques and with programmes comprising as few as 9 sessions over a period as short as two weeks (Jenkins *et al.*, 1994; Rico-Sanz, 2000). Use of RSE as training has been consistently shown to enhance its performance. However, the literature available does not currently provide evidence regarding the most effective type of training (e.g., aerobic, anaerobic, RSE, etc.) to optimise development of RSE performance. This lack of information on the best way to enhance RSE is partly attributable to the scarcity of relevant training studies and to the inconsistent test procedures which are currently used to evaluate RSE performance.

Table 4. Summary of studies which have used RSE as a training intervention

	Jenkins <i>et al.</i> (1994)	Nevill <i>et al.</i> (1994)	Dawson <i>et al.</i> (1998)	Ortenblad <i>et al.</i> (2000)	Rodas <i>et al.</i> (2000)	Dupont <i>et al.</i> (2004a)
Subjects	n = 12 (6 Ctrl, 6 Trg) M	n = 18 (9 Trg, 9 Ctrl) M/F	n = 9 M	n = 15 (9 Trg, 6 Ctrl) M	n = 5 M	n = 22 Soccer players M
Training details (Summary of all programmes)			Reps between 5 - 40 repetitions Sprint duration between 5 - 15 s Work: rest ratio between 1:3 to 1:6			
Duration ; Frequency	3 wk ; 3 / wk	4 wk ; Not given	6 wk ; 3 / wk	5 wk ; 3 / wk	2 wk ; 7 / wk	10 wk ; 2 / wk
RSE Performance	Improved	Improved	Improved	Improved	Improved	Improved
Aerobic	NC in $\dot{V}O_{2\max}$	NC in $\dot{V}O_{2\max}$	$\uparrow \dot{V}O_{2\max}$	NC in $\dot{V}O_{2\max}$	$\uparrow \dot{V}O_{2\max}$	\uparrow speed at $\dot{V}O_{2\max}$
		\uparrow aerobic contribution to RSE	\downarrow [oxidative enzymes]		\uparrow [oxidative enzymes]	
Anaerobic	\uparrow Post-RSE [La]	\uparrow post-RSE [La], [Ammonia].	NC 10 m speed Faster 40 m speed		NC 30 s maximal cycle sprint	\uparrow 40 m speed
			\uparrow [PHOS] NC [ATP, PCr, MK, PFK]		\uparrow glycogen, [PCr, CK, PFK, LDH]	
Other changes			$-\uparrow$ fibre II % & area $-\downarrow$ I % & area	$-\uparrow$ Ca ²⁺ release from SR (higher SR volume)		

Abbreviations used : M- male, F - females, Ctrl - control group, Trg - training group, PHOS - glycogen phosphorylase, PFK - phosphofructokinase, LDH- lactate dehydrogenase. \uparrow - increased, \downarrow - decreased. NC - no change, [x] - denotes concentration of 'x'

Table 5. Summary of studies which have shown enhanced RSE or game-sports performance through training that is not exclusively RSE.

	Helgerud <i>et al.</i> (2001)	Krustrup and Bangsbo (2001)	Siegler <i>et al.</i> (2003)	Spencer <i>et al.</i> (2004)	Edge <i>et al.</i> (2005)
Subjects	n = 9 Trg, 10 Ctrl junior soccer. M	n = 27 soccer referees. M	n = 34 youth soccer. F	n = 18 hockey. F	n = 10 Trg, 10 Ctrl game-sports. F
Training details	4 × (4 min: 3-min rest) dribbling task at ~90 %HRmax. In addition to usual training	- Range of intervals 4 × (4 min:2-min rest) to 24 × (30 s: 15 s) - Aim ~ 90 % HRmax	Plyometrics 3 / wk - Strength training 2 / wk Control - aerobic only	Strength training, RSE, steady runs, game play	(cycling, % $\dot{V}O_2$ max) (Ctrl) – continuous ~65%. (Trg) – repeated (2 min work ~95%, 1 min rest)
Duration ; Frequency	8 wk; <u>2 / wk</u>	12 wk; <u>3-4 / wk</u>	2 × 10 wk (expt, ctrl conditions); <u>3 / wk</u>	7 wk; <u>3-4 / wk</u>	5 wk; <u>3 / wk</u>
Performance indicators	Improved match performance. - ↑ Distance covered - ↑ Number of sprints - ↑ Involvement in game	-Improved RSE test Match performance - ↑ time at high-intensity - ↑ number of sprints - NC distance covered	Improved performance on football simulation test (Nicholas <i>et al.</i> , 2000)	Improved work done in RSE test	Improved RSE test. Trg group significantly more than ctrl
Aerobic	↑ $\dot{V}O_2$ max, anaer. threshold, running economy	Sig. lower HR, La at submaximal trial - Suggest ↑ economy - NC - $\dot{V}O_2$ max.		Improved multistage shuttle test	Both groups - significant ↑ in $\dot{V}O_2$ max, anaer. threshold
Anaerobic			↑ 20m speed - NC in vertical jump or WAnT cycle test		

Abbreviations used : M- male, F – females, Ctrl – control group, Trg – training group, ↑ - increased, NC – no change, anaer – anaerobic.

Kinetics of Oxygen Consumption

In RSE the repeated transitions between varying exercise intensities necessitate rapid adjustments of [PCr] and, accordingly $\dot{V}O_2$. Considering that an aim of the present thesis was to investigate the validity of using physiological measures as indicators of RSE performance, it might be suggested that assessment of the rate of change of $\dot{V}O_2$ could be used as an indicator of the ability to adjust between the demands of work and rest in RSE (Dupont *et al.*, 2005). A subject who could make such adjustments rapidly would require less PCr hydrolysis at the onset of activity and would resynthesise PCr faster upon completing an exercise bout. The direct assessment of [PCr] during whole-body exercise is impractical, so, even though it may be desirable to know the kinetics of PCr in exercise as a metabolic correlate of RSE performance, it is currently impossible to make such measurements. Because of the aforementioned associations between [PCr] and $\dot{V}O_2$ it is possible for $\dot{V}O_2$ to be used as a surrogate for PCr, thereby providing a physiological indicator of the ability to perform RSE. There is already a precedent for research in this area (Dupont *et al.*, 2005) but these authors quantified $\dot{V}O_2$ kinetics during submaximal activity, as opposed to the high-intensity exercise that is inherent in RSE. The reciprocal nature of $\dot{V}O_2$ and PCr, in transitions between exercise and rest, combined with the merit of being able to predict [PCr] from $\dot{V}O_2$, form the theoretical basis for the assessment of $\dot{V}O_2$ in the present thesis.

The importance of the aerobic contribution to RSE and the relationship between [PCr] and $\dot{V}O_2$ have already been considered in this review but oxygen kinetics have not yet been covered in detail. The increased metabolic requirements at the onset of exercise are buffered by the ATP-PCr reaction (Tschakovsky and Hughson, 1999). Even activity which is of a relatively low intensity will therefore cause some reduction in PCr before aerobic processes can adjust to the increased energy demand. The speed at which $\dot{V}O_2$ can be increased is quantified as the subject's $\dot{V}O_2$ on-kinetics (Hickson *et al.*, 1978).

The evaluation of $\dot{V}O_2$ kinetics usually provides two results which indicate the speed of $\dot{V}O_2$ onset. The 'fast component' represents the rapid adjustment in $\dot{V}O_2$ from rest to high levels that approach the required $\dot{V}O_2$ for a given bout of exercise while a later phase, the 'slow component' represents a slow upward drift of $\dot{V}O_2$ as the same

intensity is continued (Xu and Rhodes, 1999). Both of these components are typically modelled by exponential equations and the time constant which allows the best approximation to the observed response is taken as the indicator of the $\dot{V}O_2$ kinetics (Xu and Rhodes, 1999). The description above applies to the onset of activity ('on-kinetics') but similar principles apply in modelling the $\dot{V}O_2$ response at the completion of exercise ('off-kinetics') (Ozyener *et al.*, 2001). The fast phase is generally over within 3 min of the exercise onset (Cooke *et al.*, 1997a; Xu and Rhodes, 1999; Bell *et al.*, 2001) and broadly similar time constants are observed for the off-kinetics (Ozyener *et al.*, 2001). The fast phase, unlike the slow phase, seems to be unaffected by exercise intensity (Rossiter *et al.*, 2002). Additionally, the fast phase is the one which is most likely to be applicable to the performance of RSE where rest periods will not approach 3 min either in RSE tests or in game-sports.

Both at the onset of, and in the recovery from exercise, there is a reciprocity between $\dot{V}O_2$ and PCr concentration (McCreary *et al.*, 1996; Rossiter *et al.*, 1997; Rossiter *et al.*, 2002). Aerobic training has been shown to enhance $\dot{V}O_2$ on-kinetics, implying that the PCr contribution to that exercise bout is lower in aerobically-trained subjects (Hickson *et al.*, 1978; Chilibeck *et al.*, 1996; Short and Sedlock, 1997). This reduced PCr contribution may, in turn reduce the $\dot{V}O_2$ in the post-exercise period given that a proportion of the post-exercise $\dot{V}O_2$ is used to resynthesise PCr. This is likely to have implications for the performance of RSE, where the recovery of PCr is of great importance. At the present time, there seems to have been only one study of the relationship between RSE and $\dot{V}O_2$ kinetics (Dupont *et al.*, 2005). These authors found that subjects with the slower $\dot{V}O_2$ on-kinetics showed the highest rates of fatigue and highest total test-time in a distance-based RSE trial. This observation suggests that further research in this area is worthwhile and, for the present study, that assessment of $\dot{V}O_2$ kinetics could be seen as an indicator of recovery rate. Dupont *et al.* (2005) reported a higher relationship between RSE performance and $\dot{V}O_2$ kinetics than with $\dot{V}O_{2\max}$, consistent with the previously-reviewed literature demonstrating the associations between aerobic fitness and the lack of fatigue in RSE (Hamilton *et al.*, 1991). The mechanisms that have been claimed to explain the relationship between $\dot{V}O_2$ on-kinetics and endurance fitness include oxidative enzyme activity, fibre type proportion, oxygen availability and delivery and capillary density (Chilibeck *et al.*, 1997; Koppo *et al.*, 2004): all these are factors that are related to enhanced PCr recovery

(McMahon and Jenkins, 2002). Dupont *et al.* (2005) assessed $\dot{V}O_2$ kinetics in a submaximal exercise bout rather than in their RSE test. Their RSE trial was performed in a non-laboratory setting, making assessment of $\dot{V}O_2$ more difficult and, besides, the assessment of $\dot{V}O_2$ on-kinetics in an RSE trial is impractical as the time period between the onset of exercise and the end of the first bout would limit the amount of data required to make an assessment of on-kinetics.

Although Dupont *et al.* (2005) investigated the $\dot{V}O_2$ on-kinetics, the nature of RSE implies that rate of recovery could be at least as useful an indicator of RSE performance. For RSE, the recovery of PCr post-exercise is of great importance and using the principles of the PCr - $\dot{V}O_2$ relationship, there could be value in the assessment of $\dot{V}O_2$ off-kinetics. Evidence suggests that, particularly in high-intensity exercise, there is a difference between the time constants for on- and off- kinetics, both in PCr (McCann *et al.*, 1995) and in $\dot{V}O_2$ (Langsetmo and Poole, 1997; Rossiter *et al.*, 2002; Wells *et al.*, 2003). Far less research has been performed on $\dot{V}O_2$ off-kinetics but it is accepted as a valid indication of recovery (Chilibeck *et al.*, 1997). Only Rossiter *et al.* (2002) have directly compared the kinetics of PCr and $\dot{V}O_2$ in recovery and they showed no difference in the mean time constants for both variables over moderate and high intensities. Indeed, they contended that the PCr and $\dot{V}O_2$ responses over this fast phase of recovery, were controlled by a common mechanism and that their time constants were not influenced by intensity. No authors have so far assessed $\dot{V}O_2$ off-kinetics from bouts of RSE.

The associations between the kinetics of PCr and $\dot{V}O_2$ may be of significance for the RSE literature and this could be a key area for the development of future research in the RSE topic. Once again, the associations between oxidative processes, PCr levels and RSE performance demonstrate the complexity of RSE and the challenges that this area presents for the development and assessment of fitness.

Supplementation of creatine monohydrate

The metabolism of PCr metabolism has already been suggested to be a key factor in RSE performance. However, the body's PCr store is highly limited and is soon reduced in heavy exercise (Bemben and Lamont, 2005). Harris *et al.* (1992) were the first

investigators to demonstrate that human muscle PCr stores could be increased through ingestion of creatine monohydrate. They also suggested that such dietary supplementation could be used to enhance exercise performance (Harris *et al.*, 1992). Many authors have since demonstrated that supplementation of creatine (Cr) is, indeed an ergogenic aid for a wide range of exercise types. Enhanced exercise performance has been shown in strength performance (Volek *et al.*, 1997; Kreider *et al.*, 1998; Syrotuik and Bell, 2004), single-bout heavy exercise (90 s - 300 s; McNaughton *et al.*, 1998), prolonged interval-type cycling (Rico-Sanz and Mendez-Marco, 2000) and repeated bouts of high-intensity exercise (e.g., repeated 30-s sprints with 4-min recovery; Birch *et al.*, 1994; Greenhaff *et al.*, 1994; Casey *et al.*, 1996a). However, many authors contend that the type of activity in which Cr supplementation has been shown to have the greatest impact is the performance of short, repeated sprints where sprint duration is less than 10 s and recovery duration is around 30 - 60 s (Williams and Branch, 1998; Mesa *et al.*, 2002; Bembien and Lamont, 2005). Consequently, in the context of the present thesis Cr supplementation may be a valuable intervention with which to investigate the validity of an RSE procedure.

Procedures for supplementation of creatine monohydrate.

The original Cr supplementation study to demonstrate enhanced Cr retention by muscle used a range of Cr loading regimens of 20-30 g/day for between 4 and 10 days (Harris *et al.*, 1992). Later studies have focused almost exclusively on a loading regimen of 20 g Cr / d over 5-6 days using 4-5 daily doses to make up the daily requirement of 20 g (Balsom *et al.*, 1993b; Green *et al.*, 1996a; Greenhaff and Timmons, 1998). This regimen has been shown many times to be effective at elevating muscle PCr content and total Cr content (Greenhaff *et al.*, 1994; Casey *et al.*, 1996a; Hultman *et al.*, 1996) and is therefore, accepted by most authors as a successful procedure (Williams and Branch, 1998; Mesa *et al.*, 2002; Bembien and Lamont, 2005). There is some individuality in the response to CrS, however. Many authors who have quantified intramuscular Cr content have observed that the extent of Cr elevation after supplementation is not uniform, leading to the classification of some subjects into 'responders' and 'non-responders' (Greenhaff *et al.*, 1994; Syrotuik and Bell, 2004). The biggest factor in the degree of response shown seems to be the initial Cr levels prior to the supplementation period (Lemon, 2002). Those subjects with the lowest initial Cr stores seem to respond most

favourably in terms of exercise performance and elevated Cr stores after a period of supplementation (Greenhaff *et al.*, 1994; Mesa *et al.*, 2002; Syrotuik and Bell, 2004).

The method of Cr supplementation tends to vary between studies although most authors have administered their Cr doses in powder form to be taken with fluid. The fluid used is inconsistent in the literature with tea or coffee (Greenhaff *et al.*, 1994), warm water (Hultman *et al.*, 1996), fruit juice (Rico-Sanz and Mendez-Marco, 2000) and glucose solutions (Aaserud *et al.*, 1998; Van Loon *et al.*, 2003) all given as fluids with which the required Cr doses were taken. The use of solutions containing simple carbohydrates is often considered to be especially important as it has been shown that Cr retention by muscle is facilitated with the presence of insulin (Green *et al.*, 1996a; Green *et al.*, 1996b; Steenge *et al.*, 1998). Consequently, many authors have administered their Cr dose with fruit juice or carbohydrate-containing drinks (Aaserud *et al.*, 1998; Kreider *et al.*, 1998; Peyrebrunne *et al.*, 1998; Van Loon *et al.*, 2003). Although Cr retention is aided by taking Cr with simple carbohydrates (CHO), the amount of CHO required to have a beneficial effect is unclear. Initially a CHO solution of 93 g glucose per dose was demonstrated to be superior to Cr alone, although intermediate amounts of CHO were not investigated in these studies (Green *et al.*, 1996a; Green *et al.*, 1996b). Subsequently, Steenge *et al.* (1998) suggested, from their insulin infusion study, that anything less than around 100 g CHO with each Cr dose would be no more effective than Cr alone. However, Green *et al.* (1996b) stated that this amount was close to the limit of palatability. Additionally, the excessive energy intake with a four-dose daily loading regimen would amount to ~6000 kJ per day which would be likely to lead to nutritional inadequacies or additional weight gain. With these limitations in mind, Preen *et al.* (2003) compared a lower dose of daily CHO (140 g / d) with a Cr-alone supplementation condition and showed the additional CHO enhanced Cr uptake beyond the level observed with Cr alone. This additional energy intake was far lower than that required by the recommendations of Green *et al.* (1996b). The issue of CHO-dose to accompany Cr supplementation remains unresolved although a recent review of this area (Bemben and Lamont, 2005) merely commented that the additional use of a CHO solution helps Cr storage.

A consequence of Cr supplementation is an increased body mass. This additional mass is thought to be due to the higher water retention resulting from the greater osmotic pressure that exists with additional Cr storage (Hultman *et al.*, 1996; Mesa *et al.*, 2002).

This elevation in body mass is a common finding in studies of Cr supplementation (Balsom *et al.*, 1993a; Izquierdo *et al.*, 2002; Yquel *et al.*, 2002; Van Loon *et al.*, 2003) with typical increases of at least 1 kg found after 5-6 day loading regimes. It is noteworthy that this elevation in body mass is still observed in subjects who are otherwise classed as Cr supplementation non-responders (Syrotuik and Bell, 2004). Although the majority of research shows that Cr supplementation benefits exercise performance, increased body mass *per se* is likely to hinder performance where the body weight is not supported (Mesa *et al.*, 2002). For RSE, there are examples of studies which have shown beneficial effects of Cr supplementation for weight-bearing activity (Aaserud *et al.*, 1998; Izquierdo *et al.*, 2002) and of studies showing a lack of ergogenesis with non-weight bearing activity (Barnett *et al.*, 1996; Ahmun *et al.*, 2005), indicating that there is currently a lack of consensus on this topic.

Mechanisms of creatine action.

The mechanisms by which Cr supplementation has its ergogenic effect have been the subject of a number of studies. Greenhaff *et al.* (1994) demonstrated that supplementation led to faster PCr resynthesis using 2 repetitions of 30-s maximal cycling with 4-min recovery. Using the same procedure, Casey *et al.* (1996a) showed that Cr supplementation allowed a greater capacity for ATP rephosphorylation and that this effect was most marked in type II muscle fibres. Lemon *et al.* (1995) also showed that Cr supplementation led to faster ATP resynthesis with 20 repetitions of 16 -s ankle extensions followed by 30 s of recovery. Other authors have shown a reduced perturbation of P_i and pH (Rico-Sanz, 2000; Yquel *et al.*, 2002) and enhanced PCr recovery after supplementation with Cr (Yquel *et al.*, 2002). From these studies it would appear that elevated PCr stores allow for greater ATP resynthesis and greater use of PCr as a substrate than would otherwise be possible prior to supplementation. These observations are supported by metabolic evidence of lower concentrations of ammonia and hypoxanthine in blood samples obtained after exercise (Balsom *et al.*, 1993a; Birch *et al.*, 1994). Additionally, Balsom *et al.* (1993a) controlled for the work done in their repeated-sprint procedure and demonstrated lower [La] after creatine supplementation. Other studies showed similar post-exercise [La] but did not control for the higher work done in the post- supplementation condition (Aaserud *et al.*, 1998; Peyrebrunne *et al.*, 1998; Preen *et al.*, 2001).

Although higher capacity to use PCr within an exercise bout and the greater resynthesis of PCr possible afterwards are commonly cited as mechanisms for enhanced RSE performance after Cr supplementation (Aaserud *et al.*, 1998; Peyrebrunne *et al.*, 1998; Preen *et al.*, 2001; Van Loon *et al.*, 2003), other mechanisms have been proposed which could improve performance. These mechanisms include greater capacity for ATP diffusion between myofibrils and mitochondria (Rico-Sanz and Mendez-Marco, 2000), enhanced post-contraction calcium uptake (Van Leemputte *et al.*, 1999), greater activation of glycolysis (Bemben and Lamont, 2005) and elevated buffering capacity (Mesa *et al.*, 2002). There is potential, therefore, for all of these mechanisms to impact on RSE performance. Although it is unclear which mechanisms are most important, the evidence supports the use of Cr supplementation as an effective intervention for enhancing RSE performance.

Creatine supplementation and repeated-sprint performance

Creatine is often considered as an ergogenic aid that may enhance RSE performance (Williams and Branch, 1998; Bird, 2003). The potential metabolic links between PCr resynthesis, RSE and elevated PCr storage have been the foundation for numerous studies in this area although the previously mentioned potential ergogenic mechanisms may also explain positive findings with Cr supplementation. Considering only those studies which are relevant to RSE, Tables 6 and 7 give a summary of supplementation studies that demonstrate the existence or absence of a performance benefit, respectively. The majority of studies show an ergogenic effect from Cr supplementation and, where measured, all supplementation procedures were successful at elevating intramuscular Cr stores (McKenna *et al.*, 1999; Finn *et al.*, 2001; Preen *et al.*, 2001; Van Loon *et al.*, 2003). Most of the studies which showed a positive performance effect from Cr supplementation attributed their findings to enhanced PCr storage capacity leading to either more rapid ATP resynthesis within a bout, greater PCr resynthesis between bouts, higher potential for H⁺ buffering, lower P_i accumulation or higher pH (Jones *et al.*, 1999; Preen *et al.*, 2001; Izquierdo *et al.*, 2002; Yquel *et al.*, 2002). Of those that did not show an effect, some procedures are atypical of the RSE literature due to low sprint number (i.e., 2) (Cooke *et al.*, 1997b), high recovery duration (i.e., up to 180 s) (McKenna *et al.*, 1999) or high work:rest ratio (i.e., 1:1) (Finn *et al.*, 2001). In two of the studies which showed no effect of Cr supplementation, non-significant trends for improved performance were observed (Finn *et al.*, 2001; Ahmun *et al.*, 2005), which

Ahmun *et al.* (2005) claimed may be of potential benefit to an athlete, despite lacking statistical significance.

Table 6. Studies showing significant improvement in repeated-sprint performance with creatine supplementation.

Study	Subjects	Cr Supplementation	Study design	Performance test	Outcome
Balsom <i>et al.</i> (1993a)	n = 16 PE students	6 d. 25 g / d (5 doses)	R, DB, P-C	Cycling - 10 × (6 -s sprint: 30 s) cycle sprint	↓ fatigue in RSE
Bogdanis <i>et al.</i> (1996a)	n = 16	5 d. 75mg (kg of body mass ⁻¹) (4 doses) with 1 g CHO	R, DB, P-C	Non-motorised treadmill 6 x 10 s sprint, 30-s recovery)	↑ in performance of final sprint
Kreider <i>et al.</i> (1998)	n = 25 American footballers	28 d. 15.75 g / d (4 doses) with 99 g CHO	R, DB, matched-pairs	Cycling - 12 × (6-s sprint: 30-s recovery)	↑ work in sprints 5-6
Aaserud <i>et al.</i> (1998)	n = 14 Handballers	5 d. 15 g / d (3 doses) with 10 g CHO	R, SB, P-C	Running - 8 × (40 -m sprint: 25-s recovery)	No Δ in first sprint. ↓ fatigue in RSE
Jones <i>et al.</i> (1999)	n = 16 Ice hockey	5d. 20 g / d (4 doses). Then maintenance (5 g / d) for 10 weeks	DB, P-C	Cycling - 5 × (15 -s sprint: 15-s recovery) Skating - 6 × (~7 -s sprint: on 30 s)	↑ performance in both tests after 10 d. Gain lost at 10 wk (cycle)
Kamber <i>et al.</i> (1999)	n = 10 PE students	5 d. 20 g / d (4 doses) + 17 g CHO	DB, X-O (28 d washout)	Cycling 10 × (6 -s sprint: 30-s recovery)	↑ overall RSE performance. Due to ↑ in last 2 s of later sprints
Mujika <i>et al.</i> (2000)	n = 17 Soccer players	6 d. 20 g / d	DB, P-C	Running - 6 × (15 -m sprint: 30-s recovery) Running - 40 × (15 -m sprint: 10-s recovery)	↑ speed with 30-s recovery vs. 10-s recovery

Abbreviations used: R - randomised; SB - single blind; DB - Double blind; P-C - Placebo-control; X-O - Crossover design; Δ - Change; TCr - total creatine; CS - creatine synthase; CHO - carbohydrate solution ingested with Cr administration; M - males, F - females; ↑ - increased; ↓ - decreased. All subjects were healthy, active, males unless stated otherwise.
Contd..!

Table 6 contd. Studies showing significant improvement in repeated-sprint performance with creatine supplementation.

Study	Subjects	Cr Supplementation	Study design	Performance test	Outcome
Preen <i>et al.</i> (2001)	n = 14	5 d. 20 g / d (4 doses) with 4 g CHO	DB, P-C	Cycling - 80 min of 6 -s sprints with either 24, 54, 84-s recovery, 3-4 sets of 5-6 reps of each.	↑ Cr, PCr ↑ in RSE for 54-s and 84-s recovery bouts
Romer <i>et al.</i> (2001)	n = 9 Squash players	5 d. 0.3 g / kg BM / d (4 doses)	DB, X-O (28 d washout)	Squash speed drills 10 × (30 s: 30-s recovery)	↑ overall RSE performance. Due to ↑ in sprints 2-10
Skare <i>et al.</i> (2001)	n = 18 sprinters	5 d. 20 g / d (4 doses)	R, SB, P-C	6 × (60 -m sprint, starting every 60 s)	↑ RSE performance in Cr only
Cottrell <i>et al.</i> (2002)	n = 30 Cyclists	6 d. 0.3 g / kg BM / d	SB, P-C	Cycling 8 × 15-s sprint, 60 s, 180 s, 300-s rest	↑ RSE for 60 s and 180 s conditions
Cox <i>et al.</i> (2002)	n = 12 F Soccer	6 d. 20 g / d	DB, P-C	Soccer-specific tasks - game simulation	↑ performance in sprints & agility
Izquierdo <i>et al.</i> (2002)	n = 19 Handballers	5 d. 20 g / d	R, DB, P-C	Running - 6 × (15 -m sprint: on 60 s)	Sig 0-5 -m speed in RSE test. No other RSE Δ
Van Loon <i>et al.</i> (2003)	n = 20	5 d. 20 g / d (4 doses) with 100 g CHO / d	R, DB, P-C	Cycling - 12 × (12 -s sprint: 48 -s recovery)	↑ Cr, PCr, TCr ↑ power in RSE test. No Δ endurance trial, CS activity
Gill <i>et al.</i> (2004)	n = 11 Game-sport players	6 d. 20 g / d (4 doses) compare Cr serum with powder	R, DB, X-O (49 d washout)	Cycling 10 × (6 -s sprint: 24-s recovery)	↑ RSE performance with powder only

Abbreviations used: R - randomised; SB - single blind; DB - Double blind; P-C - Placebo-control; X-O - Crossover design; Δ - Change; TCr - total creatine; CS - creatine synthase; CHO - carbohydrate solution ingested with Cr administration; M - males, F - females; ↑ - increased. All subjects were healthy, active, males unless stated otherwise.

Table 7. Studies showing no significant improvement in repeated-sprint performance with creatine supplementation.

Study	Subjects	Cr Supplementation	Study design	Performance test	Outcome
Barnett <i>et al.</i> (1996)	<i>n</i> = 17	4 d. 0.28 g / kg BM/d (4 doses) + 40 g CHO	DB, matched pairs	Cycling - 5 × (10 -s sprint: 30-s recovery)	No Δ performance
Cooke <i>et al.</i> (1997b)	<i>n</i> = 80	5 d. 20 g / d (4 doses) + 4 g CHO	R, P-C	Cycling - 2 × (-8-s sprint: either 30, 60, 90, 120-s recovery)	No Δ performance
McKenna <i>et al.</i> (1999)	<i>n</i> = 14	5 d. 30 g / d (6 doses) + 30g CHO	DB	Cycling - 5 × (10 -s sprint : variable recovery 180 - 20 s)	↑ Cr, TCr, PCr No Δ performance
Finn <i>et al.</i> (2001)	<i>n</i> = 16 triathletes	5 d. 20 g / d (4 doses)	DB, P-C	Cycling - 4 × (20-s sprint: 20-s recovery)	↑ TCr but not PCr No Δ performance
Delecluse <i>et al.</i> (2003)	<i>n</i> = 12 sprinters (M, F)	7 d. 0.35 g / kg BM/d (5 doses) + CHO (unspecified)	DB, X-O (49 d washout)	Running - 2 × 6 × (40 -m sprint: 30-s recovery) plus 7 more 40 -m sprints, variable recovery 30 - 180 s	No Δ performance
Kinugasa <i>et al.</i> (2004)	<i>n</i> = 12	5 d. 20 g / d (4 doses) + 10 g CHO	SB, matched groups	Cycling - 10 × (6 -s sprint: 30-s recovery)	No Δ performance
Ahmun <i>et al.</i> (2005)	<i>n</i> = 14 trained rugby	5 d. 20 g / d (4 doses)	R, DB, X-O (28 d washout)	Cycling - 10 × (6 -s sprint: 24-s recovery) Running - 10 × (40 -m sprint: 24-s recovery)	No Δ performance
Glaister <i>et al.</i> (2006)	<i>n</i> = 42	5 d. 20 g / d (4 doses) + 4 g CHO	R, DB, P-C	Running - 15 × (30 -m sprint: starting on 35 s)	No Δ performance

Abbreviations used: R - randomised; SB - single blind; DB - Double blind; P-C - Placebo-control; X-O - Crossover design; Δ - Change; TCr - total creatine; CS - creatine synthase; CHO - carbohydrate solution ingested with Cr administration; M - males, F - females; ↑ - increased. All subjects healthy, active & males unless stated otherwise.

Assessment of Performance in Repeated-Sprint Exercise

Introduction to assessment of performance in repeated-sprint exercise

This review has so far demonstrated the physiological processes that may determine RSE performance. The importance of RSE for game-sports has also been discussed. As for most sports, it is valuable to be able to quantify fitness levels for competitors in the game-sports. However, the complexity of the requirements for RSE performance and, the fact that many of these requirements conflict with each other, may make assessment of performance for game-sports performers relatively difficult. For example, an individual game-sports competitor may have very good speed, strength and power but these factors could conflict with the recovery ability that is also vital for RSE (Hamilton *et al.*, 1991; Fitzsimons *et al.*, 1993).

The fact that the literature is inconclusive on the specific factors which determine performance in repeated-sprint exercise makes it even more important that assessments for game-sports competitors stress the physiological processes needed in an appropriate manner and that they do so with a high degree of experimental control. The use of RSE tests, instead of merely evaluating the discrete aerobic and anaerobic abilities which support RSE performance, was specifically recommended by Dawson *et al.* (1991). As the metabolism of RSE was known to be more than just the combination of aerobic and anaerobic quantities, it was reasoned that fitness assessment of competitors should reflect the demands of game-sports competition (Dawson *et al.*, 1991).

Procedures for repeated-sprint exercise testing

The literature on test procedures for game-sports competitors contains protocols that can be grouped into two main categories, which for the purpose of this thesis will be termed 'game-sports simulations' and the 'RSE tests'. The game-sports simulations are intended to reflect a sport's activity profile. Examples of these tests are evident in soccer where tests have used exercise of varying intensities involving either shuttle running (Nicholas *et al.*, 2000), non-motorised treadmill running (Drust *et al.*, 2000a; Abt *et al.*, 2003) or motorised treadmill running (the 'interval treadmill test' of Bangsbo and Lindquist, 1992). A practical limitation of all of the game-sports simulations is that, by necessity, they are typically as long as a competitive match (Bangsbo and Lindquist,

1992; Nicholas *et al.*, 2000; Abt *et al.*, 2003) and due to their high specificity, they may be of limited value to players of other game-sports. By far the majority of test procedures for game-sports competitors use protocols that are shorter in duration than these game-sports simulations. These tests are simply based on the repeated performance of a series of maximal sprints with a consistent rest period between sprints (i.e., repeated-sprint exercise or 'RSE tests'). These tests are shorter than the simulations and have not been developed to mimic exactly the activity patterns of a specific sport. Rather, these tests represent an attempt to assess the general ability to perform repeated, short sprints with a view to applying the outcomes to performance in a competitive game. The generality of these procedures allows for the establishment of normal values, more-standardised procedures and better models with which to assess the general components of RSE performance. A comprehensive selection of the RSE tests that are present in the literature are included in Appendix 1.

Performance outcomes from repeated-sprint testing

In some areas of fitness assessment, for example in evaluating $\dot{V}O_{2\text{ max}}$, the test outcome is a specific and definable physiological quantity. As a consequence, the test outcome is somewhat independent of the procedures used, but for the assessment of RSE this is not the case. At present the evaluation of RSE is only definable by quantification of performance-related variables such as fatigue, work done, test time or average sprint time (Fitzsimons *et al.*, 1993; Glaister *et al.*, 2003).

Of the tests most frequently used to assess RSE, the majority use either cycle ergometry or sprint-running in a field test, with only a few studies citing use of a non-motorised treadmill (Holmyard *et al.*, 1988; Hamilton *et al.*, 1991; Nevill *et al.*, 1994; Ratel *et al.*, 2004). The equipment used tends to determine the variables that can be derived from RSE testing. The sprint-running tests tend to require a specific distance to be covered (Wadley and LeRossignol, 1998; Aziz *et al.*, 2000; Dupont *et al.*, 2005) and measures of average run-time (or velocity) are taken as the main performance measures. In contrast, the cycling tests tend to require exercise for a specific time with measures of peak power, average power or work-done taken (e.g., Balsom *et al.*, 1993a; Gaitanos *et al.*, 1993; Bishop *et al.*, 2004a). Non-motorised treadmill procedures are generally time-based and both velocity and power outcomes are usually reported (Holmyard *et al.*, 1988; Hamilton *et al.*, 1991; Nevill *et al.*, 1994). In each of these cases, the performance

measures that are derived from the series of sprints are also used to quantify a fatigue index.

The performance of RSE needs to be defined by a combination of at least two variables, one a 'performance measure' (e.g., average sprint velocity), the other an expression of fatigue (Dawson *et al.*, 1993; Fitzsimons *et al.*, 1993; Dawson *et al.*, 1998). This principle is evident consistently across the literature, irrespective of exercise mode. Knowledge of both outcomes is required in order to interpret RSE test performance. In sprint-running, for example, the key variables to derive from an RSE test are typically mean sprint time (averaged across the series of sprints) and a fatigue index (Dawson *et al.*, 1993; Ahmun *et al.*, 2005). With cycle ergometers and non-motorised treadmills, greater sampling frequency is possible and it is typical to assess within-sprint values for maximal and average velocity or power and for these variables to be then used to calculate separate fatigue indices and mean performance (Holmyard *et al.*, 1988; Fitzsimons *et al.*, 1993; Gaitanos *et al.*, 1993). Although the different modes of exercise will produce different types of data, the principles of analysis are similar whether the test employs running or cycling.

As fatigue is one of the two key outcomes from an RSE test, any valid test of repeated-sprint performance would be expected to elicit fatigue. However, there are many ways to assess fatigue over a series of sprints. The most common fatigue calculation is to establish the difference between highest and lowest power outputs, expressed as a percent of the highest. This method has been used frequently in cycle testing and non-motorised treadmill procedures (Holmyard *et al.*, 1988; Gaitanos *et al.*, 1993). A number of alternative means of calculating fatigue have been used in the literature and their validity and reliability have been investigated by Glaister *et al.* (2004). Specifically, these authors performed four different fatigue calculations after performing two 20 × 5 -s sprint procedures (10 or 30 -s recovery). Their fatigue calculations are shown in Table 8 along with data from the condition of their study that used a 30-s recovery between sprints. Glaister *et al.* (2004) concluded that equations 1 and 2 lacked validity and reliability. This lack of validity was attributed to the fact that the calculations were based on only two values and were therefore not representative of general trends in the data set. The procedure recommended by Paton *et al.* (2001) involved establishing the gradient of the line of best fit performance data across the series of sprints, but this was thought to lack validity for the procedures used by Glaister

et al. (2004). Paton *et al.* (2001) had used only 10 sprints for their test and the performance decline was approximately linear. However, Glaister *et al.* (2004) used 20 sprints and the rate of decline in performance slowed as the series of sprints continued. They reasoned that this protocol would give a lower fatigue rating as the sprint number increased and that this was consequently an inappropriate calculation for the general assessment of fatigue. In conclusion the use of the ‘percent decrement score’ (Calculation 4, Table 8) was recommended due to its relatively high validity and reliability (Glaister *et al.*, 2004).

Table 8. Calculations of fatigue for 20 × (5-s sprint: 30-s recovery) as used by Glaister *et al.* (2004).

Calculation	Fatigue score (%)
1. Difference between first and last sprints as a percentage of first sprint	5.4 ± 4.9
2. Difference between highest and lowest mean power as a percentage of highest result	13.4 ± 5.7
3. Back transformation of the slope of the line of best fit for log-transformed mean power values (from Paton <i>et al.</i> , 2001)	5.2 ± 7.5
4. ‘Percentage decrement score’ derived from difference between highest mean power and average power from all sprints (from Fitzsimons <i>et al.</i> , 1993)	7.4 ± 4.6

Physiological variables measured during repeated-sprint testing.

Unlike for the evaluation of performance, physiological measurements such as $\dot{V}O_2$, post-exercise [La] and heart rate (HR) have not been shown to have a direct role in evaluating a performer’s ability to perform repeated sprints. Nevertheless, many authors have made measurements of these variables with RSE testing and they are useful in providing a description of the demands of such tests (Balsom *et al.*, 1992b; Gaitanos *et al.*, 1993; Bishop *et al.*, 2004b; Dupont *et al.*, 2005; Glaister *et al.*, 2005). For the present study this information is especially useful as it may allow comparison between the demands of game-sports and the test procedures used to assess this component of game-sports fitness.

Blood lactate.

For RSE testing, many authors have evaluated post-exercise [La] (e.g., Hamilton *et al.*, 1991; Balsom *et al.*, 1992a; Fitzsimons *et al.*, 1993; Bishop *et al.*, 2004b; Dupont *et al.*, 2005; Glaister *et al.*, 2005). Although the procedures within these studies are not consistent, the range of mean [La] is from 9 mmol.l⁻¹ after 5 × (6 -s sprint, on 30 s) (Bishop *et al.*, 2004b) to 17.2 mmol.l⁻¹ after 15 × (40 -m sprint, 30 -s recovery). Ratel *et al.* (2004) compared [La] in running and cycling and showed running to give significantly higher values. There have been suggestions that [La] is proportional to the degree of fatigue experienced within a series of sprints (Brooks *et al.*, 1990; Hamilton *et al.*, 1991; Fitzsimons *et al.*, 1993; Gaitanos *et al.*, 1993). This view would be consistent with observations that associate fatigue with fast fibre type proportion (Colliander *et al.*, 1988; Li *et al.*, 2002), initial power production (Dawson *et al.*, 1993; Wadley and LeRossignol, 1998) and anaerobic metabolic activity (Dahlstedt *et al.*, 2000) in single or repeated sprints. However, studies of RSE where post-exercise recovery duration was altered have also shown fatigue and [La] to be unrelated (Holmyard *et al.*, 1988; Balsom *et al.*, 1992b; Blanc *et al.*, 1998; Glaister *et al.*, 2005). While high [La] seems to relate to the degree of fatigue (Li *et al.*, 2002), this fatigue is not thought to be attributed to [La] or the associated lactic acidosis (Balsom *et al.*, 1992b; Bangsbo, 2000). Consequently, although [La] may be a useful indicator of glycolytic activity, it is unlikely that measures of [La] would be valuable as indicators of RSE performance.

The [La] values that have been found during the performance of game-sports are thought to be similar to those observed from RSE testing (Dawson *et al.*, 1993). However, competitive situations are hard to replicate and the assessment of blood lactate during the performance of most sports is impractical. Post-exercise [La] values are frequently quoted around 3 - 6 mmol.l⁻¹ from a range of game-sports (see Table 1) but these measurements are usually made immediately after competition. Therefore, these [La] values are probably not representative of the more stressful parts of game-sports performance (Dawson *et al.*, 1993; Reilly, 1997). The highest competitive-situation [La] values in soccer, for example have been up to 12 mmol.l⁻¹ (Mohr *et al.*, 2005). Using this result as a comparison the [La] from RSE tests and sports performance would represent similar glycolytic activity.

Heart rate and oxygen consumption.

Assessments of HR and $\dot{V}O_2$ have rarely been performed during RSE tests and, once again, the procedures adopted between studies are not directly comparable. These studies have used cycling (Glaister *et al.*, 2005), running (Balsom *et al.*, 1992b; Dupont *et al.*, 2005) or non-motorised treadmill running (Holmyard *et al.*, 1988; Hamilton *et al.*, 1991) and different combinations of repetition number, sprint duration and recovery duration (see Appendix 1). It should be pointed out that, unusually for the RSE tests, the procedures of Dupont *et al.* (2005) used an active recovery period with subjects running at 50 % of the speed-to-elicite $\dot{V}O_{2\max}$. Usually, the laboratory-based RSE tests incorporate passive recovery and the field-based studies often have a deceleration phase before subjects walk back to the timing apparatus (Balsom *et al.*, 1992b; Paton *et al.*, 2001). In the running procedures, average HR was typically around 175 - 180 beats.min⁻¹ (Holmyard *et al.*, 1988; Hamilton *et al.*, 1991; Balsom *et al.*, 1992b; Dupont *et al.*, 2005) while for cycling the corresponding result was lower at around 161 beats.min⁻¹ even though this procedure used 5-10 more sprints (Glaister *et al.*, 2005). The data for $\dot{V}O_2$ are less comparable as Holmyard *et al.* (1988) used Douglas-bag analysis while Glaister *et al.* (2005) and Dupont *et al.* (2005), used breath-by-breath analysis. The subjects of Dupont *et al.* (2005) all reached their $\dot{V}O_{2\max}$ within the RSE test (with 5 s averaging period for $\dot{V}O_2$) although mean $\dot{V}O_2$ was not stated. The highest $\dot{V}O_2$ obtained by subjects in the study of Hamilton *et al.* (1991) (30 -s averaging using Douglas bag analysis) was 72 % $\dot{V}O_2$ peak. Glaister *et al.* (2005) did not report their subjects' $\dot{V}O_{2\max}$ so direct comparisons are not possible but their 20 × (5 -s sprint, on 35 s) cycling procedure elicited lower relative $\dot{V}O_2$ than was achieved with the treadmill running procedure of Hamilton *et al.* (1991) (34.8 ml.kg⁻¹.min⁻¹ vs. 40.7 ml.kg⁻¹.min⁻¹, respectively). Collectively, these data suggest that cycling tests may elicit lower responses for $\dot{V}O_2$ and HR compared to running and that running tests give mean $\dot{V}O_2$ of around 70 % $\dot{V}O_{2\max}$ and HR of at least 175 beats min⁻¹ for the trained, but not elite, college-aged males of these studies.

A comparison of responses to game-sports performance (Table 1) and RSE suggests that RSE test procedures elicit quite similar responses to those from competitive situations. Although it is accepted that the RSE tests in Table 1 are only a small sample of the RSE tests in the literature, these procedures (with the exception of Dupont *et al.*, 2005) are quite representative of the majority of tests published. That this is the case could be

somewhat coincidental as no authors have documented the development of their RSE procedure to reflect these physiological responses to game-sports.

The oxygen-dependent, post-exercise recovery from a sprint is a vital aspect of RSE and the potential value of $\dot{V}O_2$ measures has already been presented in this review. Given the potential for an RSE test to be valuable for coaches and athletes as well as scientists, it is remarkable that so few authors have assessed HR in their RSE studies (Holmyard *et al.*, 1988; Edwards *et al.*, 2003; Glaister *et al.*, 2005), given the ease of HR analysis. Glaister *et al.* (2005) measured HR throughout two series of a 20 -repetition 5 -s sprint cycling RSE test, each series with either 10 or 30 -s recovery between each sprint. The short recovery procedure gave significantly lower HR recovery and mean power outputs. Indeed, these authors observed that HR recovery between sprints was absent when their short-recovery procedure was used. In contrast, their longer recovery procedure led to higher mean power outputs and greater HR recovery (Glaister *et al.*, 2005). Similar findings were shown by Holmyard *et al.* (1988) who compared the responses to two series of 10 -s sprints with either 30 or 60 -s recoveries. In this case, the authors only observed trends, rather than significant differences, towards higher HR recovery with higher sprint performance. Finally, using a different exercise model, Edwards *et al.* (2003) investigated HR recovery after three bouts of around 14 min of simulated soccer activity (separated by 3 -min recovery). They showed that HR recovery was faster in professional academy players than recreational players even though there were no significant differences in predicted $\dot{V}O_{2\max}$ between groups. These studies support at least the notion that HR recovery measures are sensitive to factors which relate to performance recovery, suggesting that HR could be valuable in the assessment of RSE fitness. The many practical applications of RSE assessments would imply that use of a simple measurement like HR could be a valuable addition to the performance variables as a potential method to assess RSE. The available literature that relates to this topic is inconclusive. It has been shown that HR and $\dot{V}O_2$ are not linearly related at a specific time point in the performance of RSE (Balsom *et al.*, 1992b; Glaister *et al.*, 2005) but that strong correlations exist between the time constants of the exponential increase in HR and $\dot{V}O_2$ at the onset of exercise (Chilibeck *et al.*, 1996).

Influence of procedural variation on repeated-sprint performance.

Although many RSE tests have been published which are claimed to assess repeated-sprint performance, a wide range of procedures has been adopted. For example, sprint durations range from 3 s (Wadley and LeRossignol, 1998; Paton *et al.*, 2001) to 15 s (McMahon and Wenger, 1998), recovery durations from 7 s (Paton *et al.*, 2001) to 90 s (McMahon and Wenger, 1998) and work: rest ratios range from 1:6 (Heller and Psotta, 1999; Glaister *et al.*, 2003) to 1:2 (Glaister *et al.*, 2003). From the procedures in Appendix 1, the mean ($\pm s$) values for sprint duration, number of sprints, rest duration and work:rest ratio are 6.2 ± 2.1 s, 9.4 ± 3.8 sprints, 28.2 ± 13.7 s and $1:4.2 \pm 0.07$, respectively.

The performance of RSE is known to be influenced by alterations in each of the possible procedural variables, such as sprint duration (Dawson *et al.*, 1991), sprint number (Dawson *et al.*, 1991), recovery duration (Holmyard *et al.*, 1988, Glaister *et al.*, 2005), recovery intensity (Signorile *et al.*, 1993; Dupont *et al.*, 2003) and exercise mode (Fitzsimons *et al.*, 1993; Ratel *et al.*, 2004). If RSE performance is to be quantified, then standardisation of all of these test variables needs to be considered.

Duration of sprints.

Few studies have exclusively manipulated the variable of sprint duration in RSE (Dawson *et al.*, 1991; Balsom *et al.*, 1992a). Both of the studies where this was done have shown that increasing sprint duration while maintaining recovery duration, tended to induce higher rates of fatigue. The more comprehensive of these studies showed that sprinting 15 m (compared to 30 m and 40 m) every 30 s gave better performance, lower $\dot{V}O_2$, lower [La], and lower hypoxanthine concentration (Balsom *et al.*, 1992a). In the short sprint condition (15 -m sprint, on 30 s), no decline was evident in the performance, whereas the long sprint condition (40 -m sprint, on 30 s) showed significant fatigue after only 3 sprints. The lack of hypoxanthine accumulation in the short sprint condition was taken as evidence that PCr could be resynthesised in this condition without resorting to the AK reaction (Balsom *et al.*, 1992a). Dawson *et al.* (1991) showed similar findings from their [La] and measurements of performance time.

Number of sprints.

Although the information shown in Appendix 1 illustrates that the number of sprints in RSE procedures is quite variable, only one study seems to have reported specifically on the impact of altering the number of sprints on RSE performance (Dawson *et al.*, 1991). These authors used only 2 subjects per experimental group and compared 12, 16 and 20 sprints of 7 s duration starting every 30 s. They concluded that the number of sprints did not seem to influence the rate of fatigue or the post-exercise peak [La]. Many other repeated-sprint tests have employed procedures which used 10 sprints (for example, Balsom *et al.*, 1993a; Gaitanos *et al.*, 1993; Capriotti *et al.*, 1999). Analysis of the procedures listed in Appendix 1 shows that the mean number of sprints in these RSE tests is 9.4 Other information on this area can be obtained by considering procedures which are matched for all procedural variables, except sprint duration. Such a comparison is possible between the studies of Glaister *et al.* (2005) and Heller and Psotta (1999). They both used college students on a cycle ergometry RSE test, with similar resistance and with a sprint duration of 5 s and a rest duration of 30 s. The average of the mean power output obtained with the 20 sprints of Glaister *et al.* (2005) and the 10 sprints of Heller and Psotta (1999) ($10.9 \text{ W}\cdot\text{kg}^{-1}$ vs. $13.3 \text{ W}\cdot\text{kg}^{-1}$, respectively) suggests that the longer protocol may cause greater fatigue. Additionally, most studies have shown a decline in RSE performance within their procedure as sprint number increases (Holmyard *et al.*, 1988; Nevill *et al.*, 1994; Ratel *et al.*, 2004; Glaister *et al.*, 2005) which would imply that additional sprints would cause an additional decline in performance.

Duration of recovery between sprints.

The effect of altering the duration of recovery has been investigated by a number of studies of RSE and, without exception, increasing recovery duration has been shown to improve performance (Holmyard *et al.*, 1988; Balsom *et al.*, 1992b; Holmyard *et al.*, 1994; Ratel *et al.*, 2002; Glaister *et al.*, 2005) while also decreasing heart rate, $\dot{V}O_2$ and hypoxanthine (Holmyard *et al.*, 1988; Balsom *et al.*, 1992b; Glaister *et al.*, 2005). The greater PCr resynthesis that is allowed when recovery is extended is often taken as the mechanism that explains improved performance (Holmyard *et al.*, 1988; Balsom *et al.*, 1992b). The lower hypoxanthine concentrations observed by Balsom *et al.* (1992) with longer recovery durations are consistent with a higher PCr resynthesis and resultant lower activation of the AK pathway. While many authors have tended to focus on

fatigue mechanisms with reference to the depletion of PCr, the concomitant elevation in P_i could also be associated with fatigue as P_i is known to reduce SR Ca^{2+} handling (Westerblad *et al.*, 2002; Tupling, 2004). Irrespective of the mechanisms, it is clear that alterations in recovery duration may have a significant effect on the performance of RSE.

Intensity of exercise between sprints.

It is unclear whether the performance of low-intensity activity after a sprint may promote or hinder recovery (Balsom *et al.*, 1992b; Signorile *et al.*, 1993; Dawson *et al.*, 1997; Franchini *et al.*, 2003). The elevated blood flow, lactate removal, oxygen kinetics and oxidative enzyme activity that result from exercise in a recovery period have been cited as mechanisms which could promote recovery (Signorile *et al.*, 1993; Gerbino *et al.*, 1996; Franchini *et al.*, 2003). Conversely, it has also been suggested that the additional metabolic cost of post-exercise activity could reduce the speed of recovery by limiting ATP availability for PCr resynthesis (Spriet *et al.*, 1989) or lowering [PCr] (Spencer *et al.*, 2006). Where the intensity of activity between sprints has been investigated in RSE, a lack of consensus exists with active recovery leading to either superior (Signorile *et al.*, 1993) or inferior RSE performance (Spencer *et al.*, 2006) compared to passive recovery. Although these findings represent a lack of consensus on this issue, it is accepted that the intensity of exercise between sprints has the potential to affect subsequent performance (Bogdanis *et al.*, 1995; Tomlin and Wenger, 2002; Connolly *et al.*, 2003) and therefore should be a factor which is controlled for in the context of RSE fitness assessment.

Exercise mode.

The RSE tests in Appendix 1 tend to use either sprinting (generally field-testing on a track or similar) or cycle ergometry as the mode of activity. The use of cycle ergometers, presumably representing a preference for laboratory testing, is more common than the field-based procedures. This prevalence for cycling as the mode of activity may conflict with the principles of sport-specificity when the assessment of RSE fitness in game sport competitors is considered. The comparison of exercise mode has rarely been investigated in RSE tests (Fitzsimons *et al.*, 1993; Ratel *et al.*, 2004) and, when it has it is suggested that differences in exercise mode influence the response to RSE. Fitzsimons *et al.* (1993) compared track sprinting (6 × (40 -m sprint, on 30 s))

with cycle performance (6 × (6 –s sprint, on 30 s)) showing only moderate correlations between the fatigue characteristics of the tests and a lack of correlation between the best sprint on either mode. Correlations were evident for RSE performance only when the work done in the cycle test (expressed relative to body mass) was correlated with time to complete the series of 6 running sprints. These authors concluded that a running RSE test was preferable to the cycling test due to exercise-mode specificity but that some general characteristics of RSE performance (e.g., fatigue) could be established using either mode. Ratel *et al.* (2004) compared RSE performance in different exercise modes and showed that their non-motorised treadmill running procedure elicited significantly greater fatigue throughout a series of 10 × (10 -s sprints, on 25 s) than an equivalent cycling procedure. They attributed these findings to the differences in muscle recruitment resulting from these contrasting modes of activity (Ratel *et al.*, 2004).

The conclusions from this section are that small changes in any of the procedural variables in an RSE test have the potential to alter performance. Within the context of the present thesis, there is a need for the standardisation of procedures. This is further justified when it is considered that presently, the only key outcomes of an RSE tests are based on performance variables like power or speed. The diversity of current procedures and the resultant lack of normal values are likely to be a hindrance to the development of research in the area of RSE.

Validity and reliability of repeated-sprint tests.

Many authors have investigated the effect of certain independent variables upon the performance of RSE. Examples include training status (Hamilton *et al.*, 1991; Dawson *et al.*, 1998), nutrition (Balsom *et al.*, 1999), exercise mode (Fitzsimons *et al.*, 1993; Ratel *et al.*, 2004), creatine supplementation (Balsom *et al.*, 1993a; Ahmun *et al.*, 2005), acid-base balance (Lavender and Bird, 1989; Bishop *et al.*, 2004a) and the procedural variables which have already been discussed. Few of these authors appear to have investigated the validity or reliability of their procedures. This omission may be attributed to the fact that most of these studies were not aiming to develop an RSE test, rather, they were using their RSE procedure as a model to investigate the effect of another factor on RSE performance.

Validity of repeated-sprint procedures.

One of the difficulties for research in this area is how to assess the validity of an RSE test (Fitzsimons *et al.*, 1993; Bishop *et al.*, 2001). The lack of research into the validity of such procedures may be due to the lack of consensus regarding the physiological factors that determine RSE performance, or to the test procedures and performance measures which allow its evaluation. There are three forms of validity to consider in a fitness test. Content validity refers to whether the test appears to do what it purports to do, criterion validity, whether results from the test correlate with those from established procedures with the same purpose and construct validity, whether the test discriminates between subjects of different ability for that fitness component.

One approach towards evaluating construct and criterion validity has been to compare performance or physiological responses in competition with those from testing. The game simulation procedures have, by definition, been shown to have similar physiological responses to the sport they aim to simulate (Drust *et al.*, 2000b; Nicholas *et al.*, 2000, Thatcher and Batterham, 2004). However, for the purpose of the present study these trials are fundamentally different to RSE tests due to their long test duration, the fact that they replicate the demands of only one sport and, in some cases, do not include an evaluation of performance (Drust *et al.*, 2000b). From the RSE test literature, Bishop *et al.* (2001) were the first to attempt to assess the validity of their RSE procedure ($5 \times (6\text{-s cycle sprint, on } 30\text{ s})$) by relating test results to performance in game simulations for hockey players. Their game simulation involved three 15 -min bouts of intermittent activity with each minute including a range of activities including one timed 15 -m sprint, with 5 m and 10 -m intermediate times also assessed. The study showed that some characteristics of the cycle RSE test were correlated with game-simulation performance. Specifically, total work and fatigue in the RSE test were correlated with equivalent measures in the game simulation. However, the authors did not refer to the fact that their RSE test lacked content validity due to the fact that it was performed on a cycle ergometer. This study remains the only one to assess the validity of an RSE test in this way.

An alternative approach to evaluating construct validity has been to compare performance of subjects, either with contrasting training backgrounds or after training. In this respect the RSE tests appear to show validity from the evidence available. Hamilton *et al.* (1991) showed games sport players had superior initial speed but lower

fatigue resistance than endurance athletes in their 10 × (6-s sprint: 30-s recovery) non-motorised treadmill procedure. Repeated-sprint training programmes over 4 (Nevill *et al.*, 1994) and 6 weeks (Dawson *et al.*, 1998) have been shown to cause significant improvements in the performance of running RSE tests (10 × (6 -s sprint, on 36 s) and 6 × (40 -m sprint, 24 -s recovery), respectively).

Evidence from game-sports performance may support the content validity of the RSE tests in the literature. It is accepted that the repeated performance of sprints lasting less than 10 s is certainly characteristic of most game-sports (Dawson *et al.*, 1984; Balsom *et al.*, 1992a; Bangsbo, 2000) but this form of validity is quite subjective in nature. Bishop *et al.* (2001) stated that content validity can not be determined absolutely in RSE testing and could only be concluded by assumption. The same authors concluded that sprint durations of between 5-7 s seemed appropriate to elicit fatigue in RSE test procedures even though typical sprint durations in game-sports were often shorter than this figure (Bishop *et al.*, 2001).

Reliability of repeated sprint procedures.

There are currently few studies of the reliability of RSE procedures (Fitzsimons *et al.*, 1993; Capriotti *et al.*, 1999; Glaister *et al.*, 2003; Glaister *et al.*, 2004). In one of these studies, RSE tests were repeated on three occasions and performance between the last two sessions was compared (Fitzsimons *et al.*, 1993). Intra-class correlation (ICC), technical error of measurement (TEM) and *t*-tests were used to assess the reliability of their cycling and running (6 × (~6-s sprint, on 30 s)) procedures. Results for velocity and work done were reliable but the fatigue index (percent decrement method) showed lower reliability as judged by the TEM. Glaister *et al.* (2003) and Glaister *et al.* (2004) also concluded that power output measures were reliable in their 20 -repetition, 5 -s sprint cycle RSE tests (10 -s recovery or 30 -s recovery). However, like Fitzsimons *et al.* (1993), they also found that a range of fatigue indices showed lower reliability (Glaister *et al.*, 2004) as judged by ICC and typical error. This lower reliability of fatigue has been attributed to the fact that these indices are derived from more than one measurement (Fitzsimons *et al.*, 1993).

Familiarisation to a test procedure is an important issue when considering reliability and two investigations into the familiarisation of RSE performance have been carried out

using cycle ergometry (Capriotti *et al.*, 1999; Glaister *et al.*, 2003). In both studies it was concluded that after two trials subjects could be considered habituated to their procedures as judged by a maintenance of their performance when subsequent trials were conducted. Other studies have at least incorporated familiarisation procedures into their experimental design, albeit without analysis of its effectiveness (Hamilton *et al.*, 1991; Ratel *et al.*, 2004; Ahmun *et al.*, 2005).

Development of a standardised repeated-sprint test protocol

The only attempt in the literature to develop an RSE test was initiated by Dawson *et al.* (1984). They recognised the need for a general performance test for game-sports players and proposed a 20-sprint procedure with repeated 7 -s sprints, starting every 30 s (i.e., 23 -s recovery). A number of revisions from this original test have been documented. For example, in comparison to the first protocol (Dawson *et al.*, 1984), there has been a decrease in the work : rest ratio and reductions in the number of sprints from 20 down to either 10 or 8 (Dawson *et al.*, 1991) and finally to 5 (Dawson *et al.*, 1993). The justification for reducing the number of sprints from 20 was to avoid the subjects 'pacing' their efforts. The authors stressed that a maximal effort was required throughout for a test of this nature and found the lower number of sprints overcame this problem (Dawson *et al.*, 1991). The procedure now used by the same research group is 5 × (6 -s sprint, on 30 s) (Bishop *et al.*, 2004b; Spencer *et al.*, 2004). Five sprints were first used in the investigation by Dawson *et al.* (1993), even though this contrasted with previous statements advocating the use of 10, in comparison to 8 sprints. The reduction in sprint number was made to enhance the ability to discriminate between subjects (Dawson *et al.*, 1991). The reductions in sprint duration (from 7 s to 5 s) and work : rest ratios (from ~1:3 - 1:5) with the development of this procedure were because the authors had intended to reduce the post-exercise [La] found in the early procedures. Dawson *et al.* (1991) had felt that their high post-test [La] results represented an undesirable characteristic of their test, which they had thought would specifically stress the ATP - PCr pathway as opposed to glycolysis (Dawson *et al.*, 1991). More recently it is accepted that high [La] is inevitable in RSE and that its presence is not necessarily linked with fatigue (Holmyard *et al.*, 1988; Balsom *et al.*, 1992b; Blonc *et al.*, 1998) but this adapted procedure remains in current use (Bishop *et al.*, 2001; Spencer *et al.*, 2004).

The current procedures ($5 \times (6$ -s sprint, on 30 s)) of Dawson and colleagues have been the most thoroughly examined for their validity (Dawson *et al.*, 1993; Bishop *et al.*, 2001), reliability (Fitzsimons *et al.*, 1993) and sensitivity (Spencer *et al.*, 2004) and therefore represent the most concerted attempt to develop an RSE test protocol. However, most other authors in the remaining publications on RSE testing seem to not have adopted these procedures, preferring, instead, to use a higher number of repetitions and, typically a slightly longer rest period (Capriotti *et al.*, 1999; Aziz *et al.*, 2000). A potential weakness of the procedures described by Dawson and co-workers is that they employed cycle ergometry as the exercise mode for testing. Cycling is not relevant to the mode of exercise in the game-sports. Even authors from within this group have recommended the use of running tests where the purpose is to evaluate fitness in game-sports players (Fitzsimons *et al.*, 1993; Spencer *et al.*, 2005).

Despite the prevalence of RSE tests, it is evident that few authors have set out to develop a valid and reliable test of RSA. In the one case where this has happened, the resulting procedure is one which uses cycle ergometry, a mode of exercise which lacks content validity for game-sports competitors and whose use has only been recommended, even by its proponents, as a second preference to running RSE tests. Although running RSE tests have been used in the literature, their validity and reliability have not been established and, only rarely have these procedures been laboratory-based. By building on previously established non-motorised treadmill procedures (Holmyard *et al.*, 1988; Hamilton *et al.*, 1991; Nevill *et al.*, 1994) it is possible to investigate whether a valid, reliable, laboratory-based RSE test can be developed.

Non-Motorised Treadmill Ergometry

Non-motorised treadmill ergometry.

There is an absence of valid and reliable tests to assess RSE performance during running in the current literature. Many authors have used RSE tests with a view to applying their findings to the performance of game-sports performance. Most laboratory tests of RSE have used cycle ergometry as opposed to running. The validity of exercise modes other than running has been questioned for use with game-sports competitors (Fitzsimons *et al.*, 1993; Spencer *et al.*, 2005). The development of non-motorised treadmill (NMT) systems has enabled performance characteristics (velocity, force,

power) to be assessed in a mode of exercise which replicates that required for most game-sports (Hamilton *et al.*, 1991; Sutton *et al.*, 2000; Tong *et al.*, 2001). The use of a laboratory-based NMT also allows greater ease of data collection for physiological measurements such as $\dot{V}O_2$, [La] and haematological variables (Cheetham and Williams, 1987; Hamilton *et al.*, 1991; Thatcher and Batterham, 2004) and provides a degree of environmental control which may not be available in the field testing situation.

General considerations for non-motorised treadmill sprinting.

The first publications on the use of NMT demonstrated that this equipment was a practical alternative to the use of cycle ergometers which, until then, had been the primary exercise mode for assessment of sprint performance (Cheetham *et al.*, 1986; Lakomy, 1987). For continuous sprint-running, the NMT has been shown to be sensitive to training adaptations (Cheetham and Williams, 1987) and has been used extensively to describe the physiological responses to sprinting (Cheetham *et al.*, 1986; Allsop *et al.*, 1990; Brooks *et al.*, 1990; Nevill *et al.*, 1996). Subsequent research has shown that NMT sprinting is a reliable procedure (Tong *et al.*, 2001) and that NMT sprint performance correlates highly with sprint performance in a field test (Ratel *et al.*, 2004).

Non-motorised treadmill systems are typically designed to measure force and running velocity (Lakomy, 1987; Sutton *et al.*, 2000; Tong *et al.*, 2001). The assessment of velocity is achieved by a sensor which detects the movement velocity of the belt. The application of force is assessed in the horizontal direction and is typically achieved by subjects wearing a belt attached to a tether which, in turn, is linked to a strain gauge. The frequency of data sampling in recent research is typically 100 Hz (Sutton *et al.*, 2000; Tong *et al.*, 2001) which reflects a greater precision to the measurement of performance than is possible from the timing systems typically used to assess field test sprint performance (Aziz *et al.*, 2000; Dupont *et al.*, 2005; Oliver *et al.*, 2005). An advantage of NMT ergometry is also that measures of force, power and velocity can be derived from the one exercise test. The calculation of power (W) is from the instantaneous product of force (N) and velocity ($m \cdot s^{-1}$) (Lakomy, 1984; Lakomy, 1987).

Performance measures from testing on a non-motorised treadmill

The performance outcomes from an NMT sprint test usually include a peak (within sprint) value and an average value for velocity, power or force. The peak value is usually an important consideration in sprint testing but the magnitude of the peak result for each measure is influenced by the number of data points from which the figure is derived (Tong *et al.*, 2001). If instantaneous 'raw' data (i.e., individual data from 100 Hz) are analysed the outcomes have been shown to be highly variable (Lakomy, 1987; Tong *et al.*, 2001). This variability is especially evident in the measurement of force and power. Since foot-strike is the only time when force production can occur, each contact represents a peak in force followed by a rapid reduction once foot-strike is over. Consequently, this oscillation of force production throughout a sprint also affects the assessment of power in a similar way. The acceleration of the treadmill belt is a more gradual process but oscillations with individual foot-contacts are also observed (Lakomy, 1984; Lakomy, 1987). This variability in force, power and velocity has been shown to affect the reliability of NMT data and it has been recommended that 1 s-averaged values are derived for performance outcomes when peak values are to be considered (Sutton *et al.*, 2000; Tong *et al.*, 2001). Additionally, Tong *et al.* (2001) showed force to be the least reliable of the performance measures and recommended use of only 1-s power and velocity values to enhance reliability.

Several authors have compared NMT sprinting with either cycle ergometry (Ratel *et al.*, 2004) or over-ground sprinting (Lakomy, 1987; Oliver *et al.*, 2005). Measures of velocity in both running tests have been shown to correlate closely but Lakomy (1987) concluded that average and peak velocity were lower on the NMT than in track running and that this was associated with a reduced stride length and stride frequency on the treadmill. It was also suggested that the greater force required in NMT sprinting to overcome the resistance of the treadmill contributed to the lower performance outcomes in comparison with track running. Ratel *et al.* (2004) showed that NMT sprinting gave significantly lower peak power output but significantly more fatigue than equivalent cycling values. The authors attributed the lower peak power output to the fact that sprint cycle testing often requires exercise against a resistance that should elicit optimal power output but that in NMT sprinting the resistance is not usually optimised (Ratel *et al.*, 2004). Ratel *et al.* (2004) observed a higher fatigue and a greater post-exercise [La] after their NMT test and attributed these to higher muscle recruitment from the sprint-

running activity, further illustrating the likely differences when comparing these different modes of exercise (Ratel *et al.*, 2004).

Although the use of NMT is considered preferable for assessing the response to running, very few authors have used NMT for RSE testing. Most research into NMT-RSE has been performed with the aim of describing the physiological responses to RSE rather than for the assessment of RSE performance (Cheatham *et al.*, 1986; Allsop *et al.*, 1990; Brooks *et al.*, 1990; Nevill *et al.*, 1996). These studies have used exactly the same procedure ($10 \times (6\text{-s sprint, on } 36\text{ s})$) and do not appear to have made any attempt to validate their procedure as an assessment of RSE. Additionally, there is no published evidence of the reliability of their procedures. Only two other studies have used RSE on an NMT. Ratel *et al.* (2004) used a protocol of $10 \times (10\text{-s sprint, on } 25\text{ s})$, a procedure which is far from the work:rest ratios of other RSE tests and may have questionable validity as a consequence. Oliver *et al.* (2005) have concluded good reliability of NMT performance (other than fatigue indices) from their $7 \times (5\text{-s sprint, on } 25\text{ s})$ procedure when using teenage boys as subjects.

With the combination of force, velocity and power data, all collected at high frequency within a sprint and then repeated through an RSE series, there are many data that can be obtained from RSE testing. Most authors tend to focus on reporting measures of velocity and power from NMT ergometry. Force has been shown to be the most variable (Lakomy, 1984; Lakomy, 1987) and least reliable (Tong *et al.*, 2001) of the performance outcomes. Specifically, the measures of velocity and power which are obtained from RSE testing tend to be the highest 1-s value and the mean over the entire sprint (Brooks *et al.*, 1990; Hamilton *et al.*, 1991; Ratel *et al.*, 2005). These data are then either used to derive an expression of fatigue (Brooks *et al.*, 1990; Hamilton *et al.*, 1991; Oliver *et al.*, 2005) and the performance from each sprint is then either considered individually (Brooks *et al.*, 1990; Hamilton *et al.*, 1991) or averaged to give the mean of mean performance from the series of sprints (Oliver *et al.*, 2005). Oliver *et al.* (2005) demonstrated that, as with other modes of exercise, fatigue measures in NMT-RSE were highly variable and recommended that fatigue indices from RSE tests should be viewed with caution.

The evidence presented here suggests that NMT ergometry is valid and reliable for the assessment of sprint performance. Although NMT procedures have been used to

perform RSE tests, no researchers have previously set out to develop a test procedure specifically for the assessment of RSE performance with application to competitors in the game-sports.

Summary

In conclusion, the concept of repeated-sprint exercise has been introduced with a focus on its importance to the physiological requirements of game-sports competitors. The metabolism during repeated-sprint work has been summarised and specific issues regarding the physiological and procedural factors that influence RSE performance have been discussed. In particular, the issues of training and creatine supplementation have been explored due to their potential value in judging the validity and sensitivity of the novel RSE test under consideration in this thesis. Similarly, the concept of $\dot{V}O_2$ kinetics has been introduced due to its potential value in indicating post-exercise recovery rate. While there are many RSE tests in the literature, few have been subject to the scrutiny of reliability, validity and sensitivity studies and, possibly as a result of this, no standardised procedures in terms of exercise duration, rest duration or exercise mode have been adopted. With the absence of standard tests for the assessment of the ability to perform repeated sprints and the widespread popularity of game-sports, the development of a valid and reliable test for RSE performance is likely to be a useful addition to the assessments that can be used for game-sports competitors.

CHAPTER 3. GENERAL METHODS SECTION

Subjects

Subjects for all studies were healthy, college-aged, male volunteers. Unless otherwise stated, subjects were University students of sport-related subjects and were all habitually active. Prior to participation, subjects were briefed about the requirements of participation and gave written informed consent for their participation. University ethical clearance had been granted previously for all studies by the Human Ethics Committee of Liverpool John Moores University. Subjects were instructed to prepare similarly for all repeat tests and, specifically to prepare for tests by not exercising or consuming alcohol in the previous 24 h, refraining from caffeine (3 h) and food (2 h) prior to testing.

Equipment

These studies were performed in two laboratories with similar equipment but in different locations. Studies I and II used different equipment to studies III-V but no studies combined data from the two laboratories.

Studies I-II

A Woodway NMT (Model A/B, Weil am Rhein, Germany) was used for these studies (Figure 1). All data analysis was performed using commercially available NMT data analysis software and hardware (Dragfor, Bratislava, Slovakia). For the assessment of velocity, a small spring-loaded generator was applied to the underside of the treadmill belt. Treadmill velocity was calibrated and verified using an external motor to drive the NMT at a range of velocities. Once the belt length was measured, the number of belt revolutions was counted over a minute at a specific motor speed to establish NMT belt velocity. Horizontal forces applied during running were measured using the 'Dragfor' system's wall-mounted strain gauge. The strain gauge was attached to a tether that was connected via a waist belt to the test participant. The height of the strain gauge was adjustable to ensure that the tether was horizontal when the subject stood on the middle of the treadmill belt. The strain gauge was calibrated according to manufacturer's guidelines prior to each test. Data for velocity and force were processed using the dedicated software package and power output (W), defined as the product of velocity ($\text{m}\cdot\text{s}^{-1}$) and horizontal force (N) was also obtained. Sampling frequency for velocity, power and velocity was constant at 10 Hz.



Figure 1. Non-motorised treadmill system used for repeated sprint testing in studies I & II.

Studies III-V

For these studies, an ergometry system was used that contained similar equipment to studies I-II but the treadmill for these studies was a Sprint Runner (Hoggan Health, USA) NMT and an optical counter was used to assess treadmill velocity (Figure 2). A similar set-up was used for the assessment of force but with a different strain gauge (Tedeo Huntleigh Ltd, Cardiff UK). Calibration of belt velocity and horizontal force was achieved using similar principles to those described for studies I and II. Data for velocity, power and force were processed using Picolog data acquisition software to provide raw data at a frequency of 10 Hz.

Non-Motorised Treadmill Procedures

Warm-up and familiarisation

During pilot testing it was established that NMT sprinting was a technique that was not immediately acquired and that, in contrast to cycle ergometry, more time may be required in habituating subjects to the apparatus. Some subjects initially found it difficult to keep the tension in the tether and also tended to run while looking down at their feet. In all of these test sessions the same experimenter was used and advice on running technique was always given during any familiarisation visits. Additionally, to

encourage subjects to run with their head up and to provide feedback on subjects' lateral position on the treadmill, two targets were placed in front of the subject at around 2 m and 4 m from the treadmill. These targets were directly in line with the centre of the treadmill such that any lateral movement on the treadmill would be seen by the subject as a shift in his alignment. Subjects were encouraged to look up at the targets while running and this was found to be effective in improving running technique and safety.



Figure 2. Non-motorised treadmill system used for repeated sprint testing in studies III, IV and V. Figure also shows assessment of respiratory gases by Jaeger Oxycon apparatus.

Pilot work showed that habituating subjects using a progression from walking, through jogging, running and on to sprinting was both safe and successful. Using these principles, a general familiarisation procedure was developed where subjects were also taught the procedures of dismounting the moving treadmill and performing sprint starts. The familiarisation procedure used in studies II – V was slightly more extensive than the familiarisation procedure for study I (full procedures of which are given in Chapter 5). This was due to the fact that in studies II – V, the familiarisation was performed on a different day to the subject's first test performance. The familiarisation procedure for these later studies included 3 to 4 'acceleration runs'. Each 'acceleration run' required the subject to accelerate from a standing start to perform around 5 s each of walking, jogging, running and sprinting. A summary of the familiarisation session for studies II –

V is given in table 9. In later visits subjects performed a warm-up which was comprised of the same activities as they had performed in familiarisation but with the omission of the last 60-s jog and the last pair of sprints.

Table 9. Activities and durations performed in the familiarisation session for the repeated sprint tests in studies II - V.

Activity	Duration
Walk ($\sim 1 \text{ m.s}^{-1}$)	1 min
Jog ($2.2 - 2.8 \text{ m.s}^{-1}$)	1 min
Acceleration runs	4 x (~ 5 -s each of walk, jog, run, sprint: 60 s rest)
Sprint	2 x (5 -s sprint: 15 -s rest)
Jog ($2.2 - 2.8 \text{ m.s}^{-1}$)	1 min
Sprint	2 x (5 -s sprint: 30 -s rest)
Walk ($\sim 1 \text{ m.s}^{-1}$)	1 min
Rest	3 min
Practice test	4 x (6 -s sprint: 30 -s rest)

Sprint start procedure

Previous NMT-RSE studies have used a rolling start for their sprints from a velocity of either 6-8 (Ratel *et al.*, 2004) or 8 km.h^{-1} (Holmyard *et al.*, 1988; Hamilton *et al.*, 1991). However, the time spent at this intensity prior to the sprint was not specified. The use of an absolute exercise intensity like this may provide biased results for subjects of contrasting fitness and the intensity of any activity between sprints could impact on the response to a series of sprints (Bogdanis *et al.*, 1995; Connolly *et al.*, 2003; Spencer *et al.*, 2006). Consequently, for these studies a standing start was adopted. This practice also eased the identification of the point at which each sprint began, as recommended by Gaitanos *et al.* (1993).

To perform a start, subjects were informed when there were 10 s and 5 s left to the start time. At 5 s, subjects were instructed to adopt a start position with tension in the tether, hands on the hand rails and their back straight, with one foot in front of the other. A “3-2-1, Go” countdown was then given by the experimenter who continued to give verbal encouragement for the subjects to achieve a maximal acceleration and then to cover as much distance as possible in the sprint. At the end of the 6 -s period, the experimenter

clearly instructed the subjects to stop and they dismounted the moving treadmill by lifting their feet onto the platform on either side of the belt by using the hand rails. All timings were given as verbal instructions from one experimenter who was operating an automatically-repeating countdown timer. Subjects received no visual feedback of their performance during the sprints.

Sprint duration

Sprint duration has been shown to have an impact on the responses to RSE (Dawson *et al.*, 1991; Balsom *et al.*, 1992a) and the majority of RSE studies have used either 6 s of activity or 40 -m running sprints, which are usually of a similar duration (Fitzsimons *et al.*, 1993; Ahmun *et al.*, 2005). Ruthie *et al.* (2006) have recommended the use of 40 -m sprints in a field setting in order to establish maximal sprint velocity. In game sports competition, average sprint durations are typically shorter than 6 s (Bangsbo, 1994; Bishop *et al.*, 2001) but for the testing of RSE, a 6 -s duration is the most widely used (Dawson *et al.*, 1993; Gaitanos *et al.*, 1993; Balsom *et al.*, 1994b; Tomlin and Wenger, 2002). A practical consideration for the present study was that maximal velocity on an NMT, even with a rolling start, was not normally achieved within the first 4 s (Lakomy, 1984; Lakomy, 1987). Pilot work with the current procedures and apparatus showed that peak velocity was reached within 5 s but the use of a 6 -s sprint duration seemed an appropriate compromise between sport-specificity and ensuring that maximal performance was attained.

Processing of NMT performance data

Collection of performance data was on a continual basis for each series of sprints in the RSE tests. Consequently, due to variation in the subjects' reaction times, the precise timings of the sprints may not have always coincided exactly with the performance data acquisition software. For this reason, an objective criterion had to be applied to confirm the start of a sprint. For study I, the start of the sprint was taken once power output exceeded 30 W. This was slightly modified to 100W for subsequent studies. Six seconds were counted from that point on to define each sprint. Each 6 -s sprint was then analysed for the performance variables of velocity, power and force. Mean data were defined as the mean performance throughout the whole 6 -s period and peak data were defined as the highest 1-s average for each variable. The peak data were obtained from rolling averages derived from 10 consecutive samples collected at 10 Hz. This analysis

of NMT performance data was achieved by exporting text files from the data acquisition software and processing the data using a customised Microsoft Excel spreadsheet to give all performance data on a sprint-by-sprint basis. The use of average data has previously been recommended as a means of enhancing the reliability of performance data (Tong *et al.*, 2001). These authors found that reliability was lower for force and power data compared to data for velocity. The lower reliability of the force and power data has been attributed to the fact that force (and hence, power) on the NMT is only produced during foot-contact, while belt velocity is less pulsatile in nature (Lakomy, 1984).

To obtain a quantification of fatigue, the percentage decrement method of Fitzsimons *et al.* (1993) was adopted in all studies. This procedure has been recommended by Glaister *et al.* (2004) owing to its superior validity and reliability when compared against other commonly used indices of fatigue. The procedure involved calculating fatigue as:-

$$\% \text{ Decrement} = 100 \times (1 - (\text{mean performance} \div \text{maximal performance}))$$

where ‘mean performance’ is the mean performance across the series of sprints and ‘maximal performance’ is the best single result for that performance measure across the series of sprints.

Consequently, values for velocity, power and force within each 6-s sprint were used to derive results for maximal velocity (MxSp), average velocity (AvSp), average power (AvPO) and average force (AvF) (see Table 10) and the associated percent decrement values. The 1 -s maximal power and force results were not analysed due to the lack of reliability for these variables reported in a previous study (Tong *et al.*, 2001).

Table 10. Performance outcomes for the RSE tests used in this thesis.

Performance measure	Per sprint	Per series of sprints	Abbreviation
Velocity	Best 1 s <i>(derived from 1-s rolling average)</i>	Mean of all ('Best 1 s') values	MxSp
	Mean of 6 s <i>(derived from whole 6-s sprint)</i>	Mean of all ('mean of 6 s') values	AvSp
Power	Mean of 6 s <i>(derived from whole 6-s sprint)</i>	Mean of all ('mean of 6 s') values	AvPO
Force	Mean of 6 s <i>(derived from whole 6-s sprint)</i>	Mean of all ('mean of 6 s') values	AvF

Assessment of Physiological Variables

Heart rate

In studies II-V, HR was recorded continuously throughout all tests. For this purpose, recordable short-range radio telemetry equipment (Polar Vantage NV or Polar S610, Polar Electro Oy, Finland) was used. Heart rate was recorded at 5 -s sampling rate with data collection always starting 30 s before the start of sprint 1. Mean HR throughout a series of sprints was taken from the time of the commencement of sprint 1 to the end of the final sprint plus the recovery time used in that procedure. For example, for the 10 × (6 -s sprint: 34 -s recovery procedure), average HR was calculated over 10 × (40 s) period.

Due to previous evidence suggesting that HR recovery may be more effective than $\dot{V}O_{2\text{ max}}$ as a factor to discriminate between subjects of contrasting fitness status (Edwards *et al.*, 2003), a 'HR recovery index' was proposed for these studies. This index was calculated from the mean difference between the peak HR and minimum HR associated with each sprint of an RSE test. Heart rate data were exported from Polar Precision Performance software (Polar Electro Oy, Finland) into a customised Microsoft Excel spreadsheet which analysed these data. An example of the calculations used to derive the HR recovery index is shown in Table 11.

Table 11. Example calculations used to derive the HR recovery index.

Sprint	Peak HR due to sprint (beats min ⁻¹)	Minimum HR post sprint (beats min ⁻¹)	Difference (beats min ⁻¹)
1	174	170	4
2	186	184	2
3	190	184	6
4	190	187	3
5	191	188	3
6	190	185	5
7	191	186	5
8	191	186	5
9	191	187	4
10	191	-	
HR recovery index (beats min ⁻¹)			4.1

Determination of $\dot{V}O_2$ off-kinetics

After the primary aim of questioning the validity and reliability of NMT ergometry as a means of assess performance in RSE, a secondary aim of these studies was to investigate whether there are any physiological markers that may be useful in the assessment of the ability to perform repeated sprints. The use of $\dot{V}O_2$ kinetics in RSE has already been introduced in the literature review. Based on the principle that $\dot{V}O_2$ on-kinetics are used to make inferences about [PCr] and, specifically, the evidence suggesting that PCr and $\dot{V}O_2$ in recovery are controlled by a common mechanism (Rossiter *et al.*, 2002), the present study sought to investigate whether post-exercise $\dot{V}O_2$ off-kinetics were related to PCr recovery and, hence RSE performance.

The only previous study relating $\dot{V}O_2$ kinetics with RSE testing suggested that RSE performance was more related to $\dot{V}O_2$ on-kinetics than to $\dot{V}O_{2\text{ max}}$ (Dupont *et al.*, 2005). However, previous work has suggested that $\dot{V}O_2$ on-kinetics were not necessarily equivalent to off-kinetics (Rossiter *et al.*, 2002). For these studies, with the importance of PCr recovery and its links to RSE performance, the assessment of $\dot{V}O_2$ off-kinetics may have potential as an indicator of PCr recovery. The assessment of $\dot{V}O_2$ off-kinetics is achieved by fitting an exponential equation to the $\dot{V}O_2$ response post-exercise. The time constant of the exponential function which best fits the actual

$\dot{V}O_2$ response (evaluated by least mean-square difference) represents the time constant of $\dot{V}O_2$ recovery.

There are conflicting findings regarding whether the time constant of $\dot{V}O_2$ recovery is affected by prior exercise intensity (Ozyener *et al.*, 2001; Rossiter *et al.*, 2002). The time constants from exercise above the 'anaerobic threshold' range from 42 s (Ozyener *et al.*, 2001) to 51 s (Rossiter *et al.*, 2002). Consequently, because 98 % of the total recovery response is achieved within 4 time constants (Whipp and Rossiter, 2005), $\dot{V}O_2$ was analysed over 4 min post-exercise in the present study for the subsequent analysis of $\dot{V}O_2$ off-kinetics. Since only the fundamental phase (fast component) of $\dot{V}O_2$ recovery was modelled in the present study, a monoexponential function was used to model the $\dot{V}O_2$ response (Chilibeck *et al.*, 1997; Ozyener *et al.*, 2001). The equation to quantify $\dot{V}O_2$ off-kinetics (τ) for the present study was:

$$\dot{V}O_2(t) = \dot{V}O_{2\ 0} - \dot{V}O_2\ \text{diff}(1 - e^{(-t/\tau)})$$

where ' $\dot{V}O_2(t)$ ' was the $\dot{V}O_2$ at any time (t) within the period to be modelled, ' $\dot{V}O_{2\ 0}$ ' was the initial $\dot{V}O_2$ at the start of the period to be modelled, ' $\dot{V}O_2\ \text{diff}$ ' was the difference between $\dot{V}O_2$ within the period to be modelled and ' τ ' was the time constant of the $\dot{V}O_2$ response (Rossiter *et al.*, 2002). As there was a time delay between the end of an exercise bout and the recovery in $\dot{V}O_2$, the first 20 -s period of the $\dot{V}O_2$ recovery was not included in these analyses of $\dot{V}O_2$ off-kinetics (Cunningham *et al.*, 2000).

Blood lactate concentration

Blood lactate concentrations were determined in studies II to V. Assays for [La] were always performed within 1 hour of sampling, according to manufacturer's guidelines using Biosen (Instruchemie, Delfzijl, Netherlands) 5030 (study II) or Biosen C-Line (studies III, IV, V) equipment previously calibrated using a 12 mmol.l⁻¹ standard solution. Blood was always taken from ear-lobe sampling using a 20 - μ l sample. Prior research has shown that these procedures give reliable results even when data are stored at room temperature for 24 h (Davison *et al.*, 2000).

**CHAPTER 4. - STUDY I, THE RELIABILITY OF REPEATED-SPRINT
PERFORMANCE USING NON-MOTORISED TREADMILL SPRINTING**

A peer-reviewed journal article from the findings of this study is included in Appendix three of this thesis. (Hughes et al., 2006).

Introduction

Establishing the extent of reliability is essential in the development of any data collection procedure. By making repeated measurements on the same subjects using the same procedures and with the application of appropriate statistical analyses, it is possible to evaluate the reliability of a procedure. This is especially important for the present study as the reliability of repeated-sprint exercise on a non-motorised treadmill has so far only been reported in boys, but not in adults (Oliver *et al.*, 2005).

A wide range of statistical analyses have been used in the literature for the purposes of quantifying reliability. Within the repeated-sprints literature alone, reliability has been evaluated based on *t*-tests (Balsom *et al.*, 1992b), standard error of measurement (typical error) and correlation coefficient (Fitzsimons *et al.*, 1993), repeated measures one-way analysis of variance (ANOVA) (Capriotti *et al.*, 1999) and by use of two-way repeated measures ANOVAs to derive intra-class correlation coefficients (ICC) or coefficients of variation (CV) (Glaister *et al.*, 2003; Glaister *et al.*, 2004; Oliver *et al.*, 2005). An additional test of reliability that has been used in the assessment of single-sprint performance using the NMT (Tong *et al.*, 2001) is the 95 % limits of agreement technique of Bland and Altman (1986). These analyses address different issues of reliability. Hopkins (2000) has stated that the quantification of reliability should consider within-subject variation, systematic change in mean values and test-retest correlation. Within-subject variation is assessed using techniques such as standard error of measurement, 95 % limits of agreement (95 % LoA) or CV. Systematic change in the mean is assessed using hypothesis tests such as paired *t*-tests or repeated measures ANOVA (Capriotti *et al.*, 1999). Test-retest correlation is typically evaluated using intra-class correlation. However, there is a lack of consensus on which tests are most suited to a given experimental situation and there are limitations with the use of the different reliability tests (Atkinson and Nevill, 1998; Hopkins, 2000). For example, hypothesis testing is not able to discriminate between the varying degrees of random error within a sample and ICC across different studies is not comparable when there are contrasting degrees of homogeneity between subject characteristics (Atkinson and Nevill, 1998). Therefore, comparisons between studies are difficult and it has been

recommended that a range of reliability measures is reported (Atkinson and Nevill, 1998). For the present study, the use of a range of values is especially important given the array of reliability statistics used in previous, similar studies (Balsom *et al.*, 1992b; Fitzsimons *et al.*, 1993; Capriotti *et al.*, 1999; Glaister *et al.*, 2003; Glaister *et al.*, 2004; Oliver *et al.*, 2005).

For any reliability study, it is important to minimise systematic bias by ensuring that subjects are familiarised with the procedures, particularly for this study as NMT sprinting is a novel activity for most subjects. Only two previous research groups (Capriotti *et al.*, 1999; Glaister *et al.*, 2003) have investigated the issue of familiarisation in RSE, although their procedures were performed on cycle ergometers. In both cases these authors concluded that two familiarisation visits were sufficient to achieve familiarisation (Capriotti *et al.*, 1999; Glaister *et al.*, 2003). Only one study of NMT sprinting study contained details of a familiarisation procedure, which consisted of 3 min of jogging followed by three 10 -s sprints (Ratel *et al.*, 2004). Further reports using NMT-RSE have cited the use of familiarisation bouts prior to test sessions but the procedures or the number of these sessions have not been reported (Holmyard *et al.*, 1988; Hamilton *et al.*, 1991). There are no publications which document the number of trials required before a subject is familiarised with NMT sprinting.

There are only two studies that have reported the reliability of NMT sprinting. Tong *et al.* (2001) performed three 6 -s sprints, separated by 2 -min recovery in two visits which were separated by one week. They used CV and 95 %LoA to quantify reliability and concluded that reliability in NMT sprinting was enhanced by using averaging of performance values, that velocity was more reliable than power and force and that NMT sprinting was reliable for the assessment of sprinting power and velocity. Oliver *et al.* (2005) measured the reliability of NMT sprinting in RSE using a cohort of 15 -year old boys who performed five trials of RSE ($7 \times (5 \text{ -s sprint, on } 30 \text{ s})$). They assessed reliability from an overall CV derived from two-way ANOVA, a procedure adopted in a number of recent studies (Schabert *et al.*, 1999; Glaister *et al.*, 2003; Glaister *et al.*, 2004). Oliver *et al.* (2005) also found velocity to be a more reliable performance measure than power (CVs of mean values 2.59 vs. 5.41 %, respectively).

Therefore, the purpose of the present study was to investigate the reliability of NMT-RSE using a range of reliability measures. A secondary aim was to investigate the time course of familiarisation in NMT sprinting.

Methods

Experimental design

Ten healthy male subjects, all novices to non-motorised treadmill sprinting, volunteered to participate in this study. Their physical characteristics (mean \pm s) were, age 20.0 (\pm 1.4) years, body mass 78.9 (\pm 11.0) kg and height 1.79 (\pm 0.04) m. Subjects attended the laboratory on three occasions with each visit separated by more than one day and all visits being completed within 7 days of the first test. The visits were performed at approximately the same time of day (defined as \pm 2 h of previous trials) for each subject. Each visit required the performance of 6 maximal sprints of 6 -s duration, with each sprint followed by a 30 -s recovery period. This procedure was typical of previous RSE tests (Fitzsimons *et al.*, 1993; Capriotti *et al.*, 1999; Bishop and Spencer, 2004). The full procedure for each trial is shown in Table 12.

Table 12. Activities and durations performed in the preparation for repeated sprint tests.

Activity	Trial 1	Trial 2	Trial 3
Walk (\sim 1 m.s ⁻¹)	1 min	1 min	1 min
Jog (2.2 - 2.8 m.s ⁻¹)	1 min		
Sprint	2 \times (5 s: 15 s rest)		
Jog (2.2 - 2.8 m.s ⁻¹)	2 min	2 min	2 min
Sprint	2 \times (5 s: 30 s rest)	2 \times (5 s: 15 s rest)	2 \times (5 s: 15 s rest)
Walk (\sim 1 m.s ⁻¹)	1 min	1 min	1 min
Rest	3 min	3 min	3 min
Test	6 \times (6 s : 30 s)	6 \times (6 s : 30 s)	6 \times (6 s : 30 s)

Data analysis

In accordance with previous recommendations (Tong *et al.*, 2001) the performance variables were expressed as mean values. As detailed in the general methods section of this thesis, velocity, power and force were all expressed as mean values (AvSp, AvPO, AvF, respectively) and velocity was also expressed as a maximum 1 -s rolling average

(MxSp) for the assessment of reliability. Using each of these four performance variables, the percent decrement was also obtained as an index of fatigue.

In agreement with the recommendations of Atkinson and Nevill (1998) and in order to allow comparison between previous work and the results of the present study, a range of reliability measures was used. A one-way analysis of variance (ANOVA) with repeated measures was used to investigate whether differences existed between the outcomes of the three trials. Homogeneity of variance was evaluated using Mauchly's test of sphericity and the Greenhouse-Geisser adjustment was used if assumptions of homogeneity were violated. Where significant F values were obtained, Scheffe *post hoc* analysis was performed. Overall reliability across the three trials was then obtained as a CV and ICC derived from the mean square error term of a two-way ANOVA on the log-transformed performance and fatigue variables (Schabort *et al.*, 1999; Glaister *et al.*, 2003; Oliver *et al.*, 2005). The reliability of results between consecutive trials was also assessed using a wider range of statistical tests to allow for comparison of the present study's outcomes with previous similar work (Fitzsimons *et al.*, 1993; Tong *et al.*, 2001). The following combination of reliability measures was assessed to provide a comparison between consecutive visits:- standard error of measurement (SEM), ICC, CV and 95 %LoA. Ninety-five percent confidence intervals for the CV and ICC were established using the methods recommended by Hopkins (1998). As heteroscedasticity was evident, ratio measures for 95 % LoA were established as recommended by Bland and Altman (1986). Analyses were performed using Microsoft Excel and the Statistical Package for the Social Sciences (SPSS; Version 11.5, Chicago, Illinois) software. A *P* level of 0.05 was chosen to represent statistical significance. Data were reported as mean and standard deviation (mean \pm *s*) unless stated otherwise.

Results

The overall analysis (i.e., across all three trials) showed that there were no significant differences between the three trials for any of the performance variables ($P > 0.05$). The mean values for each performance variable are shown in Table 13 and the data within each trial for AvPO are shown in Figure 3. Figure 3 also demonstrates the decline in performance within each series of sprints. Expressed as the percent decrement, this result ranges from around 8 % for the AvPO variable to below 3 % for MxSp and AvSp (Table 14). The overall analysis of the performance variables gave CVs of between 2.53

(AvSp) and 3.86 % (AvF) and ICCs ranging from 0.55 (AvF) to 0.81 (AvPO). For the decrement results, CVs of between 30.1 (AvF) and 37.6 % (AvPO) and ICCs ranging from 0.33 (AvSp) to 0.58 (AvF) were obtained.

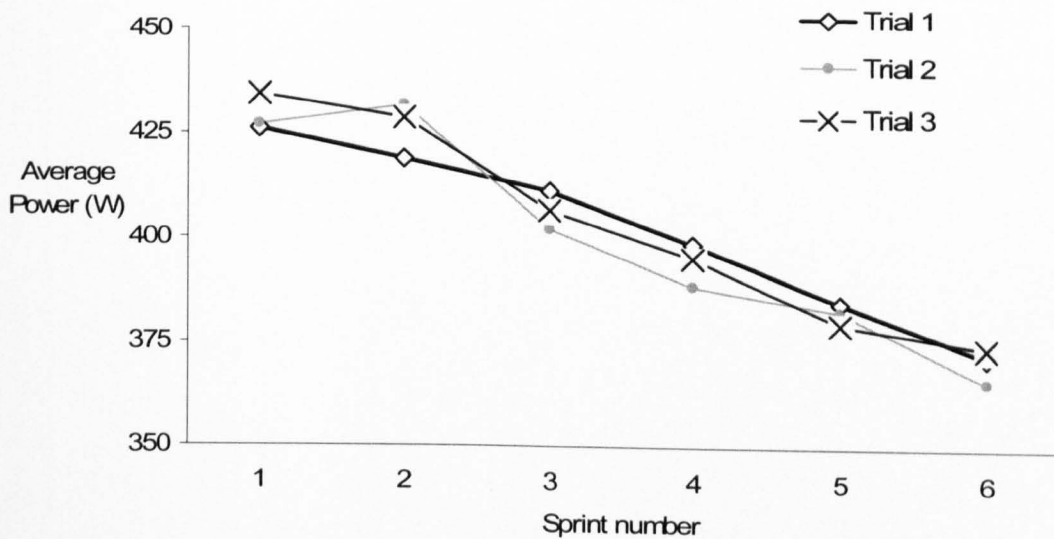


Figure 3. Average power (W) by sprint and trial number from three trials of NMT-RSE.

For the analysis of data between consecutive visits, the mean CVs were 5.0 % or lower for all of the performance measures (Tables 15 and 16). All ICC values apart from AvF (trial 2-3) were at least 0.75. The magnitude of the bias term from the 95 % LoA was between 0.98 and 1.02 for each variable. The highest reliability appeared to be evident in the MxSp as shown by the high ICCs (both 0.93) and low CVs (both 1.8 %). The lowest reliability seemed to be for AvF with ICC as low as 0.53 and CV at 5 % both for the comparison between trials 2 and 3.

Considering the percent decrement values, there is evidence of lower reliability (from CV, ICC and Ratio 95 %LoA) for all performance measures. For both velocity variables (i.e., decrement of MxSp or AvSp), CVs ranged between 22.9 (MxSp, trials 1-2) and 50.0 % (MxSp, Trials 2-3) and only one ICC value was higher than 0.5 (0.9, MxSp trials 1-2) (Table 17). Similarly for the decrement values for power and force, CVs were 20 (AvPO, trials 2-3) and 47 % (AvPO, trials 1-2) with ICCs of 0.86 (AvPO, trials 2-3) and 0.62 (AvF, trials 1-2) (Table 18). The bias terms for the 95 % LoA ranged from 0.71 (AvF, trials 1-2) to 1.65 (AvF, trials 2-3) and the highest range between upper and

lower limit from the 95 % LoA analysis was from 2.3 to 18.0 % in the decrement of AvPO from trials 1-2.

Table 13. Mean values ($\pm s$), intraclass correlation coefficients (ICC) and coefficients of variation (CV), with confidence intervals (CI) for the performance measures from three trials of NMT-RSE.

Measure	MxSp	Av Sp	AvPO	AvF
Overall mean ($\pm s$)	7.17 \pm 0.33 m.s ⁻¹	6.02 \pm 0.32 m.s ⁻¹	401.6 \pm 31.5 W	79.48 \pm 4.37 N
ICC (CI)	0.66 (0.30 – 0.89)	0.78 (0.49 – 0.93)	0.81 (0.54 – 0.94)	0.55 (0.15 – 0.84)
CV (CI)	2.75 % (1.89 to 3.88 %)	2.53 % (1.74 to 3.58 %)	3.59 % (2.47 to 5.08 %)	3.86 % (2.65 to 5.45 %)

Table 14. Mean values ($\pm s$), intraclass correlation coefficients (ICC) and coefficients of variation (CV), with confidence intervals (CI) for the fatigue measures from three trials of NMT-RSE.

Measure	Decrement of MxSp	Decrement of AvSp	Decrement of AvPO	Decrement of AvF
Overall mean ($\pm s$)	2.37 \pm 1.09 %	2.87 \pm 1.25 %	8.18 \pm 4.26 %	6.26 \pm 2.65 %
ICC (CI)	0.61 (0.23 - 0.87)	0.33 (-0.07 - 0.74)	0.56 (0.16 - 0.85)	0.58 (0.19 - 0.86)
CV (CI)	31.5 % (21.7 to 44.5 %)	37.4 % (25.7 to 52.9 %)	37.6 % (25.9 to 53.1 %)	30.1 % (20.7 to 42.6 %)

Table 15. Measures of reliability (with confidence intervals; CI) from three consecutive trials of NMT-RSE for maximal velocity (MxSp) and mean velocity (AvSp).

Measure	MxSp			AvSp		
	Trial 1-2	Trial 2-3	Trial 1-2	Trial 1-2	Trial 2-3	Trial 2-3
Mean bias (CI)	-0.02 m.s ⁻¹ (-0.11 to 0.07 m.s ⁻¹)	0.09 m.s ⁻¹ (0.00 to 0.19 m.s ⁻¹)	-0.10 m.s ⁻¹ (-0.25 to 0.04 m.s ⁻¹)	0.01 m.s ⁻¹ (-0.09 to 0.11 m.s ⁻¹)		
SEM (CI)	0.09 m.s ⁻¹ (-0.06 to 0.17 m.s ⁻¹)	0.09 m.s ⁻¹ (-0.06 to 0.18 m.s ⁻¹)	0.14 m.s ⁻¹ (0.10 to 0.26 m.s ⁻¹)	0.09 m.s ⁻¹ (0.06 to 0.17 m.s ⁻¹)		
CV (CI)	1.8 % (1.05 to 2.97 %)	1.8 % (1.02 to 3.10 %)	3.4 % (2.00 to 5.63 %)	2.1 % (1.19 to 3.61 %)		
ICC (CI)	0.93 (0.72 ± 0.98)	0.93 (0.70 ± 0.99)	0.80 (0.34 – 0.95)	0.93 (0.68 – 0.99)		
Ratio 95 %LoA (lower - upper limit)	1.00 ×/÷ 1.04 (6.90 to 7.42 m.s ⁻¹)	1.01 ×/÷ 1.04 (7.04 to 7.56 m.s ⁻¹)	0.98 ×/÷ 1.07 (5.52 to 6.29 m.s ⁻¹)	1.00 ×/÷ 1.04 (5.85 to 6.35 m.s ⁻¹)		

Abbreviations used: SEM, Standard error of the measurement; CV, coefficient of variation; ICC, Intraclass correlation coefficient; Ratio 95 %LoA, ratio term for 95 % limits of agreement.

Table 16. Measures of reliability (with confidence intervals; CI) from three consecutive trials of NMT-RSE for mean power (AvPO) and mean force (AvF).

Measure	AvPO			AvF		
	Trial 1-2	Trial 2-3	Trial 1-2	Trial 1-2	Trial 2-3	Trial 2-3
Mean bias (CI)	2.3 W (-8.4 to 13.1 W)	1.9 W (-12.6 to 16.3 W)	1.5 N (-0.8 to 3.9 N)	1.5 N (-0.8 to 3.9 N)	-0.5 N (-3.51 to 2.53 N)	-0.5 N (-3.51 to 2.53 N)
SEM (CI)	10.6 W (7.3 to 19.3 W)	13.3 W (9.0 to 25.4 W)	2.32 N (1.60 to 4.24 N)	2.32 N (1.60 to 4.24 N)	2.78 N (1.88 to 5.33 N)	2.78 N (1.88 to 5.33 N)
CV (CI)	3.7 % (2.2 to 6.1 %)	4.7 % (2.7 to 8.1 %)	4.1 % (2.4 to 6.8 %)	4.1 % (2.4 to 6.8 %)	5.0 % (2.8 to 8.5 %)	5.0 % (2.8 to 8.5 %)
ICC (CI)	0.75 (0.64 – 0.98)	0.82 (0.33 – 0.96)	0.75 (0.23 – 0.94)	0.75 (0.23 – 0.94)	0.53 (-0.21 – 0.88)	0.53 (-0.21 – 0.88)
Ratio 95 %LoA (lower - upper limit)	1.01 \times/\div 1.07 (375.5 to 432.6 W)	1.01 \times/\div 1.10 (370.8 to 444.5 W)	1.02 \times/\div 1.08 (74.6 to 87.7 N)	1.02 \times/\div 1.08 (74.6 to 87.7 N)	0.99 \times/\div 1.10 (71.6 to 86.9 N)	0.99 \times/\div 1.10 (71.6 to 86.9 N)

Abbreviations used: SEM, Standard error of the measurement; CV, coefficient of variation; ICC, Intraclass correlation coefficient; Ratio 95 %LoA, ratio term for 95 % limits of agreement.

Table 17. Measures of reliability (with confidence intervals; CI) from three consecutive trials of NMT-RSE for the % decrement scores of maximal velocity (MxSp) and mean velocity (AvSp).

Measure	% Decrement of MxSp			% Decrement of AvSp		
	Trial 1-2	Trial 2-3	Trial 1-2-3	Trial 1-2	Trial 2-3	Trial 1-2-3
Mean bias (CI)	-0.45 % (-0.61 to 2.38 %)	-0.18 % (-2.39 to 2.26 %)	-0.15 % (-1.17 to 0.87 %)	0.37 % (-0.51 to 1.25 %)		
SEM (CI)	0.38 % (0.26 to 0.70 %)	0.80 % (0.54 to 1.53 %)	1.0 % (0.69 to 1.83 %)	0.81 % (0.55 to 1.55 %)		
CV (CI)	22.9 % (13.4 to 37.9 %)	50.0 % (28.3 to 86.0 %)	48.6 % (28.5 to 80.5 %)	38.6 % (21.9 to 66.4 %)		
ICC (CI)	0.90 (0.62 to 0.98)	0.37 (-0.38 to 0.83)	0.50 (-0.19 to 0.86)	0.42 (-0.34 to 0.85)		
Ratio 95 %LoA (lower - upper limit)	1.22 \times/\div 1.55 (1.9 to 4.6 %)	0.87 \times/\div 2.45 (0.8 to 4.8 %)	0.92 \times/\div 2.61 (1.03 to 7.02 %)	1.13 \times/\div 2.33 (1.44 to 7.81 %)		

Abbreviations used: SEM, Standard error of the measurement; CV, coefficient of variation; ICC, Intraclass correlation coefficient; Ratio 95 %LoA, ratio term for 95 % limits of agreement.

Table 18. Measures of reliability (with confidence intervals; CI) from three consecutive trials of NMT-RSE for the % decrement scores of average power (AvPO) and average force (AvF).

Measure	% Decrement of AvPO			% Decrement of AvF		
	Trial 1-2	Trial 2-3	Trial 1-2	Trial 1-2	Trial 2-3	Trial 2-3
Mean bias (CI)	-1.38 % (-9.15 to 6.40 %)	2.00 % (-1.45 to 5.44 %)	-1.90 % (-3.55 to 0.25 %)	-1.90 % (-3.55 to 0.25 %)	2.96 % (1.77 to 4.14 %)	2.96 % (1.77 to 4.14 %)
SEM (CI)	2.80 % (1.93 to 5.12 %)	1.24 % (0.84 to 2.38 %)	1.63 % (1.12 to 2.98 %)	1.63 % (1.12 to 2.98 %)	1.09 % (0.74 to 2.09 %)	1.09 % (0.74 to 2.09 %)
CV (CI)	47.0 % (27.6 to 77.9 %)	20.5 % (11.6 to 35.3 %)	33.7 % (19.8 to 55.9 %)	33.7 % (19.8 to 55.9 %)	23.9 % (13.5 to 41.1 %)	23.9 % (13.5 to 41.1 %)
ICC (CI)	0.67 (0.08 to 0.92)	0.86 (0.46 to 0.97)	0.62 (-0.01 to 0.90)	0.62 (-0.01 to 0.90)	0.74 (0.15 to 0.94)	0.74 (0.15 to 0.94)
Ratio 95 %LoA (lower - upper limit)	0.76 \times/\div 2.82 (2.27 to 18.03 %)	1.25 \times/\div 1.42 (7.56 to 15.24 %)	0.71 \times/\div 1.99 (2.5 to 9.7 %)	0.71 \times/\div 1.99 (2.5 to 9.7 %)	1.65 \times/\div 1.78 (6.0 to 18.9 %)	1.65 \times/\div 1.78 (6.0 to 18.9 %)

Abbreviations used: SEM, Standard error of the measurement; CV, coefficient of variation; ICC, Intraclass correlation coefficient; Ratio 95 %LoA, ratio term for 95 % limits of agreement.

Discussion

The purpose of this study was to examine the reliability of a repeated-sprint procedure using non-motorised treadmill running. While previous authors have investigated the reliability of RSE in cycling or track-running (Fitzsimons *et al.*, 1993; Glaister *et al.*, 2003) and others have investigated the reliability of NMT running (Tong *et al.*, 2001), there has been no investigation of the combination of RSE on an NMT ergometer in adults. For the interpretation of reliability there are no universal guidelines regarding what constitutes an acceptable outcome from a reliability study (Atkinson and Nevill, 1998). Similarly, there is no consensus as to the most appropriate tests to investigate reliability. For these reasons, a range of reliability analyses was performed in order to increase the number of comparisons that can be made with previous studies.

Comparison of the performance variables from the present study with those of previous results suggests similarities in the data collected using this procedure. Firstly, the mean MxSp value (i.e., average of best 1 -s sprint velocities) of $7.17 \text{ m}\cdot\text{s}^{-1}$ in the present study was similar to the results of $7.12 \text{ m}\cdot\text{s}^{-1}$, $7.03 \text{ m}\cdot\text{s}^{-1}$ and $7.07 \text{ m}\cdot\text{s}^{-1}$ from previous studies (Lakomy, 1987; Hamilton *et al.*, 1991; Tong *et al.*, 2001, respectively) in which NMT sprinting has been used. Mean AvPO for the present study (401.6 W) was lower than the corresponding results of similar studies from another laboratory (Lakomy, 1987; Brooks *et al.* 1990; Hamilton *et al.* 1991) but in a similar range to the findings of Ratel *et al.* (2004) and Ratel *et al.* (2005). The discrepancy may be attributed to procedural differences in these studies. The present study used a standing start, as opposed to the rolling start adopted by Brooks *et al.* (1990) and Hamilton *et al.* (1991). However, a rolling start was also used in the work of Ratel *et al.* (2004) and Ratel *et al.* (2005), who showed similar power outputs to those from the present study, albeit with a longer data collection period of 10 s and a range of recovery durations (from 15 to 180 s) . When the data from the present study are expressed as AvSp, there would appear to be little difference from the data of Hamilton *et al.* (1991), which suggests that the difference in performance outcomes is not greatly affected by the standing start for the assessment of velocity but only for the assessment of force and power. The contrasting start procedures between the present work and previous studies may invalidate comparisons of force and power but the 1 -s peak values for velocity suggest the subjects in the present study achieved similar performance to those of previous similar investigations.

The data from the present study show that mean performance decrement is influenced by the performance variable from which it is derived. This interpretation is supported by previous evidence showing, for example, that the fatigue of average power is greater than that for the fatigue of peak power (Wootton and Williams, 1983; Bishop *et al.*, 2001) and, for NMT sprinting, that the fatigue-induced decline of running velocity is less than that for power or force (Holmyard *et al.*, 1988). This confirms that the mode of activity must be specified when evaluating NMT-RSE performance. For example, the mean percent decrement of both velocity variables in the present study is less than 3 % across the series of 6 sprints. In contrast, the decrement of AvPO is over 8 %. There is no previously reported use of the percent decrement method to derive a fatigue index using NMT. However, most previous RSE investigations using cycling have shown a decrement of between 5 and 10 % (Dawson *et al.*, 1993; Bishop *et al.*, 2001; Spencer *et al.*, 2004) using either 5 or 6 sprints repeated every 30 s. While these procedures clearly involved a shorter rest period than was used in the present study, it has been shown that the extent of fatigue in NMT RSE is greater than that experienced using cycle ergometry (Ratel *et al.*, 2004).

No significant differences between any performance variables were evident across the three trials of this study. This suggests that the preparation of the subjects before their first trial is adequate to ensure stable results in subsequent trials. The similarities between the best mean 1 -s sprint velocity in this work and in similar NMT sprint studies where familiarisation had already been achieved demonstrates the effectiveness of the preparation in the present study (Lakomy, 1987; Hamilton *et al.*, 1991; Tong *et al.*, 2001). These findings are in contrast to the only previous investigations of familiarisation in RSE, using cycling (Capriotti *et al.*, 1999; Glaister *et al.*, 2003). Other than exercise mode, the main factor that distinguished between the procedures of the present study and the studies of Capriotti *et al.* (1999) and Glaister *et al.* (2003) was the length of the pre-test preparation. Glaister *et al.* (2003) used a 5 -min continuous cycling warm-up, followed by 2 short sprints and Capriotti *et al.* (1999) used a 1 -min continuous warm-up. The corresponding preparation for the first trial of the present study was around twice as long as that of Glaister *et al.* (2003) and contained twice as many sprints.

The CVs from the overall analysis of the performance variables are all below 4 %. While it is accepted that no 'cut-off point' exists for concluding that data are reliable,

studies that have reported CVs below 4 % as in the present study tend to claim good reliability is evident in their procedures (Tong *et al.*, 2001; Glaister *et al.*, 2003) even based on this sole test of reliability (Capriotti *et al.*, 1999; Oliver *et al.*, 2005). For the ICC values, authors that have concluded that their procedures show reliability tend to quote ICCs of more than 0.90 (Fitzsimons *et al.*, 1993; Schabort *et al.*, 1999; Glaister *et al.*, 2003), however, it should be stressed that the value of ICC is highly affected by the homogeneity of the population concerned (Atkinson and Nevill, 1998). For this reason, Atkinson and Nevill (1998) advised against comparison of ICC values across different subject-populations. The analysis of ICC for the overall data in this study shows ICC values ranging from 0.55 (AvF) to 0.81 (AvPO). By calculation of a simple CV (from $(100 \times (s \div \text{mean}))$) for the MxSp data in the present study, an indication of homogeneity can be obtained. Using the data from trial one, for example, the CV would be $(100 \times (0.33 \div 7.18))$ or 4.6 %. By making similar calculations from equivalent studies, CVs of 13.3 % (ICC = 0.93; Glaister *et al.*, 2003) and 12.7 % (ICC = 0.97; Fitzsimons *et al.*, 1993) are given. Consequently, although the overall ICC from the present study may appear to be a little lower than the values usually quoted as being associated with an 'acceptable' level of reliability, these findings may be attributed to the lower heterogeneity of the subjects in the present study.

The analyses on the performance variables between consecutive trials in this study showed CV to be at or below 5 % for each of the between-trials comparisons. The velocity variables appeared to show especially good reliability when the results were considered in this way (less than 3.5 % in each case). The observation that velocity was more reliable than power, which was more reliable than force in NMT sprinting was consistent with the work of Tong *et al.* (2001). The greater reliability of velocity measurement has been attributed to the contrast between the gradual acceleration that occurs in the treadmill belt and the repeated oscillations in force that occur within each gait cycle during the assessment of power and force (Lakomy, 1987). For the assessment of ICC the previously-mentioned group homogeneity may invalidate the comparison of results between this study and others, but most ICCs in these comparisons were at least 0.8 (except AvPO, trials 1-2 and both AvF results). Consideration of the bias and random error terms of the 95 %LoA analysis allows for comparison between the present study and the reliability of NMT sprinting reported by Tong *et al.* (2001). As Tong *et al.* (2001) only expressed their data as 1 -s averages, direct comparison with their work is only possible for the MxSp variable of the present

study. Additionally, the data from the present study were derived from an average of 6 sprints. Their between-trials ratio 95 %LoA value was (1.03 \times/\div 1.03) compared to the findings of this study which were (1.00 \times/\div 1.04) for trials 1-2 and (1.01 \times/\div 1.07) for trials 2-3. Although it is accepted that the use of six-sprint average data for the present study may improve the reliability of these data, Tong *et al.* (2001) still concluded that their data demonstrated good reliability. The error terms for power and force in the present study were from 1.07 to 1.10 in the present study compared with 1.16 and 1.17, respectively in the work of Tong *et al.* (2001), again demonstrating comparatively high reliability of the procedures in this study.

The use of the other measures of reliability, SEM and bias in Tables 15 to 18 allows for reliability to be investigated using the same measurement units as the original data collection. Although these data are of limited use in the general evaluation of reliability, they do provide useful information which may be used in future studies to assess the effectiveness of interventions in populations with similar characteristics.

The assessment of fatigue, derived from the performance variables which have been discussed, clearly results in lower reliability using all of the reliability statistics of the present study. This observation is evident from the overall analysis as well as from the investigation of consecutive trials. With CVs above 30 % and ICC below 0.62 for each of the fatigue measures in the overall analysis, these values represent lower reliability than has been shown in RSE studies that claimed to show reliable data (e.g., Fitzsimons *et al.*, 1993; Tong *et al.*, 2001; Glaister *et al.*, 2003). A similar trend for poor reliability is also found with the analyses from consecutive trials. Glaister *et al.* (2004) investigated the reliability and validity of different calculations for fatigue and concluded that the present procedure, suggested by Fitzsimons *et al.* (1993) shows better validity and reliability than other measures of fatigue. The finding of poor reliability for fatigue measures has been observed in previous similar studies (Fitzsimons *et al.*, 1993; Glaister *et al.*, 2003; Oliver *et al.*, 2005) in spite of relatively good reliability with corresponding performance measures. The poor reliability of the fatigue indices has been attributed to the fact that they are derived from a combination of individual values, so the high variability may reflect an accumulation of smaller random errors within the series of sprints (Fitzsimons *et al.*, 1993).

In conclusion, this study demonstrated that the use of an NMT can provide reliable data for the assessment of performance in RSE. Measures of velocity produced better reliability than measures of power or force. This study, like many previous studies, demonstrated the difficulty of establishing a reliable assessment of fatigue using RSE procedures.

**CHAPTER 5. - STUDY II, THE INFLUENCE OF RECOVERY
DURATION ON REPEATED-SPRINT PERFORMANCE**

Introduction

Most RSE tests have been used because of their purported relevance to game-sports competitors (Balsom *et al.*, 1992a; Bishop and Spencer, 2004; Glaister *et al.*, 2004; Spencer *et al.*, 2004). There is still a lack of consensus regarding the timings of sprint duration, recovery durations and exercise mode for these tests. Altering these procedural factors affects test performance and so this lack of standardisation has led to the absence of normative scores for RSE procedures (Spencer *et al.*, 2005). There is also an absence of guidelines for the assessment of fitness in game-sports competitors. The only attempt so far to validate an RSE test procedure (Bishop *et al.*, 2001) used cycle ergometry and a 5-repetition, cycle procedure ($5 \times (6\text{-s sprint, on } 30\text{ s})$) that had been criticised for being too short to discriminate between athletes of contrasting fitness (Dawson *et al.*, 1991) and for using a mode of exercise that was non-specific to participants in game-sports (Fitzsimons *et al.*, 1993). Obstacles to further development in this area include that fitness for RSE can only be defined currently by performance measures and that there is no 'gold standard' of performance in RSE with which to assess the validity of a new procedure (Bishop *et al.*, 2001). Bishop *et al.* (2001) attempted to assess the validity of their cycling RSE test against a simulation of a hockey game but their findings were inconclusive. The use of cycling as the exercise mode by Bishop *et al.* (2001) was an additional factor that may have limited their test's validity (Fitzsimons *et al.*, 1993). Therefore, there is no evidence that a valid RSE test using running activity with application to game-sports players has yet been developed. Furthermore, few investigators have studied the use of NMT as an apparatus with which to perform RSE testing (Holmyard *et al.*, 1988; Hamilton *et al.*, 1991; Nevill *et al.*, 1994; Ratel *et al.*, 2004)

As there are no universally accepted physiological measures that assess the ability to perform repeated sprints, an RSE test procedure should allow quantification of sprint performance and its fatigue. A procedure must also allow at least a partial recovery to occur between sprints, implying that recovery durations that are either too long or short may render an RSE test invalid. Using 10 repeated 6-s sprints with an NMT procedure, Holmyard *et al.* (1988) showed no significant fatigue with 60-s recovery periods but when 30-s recovery periods were used there was significant fatigue evident through the series of sprints. There has been no further research involving the manipulation of rest

duration with this apparatus. With the resynthesis of PCr likely to be a key correlate of RSE performance, the half-time of this reaction should be borne in mind. This figure is usually quoted to be around 30 s (Cooke *et al.*, 1997a; McMahon and Jenkins, 2002). Therefore, assuming a maximal depletion of PCr and a typical recovery rate, a repeated-sprint procedure with recoveries of 30 s would lead to [PCr] of less than 10 % of pre-exercise values after only 4 sprints. Therefore, RSE test procedures with either very short (10 s), (Glaister *et al.*, 2005) or long recovery periods (60 s) (Holmyard *et al.*, 1988) may represent extremes of recovery duration within which a suitable RSE procedure may be established. The mean work: rest ratio for the RSE tests shown in Appendix 1 is 1:4.2 which, for a 6 -s sprint duration would be around (6 -s sprint, on 31 s). These considerations formed the basis of the timings used in the present study where procedures of long recovery (55 s between sprints), moderate recovery (40 s between sprints) and short recovery (25 s between sprints) were used.

Although there are no physiological measures to reflect performance in RSE tests, the fact that RSE tests are usually applied to competitors in game-sports would suggest that some similarity is required between the physiological responses to RSE tests and game-sports play. Such an approach has already been adopted by Dawson *et al.* (1991) who observed that post-RSE test [La] of around 13 mmol.l⁻¹ was similar to the highest results seen from soccer-play (Bangsbo, 1994). Dawson *et al.* (1991) accepted the shortcomings of this approach in that post-match lactate analysis may not reflect peak values within a game and stated that, by necessity, an RSE test would require some degree of overload, thus elevating [La]. An additional approach would be to use HR data and Table 1 would suggest that the average HR for most game-sports is around 80-85 %HRmax in competition.

The findings from study I demonstrated that NMT-RSE performance can be reliably assessed and that measures of velocity and power were more reliable than force. The low decrement of velocity (less than 3 %) with the 6 × (6 -s sprint, on 36 s) procedure of study 1 was lower than the figure of more than 5 % quoted by Wadley and LeRossignol, (1998) as being typical of repeated-sprint tests. This would suggest that a more fatiguing protocol would be required in order to discriminate between subjects of contrasting recovery characteristics (Dawson *et al.*, 1991). As a consequence of this, the number of sprints performed was increased from 6 in study I to 10 sprints in studies II, III, IV and V.

Therefore, in the present study recovery duration was manipulated with 10 × 6 -s sprint duration procedures during NMT sprinting. The aim of the study was to establish which of a range of procedures would possess the physiological and performance characteristics that would be most suited to future use as a test of repeated-sprint performance with application to competitors in game-sports.

Methods

Experimental design

Thirteen active male subjects (mean ± s, age 20.2 ± 0.9 years, body mass 78.0 ± 9.2 kg, stature 1.79 ± 0.06 m, $\dot{V}O_{2\text{max}}$ 59.0 ± 8.0 ml.kg⁻¹.min⁻¹, maximal HR 198 ± 7 beats.min⁻¹) volunteered to participate in this study. Subjects visited the laboratory on five occasions. The first visit required the subjects to perform a familiarisation on the use of the Woodway non-motorised treadmill (Weil am Rhein, Germany). The procedures for the familiarisation and for the pre-test warm-up activities are as described in the general methods section of this thesis. In the next three visits the subjects performed the three RSE tests which differed according to the recovery period allowed between sprints. Each test required ten, 6 -s sprints to be performed with sprints starting either every 25, 40 or 55 s (i.e., ‘short’, ‘moderate’, ‘long’ recovery, respectively). The order of testing was randomised for each subject. Subjects also performed a progressive maximal test to exhaustion on a separate visit to determine $\dot{V}O_{2\text{max}}$. All tests for each subject were performed within a three-week period with each visit separated by at least 48 hours.

Procedures

Repeated-sprint tests

Performance data (maximum velocity, average velocity and average power) and the percentage decrement results were derived using the procedures outlined in the general methodology section. Similar to the study of Balsom *et al.* (1992), the average performance in the first two sprints of each series was established for the velocity and power variables and compared across the three recovery conditions in order to establish consistency of baseline values. The combined performance in the first two sprints was chosen for this analysis as previous work has shown that the first in a series of sprints is not necessarily the best performance (Hamilton *et al.*, 1991; Glaister *et al.*, 2005).

Throughout each series of 10 sprints, respiratory gases were measured using a Sormedics $V_{\max}29C$ breath-by-breath respiratory gas analysis system (Sormedics, CA, USA). Respiratory gas analysis continued for at least 4 min of recovery to allow for the determination of $\dot{V}O_2$ off-kinetics. Heart rate was recorded every 5 s using short-range radio telemetry (Polar Vantage NV, Polar, Kempele, Finland) throughout the RSE test to obtain average HR (%HRmax) and HR recovery index. After the last sprint of each test subjects sat for a period of 8 min to allow for collection of earlobe blood samples at 2, 4, 6 and 8 min post-exercise and subsequent analysis of blood [La] using Biosen 5030 (Instruchemie, Delfzijl, Netherlands) apparatus. These data were used to derive a mean post-exercise [La]. A range of times was selected in accordance with the work of Fitzsimons *et al.* (1993), as the timing of blood sampling influences [La] (Cheetham *et al.*, 1986) although most studies employed only one reading, either immediately post-exercise (Bishop *et al.*, 2004b) or after 3 min (Hamilton *et al.*, 1991; Dupont *et al.*, 2005) or 4 min (Hargreaves *et al.*, 1998).

Maximal oxygen consumption test

This progressive test to exhaustion was performed on a motorised treadmill (Powerjog, Birmingham, UK) with respiratory gas analysis performed using the Sormedics $V_{\max} 29c$ apparatus. Subjects began the test with a 5-min stage at 8.5 km.h⁻¹ and 1 % gradient. This was followed by 3 -min stages all at 4 % gradient with velocity increasing from 8.5 km.h⁻¹ by 1.5 km.h⁻¹ increments until volitional exhaustion. The criteria of The British Association of Sport and Exercise Sciences (Bird and Davison, 1997) were used to determine attainment of $\dot{V}O_{2\max}$. The highest HR achieved within the test was taken as the 'HR max' for subsequent analysis of exercise intensity with the RSE tests.

Data analysis

Performance and physiological variables from these tests were analysed by two-way repeated measures ANOVA with recovery duration and sprint number as the two factors using SPSS (Version 11.5, Chicago, Illinois). Where significant interactions were found, follow-up tests were performed using one-way ANOVA on main effects, with Bonferroni correction and Tukey's HSD post-hoc analysis where required. If the assumptions of sphericity were violated, adjustments were made using the Huynh-Feldt

correction. Pearson product moment correlations were also performed between the performance variables and the measures of $\dot{V}O_2$ off-kinetics and the HR recovery index. Statistical significance was accepted at $P < 0.05$. All data are expressed as mean $\pm s$ unless otherwise stated.

Results

Performance variables in the repeated sprint test

Recovery duration had a significant effect on all of the performance measures. Specifically, in the short recovery condition, MxSp was lower compared to the results for the moderate and long recovery conditions (6.79 ± 0.43 vs. 7.06 ± 0.51 and 7.10 ± 0.36 m.s⁻¹, respectively: $F_{(2,24)} = 17.0$, $P < 0.05$). The AvPO was also lower for short, compared to moderate and long recovery conditions (381.4 ± 30.2 vs. 414.8 ± 33.5 and 430.5 ± 38.5 W, respectively: $F_{(2,20)} = 21.7$, $P < 0.05$). The decrement of performance was significantly higher in the shorter recovery conditions (see Table 19) for MxSp and AvPO, but not AvSp. There was no significant difference in the first two sprints between the performance measures. The performance data for AvPO are shown in Figure 4.

Table 19. Percent decrement for performance measures from 10×6 -s sprint exercise with short, moderate and long recovery durations (19 s, 34 s, 49 s, respectively).

	Recovery duration		
	Short	Moderate	Long
MxSp (%)	5.23 ± 1.57 % ^{a,b}	3.36 ± 1.68 % ^b	3.02 ± 1.36 % ^a
AvSp (%)	5.27 ± 1.65 %	4.33 ± 1.7 %	4.36 ± 2.7 %
AvPO (%)	14.40 ± 4.93 % ^{a,b}	10.10 ± 4.45 % ^{b,c}	7.25 ± 3.03 % ^c

^a denotes difference between short and long recovery conditions ($P < 0.05$)

^b denotes difference between short and moderate recovery conditions ($P < 0.05$)

^c denotes difference between moderate and long recovery conditions ($P < 0.05$)

Where the differences across recovery durations were considered for each sprint, the Bonferroni correction for the 10 repeated ANOVAs was used such that statistical significance was only accepted at $P < 0.005$. AvPO was different between all conditions

in sprints 4, 5 and 7 to 10. For MxSp, significantly lower performance was observed with short recoveries compared to the other recovery conditions from sprint 3 onwards. No differences in MxSp were observed between the moderate and long recovery conditions. Similarly, AvSp was only significantly lower for the short recovery duration compared to either moderate or long recovery duration in sprints 5, 6 and 8 to 10. No other differences in AvSp were observed.

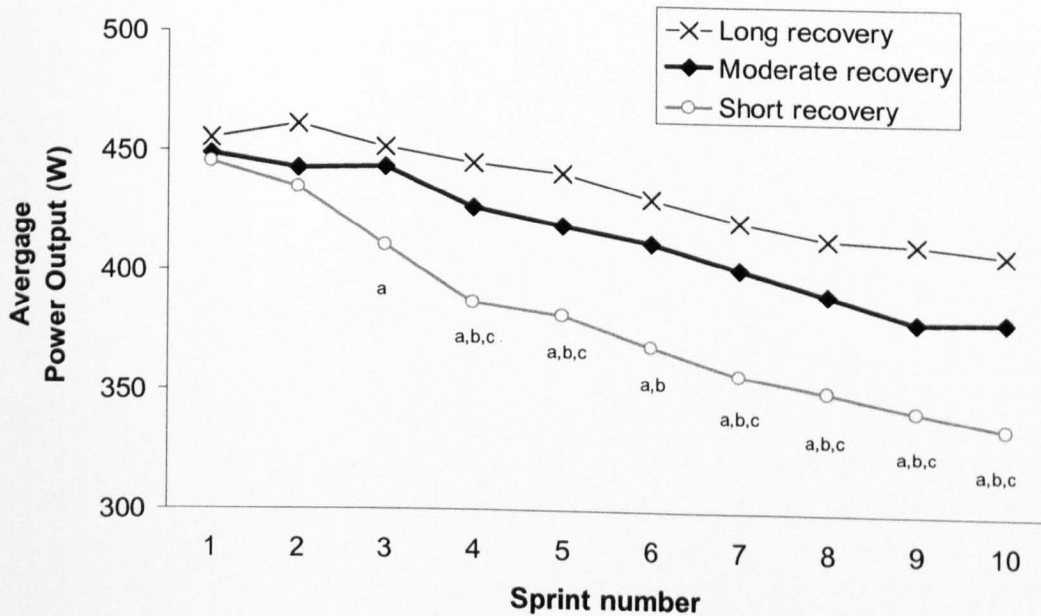


Figure 4. Mean mean power output for 10 × 6-s sprint exercise with short, moderate and long recovery durations (19 s, 34 s, 49 s, respectively).

^a denotes 'short' less than 'long' recovery ($P < 0.05$)

^b 'short' less than 'moderate' recovery ($P < 0.05$)

^c 'moderate' less than 'long' recovery ($P < 0.05$).

Physiological measures from the repeated-sprint test.

The mean $\dot{V}O_2$ throughout the repeated-sprint tests was higher in the short recovery condition compared to both the moderate and long recovery tests (66 ± 2.7 vs. 57.9 ± 2.3 and 52.8 ± 2.5 % $\dot{V}O_{2\max}$, respectively: $F_{(2,18)} = 21.9$, $P < 0.05$). Similarly, mean heart rate in the long recovery condition was lower than that recorded for both the moderate and short recovery tests (83.3 ± 7.6 vs. 86.9 ± 6.1 and 90.0 ± 4.5 % HRmax, respectively: $F_{(2,20)} = 13.4$, $P < 0.05$). Heart rate recovery index was different between short and long, and moderate and long recovery conditions ($F_{(2,20)} = 34.0$, $P < 0.05$). There was no significant difference in the mean post-exercise [La] across the three

conditions (12.3 ± 0.8 , 10.8 ± 0.8 , 11.1 ± 0.6 mmol.l⁻¹ for short, moderate and long recoveries, respectively; $P > 0.05$). The $\dot{V}O_2$ off-kinetics were not affected by recovery duration ($P > 0.05$).

Table 20. Physiological measures from 10×6 -s sprint exercise with short, moderate and long recovery durations (19 s, 34 s, 49 s, respectively).

	Recovery duration		
	Short	Moderate	Long
$\dot{V}O_2$ (% $\dot{V}O_{2\text{ max}}$)	66.0 ± 2.7 % ^{a,b}	57.9 ± 2.3 % ^b	52.8 ± 2.5 % ^a
Average post-exercise [La] (mmol.l ⁻¹)	12.3 ± 0.8	10.8 ± 0.8	11.1 ± 0.6
Heart rate (%HR max)	90.0 ± 4.5 % ^a	86.9 ± 90.0 % ^c	83.3 ± 7.6 % ^{a,c}
Heart rate recovery index (beats min ⁻¹)	2.5 ± 1.4 ^a	7.3 ± 3.1 ^c	19.2 ± 8.4 ^{a,c}
$\dot{V}O_2$ off-kinetics (τ) (s) ($n = 9$)	46.0 ± 3.7	47.6 ± 5.3	47.0 ± 6.1

^a denotes difference between short and long recovery conditions ($P < 0.05$)

^b denotes difference between short and moderate recovery conditions ($P < 0.05$)

^c denotes difference between moderate and long recovery conditions ($P < 0.05$)

Repeated-sprint test performance - relationship with $\dot{V}O_2$ off-kinetics and HR recovery

There were no significant relationships between the results for HR recovery index and performance on the RSE test for any of the three recovery conditions. Similarly, there were no significant relationships between the results for $\dot{V}O_2$ off-kinetics and performance on the RSE test. Significant relationships were observed between $\dot{V}O_2$ off-kinetics and HR recovery index in the moderate recovery condition ($r = -0.832$; $P = 0.005$; $n = 9$) but these variables were not related at either the short ($r = 0.096$; $P = 0.821$; $n = 9$) or long ($r = -0.258$; $P = 0.16$; $n = 9$) recovery durations.

Discussion

This study sought to investigate the influence of recovery duration on the performance of RSE tests made up of ten, 6-s sprints. Measures of performance were made in order to assess the extent of fatigue in the tests, as this is likely to be a requisite for an RSE

test. Physiological measures were taken to make comparisons between the physiological demands of both the test procedure and the performance of game-sports. These measures may help to guide the development of an NMT-RSE procedure for use with game-sports competitors. The results of the present study are unique in that they were derived from NMT sprinting and that the recovery durations used were selected due to their similarity with previous RSE tests using different exercise modes.

For all measures, performance tended to decline as sprint number increased and this trend was greater with lower recovery duration. For example, for AvPO, the short recovery condition elicited more fatigue than the moderate or long recovery conditions. In this short-recovery condition, performance had declined significantly after sprint 3 compared to the long-recovery condition. Additionally, in all subsequent sprints apart from sprint 6, there were differences between all of the recovery conditions. The 14.4 % mean decrement of AvPO in the short recovery condition was higher than the typical decrement scores quoted in previous RSE studies which usually fall between 5 and 10 % (Fitzsimons *et al.*, 1993; Wadley and LeRossignol, 1998; Bishop *et al.*, 2001). Indeed, only one subject achieved a decrement of AvPO below 10 % (range of values 9.33 % to 22.36 %). This high rate of fatigue may be attributed to the reduced potential for PCr recovery in the short time between sprints. Even with the long recovery condition, mean decrement of AvPO was 7.25 %: this value is typical of decrement scores from previous RSE tests (Dawson *et al.*, 1993; Fitzsimons *et al.*, 1993; Bishop *et al.*, 2001). The fact that this long-recovery condition gave similar decrement scores to those achieved in cycling RSE tests of shorter recovery duration is consistent with the findings of Ratel *et al.* (2004) which showed that sprint-running elicited a higher rate of fatigue than was seen in equivalent sprint-cycle tests. The AvPO values for the present study (approximately 400 W) are lower than those reported elsewhere using similar equipment (Holmyard *et al.*, 1988; Tong *et al.*, 2001) and this is likely to be due to the use of a standing start (compared to rolling start) and the use of 6 -s averaging periods (compared to 1 s), both of which would contribute to lower AvPO values.

The decrement of both velocity variables in the three recovery conditions range from 3.02 % to 5.27 % and are consistently lower than those of AvPO. Holmyard *et al.* (1988) also observed lower fatigue in velocity compared to power. These authors speculated that an alteration in running technique could lead to the greater fatigue of force (and hence, power output) observed in their study but gave no further explanation

on this matter. These contrasting fatigue characteristics with different variables further demonstrate the need for standardisation of procedures when measuring RSE.

Increasing the recovery duration led to an expected decrease in the mean $\dot{V}O_2$ and HR response during the RSE procedure. This effect can be attributed to the greater opportunity for recovery from the previous sprint in the longer recovery conditions (Glaister *et al.*, 2005) and is further demonstrated by the significantly higher HR recovery index when recovery duration was increased. The higher $\dot{V}O_2$ and reduced HR recovery are consistent with insufficient intramuscular recovery as evidenced by the compromised sprint performance. These findings are consistent with other studies that have addressed the influence of recovery duration on RSE (Holmyard *et al.*, 1988; Balsom *et al.*, 1992b; Glaister *et al.*, 2005). Despite these trends in $\dot{V}O_2$ and HR data, mean post-exercise [La] was not affected by alterations in recovery duration. The fact that performance decrement in RSE seems independent of [La] is consistent with the findings of previous authors (Holmyard *et al.*, 1988; Balsom *et al.*, 1992b; Glaister *et al.*, 2005) and further adds to the evidence that [La] is not proportional to fatigue in high-intensity exercise of this nature (Bangsbo *et al.*, 1996).

The physiological variables from these RSE test procedures allow for some comparison with the demands of game-sports competition. Table 1 demonstrates that a range of game-sports elicit a mean HR of around 80-85 % HRmax. Only the long recovery duration condition of the present study had a mean HR in that range, while the short recovery duration condition caused HR to exceed 90 % HR max. The similarities in the [La] data suggest that this variable will be of limited use in distinguishing between procedures of different recovery durations. However, all of the mean post-exercise [La] values reported here are similar to the 13 mmol.l⁻¹ quoted by Dawson *et al.* (1993) as being similar to a demanding period of play within a soccer match. They are also typical of the peak [La] reported after previous RSE bouts, which usually range from around 10 mmol.l⁻¹ (Fitzsimons *et al.*, 1993; Bishop *et al.*, 2004b) to 15 mmol.l⁻¹ (Hamilton *et al.*, 1991; Dupont *et al.*, 2005). The present results showed that $\dot{V}O_2$ off-kinetics appear to be unaffected by recovery duration after an RSE test. Because of the links between $\dot{V}O_2$ kinetics and [PCr], these similarities in $\dot{V}O_2$ kinetics suggest that the time constant of PCr recovery is also unaffected by such changes in recovery duration within an RSE test. A similar conclusion was drawn by Rossiter *et al.* (2002) who assessed the

time constants of both $\dot{V}O_2$ recovery and PCr resynthesis after moderate and high-intensity exercise (repeated 4-min bouts of leg extensions). The consistency of $\dot{V}O_2$ off-kinetics may reinforce the potential value of using this variable as an indicator of PCr recovery after RSE testing, although, the lack of correlation between $\dot{V}O_2$ off-kinetics and the measures of performance or fatigue in the RSE tests suggests that this respiratory measure may be of limited value in this respect. It should also be highlighted, however, that there may be little discernible difference between the post-exercise [PCr] from ten 6-s sprints with either the short or long recovery durations.

In order to provide recommendations about the future procedure for RSE tests using NMTs, the performance and physiological outcomes from different recovery conditions must be considered. The short-recovery period caused greater decrements in performance than most previous RSE tests and it also elicited higher mean HR than is observed in the performance of most game-sports (see Table 1). With due consideration of the data from the present study and even the shortest estimates of the half-time of post-exercise PCr resynthesis rate (21 -s recovery half-time; Harris *et al.*, 1976), a procedure which allows greater recovery than that allowed in the 19 s of this condition here would seem to be appropriate. Similarly, the long recovery condition elicited low decrements in all performance variables and would therefore be unsuited to the assessment of RSE performance.

In conclusion, the lack of a criterion against which to compare the results of this study may not make it possible to recommend a universal recovery duration for the assessment of RSE performance in game-sports players but the two extremes here seem inappropriate for the present population with this procedure and apparatus. The likely need to alter procedures for different populations has already been suggested by Dawson *et al.* (1991) and further refinement of these procedures may be required in the future. However, the moderate recovery condition of the present study would appear to meet the dual requirements of performance decrement, with a physiological response that approaches similarity with game-sports performance.

**CHAPTER 6. - STUDY III, THE INFLUENCE OF TRAINING ON REPEATED-
SPRINT PERFORMANCE USING NON-MOTORISED TREADMILL
SPRINTING**

Introduction

The previous studies in this thesis have shown that non-motorised treadmill, repeated-sprint exercise testing can be reliable and that a procedure of 10 × (6 s, on 40 s) gives similar physiological and performance responses to previously-established RSE tests using other exercise modes. The literature on RSE contains few test procedures that have been assessed for their validity (Bishop *et al.*, 2001). An issue within this area of fitness assessment is that there is no criterion measure against which to validate new repeated-sprint tests that are developed. Consequently, it is not possible to evaluate the criterion validity of an RSE test (Bishop *et al.*, 2001). Within this thesis, the outcomes from study II have confirmed the content validity of the 10 × (6 -s sprint, on 40 s) procedure from consideration of factors such as sprint duration, work: rest ratio and exercise mode as well as for the performance and physiological outcomes. The aim of the present study was to investigate the construct validity of the 10 × (6 -s sprint, on 40 s) procedure from study II by using a repeated-sprint training programme as an intervention.

Various approaches have been adopted in evaluating the construct validity of fitness assessments applied to game-sports competitors. This application has been achieved by comparing performances in RSE tests with those from competition or competition simulations (Bangsbo and Lindquist, 1992; Bishop *et al.*, 2001), by comparing subjects of contrasting performance level (Edwards *et al.*, 2003; Mohr *et al.*, 2003), contrasting training background (Bishop and Spencer, 2004) or by using a training programme as an intervention (Spencer *et al.*, 2004). Other studies, although not necessarily performed with a view to examining the construct validity of repeated-sprint assessments, can also be used to demonstrate the construct validity of RSE tests. For example, Hamilton *et al.* (1991) found their NMT-RSE protocol could discriminate between game-sports players and endurance athletes. The game-sports players had better initial sprint performance, but higher fatigue than endurance athletes in RSE. Using training as an intervention, Dawson *et al.* (1998) and Nevill *et al.* (1994) showed that repeated-sprint training led to enhanced RSE performance.

There are limitations in a number of the procedures previously described to examine construct validity in an RSE performance test. With cross-sectional studies, such as the

work by Hamilton *et al.* (1991), confounding variables other than the contrasting training background are likely to affect test performance. The subjects in the study by Hamilton *et al.* (1991) were heterogeneous in terms of body mass, peak post-exercise [La] and $\dot{V}O_{2\max}$ and the authors suggested that these factors would contribute to performance differences between the groups. The work of Hamilton *et al.* (1991) supports the contention that an NMT-RSE test is able to discriminate between subjects of contrasting training background but a repeated measures design would overcome some of the individual differences that have been suggested to affect results. Bishop and Spencer (2004) attempted to overcome the problem of subject heterogeneity by using a cross-sectional study with subjects who were matched for body mass and $\dot{V}O_{2\max}$. The two groups were also made up of game-sports players and endurance athletes. These authors concluded that their (5 × (6 -s sprint, on 30 s)) RSE test procedure could discriminate between groups. However, their procedure used cycling as the exercise mode so their findings may not be applicable to NMT sprinting or to over-ground sprinting. When RSE test results are compared with performance in a competitive situation (e.g., Bangsbo and Lindquist, 1992; Krustup and Bangsbo, 2001), the variability of competitive performance may restrict the value of attributing competitive performance to a purely fitness-related test outcome.

Training programmes that have used repeated-sprint exercise as an intervention have been shown on many occasions to be effective at enhancing repeated-sprint performance (e.g., Nevill *et al.*, 1994; Dawson *et al.*, 1998; Ortenblad *et al.*, 2000). These improvements in performance have been detected using over-ground sprinting (Dawson *et al.*, 1998), cycle ergometry (Ortenblad *et al.*, 2000) and non-motorised treadmill sprinting (Nevill *et al.*, 1994). The findings from Nevill *et al.* (1994) suggest that NMT-RSE testing is sensitive to training but their procedure involved a shorter rest period than that proposed for use in this thesis from the findings of study II and their subjects were from a mixed-sex group. Therefore, the aim of study III was to investigate whether the NMT-RSE procedure could be used to detect changes in performance after a programme of RSE training in male game-sports competitors. The study was performed using members of a University hockey club as they returned to training for a new season.

There were two null hypotheses examined in this study:

1. That the NMT-RSE test performance of subjects is not affected by the commencement of a period of game-sports training and competition.
2. That the NMT-RSE test performance of subjects who add repeated-sprint training to their normal programme is not different to the performance of the subjects who perform only their normal club training and competition schedule.

Methods

Subjects

Twenty-one members of the male University hockey squad volunteered to participate in the study. Their characteristics (mean \pm standard deviation (*s*)) at the start of the study were:- age 20.0 ± 1.2 years, body mass 73.9 ± 11.9 kg, stature 1.76 ± 0.07 m, $\dot{V}O_{2\max}$ 52.0 ± 6.2 ml.kg⁻¹.min⁻¹.

Experimental design

Subjects were randomly assigned to a control group ($n=9$) and an experimental (training) group ($n=12$). Subjects were tested for $\dot{V}O_{2\max}$ and NMT-RSE performance on two separate visits, both at the start and conclusion of the experimental period. At the start of the study, the players had just returned to University and, as such, the 'pre-tests' were performed within a two-week period prior to the start of competitive matches. For the duration of the study all players participated in their usual club activities. These activities comprised one or two matches and one or two training sessions for each week of this period. Consequently, for some weeks all players could have up to four, or as few as two hockey sessions. The intervention for the experimental (training) group was that they performed an additional 14 sessions of repeated-sprint training spread equally over this seven week period. 'Post' tests were performed within the ten days after completion of the training programme. The study, therefore, spanned a period of eleven weeks. All laboratory tests were performed in afternoons. Subjects were instructed to perform no vigorous activity in the 36 hours before a test, to refrain from alcohol in the 24 hours before a test and to refrain from eating or consuming caffeinated products in the 2 hours prior to testing.

Procedures

Non-motorised treadmill, repeated-sprint test.

The first visit to the laboratory for all subjects was to allow familiarisation to sprinting on the NMT. The familiarisation procedure for this session was described in the general methods section of this thesis. In their second visit subjects performed a warm-up as previously described in the general procedures, which was followed by the 10 × (6 -s sprint, on 40 s) RSE test. After the warm-up, subjects were given a 3 -min recovery before commencing the RSE test. Heart rate data were collected throughout the test and ear-lobe capillary blood samples were taken for determination of [La] 4 and 6 min into the post-exercise rest period. The average of these values was taken as the peak, post-exercise [La]. The decision to adopt this procedure was made in accordance with findings from study II and reinforced by findings that around 5 min has often been taken as the time to assess peak [La] in similar RSE tests (Holmyard *et al.*, 1988; Connolly *et al.*, 2003). The procedures for analysis of HR and [La] were as described in the general methods section. Subjects performed the RSE test with each sprint starting every 40 s. Ten sprints of 6 s each were performed in total and after the final sprint, subjects dismounted the treadmill and sat quietly for the following 6 min. Throughout the test, respiratory gases were analysed using Jaeger Oxycon Alpha breath-by-breath system (Erich Jaeger GMBH & Co., Hoechberg, Germany) which had been previously calibrated according to manufacturer's instructions. Respiratory gas analysis was continued until 4 min after the conclusion of the test. Calculation of $\dot{V}O_2$ off-kinetics was performed according to the procedures in the general methods section. Due to malfunction of the respiratory gas analysis system (2 subjects) or feelings of nausea in the post-exercise period (1 subject), data from 3 subjects were excluded for the analysis of $\dot{V}O_2$ off-kinetics.

Maximal rate of oxygen consumption test procedure

The $\dot{V}O_{2\text{ max}}$ procedure was performed on a motorised treadmill (H/P/ Cosmos, Quasar 4.0, Germany). Subjects were firstly familiarised to motorised treadmill running and informed of the procedures for terminating the maximal test. All pre-test activity was performed below the intensity of the first stage of the main procedure. Throughout the test, HR was recorded using telemetry (Polar S610, Polar Electro Oy, Finland) and respiratory gas analysis was performed using the Jaeger Oxycon Alpha system. After up

to 4 min of warm-up, subjects rested for 3 min prior to beginning the test. The procedure for the test is given in Table 21. The average of the highest two, consecutive 30 -s $\dot{V}O_2$ values ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) was taken as the $\dot{V}O_{2\text{max}}$. The highest 5 -s value was taken as the HR max.

Table 21. Test procedure used to establish $\dot{V}O_{2\text{max}}$ in this study.

Time (min)	Speed ($\text{km}\cdot\text{h}^{-1}$)	Gradient (%)
0-5	8.5	1
5-6	9	4
6-7	10	4
7-8	11	4
8-9	12	4
9-10	13	4
10-11	14	4
11-12	15	4
12-13	16	4
13-14	17	4

Training programme

A number of investigators have shown that repeated sprint performance can be improved once subjects have undertaken a training programme comprised of repeated sprints (Nevill *et al.*, 1994; Dawson *et al.*, 1998; Ortenblad *et al.*, 2000; Dupont *et al.*, 2004a). Dawson *et al.* (1998) were the only authors to use a progressive sprint-running training programme where the specific details of each training session were stated. These factors, in conjunction with the fact that the training programme of Dawson *et al.* (1998) had been shown to enhance RSE performance, led to the adoption of their programme for the present study. The subjects who participated in the present study had a lower mean $\dot{V}O_{2\text{max}}$ than those in the original work by Dawson *et al.* (1998), so a decision was made to reduce the training volume for the subjects of the present study in comparison to the programme in the original article. From week 2 of the present study, however, the details of the programme by Dawson *et al.* (1998) were adhered to for the remaining twelve sessions. The programme performed by the subjects in the present study is shown in Table 22.

Sprints were either performed at '90 %' or '100 %' of maximal effort, with maximal efforts being required for up to three sets from week 3 onwards. Sessions were performed on an artificial hockey pitch, apart from on three occasions where the straight sprint section of an athletics track was used. All sprint distances were marked by cones and each sprint in a set was followed by a walk-back recovery to the same start-point. Between sets, a total of 2 -min recovery was given. One experimenter controlled the timings for every session. Additionally, in weeks 5 to 7, one set of agility sprints were performed within the session to replace a set of straight line sprints. These involved a 5 -m sprint to a cone, followed by two 45° changes of direction, before returning back to the original straight to complete the sprint (see Figure 5). In order to gain an estimate of the physiological load during training, HR was recorded from two subjects in each training session. Subjects in the training group who missed more than two repeated-sprint training sessions were excluded from the study.

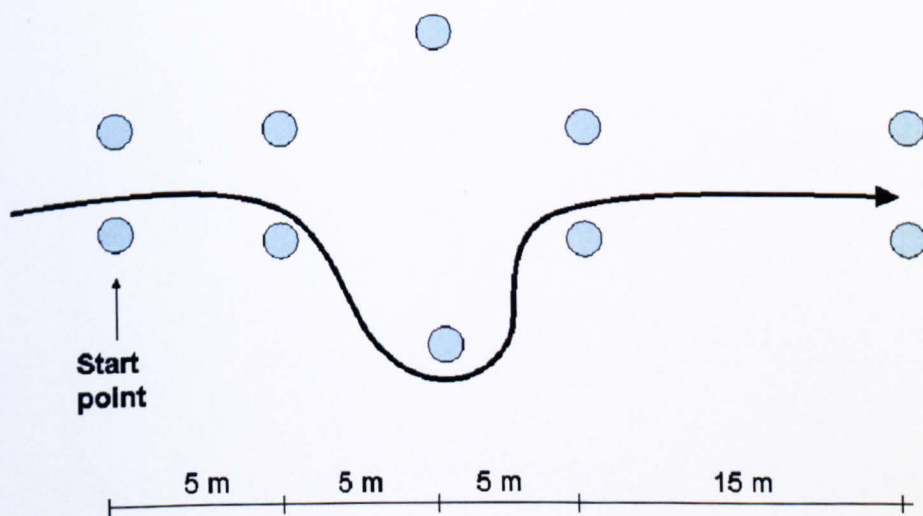


Figure 5. Representation of the course used for 30 -m agility sprint in the training programme. Blue discs represent the cones used to mark the course.

Data analysis

Statistical analyses on all data were performed using the Statistics Package for Social Scientists (SPSS; version 12.0). To investigate the influence of the training intervention, two-way repeated measures ANOVAs were performed (experimental group \times test occasion) on all dependent variables. Where significant F values were found, Tukey's post hoc was used to identify differences. For between-group differences at the start of the study, independent t -tests were performed. Pearson's product moment correlation was performed to investigate the relationships between aerobic fitness and performance.

For all analyses, significance was accepted at $P < 0.05$. All results are expressed as mean \pm standard deviation (s) unless stated otherwise.

Table 22. Details of the programme used by the training group for the repeated-sprint training sessions.

Week	Session	Set 1	Set 2	Set 3	Set 4	Set 5
1	1	5 x (80 m sprint, every 80 -s), 2 -min rest before set 2	5 x (40 m sprint, every 48 -s), 2 -min rest before set 3	5 x (60 m sprint, every 64 -s), 2 -min rest before set 4	5 x (40 m sprint, every 48 -s).	
	2	as session 1	as session 1	as session 1	as session 1	
2	1	6 x (80 m sprint, every 80 -s), 2 -min rest before set 2	6 x (40 m sprint, every 48 -s), 2 -min rest before set 3	6 x (60 m sprint, every 64 -s), 2 -min rest before set 4	6 x (40 m sprint, every 48 -s).	
	2	as session 1	as session 1	as session 1	as session 1	
3	1	6 x (80 m sprint, every 70 -s), 2 -min rest before set 2	6 x (40 m sprint, every 42 -s), 2 -min rest before set 3	6 x (60 m sprint, every 56 -s), 2 -min rest before set 4	6 x (40 m sprint, every 42 -s).	
	2	as session 1	as session 1	as session 1	as session 1	
4	1	4 x (80 m sprint, every 60 -s), 2 -min rest before set 2	6 x (30 m sprint, every 35 -s), 2 -min rest before set 3	6 x (40 m sprint, every 42 -s), 2 - min rest before set 4	6 x (50 m sprint, every 49 -s), 2 -min rest before set 5	8 x (40m sprint, every 42 -s).
	2	as session 1	as session 1	as session 1	as session 1	8 x (40m sprint, every 42 -s).
5	1	6 x (50 m sprint, every 49 -s), 2 -min rest before set 2	8 x (30 m agility, every 30 -s), 2 -min rest before set 3	6 x (40 m sprint, every 42 -s), 2 - min rest before set 4	6 x (30 m sprint, every 30 -s), 2 -min rest before set 5	8 x (30m sprint, every 35 -s).
	2	6 x (50 m sprint, every 42 -s), 2 -min rest before set 2	6 x (40 m agility, every 36 -s), 2 -min rest before set 3	6 x (60 m sprint, every 56 -s), 2 - min rest before set 4	8 x (50 m sprint, every 42 -s), 2 -min rest before set 5	6 x (60m sprint, every 56 -s).
6	1	8 x (50 m sprint, every 42 -s), 2 -min rest before set 2	8 x (40 m sprint, every 42 -s), 2 -min rest before set 3	8 x (40 m agility, every 30 -s), 2 - min rest before set 4	8 x (40 m sprint, every 42 -s), 2 -min rest before set 5	8 x (50m sprint, every 56 -s).
	2	as session 1	as session 1	as session 1	5 x (40m sprint, every 42s), 2 -min rest before set 5	5 x (50m sprint, every 56 -s).
7	1	8 x (40 m sprint, every 36 -s), 2 -min rest before set 2	8 x (50 m sprint, every 42 -s), 2 -min rest before set 3	8 x (40 m agility, every 30 -s), 2 - min rest before set 4	8 x (50 m sprint, every 42 -s), 2 - min rest before set 5	8 x (40m sprint, every 42 -s).
	2	as session 1	as session 1	as session 1	as session 1	as session 1

Note: Sessions highlighted in bold were performed at 100% maximal effort, the remainder at 90%. See text for explanation.

Results

Adherence to the training programme

Of the 21 subjects who began the study, one left the hockey club and two were injured in the early part of the experimental period. Three members of the experimental group failed to perform the minimum number of sessions (12) and were consequently dropped from the study. The following results were taken from the remaining 15 subjects ($n = 8$ training group, $n = 7$ control group).

Heart rate response to training sessions

Mean heart rate during training sessions was 150 ± 9 beats.min⁻¹, which represented 76 % HRmax. When the recovery period between sets was excluded from this analysis, the mean HR increased to 156 ± 9 beats.min⁻¹ (79 %HR max). The HR response from one subject to a typical training session is illustrated in Figure 6.

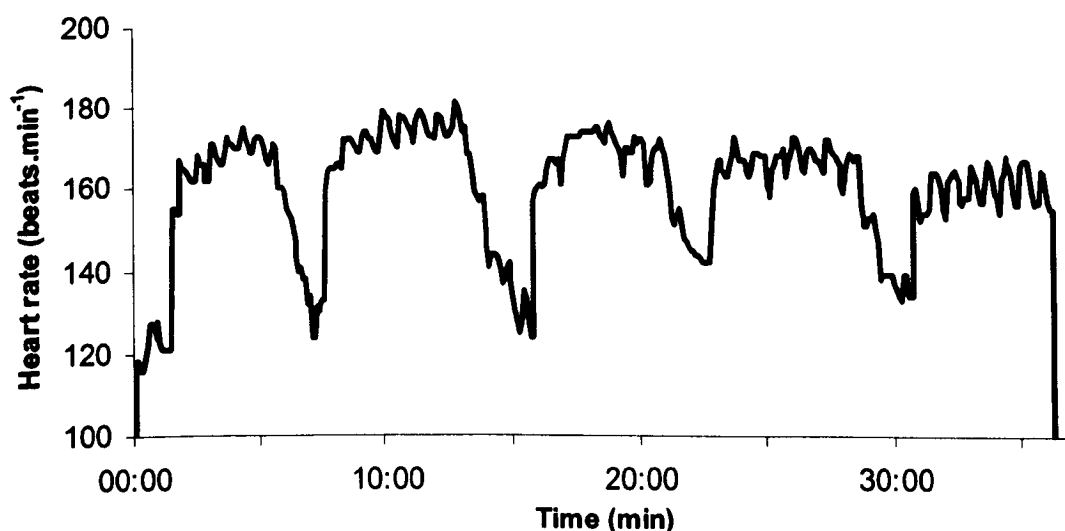


Figure 6. Heart rate response of one subject (with a HR max of 196 beats.min⁻¹) to a typical training session (session 1, week 7).

General subject characteristics

At the start of the study there were no significant differences in the body mass or $\dot{V}O_{2\text{ max}}$ of the group members (see Table 23). Mean body mass in the whole cohort of subjects was lower after the experimental period (74.9 ± 12.7 vs. 73.8 ± 11.6 kg; $P < 0.05$) but the training group did not respond differently to the control group for the change in body mass in the study. There was a significant increase in $\dot{V}O_{2\text{ max}}$ in both

groups ($P < 0.05$) but, again the effect was not different between the two groups (see Table 23). One subject from the control group was unable to perform his post-training $\dot{V}O_{2 \max}$ test within the allotted 10-day period after cessation of the training programme. The $\dot{V}O_{2 \max}$ data for this subject were therefore not analysed but the data for other analyses were included.

Table 23. Subject characteristics before ('pre') and after ('post') 7 weeks of hockey training ('control' group, $n = 7$) and with additional repeated-sprint training ('training' group, $n = 8$). Overall data are also shown as 'combined' group ($n = 15$).

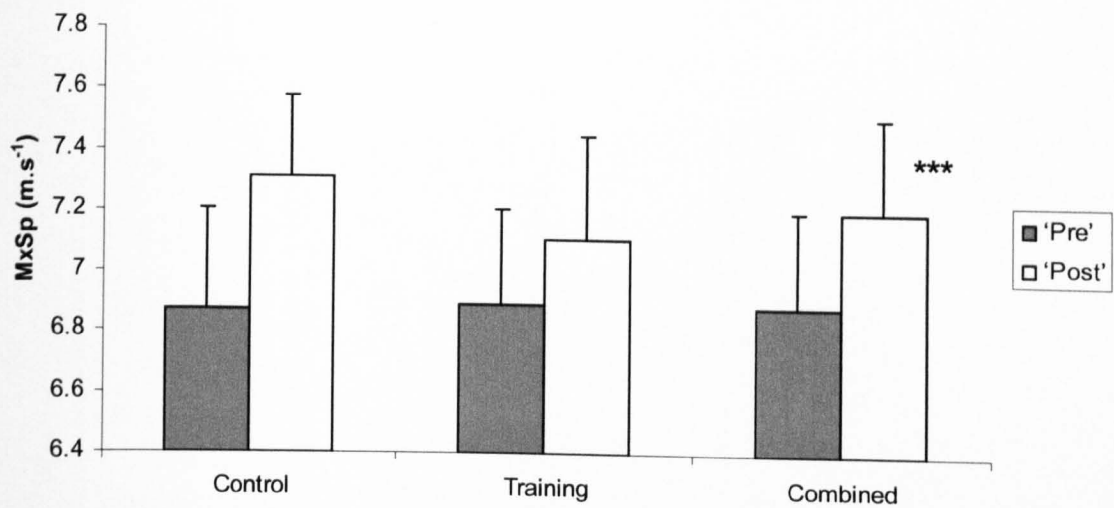
Variable	Group	'Pre'	'Post'
Body Mass (kg)	Control	76.8 ± 13.9	75.1 ± 12.5
	Training	73.2 ± 12.2	72.7 ± 11.5
	<i>Combined</i>	74.9 ± 12.7	73.8 ± 11.6 *
$\dot{V}O_{2 \max}$ (ml.kg ⁻¹ .min ⁻¹)	Control ($n = 6$)	49.3 ± 5.1	54.7 ± 4.1
	Training	53.9 ± 6.3	56.5 ± 5.6
	<i>Combined ($n = 14$)</i>	51.9 ± 6.1	55.7 ± 4.9***

*** Denotes significant difference between 'pre' and 'post' results ($P < 0.001$)

* Denotes significant difference between 'pre' and 'post' ($P < 0.05$)

Repeated-sprint test performance.

There were no significant differences in the RSE performance of the two groups at the start of the experiment (see Table 24). The training group did not respond differently to the control group in the experimental period as evidenced by the non-significant interaction term for AvSp or MxSp ($P=0.059$ and 0.055 , respectively). The main effects from the study were a general increase in AvSp (5.87 ± 0.25 vs. 6.07 ± 0.32 m.s⁻¹; $F_{(1,13)} = 18.6$; $P < 0.01$) and MxSp (6.88 ± 0.32 vs. 7.20 ± 0.31 m.s⁻¹; $F_{(1,13)} = 42.8$; $P < 0.01$) as shown in Figures 7 and 8. No changes were seen in the AvPO results. There were no differences in the decrement of performance for any of these measures (see Table 25). The changes in MxSp or AvSp through the study were not correlated with increased $\dot{V}O_{2 \max}$ ($r = 0.33$, $r = 0.10$, respectively).



*** Denotes 'post' significantly higher than 'pre' for combined group data ($P < 0.001$).

Figure 7. Mean, maximal one-second average velocity (MxSp) before ('pre') and after ('post') hockey training ('control' group, $n = 7$) and with additional repeated-sprint training ('training group, $n = 8$).

Overall data are also shown as 'combined' group ($n = 15$).

Table 24. Repeated-sprint test performance variables before ('pre') and after ('post') 7 weeks of hockey training ('control' group, $n = 7$) and with additional repeated-sprint training ('training' group, $n = 8$). Overall data are also shown as 'combined' group ($n = 15$).

Variable	Group	'Pre'	'Post'
MxSp (m.s^{-1})	Control	6.87 ± 0.34	7.31 ± 0.27
	Training	6.89 ± 0.32	7.11 ± 0.34
	<i>Combined</i>	6.88 ± 0.32	$7.20 \pm 0.31^{***}$
AvSp (m.s^{-1})	Control	5.85 ± 0.28	6.15 ± 0.30
	Training	5.89 ± 0.25	6.00 ± 0.34
	<i>Combined</i>	5.87 ± 0.25	$6.07 \pm 0.32^{**}$
AvPO (W)	Control	540 ± 46	530 ± 42
	Training	510 ± 44	502 ± 49
	<i>Combined</i>	524 ± 46	515 ± 46

*** denotes significant difference ($P < 0.001$)

** denotes significant difference ($P < 0.01$)

Table 25. Repeated-sprint test fatigue characteristics variables before ('pre') and after ('post') 7 weeks of hockey training ('control' group, $n = 7$) and with additional repeated-sprint training ('training' group, $n = 8$). Overall data are also shown as 'combined' group ($n = 15$).

Variable	Group	'Pre'	'Post'
Decrement of MxSp (%)	Control	3.7 ± 1.9	4.1 ± 2.0
	Training	4.3 ± 1.5	3.1 ± 1.5
	<i>Combined</i>	4.0 ± 1.7	3.5 ± 1.8
Decrement of AvSp (%)	Control	3.4 ± 1.8	3.4 ± 2.1
	Training	4.2 ± 1.3	4.0 ± 1.4
	<i>Combined</i>	3.8 ± 1.5	3.7 ± 1.7
Decrement of AvPO (%)	Control	8.5 ± 1.7	7.9 ± 3.8
	Training	10.3 ± 3.6	7.6 ± 3.2
	<i>Combined</i>	9.5 ± 2.9	7.8 ± 3.3

Physiological responses to repeated-sprint exercise test

The additional training sessions did not elicit different responses in the training group to those of the control group (see Table 26). Peak, post-exercise [La] was significantly lower in the post-training tests but there were no changes in exercise $\dot{V}O_2$, exercise HR, HR recovery index or $\dot{V}O_2$ off-kinetics. The mean $\dot{V}O_2$ response to the RSE test is shown in Figure 9. Due to the lack of a significance difference between groups, Figure 9 shows data which are derived from combining the results for both groups.

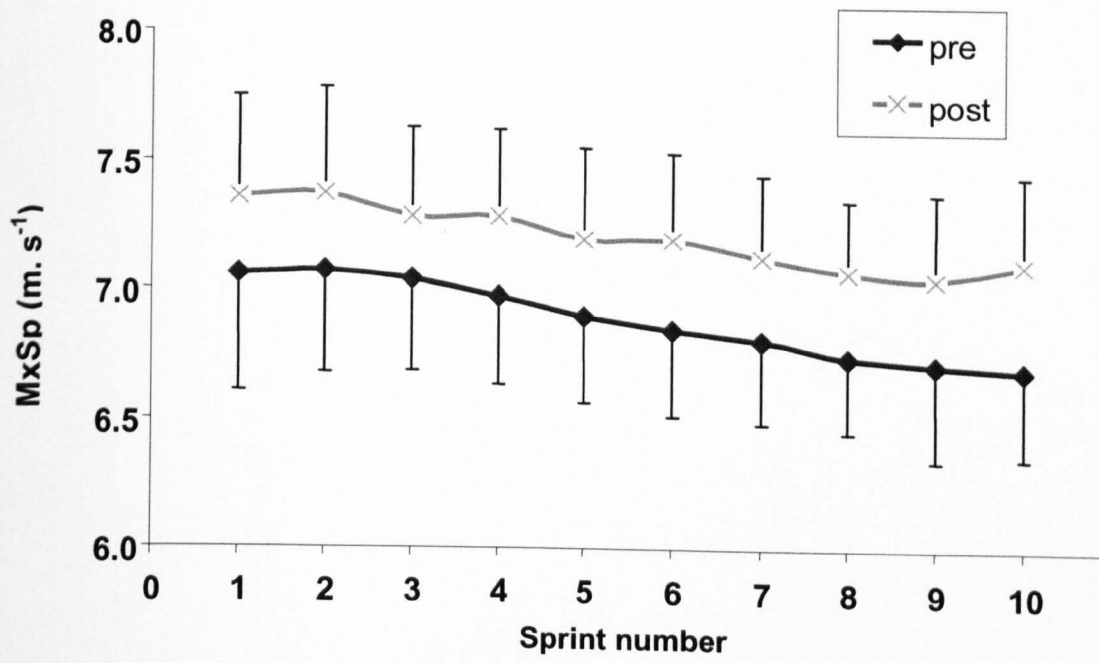


Figure 8. Combined group data for mean, maximal 1 -s average velocity (MxSp) before ('pre') and after ('post') the experimental period.

Table 26. Physiological measures taken from RSE test before ('pre') and after ('post') 7 weeks of hockey training ('control' group, $n = 7$) and with additional repeated-sprint training ('training' group, $n = 8$). Overall data are also shown as 'combined' group ($n = 15$).

Variable	Group	'Pre'	'Post'
Post-exercise peak [La] (mmol.l ⁻¹)	Control	12.7 ± 2.5	11.0 ± 2.1
	Training	10.4 ± 2.3	9.5 ± 2.0
	<i>Combined</i>	<i>11.5 ± 2.6</i>	<i>10.2 ± 2.1*</i>
Mean $\dot{V}O_2$ in RSE test (l. min ⁻¹)	Control ($n = 6$)	2.74 ± 0.31	2.76 ± 0.35
	Training ($n = 7$)	2.47 ± 0.29	2.51 ± 0.28
	<i>Combined</i> ($n = 13$)	<i>2.60 ± 0.32</i>	<i>2.62 ± 0.33</i>
$\dot{V}O_2$ off-kinetics (s)	Control ($n = 5$)	49.6 ± 2.9	49.0 ± 6.5
	Training ($n = 7$)	45.3 ± 5.7	50.1 ± 6.6
	<i>Combined</i> ($n = 12$)	<i>47.1 ± 5.5</i>	<i>49.7 ± 6.3</i>
Mean HR in RSE test (beats.min ⁻¹)	Control	170 ± 6	172 ± 7
	Training	167 ± 6	165 ± 9
	<i>Combined</i>	<i>168 ± 6</i>	<i>168 ± 8</i>
HR recovery index (s)	Control	8.7 ± 2.8	8.3 ± 3.9
	Training	7.6 ± 3.0	8.9 ± 3.5
	<i>Combined</i>	<i>8.1 ± 2.9</i>	<i>8.6 ± 3.5</i>

* Denotes 'post' significantly lower than 'pre' value ($P < 0.05$).

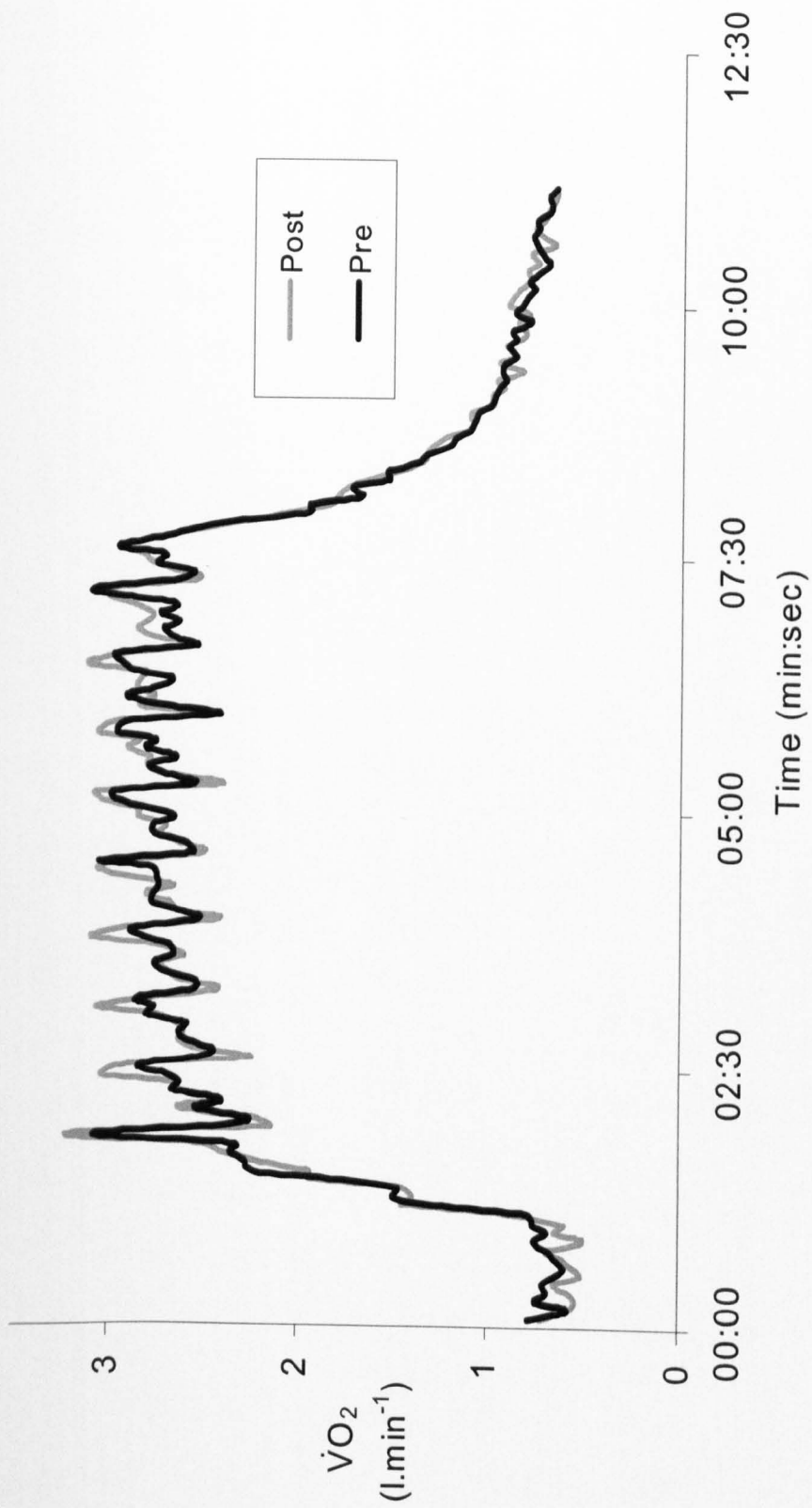


Figure 9. Mean $\dot{V}O_2$ response to RSE test before ('pre') and after ('post') the experimental period for control and training groups combined ($n = 12$). Data shown include 1 min prior to commencement of test and 4 min of recovery.

Discussion

The aim of the study was to investigate whether a period of training would influence repeated-sprint performance. The repeated-sprint training programme did not elicit any adaptations that were different from those seen with the standard hockey training performed by the control group. However, the regular hockey training and matches were effective in promoting improved RSE performance and also aerobic fitness, as evaluated by $\dot{V}O_2 \text{ max}$.

The repeated-sprint training programme of the present study was based on the work of Dawson *et al.* (1998). This programme was selected because it had been shown to be effective at increasing RSE test performance in six weeks and because it was specific to the exercise mode for the NMT test and for the hockey players of this study.

The absence of adaptations due to the repeated-sprint training programme in the present study might be attributed to the slight differences compared with the experiment of Dawson *et al.* (1998). Dawson *et al.* (1998) did not use a control group and did not state whether their subjects' were participating in any other activities during the course of their study. The subjects in the work of Dawson *et al.* (1998) also trained three times per week, thereby performing four more sessions than the subjects in the present study. It is possible that 14 sessions over 7 weeks presented an insufficient training stimulus, but evidence suggesting that training programmes lasting only 3 weeks (Jenkins *et al.*, 1994), or using training frequencies of 2 per week (Helgerud *et al.*, 2001; Dupont *et al.*, 2004a) were effective at improving RSE performance would suggest otherwise. The fact that the control group experienced similar adaptations to the training group may suggest that the use of further training in addition to an already-effective training stimulus may diminish the adaptations to the additional training programme. Alternatively, the relative lack of recovery time experienced by the training group may have led to a reduced stimulus for improved performance linked to overtraining or muscle damage, as previously observed by Parra *et al.* (2000).

The present study most resembles the work of Helgerud *et al.* (2001) which involved two sessions per week for 8 weeks of additional training to a group of soccer players, while members of a control group with similar characteristics performed only their normal soccer training. The decision to use two sessions per week was reinforced by

the findings of Helgerud *et al.* (2001) and it was also felt that the use of more repeated-sprint training sessions would be detrimental to performance of the subjects in the training group of the present study.

The current training programme also included two preliminary sessions that were performed prior to subjects beginning to use the programme employed by Dawson *et al.* (1998). The use of these two sessions, which involved a reduction in training volume compared to the first week of the programme from Dawson *et al.* (1998), was based on the comparatively low initial fitness levels in the subjects of the present study. The subjects in the present study had a lower mean $\dot{V}O_{2\max}$ than those used by Dawson *et al.* (1998) (51.9 vs. 57.0 ml.kg⁻¹.min⁻¹, respectively) and the average MxSp for the subjects in this study was also lower than for subjects in studies I and II of this thesis (6.88 m.s⁻¹ vs. 7.06 and 7.17 m.s⁻¹, respectively). The training volume in week 1 was only lower by 4 sprints and it was felt this was a justifiable decision that would not harm the effectiveness of the programme.

There were significant increases in the $\dot{V}O_{2\max}$ and RSE performance (AvSp and MxSp) of both groups within the study over the 7 weeks of the experiment. However, there were no differences between the adaptive responses of the two groups. The similarities in the adaptations of the two groups mean that, unless stated otherwise, this discussion will consider both groups together.

Through the period of the experiment, the subjects experienced significant increases in $\dot{V}O_{2\max}$ and the velocity variables (i.e., AvSp and MxSp) of RSE performance. These adaptations may be attributed to the general hockey training and competition which all subjects were performing. In this respect, their adaptations are similar to other studies that used a range of game-sports training activities to enhance RSE performance (Krustrup and Bangsbo, 2001; Spencer *et al.*, 2004) and $\dot{V}O_{2\max}$ (Helgerud *et al.*, 2001; Spencer *et al.*, 2004). The improvement in performance (as measured by AvSp or MxSp) appears to be consistent throughout the RSE test as there were no differences in the rate of decrement for these variables (see Table 25 and Figure 8). The higher running velocity maintained throughout the RSE test appears to be associated with improved general aerobic fitness, however the results of correlation analysis failed to show a relationship between the changes in $\dot{V}O_{2\max}$ and those seen in AvSp and MxSp.

The improved performance was not associated with any effect on the $\dot{V}O_2$ or HR response to the RSE test, suggesting that there may have been alterations in running exercise economy during the experiment. The same conclusion has been made after similar training programmes in junior soccer players (Helgerud *et al.*, 2001) and referees (Krustrup and Bangsbo, 2001). The improved economy, in combination with the lower post-exercise [La], could be due to fibre type transformation away from the IIb fibre population, a response frequently observed in the sprint-training literature, (Cadefau *et al.*, 1990; Allemeier *et al.*, 1994; Linossier *et al.*, 1997a) although confirmation of that suggestion is not possible with the current procedures. The improved performance in the RSE test is unlikely to be attributable to psychological factors, such as increased motivation or a learning effect, owing to the similarities between the physiological variables $\dot{V}O_2$ and HR, coupled with the trend in both groups for a lower post-exercise [La] in the post test, compared to the pre test. .

The enhanced sprint performance and improved $\dot{V}O_{2\max}$ did not influence the $\dot{V}O_2$ off-kinetics or HR recovery index. Given that these variables have been postulated in this thesis as potential physiological correlates of RSE performance, their lack of adaptation in this study may suggest that they have limited value in this regard. If these variables do not respond after a study where performance has been improved, they are unlikely to be of practical use as physiological indices of RSE in future studies.

The improved performance in the RSE test was only observed in the velocity variables, AvSp and MxSp. There was a non-significant trend towards a reduction in the group mean AvPO (from 524 to 515 W) between the start and end of the experiment although this difference was diminished when the data were expressed relative to body mass (7.00 vs. 6.98 W/kg, respectively) which decreased during period of the study. In contrast to the velocity variables, there were no significant differences in power output, implying that there may be some disassociation between measures of velocity and power using the NMT. The higher content validity of sprint velocity for game-sports competitors and the fact that measures of power have been previously shown to be less reliable than velocity on the NMT (Tong *et al.*, 2001; study I of this thesis) may suggest that velocity is the most appropriate measure of performance for RSE testing.

The conclusions from this study are that RSE testing on the NMT appears to be sensitive to improved fitness, although the repeated-sprint programme adopted in this

study was not effective in promoting additional adaptations compared with those found in the control group. Consequently, null hypothesis 1 - that the NMT-RSE test performance is not affected by commencement of a period of training and competition - can be rejected and null hypothesis 2 - that the NMT-RSE performance of the subjects who added repeated-sprint training to their normal programme is not different to the performance of subjects who perform only their normal club training and competition schedule - can be accepted.

**CHAPTER 7. - STUDY IV, A COMPARISON OF LABORATORY AND FIELD
TESTS OF REPEATED-SPRINT EXERCISE PERFORMANCE**

Introduction

From studies I and II, it has been shown that an RSE performance test on an NMT can be used to give reliable data and that a series of ten 6 -s sprints, starting every 40 s appears to be a valid test of RSE performance for the population sample in this thesis. Study III has shown that the NMT-RSE test is sensitive to improved fitness. For game-sports competitors, repeated bouts of over-ground sprinting should be considered as a key activity. As one of the aims of this thesis is to investigate the validity of the NMT-RSE test, the construct validity of the procedure can be investigated by comparing the responses to the NMT test to those achieved from over-ground sprinting. While Oliver *et al.* (2005) have previously compared ‘field’ RSE test performance with that from NMT exercise, no research group has also investigated the physiological responses in these contrasting settings. Similarly, there has been no previous comparison of the responses to laboratory and field tests in adults.

The earliest RSE tests were developed either for over-ground sprinting (Dawson *et al.*, 1984) or cycle ergometry (Wootton and Williams, 1983). Performance in the 7 -s sprint procedure of Dawson *et al.* (1984) was evaluated only to a sensitivity of 1 m, a distance equivalent to around 1/6th of a second. In comparison to the cycle RSE procedure of Wootton and Williams (1983), the running field test of Dawson *et al.* (1984) had higher specificity for application to game-sports performers but lacked the sensitivity and experimental control that is possible from laboratory-based testing. Holmyard *et al.* (1988) and Hamilton *et al.* (1991) were the first to combine the performance of running sprints with the laboratory control and precision of laboratory assessment, owing to their use of a non-motorised treadmill. However, few authors have subsequently used this apparatus for the assessment of RSE performance in spite of the higher specificity for the game-sports performer when running is used. Instead, most research continues to be performed with over-ground sprinting (Wadley and LeRossignol, 1998; Aziz *et al.*, 2000; Dupont *et al.*, 2005) or cycle ergometry (Fitzsimons *et al.*, 1993; Balsom *et al.*, 1994b; McMahon and Wenger, 1998; Bishop *et al.*, 2001).

Sprinting on a non-motorised treadmill has previously been stated to be “similar” to over-ground sprinting (Lakomy, 1987) although this statement was not supported by statistical analysis. Strong correlations have been identified between power outputs in

NMT sprinting and cycling, both in single sprints (Sutton *et al.*, 2000) and in RSE (Ratel *et al.*, 2004). Similarly, in RSE testing, Fitzsimons *et al.* (1993) have shown that the extent of fatigue found in over-ground running and cycling is highly related. These authors also observed a lack of correlation between other performance variables and concluded that running should be used as the preferred mode of activity for the assessment of RSE performance in game-sports players (Fitzsimons *et al.*, 1993). Only Oliver *et al.* (2005) have looked at the relationship between performance on NMT sprints and performance on over-ground sprints in RSE. They showed that outcomes from field testing and NMT testing were highly correlated, and that the correlation was stronger with the velocity variables from the NMT test than with power variables. Oliver *et al.* (2005) did not assess the physiological variables to their procedures, however, and the tests were only performed on boys. Therefore the purpose of the present study was to investigate the validity of the NMT-RSE test by comparing the physiological and performance responses in adult males with those derived from a field test situation.

The null hypotheses for this study are as follows:-

1. That differences exist between the responses to the laboratory and field-test procedures.
2. That there are no correlations between the responses to the laboratory and field-test procedures.

Methods

Experimental design

Ten male subjects (mean \pm s, age 20.9 ± 1.4 years, body mass 76.3 ± 9.4 kg, stature 1.79 ± 0.06 m) volunteered to participate in this study. Subjects were tested on three occasions, with each visit separated by at least 48 hours and with less than 7 days between the second and third tests. The first visit was to familiarise subjects with NMT sprinting as described in the general methods section. Stature and body mass were also measured on this visit. The order of testing for the subsequent visits was randomised. One of these trials required the subjects to perform the $10 \times (6$ -s sprint, on 40 s) NMT-RSE procedure. The other trial required subjects to perform an equivalent field-based RSE procedure on an indoor athletics track ($10 \times (40$ -m sprint, on 40 s)). Measures of performance characteristics and physiological variables were taken from both test-types.

Procedures

Non-motorised treadmill sprinting.

During the first of their two laboratory visits, subjects performed the familiarisation procedure described in the general methods section of this thesis. In their second visit the subjects performed the standard warm up given in the general methods section followed by a 3 -min recovery before commencing the RSE test. Heart rate was recorded throughout the test using telemetry and ear-lobe capillary blood samples were taken for determination of [La]. The procedures for analysis of HR and [La] were as stated in the general methods section. Subjects performed the RSE test with each sprint starting every 40 s. Ten sprints of 6 s each (starting every 40 s) were performed in total. After the final sprint, subjects dismounted the treadmill and rested for the following 6 min while blood samples were taken to allow for the determination of peak, post-exercise [La] after 4 and 6 min of recovery.

Field testing.

The field test procedure was chosen to be similar to the NMT test in terms of the timings used. Previous work that has compared field test sprinting with a 6-s laboratory RSE trial has used a 40 -m distance (Fitzsimons *et al.*, 1993) and pilot testing confirmed that subjects from within this sample typically covered around 40 m in this time. A section of an indoor athletics sprint track, approximately 60 -m long, was used for testing and, specifically, an exact distance of 40 m was measured within that area. Thus, a single test distance of 40 m was established with a 10 -m long deceleration zone at each end. The ten sprints of the RSE test were performed starting from alternating ends of this 40 -m sprint track. Electronic timing gates (Time-It, Eleiko Sport, Sweden) were used to record 40 -m sprint time to the nearest 0.01 of a second. The timing gates were mounted on tripods, positioned exactly 40 m apart. To avoid false starts due to arm movement through the timing beam, subjects were instructed to start each sprint from around 50 cm behind the light beam. Administration of the test was always overseen by the same experimenter operating a countdown timer with automatic-repeat function. A verbal countdown was given to all subjects from 5 s prior to each sprint and verbal encouragement was given throughout all sprints.

Data analysis

The field test data were converted from 40 -m sprint times to running velocities for each sprint. Data were then subsequently processed to give mean sprint time and percent decrement. The NMT test data were processed, as previously outlined, into MxSp, AvSp and AvPO and the resulting mean and decrement results were calculated. Mean HR and HR recovery index were derived from each test-type. Similarly, the peak [La] was derived from the mean of the two post-exercise samples. Correlations were analysed using Pearson's product moment correlation and paired *t*-tests were performed to establish differences between mean values. Statistical significant was accepted at $P < 0.05$ and all analyses were performed using Microsoft Excel. All results quoted are mean $\pm s$ from ten subjects unless stated otherwise.

Results

Performance data

Mean velocity in the field-test sprints was significantly higher than the equivalent measurement (AvSp) from NMT sprinting (6.84 ± 0.30 vs. 6.33 ± 0.29 m.s⁻¹, respectively; $P < 0.05$) (see Figure 10). The mean velocity in the field test was lower than the mean highest 1 s of NMT sprinting (i.e., MxSp) (6.84 ± 0.30 vs. 7.37 ± 0.35 m.s⁻¹, respectively; $P < 0.05$). Mean velocity in the field test was significantly related to both AvSp and MxSp ($r = 0.83$ and 0.85 , respectively; $P < 0.01$) (see Figure 11). No relationships were evident between the field test performance and AvPO. For the decrement in running velocity, there was no difference between field test performance (3.3 ± 1.4 %) and either of the NMT velocity variables (MxSp, 2.8 ± 1.3 %; AvSp 3.6 ± 2.1 %; $P > 0.05$). The decrement of RSE performance during the field test was related to the decrement of MxSp on the NMT ($r = 0.68$; $P < 0.05$) but not to the decrement of AvSp ($r = 0.35$; $P > 0.05$) or AvPO ($r = 0.21$; $P > 0.05$).

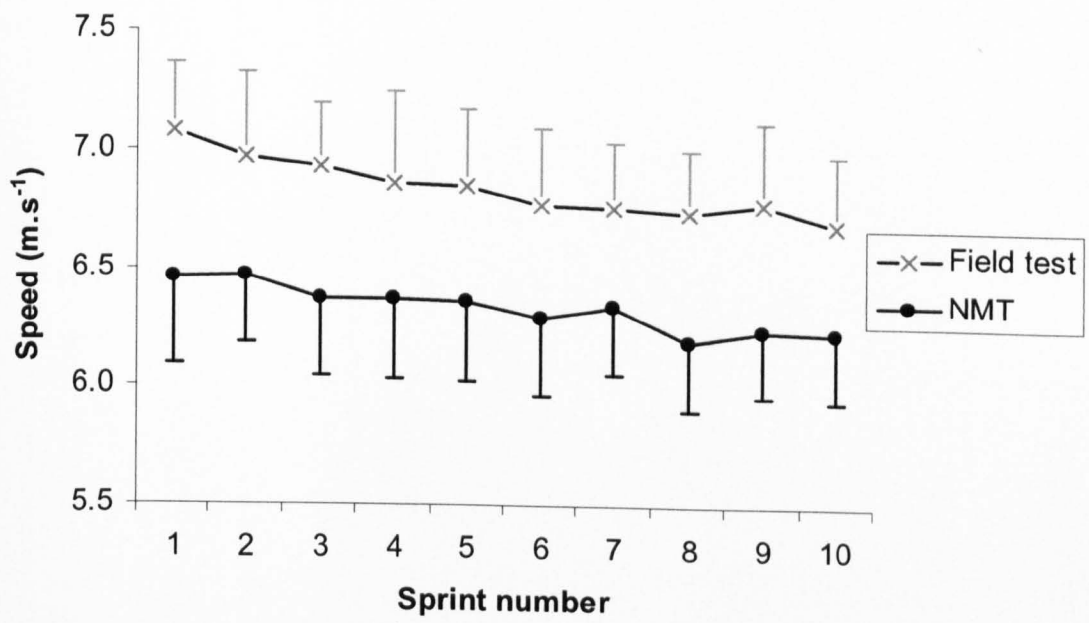


Figure 10. Mean velocity for the field and NMT-RSE tests. Error bars denote standard deviations.

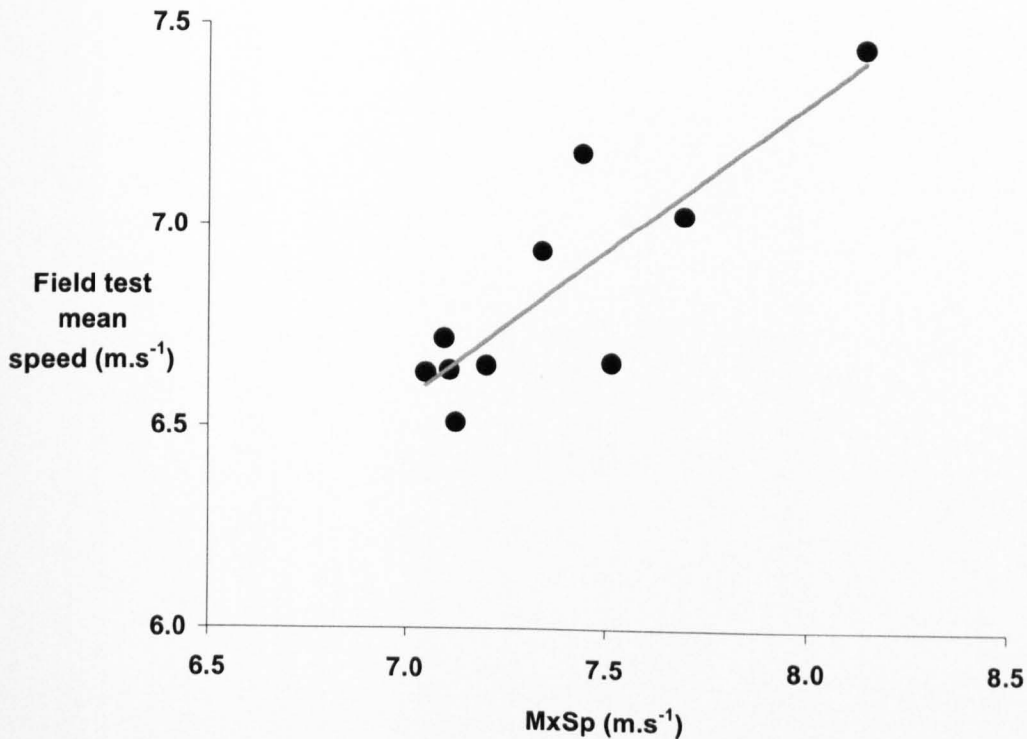


Figure 11. Scatterplot and linear trend line for mean field test sprint velocity and NMT ‘MxSp’.

Physiological data

Post-exercise [La] was not different between the field test and the NMT test (9.1 ± 2.4 mmol.l⁻¹ vs. 9.2 ± 2.6 mmol.l⁻¹; $P > 0.05$, respectively) and between the two test-types, the post-exercise [La] was significantly correlated ($r = 0.83$; $P < 0.01$). Average HR was highly correlated between tests ($r = 0.94$; $P < 0.01$, $n = 9$) although the field test elicited higher HR than the NMT (173 ± 8 vs. 170 ± 9 beats min⁻¹; $P < 0.05$, $n = 9$) (see Figure 12). The HR recovery index was not different between test-types but there was no significant relationship between these data ($r = 0.60$; $P > 0.05$, $n = 9$).

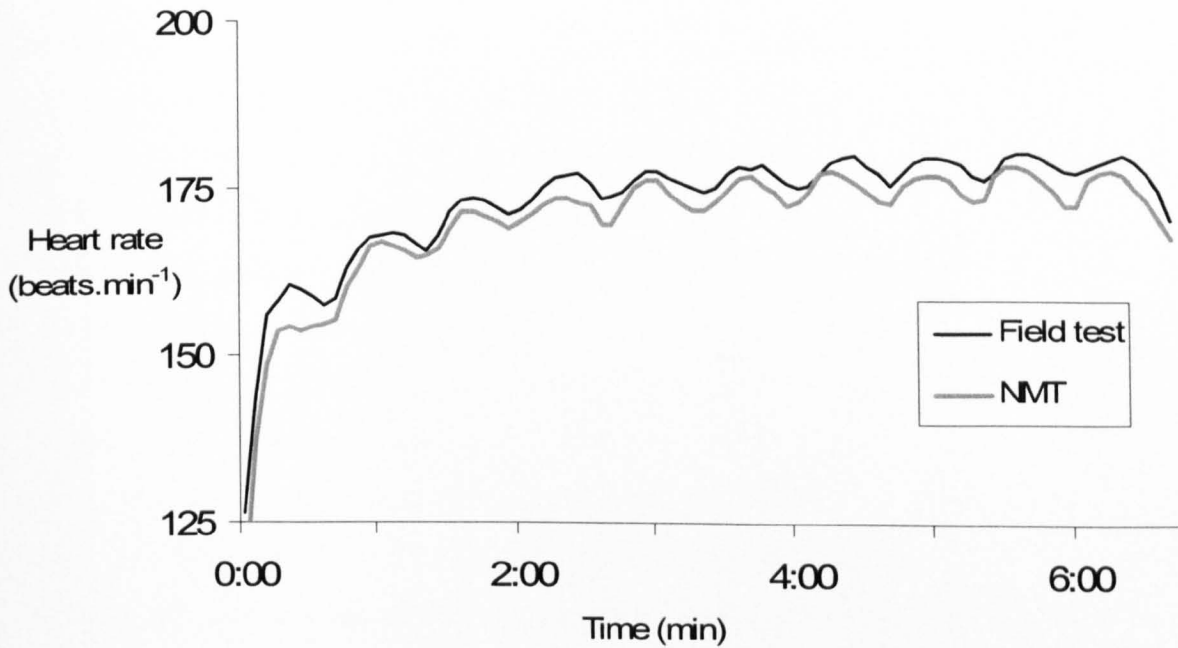


Figure 12. Mean heart rate response to repeated-sprint tests performed on an NMT or using field-test sprinting ($n = 9$).

Post-exercise [La] was significantly correlated with average 40 -m sprint speed and the decrement of velocity in the field test ($r = 0.68$; $P < 0.05$, $r = 0.83$; $P < 0.01$, respectively). Similarly, post-exercise [La] in the laboratory tests was correlated with AvSp and MxSp ($r = 0.80$; $P < 0.01$, $r = 0.74$; $P < 0.01$, respectively) but not with AvPO ($r = 0.19$; $P > 0.05$). For the measures of performance decrement in the laboratory testing, decrement of AvSp was the only performance variable that was related to [La] ($r = 0.61$; $P < 0.05$).

Discussion

The aim of this study was to compare the performance and physiological responses to RSE tests using NMT and field testing in adult males. The mean running velocity for the field test ($6.84 \text{ m}\cdot\text{s}^{-1}$) was similar to the mean sprint times (both $6.9 \text{ m}\cdot\text{s}^{-1}$) from studies by Fitzsimons *et al.* (1993) and Aziz *et al.* (2000) using RSE tests over 40 -m. Additionally, the mean MxSp data from the present study ($7.37 \text{ m}\cdot\text{s}^{-1}$) are a little higher than the 1 -s peak velocity data recorded from single sprints in previous NMT studies ($7.07 \text{ m}\cdot\text{s}^{-1}$ from Tong *et al.*, 2001; $7.03 \text{ m}\cdot\text{s}^{-1}$ from Hamilton *et al.*, 1991). These points, along with the high HR and post-exercise [La] suggest that the subjects were exercising at the required, maximal intensity and were habituated for these procedures.

The results from the sprint velocity data show that performance was significantly correlated in the two test-types. This outcome is similar to the findings of Oliver *et al.* (2005) using RSE testing in boys. Indeed, similar correlations were found between field test velocity and NMT velocity ($r = 0.85$ or more for Oliver *et al.*, 2005 compared to $r = 0.83$ and 0.85 , respectively for the present study). There were differences between equivalent measures of velocity in the two test-types showing that mean sprint velocity in the field test is higher than on the NMT. This finding has already been observed by Lakomy (1987) in single sprints and was attributed to the added resistance of the treadmill belt when using the NMT. For the purposes of the present study, achieving identical velocities is not considered essential, although Thatcher *et al.* (2004) suggested that altering the gradient of the NMT could be used to correct for the discrepancy in running velocities that are attributed to the resistance in the treadmill apparatus.

Although strong relationships are evident when the velocity results from NMT testing and field tests are considered, that relationship is not evident when the NMT power data are related to field test performance. Oliver *et al.* (2005) also reported that power was less related to field test performance than the NMT velocity measures. This lack of relationship could be attributed to the fact that power data are usually shown to be less reliable than velocity data (Tong *et al.*, 2001 and study I of the present study). Alternatively, it is perhaps not surprising that the comparison of velocity measures from two different test-types gives a higher correlation than when comparing velocity and power. Given the importance of running velocity, this finding suggests that the velocity results from the NMT test are likely to be the most important when applying results to game-sports competitors.

The mean decrement of velocity in the field test (3.3 ± 1.4 %) was not significantly different from that of the NMT trial for either AvSp (3.6 ± 1.4 %) or MxSp (2.8 ± 1.3 %). The decrement of velocity in the field test was only related to the decrement of MxSp from the NMT trial. Neither the decrements of AvSp or AvPO were correlated to the decrement of field test performance. This lack of correlation may be attributed to the additional resistance encountered by subjects in accelerating the treadmill which would not be a factor in over-ground sprinting.

The physiological variables obtained in the present study demonstrate the strong similarities and relationships between the field test and the NMT test. Average HR and

post-exercise [La] data were significantly related between the two test types and the [La] variable was not different between the two conditions. The HR recovery index was not different between the tests although the use of this variable may be questioned due to the lack of relationship between the outcomes of either trial. Only average HR was different between the two tests. A possible explanation for this finding is the slight, but inevitable, extra load of decelerating and walking back to the start point while performing the field test.

Post-exercise [La] was positively related to average sprinting speed across the RSE tests, supporting previous investigators in NMT sprinting (Hamilton *et al.*, 1991) and cycle ergometry (Gaitanos *et al.*, 1993). Previous authors have also shown that post-exercise [La] results are related to the extent of fatigue in RSE testing (Brooks *et al.*, 1990; Fitzsimons *et al.*, 1993). This was also evident in the present study but only for the decrement in field test velocity and AvSp in the NMT trial. The relationships between [La] and both sprint speed and fatigue across the RSE test may be attributed to the relative proportions of fibre types in the subjects. For example, a high proportion of fast fibres will be associated with higher speed, a tendency to favour the glycolytic pathway and a tendency to fatigue at a faster rate than would be seen with subjects who expressed a higher proportion of slow fibres.

With reference to the hypotheses under investigation, the first null hypothesis - that differences exist in the responses to the tests - can be accepted for the average HR and average sprint velocity. For the other variables that can be compared ([La] and decrement of sprint velocity), the null hypothesis can be rejected. The second null hypothesis - that the responses to the test are not correlated - can be accepted for HR recovery index and for the relationship between field test performance and AvPO from the NMT test. For the other relevant outcomes, this null hypothesis can be rejected.

In conclusion, the findings from the present study for NMT repeated sprints support the conclusions of Lakomy (1987) from single sprints that the NMT allows valid assessment of sprinting performance. It would appear that NMT sprinting can be used to elicit very similar physiological and performance responses in the assessment of repeated-sprint performance. The validity of the NMT test, in comparison to the field test seems to be enhanced when velocity, as opposed to power variables, is assessed

using the NMT. Use of the NMT power results to predict field test performance would appear to be inappropriate from the evidence of the present study.

**CHAPTER 8. – STUDY V, THE INFLUENCE OF CREATINE
MONOHYDRATE SUPPLEMENTATION ON REPEATED-SPRINT
PERFORMANCE**

Introduction

The studies in this thesis have suggested that RSE on a non-motorised treadmill is reliable, valid and that it replicates over-ground sprinting. Study III showed that the NMT-RSE test was sensitive to the improved fitness achieved when a group of game-sports competitors resumed sport-specific training accompanied by improved aerobic fitness. In addition to training, it is widely accepted that the supplementation of creatine monohydrate is a nutritional intervention that is an effective means of enhancing the performance of RSE (Bogdanis *et al.*, 1996a; Aaserud *et al.*, 1998; Mujika *et al.*, 2000; Bemben and Lamont, 2005). Therefore, given that the NMT-RSE test has already been shown to be sensitive to the long-term intervention of enhanced fitness, further investigation of the sensitivity of the test can be achieved by using creatine supplementation as a short-term intervention that has been shown to promote RSE performance.

During short sprints the hydrolysis of phosphocreatine (PCr) stores is the most significant pathway for rapid ATP resynthesis in muscle (Gaitanos *et al.*, 1993). The PCr stores are rapidly depleted after the onset of exercise (Hirvonen *et al.*, 1987). Creatine (Cr) is usually obtained from dietary sources (Engelhardt *et al.*, 1998) and additional supplementation of creatine monohydrate has been shown to further elevate intramuscular PCr stores (Harris *et al.*, 1992). A recent review suggested that Cr supplementation may be effective at improving strength as well as a range of activities including jumping, cycling and sprinting (Bemben and Lamont, 2005). The mechanisms to explain the ergogenic effects of Cr include:- increased ATP resynthesis due to elevated PCr stores, increased buffering of H⁺ ions and, enhanced rate of PCr resynthesis and enhanced PCr depletion rate (Greenhaff *et al.*, 1994; Francaux *et al.*, 2000; Mesa *et al.*, 2002). Given that Cr supplementation may enhance PCr resynthesis, many authors have investigated the effects of Cr loading on repeated-sprint activity (see Tables 6 and 7). Most, but not all of these studies have indicated that Cr supplementation has ergogenic effects on the performance of repeated sprints (Balsom *et al.*, 1993a; Aaserud *et al.*, 1998; Kamber *et al.*, 1999).

Although Cr supplementation is widely considered to be effective at increasing repeated-sprint performance (Mesa *et al.*, 2002; Bird, 2003; Bemben and Lamont, 2005)

the evidence is not conclusive and a number of factors may be associated with these inconsistencies. Of the eight repeated-sprint studies in Table 7 which did not show an ergogenic effect from Cr supplementation, four used a very low number of sprints (5 or less). None of the studies in Table 6, where Cr loading was effective, used so few sprints. Bearing in mind the proposed mechanisms of Cr loading in repeated sprints, it may be that a cumulative fatigue is required from a higher number of sprints before the benefits of additional PCr stores may become discernible. The requirement of cumulative fatigue is confirmed from a number of studies where Cr loading only improved performance in the later part of a repeated-sprint test (Aaserud *et al.*, 1998; Romer *et al.*, 2001). Therefore, repeated-sprint tests with a relatively high number of sprints may be more likely to be affected by Cr supplementation.

Evidence also exists that duration of recovery between sprints may affect the likelihood of Cr supplementation enhancing repeated-sprint performance. Preen *et al.* (2001) used 6 -s sprints followed by either 24, 54 or 84 -s recovery and only showed Cr loading to be ergogenic for the 54 -s and 84 -s conditions. Similarly, Mujika *et al.* (2000) showed in a (6 × (15 -m sprint, 30 -s recovery)) procedure that performance was improved, whereas the performance in a 40 × (15 -m sprint, 10 -s recovery) protocol was unaltered. Ahmun *et al.* (2005), like Preen *et al.* (2001), used a 10 × (6 -s sprint, on 30 s recovery) procedure and found no benefit of Cr supplementation in either running or cycling exercise. The importance of recovery duration was also demonstrated after more prolonged exercise by Greenhaff *et al.* (1994) who showed that Cr supplementation only enhanced post-exercise PCr resynthesis once recovery had exceeded 60 s. However, the majority of Cr supplementation studies have shown it to be an effective stimulus for enhanced RSE performance (Table 6).

The effectiveness of Cr loading generally seems to be influenced by the subjects' initial PCr storage and the supplementation protocol (Syrotuik and Bell, 2004, Green *et al.*, 1996b). The highest ergogenic benefit of Cr supplementation seems to be associated with the achievement of the greatest gain in PCr stores (Casey *et al.*, 1996a). Consequently, the uptake of Cr into the muscle is an important factor to be optimised. The amount of Cr that is supplemented to the diet is quite consistent in the literature and most authors agree that a loading regime of 5 to 6 days of 20 g daily doses is effective at raising muscle Cr stores (Harris *et al.*, 1992; Balsom *et al.*, 1993b; Greenhaff *et al.*, 1994; Williams and Branch, 1998). In addition to the amount ingested, the uptake of Cr

also appears to be facilitated in the presence of insulin (Green *et al.*, 1996b; Steenge *et al.*, 1998) so many authors have advocated the supplementation of Cr in conjunction with ingestion of simple carbohydrate to raise insulin levels (Green *et al.*, 1996b; Steenge *et al.*, 1998; Preen *et al.*, 2003).

It is typical for Creatine loading procedures to enhance water retention and increased body mass is often a consequence of participation in such studies (Izquierdo *et al.*, 2002; Yquel *et al.*, 2002; Van Loon *et al.*, 2003). Elevated body mass is also a likelihood with Cr loading studies because some investigations have recommended that Cr ingestion should be achieved in conjunction with the ingestion of high amounts of CHO. For example, Green *et al.* (1996a) used four daily doses of 93 g CHO each, with their 5 -day Cr loading regime. This would represent an additional energy intake of approximately 40 mJ over a 5 -day loading period and could further contribute to increased body mass. As the present study used running, where the subject's body mass is not supported, the possibility exists that increased body mass could reduce the effectiveness of the intervention (Mesa *et al.*, 2002). However, the recent findings of Preen *et al.* (2003) have shown the effectiveness of a combination of 2 g.kg of body mass⁻¹ glucose with 20 g Cr per day and have recommended this CHO dose instead of the larger amounts previously advocated by Green *et al.* (1996a), partly due to the lower additional energy intake that was experienced by subjects.

The individual differences that exist in the response to a period of Cr supplementation have been used to explain some of the inconsistencies regarding the use of Cr as an ergogenic aid (Lemon, 2002). Lemon (2002), advocated the use of repeated measures, cross-over designs in Cr supplementation studies for this reason and suggested that a minimum of 7 subjects was required for such a study provided that sufficient wash-out period was employed. Hultman *et al.* (1996) recommended that a minimum 4-week wash-out period should be used in studies adopting a cross-over design. Preen *et al.* (2003) subsequently extended this recommendation to 5 weeks.

The majority of previous authors have shown that the performance of repeated sprints is improved after Cr loading. Therefore, this study will use a Cr loading regime as an intervention with which to further investigate the sensitivity of the NMT-RSE test already developed in the earlier studies of this thesis.

The null hypothesis for this study is that creatine loading does not improve RSE performance compared to results from a placebo condition.

Methods

Experimental design

Eleven healthy male subjects (mean \pm s, age 21.0 ± 2.3 years, body mass 75.4 ± 8.9 kg, stature 1.80 ± 0.07 m at commencement of the experiment) volunteered to participate in the study. A condition of participation in the study was that subjects had not used creatine supplementation in the three months prior to the study. Subjects were required to attend the laboratory on a total of five occasions. On their first visit, the body mass and stature of all subjects were measured and they became familiarised to the use of the non-motorised treadmill. This study used a randomised, double-blind, cross-over design so after their first visit subjects were randomly assigned to either the placebo or creatine condition.

In their second visit, the RSE test ($10 \times$ (6-s sprint, on 40 s)) was performed. After this trial, subjects were given a pack of creatine or placebo supplement that they were instructed to take over the following 6 days. Seven days after their first RSE test, subjects were tested again. After at least a five-week washout period, subjects returned to the laboratory to perform another RSE test, which was followed by a week of receiving the supplement (i.e., placebo or creatine) that they had not already received in the first part of the study. After 6 more days of taking the supplement, subjects performed their final RSE test.

Repeated-sprint exercise test.

The first visit to the laboratory for all subjects was to allow familiarisation to sprinting on the NMT. The procedures for this session were as described in the general methods section of this thesis. In their subsequent visits subjects performed the warm-up (given in the general methods) followed by the RSE test (10×6 -s sprint, on 40 s). After the warm-up, subjects were given a 3-min recovery before commencing the RSE test. Heart rate data were collected throughout the test and ear-lobe capillary blood samples were taken for determination of [La], 4 and 6 min into the post-exercise rest-period. The average of these values was taken as the peak, post-exercise [La]. The procedures for

analysis of HR and [La] were as described in the general methods section. After the final sprint, subjects dismounted the treadmill and sat quietly for the following 6 min.

Supplementation protocol

In accordance with recent recommendations (Green *et al.*, 1996b; Steenge *et al.*, 1998; Preen *et al.*, 2003), creatine monohydrate powder prepared in a mixture with simple carbohydrates (Sports Food PSP11, Science in Sport, Blackburn, UK). The daily dosage of creatine monohydrate ($0.3 \text{ g.kg of body mass}^{-1}$; Hultman *et al.*, 1996, Syrotuik and Bell, 2004) was mixed in a sealable container with CHO powder to make up a total mass of 80 g. For the placebo condition, only 80 -g CHO were given to the subjects for each daily dose. Six containers, representing the required powder for six days, were given to subjects along with the guidelines for the supplementation procedure. Specifically, subjects were instructed to take the daily doses spread equally on four occasions throughout the day at breakfast, lunch, mid-afternoon and evening time. It was previously established that six level teaspoons gave the required 20 g powder per dose and subjects were given such a spoon with their supplementation instructions. They were also instructed to consume any additional powder remaining in the container for the last of each day's dose. Subjects were asked to mix this powder in a drink bottle with 400 ml of water at room-temperature and consume straight after preparation of the drink. Subjects were advised that both supplementation regimes represented around 1200 kJ additional daily energy intake but they were not instructed to alter their diets.

Data analysis

Statistical analyses were performed using Microsoft Excel and SPSS version 12.0. Dependent *t*-tests were performed on the difference between pre- and post-supplementation RSE tests for the measures of RSE test performance and fatigue, as defined in the general methods section. One-way repeated measures ANOVA was performed on the peak [La] and HR data. For all analyses, significance was accepted at $P < 0.05$. All results are expressed as mean \pm s for 11 subjects, unless stated otherwise.

Results

The Cr supplementation period elicited a mean increase in body mass of $0.94 \pm 1.04 \text{ kg}$. The placebo supplementation also elicited an increased body mass of $0.55 \pm 0.52 \text{ kg}$.

The Cr supplementation period did not elicit any significant difference in body mass compared to the placebo condition ($P = 0.36$).

Repeated-sprint test performance

For repeated-sprint test performance there were no differences in the change in performance due to Cr supplementation for any of the performance variables ($P > 0.05$) (Table 27). Similarly, the decrement of performance was not influenced by Cr supplementation for any of the performance variables ($P > 0.05$).

Table 27. Repeated-sprint test performance variables before ('pre') and after ('post') 6 days of supplementation with either creatine or placebo.

Variable	Group	'Pre'	'Post'
MxSp (m.s ⁻¹)	Creatine	7.41 ± 0.32	7.46 ± 0.30
	Placebo	7.28 ± 0.34	7.37 ± 0.31
AvSp (m.s ⁻¹)	Creatine	6.39 ± 0.27	6.42 ± 0.28
	Placebo	6.24 ± 0.23	6.27 ± 0.23
AvPO (W)	Creatine	516 ± 39	519 ± 48
	Placebo	503 ± 56	512 ± 48

Physiological responses to repeated-sprint tests

There were no significant differences in any of the physiological responses to the four RSE tests ($P > 0.05$) (Table 28).

Table 28. Physiological measures taken from repeated-sprint testing before ('pre') and after ('post') 6 days of supplementation with either creatine or placebo.

Variable	Group	'Pre'	'Post'
Post-exercise peak [La] (mmol.l ⁻¹)	Creatine	10.8 ± 3.2	10.1 ± 3.1
	Placebo	10.2 ± 3.1	10.1 ± 3.2
Mean HR in RSE test (beats.min ⁻¹) (n = 9)	Creatine	174 ± 11	174 ± 11
	Placebo	172 ± 9	170 ± 8
HR recovery index (s) (n = 9)	Creatine	5.4 ± 2.8	5.1 ± 3.3
	Placebo	4.5 ± 1.8	5.6 ± 2.0

Discussion

The aim of this study was to investigate whether a 6 -day period of Cr supplementation would influence repeated-sprint performance on an NMT. The Cr supplementation period did not elicit any adaptations that were different from those experienced by subjects in the placebo condition. There were no changes in performance either due to the placebo or Cr supplementation condition. The physiological responses to the test were also unaffected by the Cr supplementation.

Only one study has previously investigated the effect of Cr supplementation on repeated sprint performance from NMT sprinting (Bogdanis *et al.*, 1996a). The majority of research in has shown that Cr supplementation increases repeated-sprint performance in a range of exercise modes (Mesa *et al.*, 2002; Bird, 2003), including running (Aaserud *et al.*, 1998; Skare *et al.*, 2001; Cox *et al.*, 2002). Of the previous repeated-sprint investigations to have shown that Cr supplementation does not affect performance (See Table 7), only three used procedures that were typical of most RSE test protocols and which are broadly similar to the procedures of the present study (Delecluse *et al.*, 2003; Kinugasa *et al.*, 2004; Ahmun *et al.*, 2005). Both Delecluse *et al.* (2003) and Ahmun *et al.* (2005) demonstrated that Cr supplementation had caused a trend towards improvements which would have represented beneficial performance gains but the extent of those changes was not enough to be statistically significant. In the present study there was no evidence of a trend towards improved performance in the Cr condition.

A number of factors could be used to explain the absence of an effect from Cr supplementation in the present study. Previous authors have suggested that issues such as experimental design, supplementation protocol, the subjects' training status and the Cr-induced increase in body mass could all be factors that influence the effectiveness of Cr supplementation (Mujika and Padilla, 1997; Lemon, 2002; Mesa *et al.*, 2002).

For the present study, the experimental design and the supplementation protocol were in accordance with recent recommendations for Cr supplementation studies (Lemon, 2002; Preen *et al.*, 2003) in terms of subject numbers, wash-out period and the use of a cross-over design. The discrepancy between the results of the present study and those of Bogdanis *et al.* (1996a) could be attributed to the lack of a cross-over design in their study or due to the use of a longer sprint duration (10 s), one which exceeds that used in most RSE test research. Additionally, their findings only showed significant differences in the final sprint of their trial. Using RSE testing, the mean performance through a series of sprints is usually considered, as opposed to performance in individual sprints. Confirmation of the effectiveness of the Cr supplementation can be gleaned from the gain in body mass that was experienced by the subjects in the Cr condition. Although the mean increase in body mass (0.9 kg) was not significantly greater than that found in the placebo group (0.5 kg), the Cr group experienced a typical increase in mass for such a study (Yquel *et al.*, 2002; Van Loon *et al.*, 2003). It has previously been shown that the Cr-induced increase in body mass is achieved even in subjects who do not respond to Cr loading with an increase in exercise performance (Syrotuik and Bell, 2004). The use of a cross-over design should have also overcome other potential weaknesses of previous Cr supplementation such as the potential placebo-effect, order of testing and between-group variability.

The increase in body mass that was experienced, especially in the Cr condition of the present study, could have been detrimental to performance on the NMT. It has previously been suggested that it may be more difficult to establish ergogenic effects from Cr loading in weight-bearing activities like running (Mesa *et al.*, 2002). However, an overall view of the experimental findings from this area (see Tables 6 and 7) would not necessarily support that view. Using a NMT for steady-speed running, Lakomy (1987) compared the performance of subjects with high and low body mass. This investigation showed that less force was needed for a subject of high body mass to

move the treadmill belt, compared to one of low body mass. While it is accepted that a comparison of subjects with different body mass may not be applicable to the situation in the present study where the subjects' body masses were altered, this evidence at least fails to support the possibility that increased body mass hinders NMT-RSE performance. Therefore, the slightly elevated body mass attributed to Cr supplementation is unlikely to be associated with a detrimental effect on performance using the NMT.

A criticism of the Cr supplementation literature has been that its findings may have limited implications for the use of highly-trained subjects (Mujika and Padilla, 1997). Since the publication of their work, a number of studies have demonstrated the ergogenic effect of Cr supplementation in highly-trained subjects (Kreider *et al.*, 1998; Cox *et al.*, 2002; Izquierdo *et al.*, 2002). However, it is noteworthy that among the Cr loading studies which did not show an ergogenic effect, but used procedures that are typical of the RSE literature, two of the three studies used highly-trained subjects (Delecluse *et al.*, 2003, Ahmun *et al.*, 2005). For the present study, no formal indications of the subjects' training status were taken but they were all chronically active sports students who had achieved a minimum of county-level representative status in their chosen sport. Their performance on the RSE test (overall mean $MxSp = 7.38 \text{ m}\cdot\text{s}^{-1}$) was higher than the best equivalent (maximum 1 -s velocity) result in the literature ($7.12 \text{ m}\cdot\text{s}^{-1}$) (Lakomy, 1987) and superior to the equivalent values for the other studies of this thesis. It is possible, therefore, that the relatively high level of fitness seen with the subjects in the present study may have contributed to the lack of ergogenic effect.

In conclusion, creatine supplementation does not appear to influence the performance of NMT-RSE using the present procedures. Therefore the null hypothesis for the present study is accepted. While this finding is in opposition to the majority of Cr supplementation studies, these findings are not without precedent in the repeated-sprints literature. Indeed, two of the most recent RSE studies have shown no effect from a period of Cr supplementation (Ahmun *et al.*, 2005; Glaister *et al.*, 2006). The results of this study offer little explanation for the lack of effect from Cr loading. An implication of these findings is that NMT-RSE may not be sufficiently sensitive to detect the improvement in performance induced by Cr supplementation. Alternatively, Cr

supplementation in relatively well-trained game-sport players is not effective at improving repeated-sprint performance with the procedures used in the present study.

CHAPTER 9. SYNTHESIS OF FINDINGS

Background

The ability to perform repeated bouts of short-duration, high-intensity exercise is a requirement of many sports. Understanding the physiological requirements of RSE is, therefore vital for the preparation of competitors in sports where high-intensity exercise is interspersed with rest periods. The performance of high-intensity exercise is dependent on high strength, power and use of the anaerobic pathways of energy metabolism. In contrast, the ability to recover after bouts of high intensity exercise is oxygen-dependent and has often been shown to relate to high levels of aerobic fitness (for example, $\dot{V}O_2$ max, anaerobic threshold, economy) (Bogdanis *et al.*, 1996b; Tomlin and Wenger, 2002; Chamari *et al.*, 2004). Because these contrasting processes are mutually dependent during the performance of RSE, it has been proposed (Dawson *et al.*, 1991) that the assessment of RSE fitness must involve more than merely the quantification of aerobic and anaerobic fitness in isolation and, therefore, many investigators have attempted to quantify RSE performance using test procedures which use repeated bouts of high-intensity exercise, interspersed with recovery periods.

There are many investigations into the assessment of RSE performance using repeated-sprint fitness tests (see Appendix 1) but there is no consensus as to the procedures which should be employed to meet this aim. The wide variation in the procedures that have been published so far in this area means that no normal values exist for the performance of RSE. Similarly, the evaluation of 'RSE fitness' is only possible through a series of sprints by analysis of performance variables such as running speed and its fatigue (Fitzsimons *et al.*, 1993; Glaister *et al.*, 2003). There are currently no physiological variables which have been shown to relate to RSE performance. In spite of the diverse practical applications where the ability to quantify RSE performance would be advantageous, further developments in our understanding of the physiology of RSE may be inhibited by the absence of standard procedures, along with the lack of physiological measures which relate to RSE performance.

Many previous investigators have devised their own intermittent exercise test protocols (Appendix 1) and considered them to be valid indicators of RSE performance (Balsom *et al.*, 1992a; Bishop *et al.*, 2001; Glaister *et al.*, 2003), although only one research group have made a systematic attempt to develop a procedure which was reliable, sensitive and valid for this purpose (Dawson *et al.*, 1984; Dawson *et al.*, 1991; Dawson

et al., 1993; Bishop *et al.*, 2001; Spencer *et al.*, 2004) . However, the procedure resulting from the developmental work of these authors used cycling as the mode of activity, as opposed to sprint running - the exercise that is most frequently seen in the game sports. The development of NMT systems has allowed for the laboratory-based assessment of sprint performance (Lakomy, 1987; Tong *et al.*, 2001), but NMT ergometry has rarely been used for the assessment of RSE performance (Oliver *et al.*, 2005; Ratel *et al.*, 2005) and no studies have attempted to validate an RSE test procedure specifically using an NMT system. The absence of valid, reliable and sensitive procedures to assess RSE performance using sprint-running forms the basis of the studies which are reported in this thesis.

The primary aim of this thesis was to investigate whether a valid, reliable and sensitive assessment of the ability to perform RSE could be developed using an NMT system. A secondary aim was to establish whether certain physiological indicators of recovery could be used as correlates of RSE exercise performance for game-sports competitors.

Summary of these studies

Study I of this thesis investigated the reliability of an NMT-RSE procedure. The procedure that was selected for this purpose was typical of previously-reported RSE tests that had employed either cycling (Dawson *et al.*, 1993; Gaitanos *et al.*, 1993) or over-ground running (Fitzsimons *et al.*, 1993; Aziz *et al.*, 2000) as the mode of activity. The performance of ten subjects was assessed during a 6 × (6 -s sprint, on 36 s) repeated-sprint procedure. The performance in the NMT-RSE test was assessed with measures of force, power and velocity.

There were no significant differences between the data derived from three separate trials and the various measures of reliability used to analyse the data suggested that the procedures adopted in this study were reliable, especially when velocity was used as the performance variable. The results obtained suggested that force was slightly less reliable than power and velocity. The pre-test preparation procedures adopted in study I were adequate to overcome any learning effect between the three reliability trials. Comparisons with similar investigations implied that the procedures used in this study seemed to be reliable. The only exception to the high reliability that was evident from these findings was in the results for the assessment of fatigue. The poor reliability of

fatigue measures is a finding that has already been shown in previous, similar studies (Fitzsimons *et al.*, 1993; Glaister *et al.*, 2004) and establishing reliable, valid fatigue measures during the assessment of RSE fitness remains a challenge for researchers in this subject area.

The results of the reliability study (study I) informed the later studies in a number of ways. Firstly, it was concluded that the NMT could be used as a reliable means of assessing RSE performance. Secondly, the preparation given to subjects before their first test appeared to be adequate to overcome any learning effect for the use of NMT sprinting. However, as a precaution, the novelty of using the NMT was borne in mind and, in spite of the high reliability reported in this study, it was decided that subjects in subsequent studies should experience at least one habituation visit prior to returning to the laboratory for any further testing. Finally, the rate of fatigue displayed by subjects in this protocol was low compared to similar RSE tests. To accommodate the need to use fatigue as a performance measure (Fitzsimons *et al.*, 1993; Dawson *et al.*, 1998), it was decided to increase the number of sprints from six to ten for subsequent RSE testing in this thesis.

To the author's knowledge, study I was the first to demonstrate the reliability of a repeated-sprint procedure on a non-motorised treadmill in adult males and the first whose results provided guidelines for the familiarisation of subjects undertaking such tests. The completion of this study represented the completion of the first objective of this thesis: to demonstrate the reliability of non-motorised treadmills during repeated-sprint performance.

Having established the reliability of the apparatus and of a RSE procedure, study II was performed in order to establish the effect of recovery duration of repeated sprint performance. The application of this study was that the findings would be used to make recommendations as to the most appropriate recovery duration for use in NMT-RSE testing. Subjects performed three separate tests where ten repetitions of 6 –s sprints were performed with different recovery durations. The recovery durations were chosen to represent the range of work: rest ratios commonly seen in previous RSE tests (Appendix 1). Given the fact that no physiological variables have so far been established which can be used to evaluate RSE performance, any prospective RSE test

procedure should elicit fatigue in all subjects. The demands of the test would also have to resemble the demands of performance in the game-sports.

The findings of this study were that a short-recovery procedure, where sprints were repeated every 25 s, tended to give very high rates of fatigue in comparison to previous published RSE tests. The long-recovery condition (sprints beginning every 55 s), in contrast, elicited very low rates of fatigue, thereby rendering it unsuited to the assessment of RSE performance. The moderate-recovery condition (sprints beginning every 40 s) elicited similar rates of fatigue to previously established RSE procedures and caused physiological responses which approximated to those that have been assessed in game-sports competition. This procedure (10 × (6 -s sprint, on 40 s)) was therefore adopted as the one to be used in the remaining studies of this thesis. Although previous research has investigated the effect of recovery duration on repeated sprint performance, this had not previously been performed using a range of recovery durations commonly used in repeated-sprint testing. Consequently, the findings of this study allowed completion of the second objective of this thesis: that a decision could be made regarding the most appropriate recovery duration for use in repeated-sprint performance testing with college-aged, healthy male subjects.

Studies III, IV and V were performed to address whether the NMT-RSE procedure (10 × 6 -s sprint, on 40 s) showed validity and sensitivity with respect to interventions that had been previously shown to enhance RSE performance and to address whether NMT sprinting elicited similar responses to over-ground running during equivalent RSE procedures.

In study III, game-sports competitors from a University men's hockey club participated in a training study. Participants in the study all performed their usual hockey club commitments of training and matches while half of the group performed an additional repeated-sprint training programme twice a week for 7 weeks. Subjects were assessed for their NMT-RSE performance and $\dot{V}O_{2\max}$ before and after the period of the experiment. The combined data from both groups showed that subjects improved their mean $\dot{V}O_{2\max}$ and NMT-RSE performance although no differences were seen within either group in isolation. The findings from this study therefore demonstrated that the NMT-RSE procedure showed construct validity in that improved $\dot{V}O_{2\max}$ in the combined group data was accompanied by improved RSE performance.

Study III was also important in addressing the issue of whether there were physiological measurements that could be made to reinforce the performance-based assessment of the ability to perform RSE. As the control group data from the training study did not differ from the experimental group, combined group data were considered and the only physiological measurement (from $\dot{V}O_2$ off-kinetics, HR recovery index, mean $\dot{V}O_2$ and HR in the test and post-exercise [La]) to be altered with the improved RSE performance was post-exercise [La]. Consequently, the use of $\dot{V}O_2$ off-kinetics and HR recovery as potential physiological indicators of the ability to perform RSE was not supported by the results of this study. This informed the procedures of studies IV and V in that no measurements of $\dot{V}O_2$ during the NMT-RSE tests were taken in those studies.

In study IV the field-test procedure used to compare with the NMT-RSE protocol ($10 \times (6 \text{ s sprint, on } 40 \text{ s})$) was $10 \times (40 \text{ -m sprint, on } 40 \text{ s})$. The 40 -m sprint distance had previously been shown in pilot work to take around 6 s for subjects from this population of college-aged, healthy male subjects. This study was the first to compare both the performance and physiological responses to RSE performance between the NMT and over-ground sprinting. The findings demonstrated that velocity results from the NMT-RSE procedure were highly correlated to those obtained from over-ground running, but this relationship was not evident when power was taken as the dependent variable. Lower sprint velocities were produced by subjects on the NMT and this was attributed to the greater inertia characteristics of the treadmill, in comparison to over-ground running. There were high correlations between the mean HR and post-exercise [La] from field tests and laboratory tests and there was no effect of test-type on the post-exercise [La] response. The similarities between the laboratory and field-test procedures for both physiological and performance measurements show the validity of NMT sprinting in comparison with over-ground sprinting. However, caution should be exercised when using power output from the NMT to infer about over-ground running speed.

Creatine monohydrate ('creatine') supplementation was used as an intervention to expand the investigation of the validity and sensitivity of the NMT-RSE procedure to detect changes in RSE performance. The purpose of this study was to investigate whether a short-term intervention could also elicit improved performance on the RSE test. Supplementation of creatine has frequently been shown to enhance RSE

performance (Mesa *et al.*, 2002; Bembem and Lamont, 2005) but this had not been investigated using NMT sprinting.

The findings of study V were that creatine supplementation had no effect on RSE performance. Although the majority of creatine supplementation studies do show an ergogenic effect on the performance of RSE (see Tables 6 & 7), the literature is not unequivocal in this issue. It remains unclear whether the absence of an ergogenic effect from Cr supplementation is attributable to an inability of the NMT-RSE procedure to detect improved performance or to a failure of creatine supplementation to consistently improve repeated sprint performance. While these findings do not add inference to the view that the NMT-RSE test is sensitive and shows construct validity, neither do they detract from this claim.

The large number of subjects who have been tested altogether in these studies, allowed for additional analyses, beyond those considered in each individual study, to be carried out. By taking data on a cohort of subjects ($n=22$) who were participants in studies III, IV and V further information of relevance to the aims of this study were be gained. The outcomes from this analysis are given in Appendix 2. In summary, further confirmation is given that the 'HR recovery index' proposed in this thesis was not related to any performance characteristics (i.e., maxima and averages for velocity and power or the decrement derived from velocity or power). Additionally power output in NMT sprinting, whether expressed in W or in $W \cdot kg^{-1}$ did not relate strongly with measures of RSE velocity. The only significant correlation for power output was between 6 -s averages of velocity and power (W) ($r = 0.43$; $P < 0.05$).

The primary aim of these studies was to investigate whether a valid, reliable and sensitive assessment of the ability to perform repeated sprints could be developed using a non-motorised treadmill system. The collective outcomes from the studies presented here suggest that the procedures used in this thesis were reliable and generally showed validity. Validity was demonstrated by the physiological and performance responses that were elicited in RSE test (10 x 6 -s sprint, on 40 s) and by the relationships that were observed between over-ground, compared to treadmill, running. Validity and, to an extent, sensitivity were also demonstrated in study III by the fact that improved aerobic fitness was accompanied by improved RSE performance. However, the sensitivity of the procedure may need further investigation as the training group of study

III did not show superior adaptations in performance compared to the remaining subjects in that study. The use of creatine supplementation as the short term intervention with which to further investigate construct validity led to inconclusive results. The failure of the supplementation period to improve RSE performance could be explained by the fact that a minority of creatine studies have not observed improved RSE performance.

The secondary aim of these studies was to investigate whether physiological measures of the recovery rates of HR and $\dot{V}O_2$ from RSE trials could be used as indicators of RSE performance. However, neither of these variables was shown to be affected in the training period of study III and the $\dot{V}O_2$ -off kinetics were also unaffected by recovery duration in the results of study II. The HR recovery index was shown to not relate to any performance variable in the additional analyses displayed in Appendix 2. Further work is necessary to investigate whether it may be possible to relate the ability to perform RSE with physiological measures, however, the two measures suggested in this thesis would appear to be unsuited as physiological correlates of RSE performance.

Applications of the findings of these studies.

The studies reported in this thesis represent the first attempt to develop an NMT-RSE test and investigate its reliability, sensitivity and validity. It is hoped that future researchers who wish to assess the RSE performance of college-aged, healthy male subjects will adopt the 10 × (6 -s sprint, on 40 s) procedure that has been developed in this thesis. This procedure has been shown by the outcomes of these studies to be reliable and valid. The literature on the physiology of RSE currently shows a wide array of test procedures for the assessment of RSE performance (see Appendix 1). The fact that manipulation of each test-protocol variable has previously been shown to alter RSE performance (Dawson *et al.*, 1991; Balsom *et al.*, 1992a; Holmyard *et al.*, 1994; Ratel *et al.*, 2004) demonstrates the need for standardisation in these protocols, especially when it is appreciated that the only way to assess this component of fitness is from performance-based measures, such as velocity, power and the fatigue of power or velocity across a series of sprints (Fitzsimons *et al.*, 1993; Dawson *et al.*, 1998).

Throughout these studies, a range of performance variables has been reported and analysed. In study I it was established that measures of velocity were the most reliable,

while results of force tended to be the least reliable. Additionally, because force measures are incorporated into power calculations, in the interests of conciseness later studies used only velocity and power measures. In study IV, it was shown that the NMT-derived assessment of average power did not relate to over-ground sprint speed and overall analysis from a larger group of subjects from studies III, IV and V combined (see Appendix 2) also showed that power was not strongly related to treadmill running velocity. The value of using NMT power may be questioned on this evidence if the test results are being applied to sprinting. Resulting from these findings, future researchers may choose to concentrate on the interpretation of performance from velocity measures, as opposed to those from power or force, when the subjects are game-sports players who are most interested in applying their findings to their sprint-running velocity.

Distinctions were made earlier in this thesis between fitness assessments which attempt to replicate the performance of a specific sport and more general assessments of the ability to perform repeated sprint exercise. The NMT-RSE test of this thesis is not an attempt to replicate the demands of a specific sport and its use should reflect the more generic applications which are therefore implied. An analogy may be drawn with the use $\dot{V}O_{2\max}$ testing in the assessment of endurance performance. For example, a $\dot{V}O_{2\max}$ test result is useful to give an indication of the general capacity of the cardiovascular system but is not necessarily proportional to the level of performance in an endurance activity (Coyle, 1995). In the same way, the NMT-RSE procedure of these studies is likely to be most useful in indicating the general capacity to recover from high-intensity exercise, without necessarily being a predictor of performance in a specific sport. In this respect, the NMT-RSE test of this thesis should be seen as a procedure to reflect the general ability to perform RSE. The current lack of standardised procedures for this purpose should mean that its development helps to advance our understanding of the physiology of RSE performance.

Although the purpose of this thesis was to develop a test to use on the NMT, it appears that similarities exist between the responses to the NMT-RSE test and an equivalent over-ground sprinting procedure. The implication of this finding is that researchers and practitioners who do not have access to NMT apparatus could adopt the field test procedures used in the present study in order to perform a test that gave related results to the laboratory-based, NMT procedure.

Limitations to these studies

The findings of these studies are likely to be limited to the population of college-aged, healthy male subjects used in this thesis. While standardisation of procedures should be a goal for future researchers in the area of RSE testing, the requirement for the procedure to elicit fatigue may warrant slight modification of the procedure used in studies III, IV and V if testing is to be carried out on subject groups with contrasting gender, age and training status.

There are currently a large number of RSE test procedures that have been published and very few attempts have been made to relate their findings with performance characteristics during game-sports competition. A limitation of the procedures in this thesis and of the majority of the previously-published tests is that the relationship between test-performance and competitive characteristics has not been established. Although this is acknowledged as a limitation of the work in this thesis, the same is true of many other similar investigations which have proposed RSE test procedures without consideration of the key issues of reliability, sensitivity and validity that have been addressed in these studies. To the author's knowledge the present studies are the first attempt to address the issues of reliability, validity and sensitivity for a RSE test procedure that employs sprint-running as the exercise mode.

It is not always possible to ensure that subjects are equally prepared or motivated for a RSE performance test. Any discrepancies in preparation or motivation may affect the interpretation of any data obtained in such experiments. Therefore, a limitation in any high-intensity performance testing is that equivalent levels of motivation and preparation may not be achieved. In the present studies it is accepted that this may have been a possibility but the reliability of the procedure demonstrated in study I, the use of a separate familiarisation session prior to any test-visits, the favourable results of subjects in these studies compared to previously published work and similarities between physiological and performance variables where test-retest was used suggest that these factors may have played little part in the studies presented in this thesis.

Future research

The area of research into the physiology of RSE performance is still in its formative stages. This is partly due to the wide variety of procedures that have been adopted in the studies that have already been performed in this area. Future research needs to use standardised procedures in order that comparisons can be made across studies: a situation which is currently impossible. With standard procedures, it will be possible to establish normal values, thereby enabling the interpretation of RSE fitness from test results.

Referring to the RSE test procedure itself, further work is necessary to develop reliable techniques to assess the rate of fatigue across a series of sprints. Because the combination of fatigue and peak performance probably represents the minimum number of test-outcomes that can be used to describe test performance, it is essential that reliable procedures for establishing the rate of fatigue are developed.

With the development of reliable procedures and standard scores, the NMT-RSE test can then be used to address a range of key questions including:-

What is the most effective training to enhance RSE fitness?

How does aerobic fitness relate to RSE fitness?

How do NMT-RSE results relate to match performance in game-sports competition?

It is also essential that more mechanistic work is performed to provide an insight into the physiological factors that limit RSE performance. The attempts in this thesis have shown that cardiovascular and respiratory measurements are probably too general to be predictors of RSE fitness. If the findings of this thesis are only to be applied to the fitness assessment of sports performers, then the use of more invasive measures is probably not feasible. By application of the same logic that led to the use of $\dot{V}O_2$ -off kinetics in the present work, the use of NIRS may have some value as an indicator of muscle metabolism (Behnke *et al.*, 2005).

Conclusion

In summary, the findings of this thesis support the use of NMT procedures for the assessment of RSE performance. The reliability of the NMT for RSE testing was high when the familiarisation protocol and data analysis of this thesis were adopted. A 10 × (6 –s sprint, on 40 s) procedure was shown to demonstrate content and construct validity and was shown to be sensitive to improved aerobic fitness. The assessment of velocity measures, as opposed to power, is advised when future investigators intend to apply their findings to RSE in over-ground running. It is recommended that future researchers in this area adopt standardised procedures like those proposed here and that there is a continued quest to establish physiological variables which may be predictive of RSE performance.

Table 29. Summary of the findings of the studies in this thesis.

Study / Procedure	Main findings	Implications
<p>Study I - The reliability of an NMT-RSE procedure. -6×6 -s sprint, on 36 s</p>	<ul style="list-style-type: none"> • Use of velocity and power measures gives reliable results using the procedures adopted in this study. • Expressing any of the performance measures as a fatigue index leads to unreliable results. • This procedure elicited low rates of fatigue and this may limit its value due to the need to elicit fatigue in RSE testing. 	<ul style="list-style-type: none"> • The habituation and data processing in the present procedures provide reliable results for NMT-RSE testing. • The use of ten sprints, as opposed to six is recommended to increase fatigue through the RSE test.
<p>Study II - The influence of recovery duration on NMT-RSE. -10×6 -s sprints, on either 25, 40 or 55 s</p>	<ul style="list-style-type: none"> • The moderate recovery condition elicited the performance and physiological responses that make it most suited for subsequent adoption as the repeated sprint performance test for this thesis. • Unlike HR recovery, $\dot{V}O_2$ -off kinetics and [La] are unaffected by manipulations of recovery duration. 	<ul style="list-style-type: none"> • The $10 \times (6$ s sprint, on 40 s) test should be adopted as the procedure for further investigation of the validity and sensitivity of NMT-RSE performance.
<p>Study III - The influence of training on NMT-RSE performance. -10×6 -s sprints, on 40 s</p>	<ul style="list-style-type: none"> • The greater fitness levels of the subjects after the training period was evidenced by increased $\dot{V}O_{2\text{ max}}$ and improved RSE performance. • Improvements in NMT-RSE test velocity measures were not matched by increased power. • There were no changes in $\dot{V}O_2$ -off kinetics or HR recovery despite improved RSE performance and aerobic fitness. 	<ul style="list-style-type: none"> • The NMT-RSE test is sensitive to the improved RSE fitness which is achieved after a period of game-sports training. • Power and velocity on the NMT may not be equivalent. • Measurement of $\dot{V}O_2$ -off kinetics or HR recovery may not provide physiological indices of RSE performance.

Contd..!

Table 29 (Contd.). Summary of the findings of the studies in this thesis.

Study / Procedure	Main findings	Implications
<p>Study IV – The comparison of NMT and field-test RSE performance.</p> <p><i>-10 × 6 –s sprint or 40 -m sprint, on 40 s</i></p>	<ul style="list-style-type: none"> • The physiological and performance responses to field-testing are related to those from NMT testing • Power on the NMT may be unrelated to over-ground running velocity in these procedures. • Velocity measures on the NMT are generally lower than those from NMT sprinting. 	<ul style="list-style-type: none"> • Velocity results between the two test-types are different, yet related. • Power on the NMT and field-test sprint velocity are not related. • The physiological stress of the two test-types is similar.
<p>Study V – The influence of creatine loading on NMT-RSE performance.</p> <p><i>-10 × 6 –s sprints, on 40 s</i></p>	<ul style="list-style-type: none"> • The period of creatine loading did not elicit any changes in NMT-RSE performance 	<ul style="list-style-type: none"> • This procedure may be unable to detect the effects of creatine loading on RSE performance.
<p>Additional analyses (Appendix 2).</p> <p><i>Data collated from a group of 22 subjects (from studies III, IV and V)</i></p>	<ul style="list-style-type: none"> • HR recovery is not related to any RSE-test performance measures • Power output is not strongly correlated with running velocity on the NMT 	<ul style="list-style-type: none"> • HR recovery should not be considered to be a physiological correlate of RSE performance. • Power and velocity on the NMT are not necessarily related.

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APPENDIX 1 - REPEATED-SPRINT EXERCISE (RSE) TESTS

Specifically for the purposes of this thesis, an RSE test has been defined as a procedure requiring the repeated performance of all-out exercise bouts of a short exercise duration within the following constraints:-

Exercise duration 2 – 15 s
 Number of repetitions 5 – 20
 Work : rest ratio 1:2 – 1:15

Investigation	Mode	Procedures	Reps	Duration	Work : rest
Dawson <i>et al.</i> (1984)	F /t sprint	20 × (7 -s sprint, on 30 s)	20	7	1:3.3
Wadley and LeRossignol, (1998)	F /t sprint	12 × (20 -m sprint, on ~ 20 s)	12	*3	1:5.7*
Dawson <i>et al.</i> (1991)	F /t sprint	8 × (7 -s sprint, on 30 s)	8	7	1:3.3
Aziz <i>et al.</i> (2000)	F /t sprint	8 × (40 -m sprint, 30 -s recovery)	8	6*	1:5*
Mujika <i>et al.</i> (2000)	F /t sprint	6 × (15 -m sprint, 30 -s recovery)	6	2	1:15
Paton <i>et al.</i> (2001)	F /t sprint	10 × (20 -m sprint, on 10 s)	10	3*	1: 2.5*
Dupont <i>et al.</i> (2005)	F /t sprint	15 × (40 -m sprint, 25 -s recovery)	15	6*	1:4*
Fitzsimons <i>et al.</i> (1993)	Cycle ergometer	6 × (6 -s sprint, on 30 s)	6	6	1:4
	F/t sprint	6 × (40 -m sprint, on 30 s)	6	6*	1:4*

Dawson <i>et al.</i> (1993)	Cycle ergometer	6 × (6 -s sprint, on 30 s)	6	6	1:4
	F/t sprint	6 × (40 -m sprint, on 30 s)	6	6*	1:4*
Ahmun <i>et al.</i> (2005)	Cycle ergometer	10 × (6 -s sprint, on 30 s)	10	6	1:4
	F/t sprint	10 × (40 -m sprint, on 30 s)	10	6*	1:4*
Balsom <i>et al.</i> (1993a)	Cycle ergometer	10 × (6 -s sprint, on 36 s)	10	6	1:5
Dawson <i>et al.</i> (1993)	Cycle ergometer	5 × (6 -s sprint, on 30 s)	6	6	1:4
Gaitanos <i>et al.</i> (1993)	Cycle ergometer	10 × (6 -s sprint, on 36 s)	10	6	1:5
Signorile <i>et al.</i> (1993)	Cycle ergometer	10 × (10 -s sprint, on 60 s)	10	10	1:5
Balsom <i>et al.</i> (1994b)	Cycle ergometer	10 × (6 -s sprint, on 36 s)	10	6	1:5
Jenkins <i>et al.</i> (1994)	Cycle ergometer	10 × (6 -s sprint, on 30 s)	10	6	1:4
Nevill <i>et al.</i> (1994)	Cycle ergometer	10 × (6 -s sprint, on 36 s)	10	6	1:5
McMahon and Wenger (1998)	Cycle ergometer	6 × (15 -s sprint: 90 -s active recovery)	6	15	1:6
Heller and Psotta (1999)	Cycle ergometer	10 × (5 -s sprint, on 35 s)	10	5	1:6
Capriotti <i>et al.</i> (1999)	Cycle ergometer	10 × (7 -s sprint, on 37 s)	10	7	1:4.3
Ortenblad <i>et al.</i> (2000)	Cycle ergometer	10 × (8 -s sprint, on 38 s)	10	8	1:4
Bishop <i>et al.</i> (2001)	Cycle ergometer	5 × (6 -s sprint, on 30 s)	5	6	1:4

Ratel <i>et al.</i> (2002)	Cycle ergometer	10 × (10 -s sprint:variable recovery) 30, 60, 300 s	10	10	10	See left
Tomlin and Wenger (2002)	Cycle ergometer	10 × (6 -s sprint, on 36 s)	10	6	1:5	
Glaister <i>et al.</i> (2003)	Cycle ergometer	20 × (5 -s sprint, on 15 s)	20	5	1:2	
	Cycle ergometer	20 × (5 -s sprint, on 35 s)	20	5	1:6	
Bishop and Spencer (2004)	Cycle ergometer	5 × (6 -s sprint, on 30 s)	5	6	1:4	
Bishop <i>et al.</i> (2004b)	Cycle ergometer	5 × (6 -s sprint, on 30 s)	5	6	1:4	
Bishop <i>et al.</i> (2004a)	Cycle ergometer	5 × (6 -s sprint, on 30 s)	5	6	1:4	
Kinugasa <i>et al.</i> (2004)	Cycle ergometer	10 × (6 -s sprint, on 36 s)	10	6	1:5	
Spencer <i>et al.</i> (2004)	Cycle ergometer	5 × (6 -s sprint, on 30 s)	5	6	1:4	
Holmyard <i>et al.</i> (1988)	NMT	10 × (6 -s sprint, on 36 s)	10	6	1:5	
	NMT	10 × (6 -s sprint, on 66 s)	10	6	1:10	
Brooks <i>et al.</i> (1990)	NMT	10 × (6 -s sprint, on 36 s)	10	6	1:5	
Hamilton <i>et al.</i> (1991)	NMT	10 × (6 -s sprint, on 36 s)	10	6	1:5	
Nevill <i>et al.</i> (1994)	NMT	10 × (6 -s sprint, on 36 s)	10	6	1:5	
Ratel <i>et al.</i> (2004)	Cycle ergometer & NMT	10 × (10 -s sprint on 25 s)	10	10	1:1.5	
Oliver <i>et al.</i> (2005)	NMT	7 × (5 -s sprint, on 25 s)	7	5	1:4	

Abbreviations used: 'F /t sprint' – field test sprinting, 'Work : rest' – work : rest ratio, 'reps' – repetitions, '*' denotes approximate timing.

APPENDIX 2 – ADDITIONAL DATA ANALYSES

In order to more fully investigate associations among the data that have been collected in the course of the studies in this thesis, additional analyses were performed on the key physiological and performance variables that were collected throughout the studies. These analyses mainly took the form of a series of Pearson’s product moment correlation calculations. Specifically, the purpose of these analyses were twofold; firstly to further investigate the relationship between heart rate recovery and the repeated-sprint test performance variables and secondly to investigate the correlations among performance variables. The results from 22 different subjects were taken from their first RSE trial from data collected in studies III, IV and V. Because many subjects participated in both studies IV and V and because some of those subjects were also participants in study III, the ‘*n*’ value for this analysis was lower than the sum of the ‘*n*’ values for each of these studies in isolation. The mean characteristics of these subjects are given in Appendix 2 – Table 1. Statistical significance for these correlations was accepted at $P < 0.05$ but where P was less than 0.01 or 0.001, this was also highlighted (see Appendix 2 – Table 2). The abbreviations used below were defined in the main text.

Appendix 2 – Table 1. Mean \pm *s* of the variables used in these analyses.

MxSp ($m.s^{-1}$)	Decrement of MxSp (%)	AvSp ($m.s^{-1}$)	Decrement of AvSp (%)	AvPO (W)	AvPO ($W.kg^{-1}$)	Decrement of AvPO (%)	HR recovery ($beats.min^{-1}$)
7.06 \pm 0.43	3.66 \pm 1.58	6.05 \pm 0.37	3.83 \pm 1.77	523 \pm 43	7.05 \pm 0.90	10.8 \pm 3.9	7.41 \pm 2.69

Appendix 2 – Table 2. Correlation matrix for the variables used in these analyses.

	Body mass (kg)	MxSp (m.s ⁻¹)	Decrement of MxSp (%)	AvSp (m.s ⁻¹)	Decrement of AvSp (%)	AvPO (W)	AvPO (W.kg ⁻¹)	Decrement of AvPO (%)
Body mass (kg)								
MxSp (m.s ⁻¹)	-0.03							
Decrement of MxSp (m.s ⁻¹)	-0.22	-0.22						
AvSp (m.s ⁻¹)	0.09	0.92 ^{***}	-0.28					
Decrement of AvSp (%)	-0.20	-0.10	0.65 ^{**}	-0.05				
AvPO (W)	0.56 ^{**}	0.42	-0.11	0.43 [*]	-0.35			
AvPO (W.kg ⁻¹)	-0.82 [*]	0.27	0.24	0.14	0.03	0.00		
Decrement of AvPO (%)	0.02	0.37	0.11	0.42	0.17	0.08	0.06	
HR recovery (beats.min ⁻¹)	-0.23	-0.35	0.10	-0.38	-0.04	-0.31	0.09	-0.42

*** - denotes statistical significance at $P < 0.001$, ** , denotes significance at $P < 0.01$, * denotes significance at $P < 0.05$.

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