Short Title: The physiological assessment of elite athletes

Long Title: The reliability and validity of gas exchange kinetics, maximal aerobic power, anaerobic threshold and sport specific protocols as determinants of fitness in elite athletes.

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Contents

Abstract

The aim of this research was to produce reliable and valid new fitness assessments utilising both gas exchange kinetics and sport specific field testing for the determination of fitness in elite athletic groups. A series of studies were conducted on both track runners and soccer players to examine the usefulness of maximal, submaximal and sport specific procedures. The physiological measurements utilised in this research were: gas exchange kinetics, maximum aerobic power ($\dot{V}O_2$ max), anaerobic threshold and a soccer specific fitness test. The research developed new procedures and modified existing protocols to challenge athletes appropriately in the examination of relevant athletic performance indicators. For the determination of test reliability and validity, test-retest analysis was performed and cross-sectional comparisons were made between performers of both different standards of performance and event specialisms. The submaximal gas exchange kinetics test enabled the differentiation of elite sprinters from elite endurance runners. A test-retest reliability study of that procedure revealed high test variability (measurement error range: 18 – 35%), possibly due to breath-by-breath fluctuations. The development of a mean response time through a mathematical modelling technique improved the confidence in this procedure (test – retest measurement error: 16%) and produced a single, overall, measurement to enhance the future application of the procedure for the assessment of aerobic fitness in different population groups. Nevertheless, relatively high test-retest variability remains a feature of the test. Further research examined the validity of standard laboratory and sport specific measurements in the determination of training status in professional soccer players. Maximal aerobic power was shown to be unaffected by short-term (5 weeks) changes in training status (63.3 ±5.8 $ml \cdot kg^{-1} \cdot min^{-1}$ and 62.1 ±4.9 $ml \cdot kg^{-1} \cdot min^{-1}$), questioning the relevance of this measurement to routine assessment of fitness and training status. Conversely, the soccer specific fitness test enabled the differentiation between soccer players performing at different standards where there was no difference in estimated $\dot{V}O_2$ max, however there was no relationship between $\dot{V}O_2$ max and the soccer test which questions the validity of the new field test. Nevertheless, it is possible that this result reflects a greater sensitivity of the new test to detect soccer specific differences in the fitness of soccer players. In conclusion, the research has demonstrated that gas exchange kinetics test has limited use for the identification of aerobic fitness in elite athletes. Future investigations might clarify the relationship between the soccer specific fitness test and match performance.

Introduction

Physiological assessment is an important part of the training process for athletes aspiring to achieve or maintain an elite standard of performance. Appropriately designed fitness assessment procedures provide constructive feedback about specific aspects of performance related fitness which would prove useful to gauge training intensities accurately, monitor progress and identify strengths and weaknesses.

The aim of this research was to produce reliable and valid measurements of fitness, utilising new and innovative procedures which incorporate the application of gas exchange kinetics (Edwards et al. 1999, 2000, 2001a, 2001b, 2002b, 2003a), maximal aerobic power and anaerobic threshold (Clark and Edwards 2003, Edwards et al. 2003c, Fysh et al. 1999) and sport specific fitness testing (Edwards et al. 2002a, 2003b, 2003d) in the identification of fitness in elite athletes. A prominent consideration of the research was to utilise procedures that provide constructive feedback for athletes and their coaches with minimum imposition to training routines. Therefore, practicality, validity and test re-test reliability were of great importance to the successful application of the procedures.

The fitness assessment procedures utilised in this research applied physiological principles underlying the mechanisms of both aerobic and anaerobic energy provision. The studies of oxygen uptake ($\dot{V}O_2$) and carbon dioxide output ($\dot{V}CO_2$) kinetics investigated whether low intensity dynamic exercise could reflect aerobic fitness as an alternative to maximal intensity testing (Edwards et al. 1999, 2000, 2001a, 2001b, 2003a, Fysh et al. 1999). Previous studies have shown $\dot{V}O_2$ kinetics to be faster in individuals possessing better aerobic fitness (Eβfeld et al. 1987, Hagberg et al. 1980, Hickson et al. 1978, Powers et al. 1985, Zhang et al. 1991), but there have only been a few studies where $\dot{V}O_2$ and $\dot{V}CO_2$ kinetics have been applied to sport (Fukuoka et al. 1995, 1997). This is surprising since pulmonary $\dot{V}O_2$ kinetics provides a useful non-invasive estimate of muscle $\dot{V}O_2$ kinetics (Eβfeld et al. 1991, Hoffmann et al. 1992).

Aerobic power, aerobic capacity, anaerobic power and anaerobic capacity are key physiological variables that have previously been identified as important factors in the physical capacity of a sports performer (Reilly et al. 2000). However, none of these measures in themselves accurately predicts the ability to perform a running race or prolonged intermittent exercise with alternating intensities, as performed in sports such as soccer (Bangsbo and Lindquist 1992). Consequently, an innovative and practical fitness test was developed in this research to examine the specific fitness requirements of elite athletes who in this case were professional soccer players (Edwards et al. 2002a, 2003b, 2003d).

The aims of this research were to:

1. Devise a new, low intensity procedure for the assessment of aerobic fitness utilising the principles of moderate intensity gas exchange kinetics.
2. Determine the reliability of the new procedure for the assessment of breath-by-breath responses to a pseudo-random binary sequence protocol.
3. Examine test validity for the pseudo-random binary sequence test through a cross-sectional comparison of test performances in elite endurance and sprint runners.

4. Propose a standard form of results expression for oxygen uptake responses to pseudo-random binary sequence exercise, following examination of current and new procedures.
5. Examine the validity of existing laboratory based aerobic fitness assessments to the identification of aerobic fitness in professional soccer players.
6. Determine the practical application and validity of a new sport specific through a comparison of test performances between elite and sub elite athletes.

<u>Analysis of the component parts</u>

i) Gas exchange kinetics in elite athletes

Gas exchange kinetics describes the rate of change of $\dot{V}O_2$ and $\dot{V}CO_2$ in response to the onset of exercise or to a change in work rate (Whipp and Wasserman 1972, Whipp et al. 1982). It has previously been shown that individual variations in either $\dot{V}O_2$ or $\dot{V}CO_2$ kinetics could describe aerobic fitness (Eβfeld et al. 1987, Fukuoka et al. 1995, 1997, Zhang et al. 1991) and, consequently, a reliable and valid low intensity test would have potential for both the assessment of aerobic fitness in elite athletes and also in a clinical context in patients unable to perform high intensity exercise (Massin et al. 1998, 2000).

Two studies completed as part of this research (Edwards et al. 2002b and Fysh et al. 1999) identified a significant relationship between $\dot{V}O_2$ max and $\dot{V}O_2$ kinetics. These studies demonstrated that $\dot{V}O_2$ kinetics could be used to assess cardiovascular fitness, but it seems likely that $\dot{V}O_2$ kinetics may be more indicative of other aspects of aerobic fitness than $\dot{V}O_2$ max since an R^2 of 0.46 (Edwards et al. 2002b) shows that $\dot{V}O_2$ kinetics are not solely reflective of $\dot{V}O_2$ max.

Both $\dot{V}O_2$ and $\dot{V}CO_2$ are characterised by three time related phases (Whipp et al. 1982). Phase I is the initial period, lasting ~15-20 s and covers the period in which venous blood from the active muscle has not yet reached the lungs (Whipp and Wasserman 1972). Phase II describes the period in which venous blood from the active muscle arrives at the lungs and has a lower O_2 content and higher CO_2 content than during Phase I. Consequently, phase II reflects the period of major increase in cellular respiration and lasts from about 15 s to 3 min. The phase II response was the area of interest in this research (Edwards et al. 1999, 2000, 2001a, 2001b, 2002b, 2003a) as dynamic, low intensity assessment of gas exchange kinetics offers a novel approach to the assessment of aerobic fitness. Phase III starts 3 min after exercise onset, and reflects the start of the $\dot{V}O_2$ steady state period if the work rate is below the anaerobic threshold. If the work rate is above the subject's anaerobic threshold, the rate of increase in $\dot{V}O_2$ correlates with the magnitude of the lactate increase (Whipp and Wasserman 1972, Zhang et al. 1993). Carbon dioxide output is slower to reach phase III, due to the enhanced capacity to store CO_2 in the tissues, and is consequently reached at ~4 min (Whipp et al. 1982).

A pseudo-random binary sequence exercise protocol was selected for the research (Edwards et al. 1999) as it switches between two work loads over a predefined period of time (Bennett et al. 1981, Kerlin 1974). Several identical sequences of exercise can be placed in series over the duration of the exercise test and consequently each sequence can be utilised as a repeated test measure for ensemble averaging purposes. This potentially reduces non-physiological noise associated with breath-by-breath procedures (Lamarra et al. 1987). It was anticipated that the dynamic metabolic challenges of the pseudo-random binary sequence exercise would provide a more representative test of aerobic fitness than the traditional assessment of exercise capacity (Kowalchuk and Hughson 1990) and because it is a sub-maximal test, it can be applied repeatedly with minimal imposition to the subjects (Hughson et al. 1990). This is advantageous for testing of large groups and subjects with limited available time, as assessment would require minimal laboratory contact. The pseudo-random changes in work rate were designed to reflect the Phase II response of gas exchange kinetics (Figure 1) through a series of low-intensity dynamic challenges within a single test, whereby O_2 uptake and CO_2 output at the lungs reflect the O_2 consumed by the cells and the CO_2 produced from muscle metabolism (Eβfeld et al. 1987, Hoffmann et al. 1994).

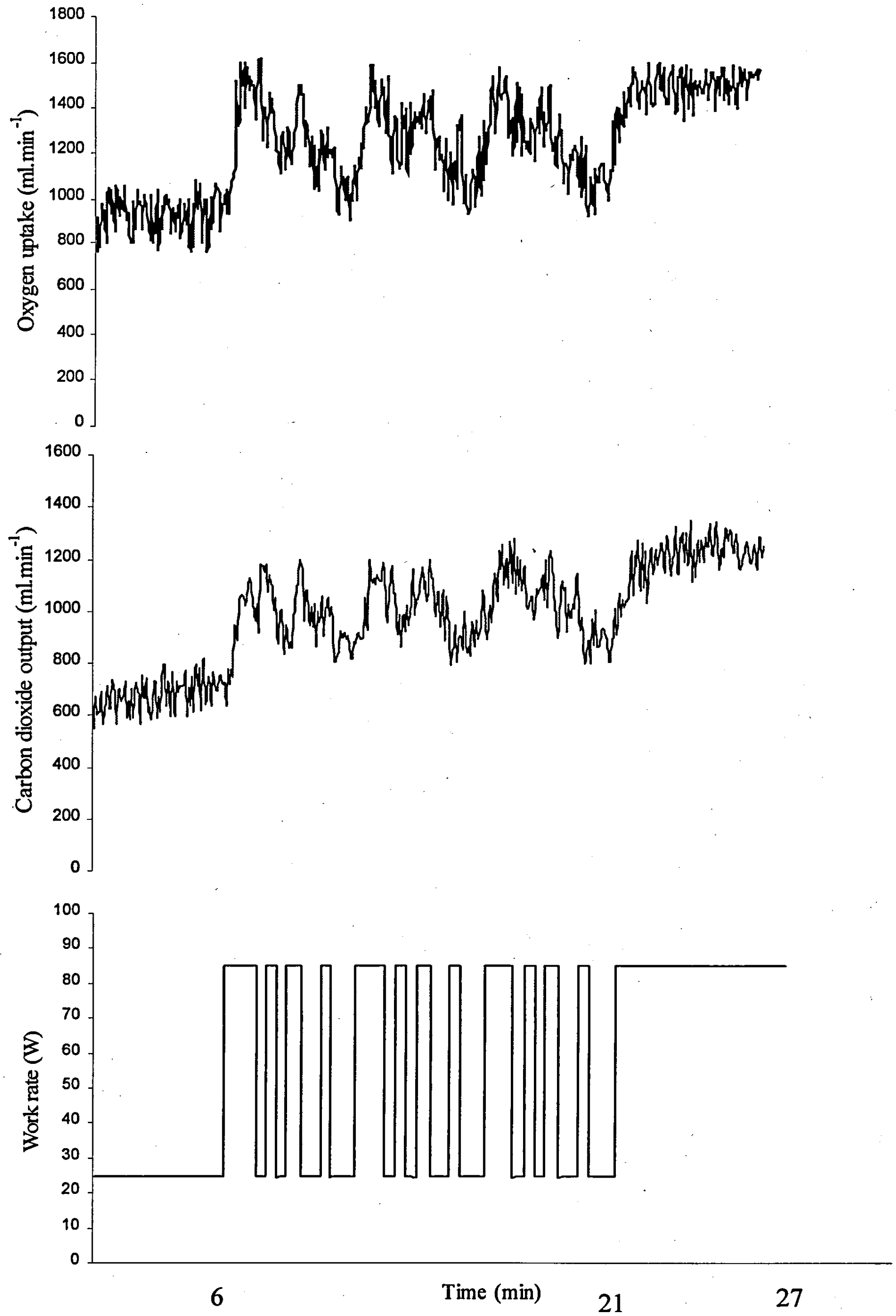

Figure 1. Breath-by-breath oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$) and work rate (25 W and 85 W) during pseudo-random binary sequence exercise for a single subject.

A standard method of analysis for multifrequent tests, such as the pseudo-random binary sequence test, is in the frequency domain by application of Fourier analysis (Eβfeld et al. 1987, 1991, Hoffmann et al. 1992, 1994). In this technique, the length of the pseudo-random binary sequence is treated as a sine wave with different composite harmonic frequencies. The lowest frequency that completes a full sine wave in the length of the pseudo-random binary sequence cycle is known as the fundamental frequency and displays the highest power output (Eβfeld et al. 1991, Hoffmann et al. 1992, 1994). As the frequencies become progressively higher, the input power (work rate power) becomes dissipated leading to progressively output power (individual gas exchange kinetics response) being retained at each frequency and thus the underlying response becomes less discernible from non-physiological background noise (Eβfeld et al. 1991, Hoffman et al. 1992, Lamarra et al. 1987).

Fourier analysis yields estimates of the response to a pseudo-random binary sequence protocol at each harmonic frequency, but the standard expression of results for multi frequent tests such as the pseudo-random binary sequence are difficult to reconcile with physiological conclusions. This is due to the method of expression within Fourier analysis according to the terms 1) amplitude ratios (the magnitude of the response) and 2) phase shift angles (the delay in the response). Although amplitude ratios and phase shift angles are calculated for each harmonic, they correspond to a frequency, which is determined by the design of the particular pseudo-random binary sequence utilised. As the construction of pseudo-random binary sequences vary according to the requirements of researchers, it is difficult to attach specific physiological conclusions to each frequency. For example, the first frequency in a 300 s protocol (15 units of 20 s) is calculated as 1/300 = 0.0033 Hz (3.3 mHz). The first frequency of a 450 s protocol (15 units of 30 s) is thus calculated as 1/450 = 0.0022 Hz (2.2 mHz). Therefore direct comparison of the output response between protocols is difficult as the frequencies representing the responses differ. As the base units are also different (20 s and 30 s respectively), each protocol examines different aspects of the dynamic response which further complicates accurate comparisons.

In the first study of this research (Edwards et al. 1999), standard Fourier analysis was applied for the expression of $\dot{V}O_2$ kinetics. That study provided evidence that the 300 s pseudo-random binary sequence exercise test could be used to elicit significantly faster gas exchange kinetics in elite endurance runners compared with elite sprinters. However, this finding was not of statistical significance at each harmonic frequency measured and the physiological implications of this observation remain unclear, although it is most likely related to the progressive decline in input power at the higher frequencies.

It was expected that the elite endurance runners would display faster $\dot{V}O_2$kinetics that the elite sprinters as there are many characteristic physiological differences between these groups (Andersen and Henriksson 1977, Bergh et al. 1978, Bernus et al. 1993). The findings were also consistent with the theory that endurance training adaptations interact to accelerate the adjustment of O_2 supply to O_2 demand during submaximal exercise (Hagberg et al. 1980, Hickson et al. 1978). This further supports earlier studies in which $\dot{V}O_2$ kinetics were shown to improve in response to endurance training (Babcock et al. 1994, Berry and Moritani 1985, Fukuoka et al. 1997, Phillips et al. 1995a). One study did not show an overall improvement in phase II $\dot{V}O_2$ kinetics after six weeks of endurance training (Carter et al. 2000). However, when their subjects were subdivided according to levels of training, the less well trained displayed improved $\dot{V}O_2$ kinetics where there was no change in the well trained subjects. This finding supports the view that $\dot{V}O_2$ kinetics might be of use in the identification of aerobic fitness in the general population but is likely to be less useful among previously well trained elite athletes.

Following the observation of faster $\dot{V}O_2$ kinetics in elite endurance runners utilising the pseudo-random binary sequence fitness test, examination was made of $\dot{V}CO_2$kinetics (Edwards et al. 2000). Since a previous study (Fukuoka et al. 1997) showed $\dot{V}CO_2$ kinetics to be delayed after 6 months sprint and strength training in footballers, it might be expected that $\dot{V}CO_2$ kinetics would also differentiate elite endurance runners from elite sprinters. This was not shown to be the case in this research (Edwards et al. 2000). Although both amplitude ratio and phase shift for $\dot{V}CO_2$ kinetics were consistently slower in the sprinters compared with the endurance runners at all frequencies, this observation was not of statistical significance. This is most likely due to the high standard deviations observed for $\dot{V}CO_2$ kinetics in comparison to $\dot{V}O_2$ kinetics, which could either be attributable to the effects of higher tissue capacitance for CO_2 than O_2, or technical imprecision of CO_2 measurement.

The main finding of this element of the research (Edwards et al. 1999a, 2000) was that the pseudo-random binary sequence exercise test might become a useful assessment of $\dot{V}O_2$ kinetics, but an issue of reliability emerged from the variability observed in $\dot{V}CO_2$ kinetics. A test-retest study was therefore conducted to establish the reliability of the procedure (Edwards et al. 2001a).

The results of the test-retest study (Edwards et al. 2001a) demonstrated that the limits of agreement as defined by Bland and Altman (1986) were substantially closer for $\dot{V}O_2$ kinetics than $\dot{V}CO_2$ kinetics. This offered some explanation for the failure of $\dot{V}CO_2$ kinetics to differentiate between the elite endurance runners and elite sprinters (Edwards et al. 2000). Likely causes for the observed variability are differences in the signal to noise ratio between $\dot{V}O_2$ kinetics and $\dot{V}CO_2$ kinetics, greater variations in ventilation in $\dot{V}CO_2$ kinetics compared with $\dot{V}O_2$ kinetics, or a change in CO_2 storage during the test period.

In this research, both $\dot{V}O_2$ kinetics and $\dot{V}CO_2$ kinetics displayed levels of test-retest variability, which question the practical application of the pseudo-random binary sequence test. For comparison between test-retest reliability across amplitude ratios and phase shift angles, measurement error was calculated according to the definition of Atkinson and Nevill (1998) (Edwards et al. 2001a). Measurement error for $\dot{V}O_2$ kinetics ranged between 18-35% and $\dot{V}CO_2$ kinetics between 39-108%. It is therefore unsurprising that $\dot{V}CO_2$ kinetics did not differentiate between the athletic groups and, consequently, the subsequent development of this research concentrated on $\dot{V}O_2$ kinetics rather than $\dot{V}CO_2$ kinetics utilising the pseudo-random binary sequence exercise test (Edwards et al. 2001a).

Conclusions drawn from the research suggest that further development of the pseudo-random binary sequence exercise test would be dependent on improved test-retest reliability and a less complex interpretation requirement than Fourier analysis

(Edwards et al. 2001a). Either sporting or clinical application of an exercise test would have greater relevance when expressed by a single quantifiable test score or time. Oxygen uptake kinetics in response to step test procedures have been routinely expressed in the time domain by description of the time constant of the response (Hughson et al. 1988, Whipp et al. 1982). In this method, a mathematical model is fitted to the test data for the subsequent calculation of a mean response time. A limitation of the step test procedure is that it requires multiple repeats of the step to generate sufficient data for analysis (Hughson et al. 1988, Stegemann et al. 1985). In comparison, the pseudo-random binary sequence test has the advantage of being able to generate adequate information about $\dot{V}O_2$ kinetics from a single test, although the physiological interpretation of frequency responses is more complex.

The development of a single time score for $\dot{V}O_2$ kinetics would enable researchers or clinical practitioners to compare subjects test performances quickly and in a meaningful way. For example, a typical 300 s (15 units of 20 s) pseudo-random binary sequence $\dot{V}O_2$ kinetics test response analysed in the frequency domain yields three usable values for amplitude ratio at frequencies 3.3 mHz (typically ~ 8.02 ±0.7 $ml \cdot min^{-1} \cdot W^{-1}$, 6.7 mHz (5.47 ±0.9 $ml \cdot min^{-1} \cdot W^{-1}$), 10 mHz (3.56 ±0.7 $ml \cdot min^{-1} \cdot W^{-1}$) and a further three for phase shift (typically ~ -41.26 ±5.82 degrees, -73.74 ±7.93 degrees and –99.53 ±9.29 degrees), i.e. before the underlying physiological response is obscured by breath-by-breath background noise. This research has not shown a consistent pattern of reliability for individual frequencies of either amplitude ratio or phase shift and it is therefore difficult to attach meaningful physiological conclusions to the test results. The high test retest variability of the frequency domain results is a probable cause for this, but a reliable single test score would remove the uncertainty surrounding the meaning of individual frequencies.

To generate a single overall test response from the pseudo-random binary sequence exercise test, two time domain procedures have been proposed as alternatives to frequency domain analysis (Hughson et al. 1991, Massin et al. 1998, 2000, Stegemann et al. 1997). The test-retest reliability of the two procedures has not been reported and therefore this research compared both methods with frequency domain results (Edwards et al. 2001, 2003) for the identification of the most reliable and practical method of result expression.

The procedure described by Hughson et al. (1991) utilised a mathematical modelling technique to generate a mean response time that might be comparable with the analysis procedures used in step tests (Linnarsson 1974, Whipp et al. 1982). This procedure utilises the auto- (work rate correlated with itself) and cross-correlation (work rate correlated with $\dot{V}O_2$ response) functions for the model fitting. As the auto-correlation appears in the shape of a triangular pulse, the mean response time method is derived by fitting a linear summation of the ramp form of a two-component exponential function to the test data. Although complex, this method utilises time delays and gains in the calculation of the mean response time and is an example of a functional, rather than empirical model.

A second, and simpler, approach is possible utilising the known lag in time between auto and cross-correlation functions derived from the pseudo-random binary sequence work rate and $\dot{V}O_2$ response and does not require the fitting of a mathematical model

(Massin et al. 1998, 2000). This approach merely describes the time lag between auto- and cross-correlation functions and has been termed a 'peak cross-correlation time' (Edwards et al. 2003a).

Preliminary analysis was conducted to examine the application of the mean response time method on the data previously reported for elite sprinters and elite endurance runners (Edwards 1999, 2001b). That study demonstrated the mean response time could be used to differentiate between the $\dot{V}O_2$ kinetics of the two groups and consequently further research was conducted to compare the application of the two time domain procedures on both the sprint and endurance data and the test-retest data previously reported in the frequency domain (Edwards et al. 2003a).

The results of this research demonstrated different reliability between the assessment procedures (Edwards et al. 2003a). The most reliable method in this research was the mean response time method with a measurement error of 16%. This compared favourably with the previously reported measurement error of 18-35% in the frequency domain (Edwards et al. 2001a) and the peak cross-correlation time of 25% (Edwards et al. 2003a).

The expression of an overall response either by mean response time or peak cross-correlation time potentially offers greater application of the pseudo-random binary sequence exercise test to either sports groups or in a clinical context through the expression of a single test result. Test-retest reliability of $\dot{V}O_2$ kinetics was improved using the mean response time and the most likely explanation for this is a reduced susceptibility to breath-by-breath noise in an overall response.

ii) Anaerobic threshold and maximal oxygen uptake

Maximal aerobic power ($\dot{V}O_2$ max) is widely considered the most objective measure of endurance capacity. However, the specificity principle of training suggests that care must be taken when interpreting $\dot{V}O_2$ max as an absolute indicator of fitness (Kemi et al. 2003, Pechar et al. 1974). The $\dot{V}O_2$ max is poorly related to the demands of many sports and an improvement or change of $\dot{V}O_2$ max does not necessarily lead to a practical change in sports performance (Gergley et al. 1984).

Although an individual's highest attainable $\dot{V}O_2$ max is usually reached within two years of endurance conditioning (Saltin et al. 1977), endurance performance continues to improve with continued training for many additional years. Improvement in endurance performance without improvements in $\dot{V}O_2$ max is probably due to the body's ability to perform at increasingly higher percentages of $\dot{V}O_2$ max for extended periods following training (Donovan and Pagliassotti 1990, Phillips et al. 1995b). It seems likely that this increase in performance without an increase in $\dot{V}O_2$ max is the result of an increase in lactate threshold (Denis et al. 1982), because endurance steady state is directly related to the $\dot{V}O_2$ value at lactate threshold (Bassett and Howley 2000, Denis et al. 1982, Donovan and Pagliassotti 1990).

The purpose of the maximal aerobic power ($\dot{V}O_2$ max) and anaerobic threshold research was to compare the sensitivity of both measurements after changes in training activities (Clark and Edwards 2003, Edwards et al. 2003c). Although measurement of $\dot{V}O_2$ max, in particular, has often been used as a standard fitness assessment procedure for athletes in endurance based sports, the identification of specific fitness in multi sprint sports such as soccer is more complex due to the diverse requirements of the game (Bangsbo and Lindquist 1992, Kemi et al. 2003, Reilly et al. 2000). Nevertheless, research suggests that a $\dot{V}O_2$ max of 60 $ml \cdot kg^{-1} min^{-1}$ as a minimum requirement for professional soccer performance (Tumilty 1993) and many soccer clubs continue to utilise the multi-stage fitness test (MSFT) (Ramsbottom et al. 1988) to estimate $\dot{V}O_2$ max. For this purpose, a group of English 1st team Professional Division 1 soccer players were tested both in a highly trained state and also following a 5 weeks off season period (Clark and Edwards 2003, Edwards et al. 2003c).

It has previously been shown that an inclined treadmill recruits a larger muscle mass than when running on the flat and a slower cadence allows the individual to reach a 'true' $\dot{V}O_2$ max (Astrand et al. 2003). In consideration of this, a series of flat running incremental steps were used for the assessment of anaerobic threshold prior to a subsequent series of increases in incline at a constant speed of 14.5 $km \cdot h^{-1}$ for the measurement of $\dot{V}O_2$ max (Figure 2).

Measurement of anaerobic threshold can be assessed by a number of measures but in this research was identified by both the initial rise in lactate above the resting baseline and also by the V slope method for assessment of ventilatory parameters $\dot{V}O_2$ and $\dot{V}CO_2$. Onset of blood lactate accummulation (OBLA) at a fixed concentration of $4 mmol \cdot l^{-1}$ was not used in this research as it has been criticised due to variability between subjects (Coyle 1995) and because it may be a result of not only muscle anaerobisis, but also a decreased total lactate clearance or increased lactate production in specific muscles (Hermansen 1971).

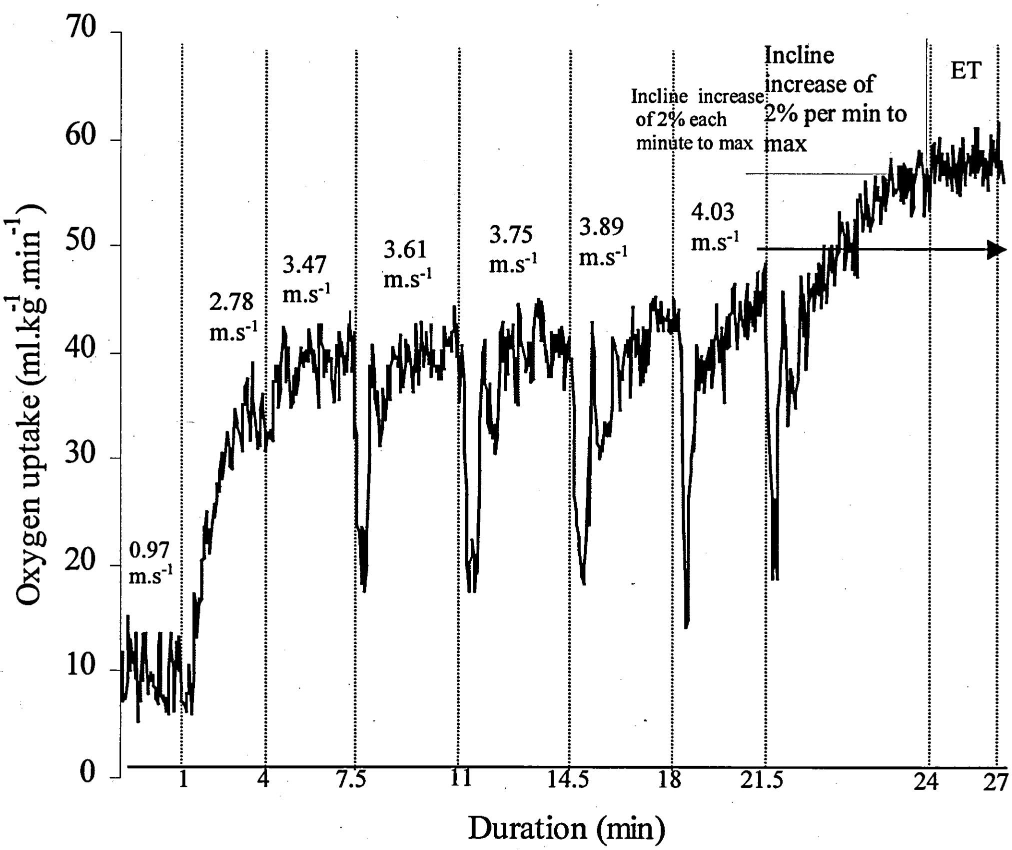

Figure 2. Breath-by-breath oxygen uptake ($\dot{V}O_2$) of a single subject in response to the combined test of anaerobic threshold and maximal aerobic power.

The main finding of this work was that $\dot{V}O_2$ max was not significantly affected by the 5-week off-season period, while the oxygen uptake corresponding to both ventilatory threshold and lactate threshold was significantly reduced following the off-season

(Clark and Edwards 2003, Edwards et al. 2003c). Although a limited amount of training was conducted over the off-season, it was performed at lower intensities and on a less demanding schedule compared to the regular match play and training of the on-season. The change observed in $\dot{V}O_2$ corresponding to both lactate threshold and ventilatory threshold suggests that either measure of anaerobic threshold is a more useful indicator of training status than $\dot{V}O_2$ max. Consequently, although a maximal intensity test is certainly of importance in the identification of maximum heart rate and the production of a $\dot{V}O_2$ max 'score', the place of regular and routine direct assessment of $\dot{V}O_2$ max during soccer training is questionable. Therefore, although maximal aerobic power is undoubtedly of importance to soccer performance, it represents only one of several strands in the fitness requirements of soccer.

The failure of $\dot{V}O_2$ max assessment to identify a change in the training state of the soccer players might be explained by the duration of exercise tolerance at $\dot{V}O_2$ max (Edwards et al. 2003c). This aspect of the research demonstrated that when the players were in the highly trained state they were able to sustain maximal exercise for significantly longer than when less well trained. This is consistent with the theory that sustained running speed is directly related to the accumulation of lactic acid in the muscle (Bassett and Howley 2000, Denis et al. 1982, Donovan and Pagliassotti 1990). In the highly trained state, lactate threshold was improved which demonstrated that higher steady state running speeds could be achieved prior to the onset of acidosis. This finding suggests that $\dot{V}O_2$ max has little scope for further improvement in elite well-trained subjects who may have reached a genetic ceiling of aerobic performance, but it is also possible that existing training methods are not sufficiently focused to change maximal aerobic power.

iii) Sport specific fitness: Soccer specific fitness test

A progression of this research was the development of a sport specific fitness testing procedure that might prove an accurate method of obtaining objective information about fitness and training for coaches and athletes. Physiological adaptations in response to physical training are highly specific to the nature of the training activity (Kemi et al. 2003, Saltin et al. 1976) and research demonstrates that the more specific the training programme is to the given sport or activity, the greater the improvement in performance in that sport or activity (Gergley et al. 1984, Helgerud et al. 2001).

Bangsbo and Lindquist (1992) proposed that to measure performance-related improvements in fitness accurately, athletes should be tested while they are engaged in an activity similar to the sport or activity in which they usually participate. No single measure of overall muscular strength or aerobic fitness exists, instead, an individual displays an array of qualities relevant to the fitness requirements of the sport undertaken. It is possible that these qualities of muscle function and performance relate poorly to each other, if at all, and likewise, testing a person for aerobic fitness could produce different fitness results, depending on the mode of activity (McArdle et al. 1971, Toner et al. 1983).

Measurement of fitness should most closely resemble the actual requirements of the activity, not only for specific tasks but also in a manner that reflects the intensity, duration and pace of the task. Therefore, it is likely that the most effective evaluation of sport-specific fitness occurs when laboratory or field measurement closely simulates the actual sport activity and uses the muscle mass required by the sport (Bilodeau et al. 1995, Gergley et al. 1984).

The aim of this section of the research was to develop a fitness testing procedure of specific relevance to a selected sport. Reilly et al. (2000) identified a need for representative assessment of fitness or training status for soccer and although other researchers have devised and developed soccer specific protocols (Bangsbo et al 1991, Bangsbo and Lindquist 1992, Bangsbo 1994, Drust et al. 2000, Nicholas et al. 1995, Wragg et al. 2000), many of these have been designed to replicate the full demands of the game (Drust et al. 2000, Nicholas 1995, 2000) for the assessment of match like intervention measures in isoloation from matchplay, while others represent single strands of fitness (Bangsbo 1994, Wragg et al. 2000) or were designed as training ground ‘drills’ (Bangsbo and Lindquist 1992, Bangsbo 1994). Bangsbo and Lindquist (1992) compared various exercise tests with the endurance performance of professional soccer players and suggested that specific interval field tests could be used to evaluate long-term endurance performance of elite soccer players. They further concluded that $\dot{V}O_2$ max and blood lactate concentration during submaximal running were not sensitive measurements of endurance capacity for intermittent exercise. Their observation is consistent with the findings in this research (Edwards et al. 2003b) but are in contrast to the results reported by Helgerud et al. (2001) in which $\dot{V}O_2$ max increased from 58.1 to 64.3 $ml \cdot kg^{-1} \cdot min^{-1}$ over eight weeks of aerobic training in youth team professional trainees. However, the magnitude of the increase in that study could be related to the initial training status of the athletes, genetic characteristics or maturation.

In this research, a single and practical exercise test was developed to assess soccer specific fitness over a range of indicators. The basic movement pattern of an existing protocol was used (Nicholas et al. 1995, 2000), although that procedure was designed to replicate the demands of a full 90 min game with which to investigate dietary interventions and hydration status. While the 90 min protocol did not offer immediate indication of practical use as a fitness test, the close resemblance of the test to the demands of the game suggested that it might have application in a modified form.

A limits of agreement study conducted by Nicholas and co-workers (2000) provided a solid base for further development of the procedure as a fitness test. Modifications were made to condense the new protocol and to facilitate multiple testing of subjects at one time (Edwards et al. 2003b). A combination of verbal and audio cues was used to improve pace judgement in the multi-speed test and physiological assessment was introduced across a range of fitness indicators. The fitness indicators designed in this research were developed to represent both aerobic and anaerobic components of the test. The selected fitness indicators were: Exercise heart rates, recovery heart rates, blood lactate concentration, peak and average sprint times, and a fatigue rate expressed as the drop off from peak sprint performance. Therefore, consideration was made to ensure that the aerobic and anaerobic components of multi sprint activities were reflected in the test (Figure 3).

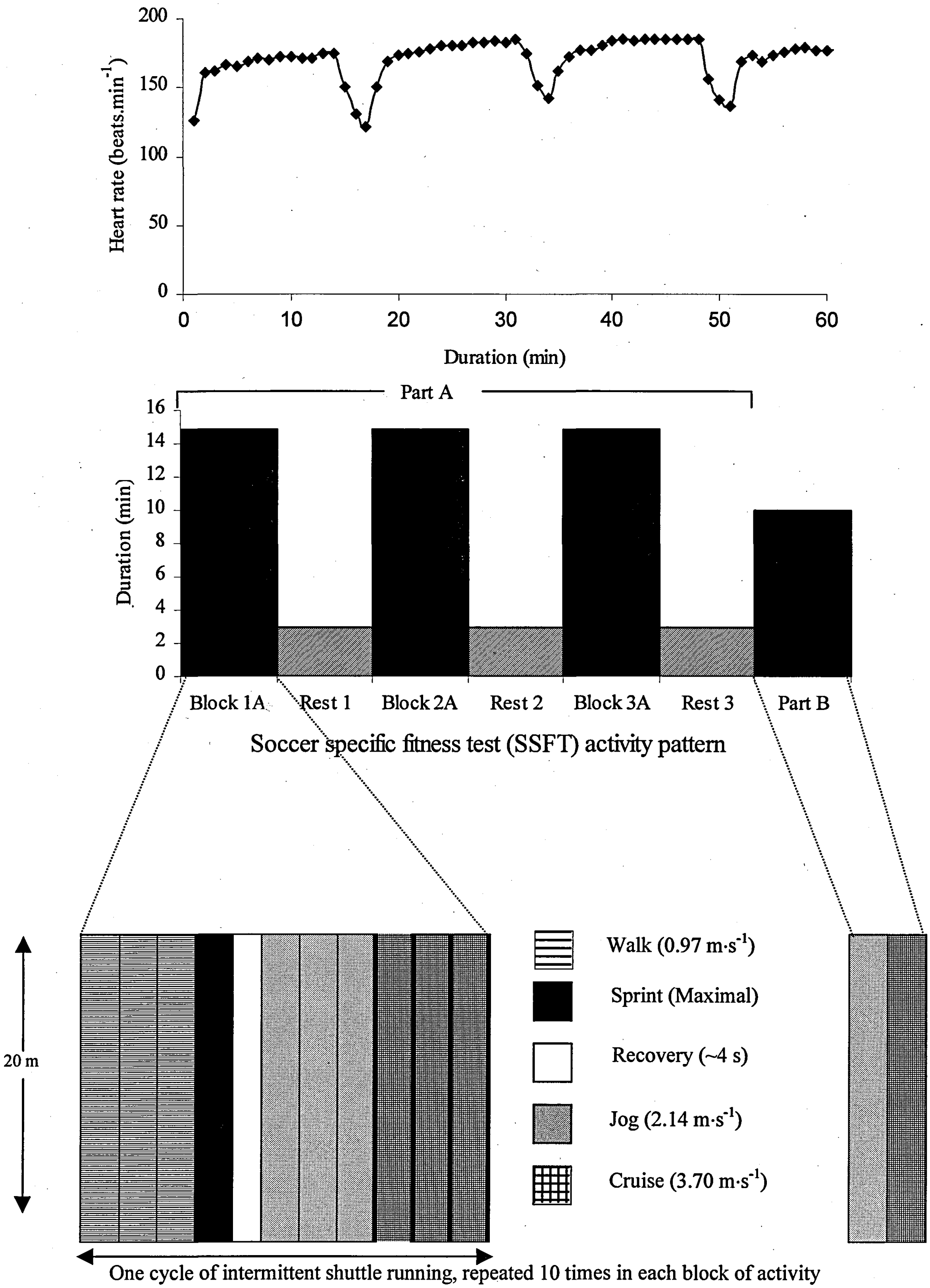

Figure 3. The heart rate (1 min average) response of a single subject to a schematic representation of the Soccer Specific Fitness Test protocol.

The results of the first study utilising the soccer specific fitness test (Edwards et al. 2003b) demonstrated that Academy players from a professional soccer club performed the test at a significantly different level compared to a group of recreational players. An important observation in this study was that a progressive shuttle run test to exhaustion did not differentiate between the predicted aerobic capacities of the two groups. This further demonstrated that a generic and non-specific test is less likely to prove useful to athletes and coaches on fitness or training status. The results of the first study (Edwards et al. 2003b) showed that the highly trained players were able to sustain and recover more quickly from the high intensity intermittent work which was evidenced by a faster sustained maximal sprint time and a more rapid decline in heart rate following each of the activity blocks. The Academy players also completed the test with a significantly higher blood lactate concentration and it seems likely that this represents a more pronounced activation of anaerobic glycolysis in comparison to the less highly trained Recreational players. The most likely explanation for the observed difference in test performances between the two groups is that the standardised speeds utilised in the test imposed less of an overall stress on the Academy players due to their enhanced soccer specific fitness. In addition, maturation could have been a factor between the two groups which may have contributed to the surprising observation of no difference between the estimated $\dot{V}O_2$ max between the Academy and Recreational players.

In a second study (Edwards et al. 2003d), the test procedure was further modified to remove Part B of the test, which had not differentiated between groups. Practical use of the soccer specific fitness test identified that the point of subject exhaustion may be more closely related to motivation than an accurate assessment of exercise capacity. The removal of this section reduced the exercise time to 45 min.

In the second study (Edwards et al. 2003d), a group of 1st team professional soccer players and a group of Academy players completed the procedure. The aim of this work was to identify whether the test might be sensitive to the different soccer performances between two well-trained groups of soccer players performing and training regularly. The main finding of this study was that the 1st team players were able to sustain sprint times and recover from exercise bouts more quickley, consistent with previous observations of different test performances between Academy and recreational players. This finding supports the development of the soccer specific fitness test as a relatively sensitive assessment of soccer specific fitness.

A consistent finding from the two studies was that the more highly trained group in each study completed the test with significantly elevated blood lactate concentrations. It seems likely that the ability to attain and sustain elevated blood lactate concentrations is an important consideration in the specific fitness assessment of soccer players.

Research synthesis

The common theme for the research was the identification of fitness in elite athletes across both gas exchange kinetics and sport specific fitness testing. This research contributed new knowledge in the identification of appropriate analysis procedures and the test reliability of gas exchange kinetics in response to pseudo-random binary sequence testing. That work presented a novel alternative to maximal testing for the identification of aerobic fitness where previously gas exchange kinetics had not been applied in such a context. A subsequent study revealed greater sensitivity to training status in the measurement of anaerobic threshold than maximal aerobic power testing and further research developed a new soccer specific fitness test that demonstrated differentiated test performances according to levels of soccer performance.

The gas exchange kinetics studies (Edwards et al. 1999, 2000, 2001a, 2001b, 2002b, 2003a) demonstrated a distinctive contribution to gas exchange kinetics research through the use of the dynamic pseudo-random binary sequence protocol as an aerobic fitness test. Before this research, there had not been a consistent rationale for either the potential of the procedure or the method of analysis for gas exchange kinetics assessed by this technique.

The first study of this research (Edwards et al. 1999) was one of the earliest occasions where gas exchange kinetics has been utilised as a sports fitness test for elite athletes and was the first utilising the pseudo-random binary sequence test. Equally, test-retest reliability for pseudo-random binary sequence exercise testing had not previously been reported and so Edwards et al. (2001a) demonstrated new knowledge in this area. As Edwards et al. (2001a) demonstrated high test-retest variability, further work was required to improve reliability. Edwards et al. (2003a) provided further evidence supporting alternative data analysis procedures that both identified more reliable and more useful forms of results expression.

The practical application of $\dot{V}O_2$ kinetics by pseudo-random binary sequence remains limited by the issue of breath-by-breath noise (Lamarra et al. 1987). This questions the use of the procedure as a sports fitness test, although further development might be possible in a clinical context for patients undergoing rehabilitation programmes. In that context, the low intensity demands of the procedure would be useful for subjects for whom maximal work is inappropriate. As the pseudo-random binary sequence test enables aerobic fitness assessment in the non-steady state, it might also be of particular relevance to the lifestyle demands of the general population. However, the research reported in this thesis does not currently support the application of the test for individual assessment of fitness in elite athletes, where a small change in training status might not be accurately reflected in pseudo-random binary sequence test performance.

Further research demonstrated a correlation between $\dot{V}O_2$ kinetics and $\dot{V}O_2$ max (Edwards et al. 2002b, Fysh 1999). However, mechanistic research (Bassett and Howley 2000, Pringle et al. 2003, Rossiter et al. 1999, Tschakovsky and Hughson 1999, Whipp et al. 1999) suggests that the two measurements may reveal different aspects of aerobic fitness, which would explain the relatively low statistical significance in their relationship.

The role of $\dot{V}O_2$ max and anaerobic threshold in the ongoing assessment of aerobic fitness in elite athletes was examined (Clark and Edwards 2003, Edwards et al. 2003c). This work reinforced previous observations that $\dot{V}O_2$ max seems less responsive to change in training state than measures of anaerobic threshold (Donovan and Pagliassotti 1990, Katz and Sahlin 1990). A novel and interesting finding was that the duration of exercise tolerance at $\dot{V}O_2$ max increased in the highly trained state (Clark and Edwards 2003, Edwards et al. 2003c). This supports the view that aerobic event performance might improve without an increase in maximal aerobic power, especially in elite athletes. The research findings further suggest that measures of anaerobic threshold or maximal exercise tolerance might be more relevant as performance indicators than $\dot{V}O_2$ max in highly trained subjects where changes could be minimal.

The soccer specific research made a distinctive contribution to the development of a representative measure of fitness for soccer. Reilly et al. (2000) identified the need for such measurement and future research and practical application of the soccer specific fitness test will identify whether the test might perform such a function.

An advantage of the soccer specific fitness test procedure was that the speeds of the test were standardised to enable comparison of players in one session. This maximised the test opportunity with minimal time imposition, which was a key consideration for the coaches seeking to identify players' strengths and weaknesses. Therefore, players performed the maximal sprint elements of the test at different intensities corresponding to their fitness, and their physiological responses to the requirements of the test became their test results.

The common themes of this research are demonstrated in Table 1 in which the tests have been assessed by a series of relevant factors. The factors specified examine the issues of reliability, cross-sectional and longitudinal evidence supporting the procedures and their practical application for the routine assessment of fitness in elite athletes.

Table 1. The reliability and validity of selected exercise protocols.

Tests	Factors			
	Reliability	Cross-sectional	Longitudinal	Practical application To elite athletes
$\dot{V}O_2$ kinetics PRBS test	Medium	Medium	Medium	Weak
$\dot{V}O_2$ max	Strong	Strong	Medium	Medium
Anaerobic threshold (VT & LT)	Strong	Strong	Strong	Medium
SSFT	Medium	Medium	Medium	Medium Strong

PRBS = Pseudo-random binary sequence, VT = Ventilatory threshold, LT = Lactate threshold, SSFT = Soccer specific fitness test. Links between test and factor: weak to strong.

It is evident from Table 1 that the traditional laboratory tests of $\dot{V}O_2$ max and anaerobic threshold compare favourably with both the $\dot{V}O_2$ kinetics test and the soccer specific fitness test. However, the soccer specific fitness test has the strongest practical validity, although it remains unclear to what extent it is related to match performance as estimated $\dot{V}O_2$ max was not correlated with test performance indicators.

Although sport specific tests present difficulties in cross comparisons and regulation of test conditions outside the laboratory, they might prove the most relevant to sports performers. Improved technology such as portable gas analysers makes comparisons of exercise intensity more practical and results from this research suggest that the soccer specific fitness test in particular is of direct relevance to performance (Edwards et al. 2003b, 2003d).

Conclusions

In conclusion, this research utilised the principles of moderate intensity $\dot{V}O_2$ kinetics to develop a new aerobic fitness test (aim one). The reliability of pseudo-random binary sequence exercise had not previously been reported and this research identified greater reliability in $\dot{V}O_2$, compared with $\dot{V}CO_2$ kinetics in this form of exercise (aim two). Oxygen uptake kinetics differentiated between elite sprinters and elite endurance runners (aim three), however, the relatively high test retest variability observed questioned the application of this procedure as a sensitive fitness test. An evaluation of methods to express $\dot{V}O_2$ kinetics results revealed that there was no common procedure for this form of test and therefore research was undertaken to identify the most reliable and practical methods (aim four). This resulted in the identification of the mean response time procedure as both a more reliable form of analysis and also produced a single test score compared with the series of values derived from Fourier analysis. This method can therefore be taken forward as a standard method of expression for pseudo-random binary sequence tests in the future.

Relatively high test-retest variability remains a feature of pseudo-random binary sequence testing and this poses clear difficulty in accurately determining fitness in athletic populations where a small change in test performance could be of great importance. Further investigation of traditional laboratory tests of in a longitudinal study and cross-sectional studies of sport specific fitness testing revealed contrasting results (Table 1). The traditional maximal test of $\dot{V}O_2$ max is known to display good reliability but did not reflect seasonal changes soccer players' fitness (aim five). The development of a new soccer specific fitness test resulted in significant differences in the test performances of elite and sub elite players (aim six) suggesting it might have more relevance to sport specific fitness than the other measures examined.

For the future direction of similar research, the low intensity demands of the pseudo-random binary sequence exercise test provide a reasonable premise for the further development of the procedure for subjects of low aerobic fitness such as the elderly or those recovering from serious illness. Further investigation of noise reduction methods might increase the confidence in the procedure and ultimately provide a low intensity alternative aerobic fitness test for subjects unable to perform maximal intensity exercise. In terms of elite athletes, specificity of testing is a key concern and the soccer specific fitness test warrants further investigation as a method of identifying fitness requirements of match performance.

References

Andersen P, Henriksson J. (1977). Capillary supply of the quadriceps femoris muscle of man: adaptive response to exercise. *Journal of Physiology* 270: 677-690.

Astrand PO, Rodahl K, Dahl HA, Stromme SB. (2003). Textbook of work physiology: *Physiological bases of exercise* 4th Edition. Human Kinetics.

Atkinson G, Nevill AM. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine* 26(4): 217-238.

Babcock MA, Paterson DH, Cunningham DA, Dickinson JR. (1994) Exercise on-transient gas exchange kinetics are slowed as a function of age. *Medicine and Science in Sports and Exercise* 26(4): 440-446.

Bangsbo J. (1994). Fitness training in football – a scientific approach. HO Storm, Bagsvaerd.

Bangsbo J, Lindquist F. (1992). Comparison of various exercise tests with endurance performance during soccer in professional players. *International Journal of Sports Medicine* 13: 125-132.

Bangsbo J, Norregaard L, Thorso F. (1991). Activity profile of competition soccer. *Canadian Journal of Sports Science* 16(2): 110-116.

Bassett DR, Howley ET. (2000). Limiting factors for maximal oxygen uptake and determinants of endurance performance. *Medicine and Science in Sports and Exercise* 32(1): 70-84.

Bennett FM, Reischl P, Grodins FS, Yamashiro SM, Fordyce WE. (1981). Dynamics of ventilatory response to exercise in humans. *Journal of Applied Physiology* 51(1): 194-203.

Bergh U, Thorstensson A, Sjodin B, Hulten B, Piehl K, Karlsson J. (1978). Maximal oxygen uptake and muscle fibre types in trained and untrained humans. *Medicine and Science in Sports* 10(3): 151-154.

Bernus G, Gonzales De Suso JM, Alonso J, Martin PA, Prat JA, Arus C. (1993). ^{31}P-MRS of quadriceps reveals quantitative differences between sprinters and long-distance runners. *Medicine and Science in Sports and Exercise* 25: 479-484.

Berry M, Moritani T. (1985). The effects of various training intensities on the kinetics of oxygen consumption. The Journal of Sports Medicine and Physical Fitness Quarterley Review 25: 77-83.

Bilodeau B, Roy B, Boulay MR. (1995). Upper-body testing of cross-country skiers. *Medicine and Science in Sports and Exercise* 27: 1557-1562

Bland JM, Altman DG. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* I: 307-310.

Carter H, Jones AM, Barstow TJ, Burnley M, Williams C, Doust J. (2000). Effect of endurance training on oxygen uptake kinetics during treadmill running. *Journal of Applied Physiology* 89: 1744-1752.

Clark N, Edwards AM. (2003). Anaerobic threshold and exercise tolerance are improved following training in elite soccer players where $\dot{V}O_2$ max is unchanged. *5th World Congress on Science and Football* (Portugal).

Coyle EF. (1995) Integration of the physiological factors determining endurance performance in athletes. Exercise and Sports Sciences Reviews 23: 25-31.

Denis C, Fouquet R, Poty P, Geyssant A, Lacour JR. (1982). Effect of 40 weeks of endurance training on anaerobic threshold. *International Journal of Sports Medicine* 3: 208-214.

Donovan CM, Pagliassotti MJ. (1990). Enhanced efficiency of lactate removal after endurance training. *Journal of Applied Physiology* 68: 1053.

Drust B, Reilly T, Cable NT. (2000). Physiological responses to laboratory-based soccer-specific intermittent and continuous exercise. *Journal of Sports Sciences* 18: 885-92.

Edwards AM, Claxton DB, Fysh ML. (2003a). A comparison of two time domain analysis procedures in the determination of $\dot{V}O_2$ kinetics by PRBS exercise testing. *European Journal of Applied Physiology* 88 (4-5): 411-416.

Edwards AM, Clark N, Macfadyen AM. (2003b). Test performance indicators from a single soccer specific fitness test differentiate between highly trained and recreationally active soccer players. *Journal of Sports Medicine and Physical Fitness* 43: 14-20.

Edwards AM, Clark N, Macfadyen AM. (2003c). Lactate and ventilatory thresholds reflect the training status of professional soccer players where maximum aerobic power is unchanged. *Journal of Sports Science and Medicine* I: 23-29.

Edwards AM, Clark N. (2003d). A soccer specific fitness test differentiates between 1st team professional soccer players and academy trainees. *5th World Congress on Science and Football* (Portugal): 189-190.

Edwards AM, Macfadyen AM, Clark N. (2002a). A comparison of soccer specific performance test indicators in highly trained and recreationally active soccer players. *Journal of Science and Medicine in Sport* 5 (4): 34.

Edwards AM, Fysh MF, Claxton DB, Bacon CB. (2002b). $\dot{V}O_2$ kinetics expressed as MRT is correlated with $\dot{V}O_2$ max when measured using a PRBS protocol. *7th Annual Congress of the European College of Sport Science* (Athens): 222.

Edwards AM, Claxton DB, Challis NV, Chapman JH, Fysh ML. (2001a). The test-retest reliability of gas exchange kinetics using a pseudo-random binary sequence exercise test. *European Journal of Applied Physiology* 85 (3-4): 333-338.

Edwards AM, Claxton DB, Challis NV, Chapman JH, Fysh ML. (2001b). Time domain analysis of oxygen uptake kinetics in elite runners by pseudo-random binary sequence exercise. *Medicine and Science in Sports and Exercise* 33 (5): S21.

Edwards AM, Challis NV, Chapman JH, Fysh ML. (2000). Gas exchange kinetics in elite runners. *Journal of Sports Sciences* 18 (7): 535-536.

Edwards AM, Claxton DB, Challis NV, Chapman JH and Fysh ML. (1999). Oxygen uptake kinetics determined by PRBS techniques differentiate elite endurance runners from elite sprinters. *International Journal of Sports Medicine* 20: 1-6.

Fysh M, Chapman JH, Edwards AM and Paggiosi MA. (1999). Relationships between oxygen uptake kinetics and maximal oxygen uptake. *4th Annual Congress of the European College of Sport Science* (Rome): 610.

Eβfeld D, Hoffmann U, Stegemann J. (1987). $\dot{V}O_2$ kinetics in subjects differing in aerobic capacity: investigation by spectral analysis. *European Journal of Applied Physiology* 56: 508-515.

Eβfeld D, Hoffmann U, Stegemann J. (1991). A model for studying the distortion of muscle oxygen uptake patterns by circulation parameters. *European Journal of Applied Physiology* 62: 83-90.

Fukuoka Y, Gwon O, Sone R, Ikegami H. (1995). Characterization of sports by the $\dot{V}O_2$ dynamics of athletes in response to sinusoidal workload. *Acta Physiologica Scandinavica* 153: 117-124.

Fukuoka Y, Shiematsu M, Itoh M, Fujii N, Homma S, Ikegami H. (1997). Effects of football training on ventilatory and gas exchange kinetics to sinusoidal workload. *Journal of Sports Medicine and Physical Fitness* 37: 161-167.

Gergley TJ, McArdle WD, DeJesus P, Tonert MM, Jacobowits S. (1984). Specificity of arm training on aerobic power during swimming and running. *Medicine and Science in Sports and Exercise* 16(4): 349-54.

Hagberg J M, Hickson RC, Ehsani AA, Holloszy JO. (1980). Faster adjustment to and recovery from submaximal exercise in the trained state. *Journal of Applied Physiology* 48 (2): 218-224.

Helgerud J, Engen LC, Wisloff U, Hoff J. (2001). Aerobic endurance training improves soccer performance. *Medicine and Science in Sports and Exercise* 33(11): 1925-1931.

Hermansen L. (1971) Lactate production during exercise. In: Muscle metabolism during exercise. Ed: Pernow B, Saltin B. New York: Plenum.

Hickson RC, Bomze HA, Holloszy JO. (1978). Faster adjustment of O_2 uptake to the energy requirement of exercise in the trained state. *Journal of Applied Physiology* 45: 877-881.

Hoffmann U, Eβfeld D, Leyk D, Wunderlich HG, Stegemann J. (1994). Prediction of individual oxygen uptake on-step transients from frequency responses. *European Journal of Applied Physiology* 69: 93-97.

Hoffmann U, Eβfeld D, Wunderlich H, Stegemann J. (1992). Dynamic linearity of $\dot{V}O_2$ responses during aerobic exercise. *European Journal of Applied Physiology* 64: 139-144.

Hughson RL, Cuervo LA, Patla AE, Winter DA, Xing HC, Dietrich BH, Swanson, GD. (1991). Time domain analysis of oxygen uptake during pseudo-random binary sequence exercise tests. *Journal of Applied Physiology* 71: 1620-1626.

Hughson RL, Winter DA, Patla AE, Swanson GD, Cuervo LA. (1990). Investigation of kinetics in humans with pseudo-random binary sequence work rate change. *Journal of Applied Physiology* 68: 796-801.

Hughson RL, Sherrill DL, Swanson GD. (1988). Kinetics of $\dot{V}O_2$ with impulse and step exercise in humans. *Journal of Applied Physiology* 64: 451-459.

Katz A, Sahlin K. (1990). Role of oxygen in regulation of glycolysis and lactate production in human skeletal muscle. *Exercise and Sport Science Review* 18: 1-28.

Kemi OJ, Hoff J, Engen LC, Helgerud J, Wisloff U. (2003). Soccer specific testing of maximal oxygen uptake. *The Journal of Sport Medicine and Physical Fitness* 43: 139-144.

Kerlin TW. (1974). Properties of important test signals. Frequency Response Testing in *Nuclear Testing*, New York: Academic Press: 52-83.

Kowalchuk JM, Hughson RL. (1990). Effect of β-adrenergic blockade on $\dot{V}O_2$ kinetics during pseudorandom binary sequence exercise. *European Journal of Applied Physiology* 60: 365-369.

Lamarra N, Whipp BJ, Ward SA, Wasserman K. (1987). Effect of interbreath fluctuations on characterizing exercise gas exchange kinetics. *Journal of Applied Physiology* 62: 2003-2012.

Linnarsson D. (1974). Dynamics of pulmonary gas exchange and heart rate exchanges at the start and end of exercise. *Acta Physiologica Scandinavica* 415: 1-68.

Massin M, Derkenne B, Leclercq-Foucart J, Sacre J-P, Chantraine J-M. (1998). Oxygen uptake kinetics during PRBS exercise in children. *Cardiovascular Engineering* 3(1): 16-21.

Massin MM, Leclercq-Foucart J, Sacre J-P. (2000). Gas exchange and heart rate kinetics during binary sequence exercise in cystic fibrosis. *Medical Science Monitor* 6(1): 55-62.

McArdle WD, Glaser RM, Magel JR. (1971). Metabolic and cardiorespiratory response during free swimming and treadmill walking. *Journal of Applied Physiology* 30: 733-738.

Nicholas CW, Nuttall FE, Williams C. (2000). The Loughborough Intermittent Shuttle Test: A field test that simulates the activity pattern of soccer. *Journal of Sports Sciences* 18: 97-104.

Nicholas CW, Williams C, Lakomy HKA, Phillips G, Nowitz A. (1995). Influence of ingesting a carbohydrate-electrolyte solution on endurance capacity during intermittent, high-intensity shuttle running. *Journal of Sports Sciences* 13: 283-290.

Nummela A, Alberts M, Rjintjes RP, Luhtanen P, Rusko H. (1996). Reliability and validity of the maximal anaerobic running test. *International Journal of Sports Medicine* 17: S97-S102.

Pechar GS, McArdle WD, Katch FI, Magel JR, DeLuca J. (1974). Specificity of cardiorespiratory adaptation to bicycle and treadmill training. *Journal of Applied Physiology* 36 (6): 753-756.

Phillips SM, Green HJ, MacDonald MJ, Hughson RL. (1995a). Progressive effect of endurance training on $\dot{V}O_2$ kinetics at the onset of submaximal exercise. *Journal of Applied Physiology* 79: 1914-1920.

Phillips SM, Green HJ, Tarnopolsky MA, Grant SM. (1995b). Increased clearance of lactate after short term training in men. *Journal of Applied Physiology* 79: 1862-1869.

Powers SK, Dodd S, Beadle RE. (1985). Oxygen uptake kinetics in trained athletes differing in $\dot{V}O_2$ max. *European Journal of Applied Physiology* 54: 306-308.

Pringle JS, Doust JH, Carter H, Tolfrey K, Campbell IT, Jones AM. (2003). Oxygen uptake kinetics during moderate, heavy and severe intensity 'submaximal' exercise in humans: the influence of muscle fibre type and capillarisation. *European Journal of Applied Physiology* 89(3-4): 289-300.

Ramsbottom R, Brewer J, Williams C. (1988). A progressive shuttle run test to estimate maximal oxygen uptake. *British Journal Sports Medicine* 22: 141-144.

Reilly T, Bangsbo J, Franks A. (2000). Anthropometric and physiological predispositions for elite soccer. *Journal of Sports Sciences* 18(9): 669-683.

Rossiter HB, Ward SA, Doyle VL, Howe FA, Griffiths JR, Whipp BJ. (1999). Inferences from pulmonary O_2 uptake with respect to intramuscular [phosphocreatine] kinetics during moderate exercise in humans. *Journal of Physiology* 518 (3): 921-932.

Saltin B, Henriksson J, Nygaard E, Andersen P, Jansson E. (1977). Fibre types and metabolic potentials of skeletal muscles in sedentary man and endurance runners. *Annals New York Academy of Sciences* 301: 3-29.

Saltin B, Nazar K, Costill DL, Stein E, Jansson E, Essen B, Gollnick PD. (1976). The nature of the training response: peripheral and central adaptations to one-legged exercise. *Acta Physiologica Scandinavica* 96: 289-302.

Stegemann J, Hoffmann U, Erdmann R, Eβfeld D. (1997). Exercise capacity during and after spaceflight. *Aviation, Space, and Environmental Medicine* 68(9): 812-817.

Stegemann J, Eβfeld D, Hoffmann U. (1985). Effects of a 7-day head-down tilt (-6^{O}) on the dynamics of oxygen uptake and heart rate adjustment in upright exercise. *Aviation, Space and Environmental Medicine*: 410-414.

Toner M, Sawka MN, Levine L, Pandolf KB. (1983). Cardiorespiratory responses to exercise distributed between the upper and lower body. *Journal of Applied Physiology* 54: 1403-1407.

Tschakovsky ME, Hughson RL. (1999). Interaction on factors determining oxygen uptake at the onset of exercise. *Journal of Applied Physiology* 86(4): 1101-1113.

Tumilty D. (1993). Physiological characteristics of elite soccer players. *Sports Medicine* 16(2): 80-96.

Whipp B J, Rossiter HB, Ward SA, Avery D, Doyle VL, Howe FA, Griffiths JR. (1999). Simultaneous determination of muscle ^{31}P and O_2 uptake kinetics during whole body NMR spectroscopy. *Journal of Applied Physiology* 86(2): 742-747.

Whipp B J, Ward SA, Lamarra N, Davis JA, Wassermann K. (1982). Parameters of ventilatory and gas exchange dynamics during exercise. *Journal of Applied Physiology* 52: 1506-1513.

Whipp B.J, Wasserman K. (1972). Oxygen uptake kinetics for various intensities of constant-load work. *Journal of Applied Physiology* 33: 351-356.

Wragg CB, Maxwell NS, Doust JH. (2000). Evaluation of the reliability and validity of a soccer-specific field test of repeated sprint ability. *European Journal of Applied Physiology* 83(1): 77-83.

Zhang YY, Johnson IMC, Chow N, Wasserman K. (1991). The role of fitness on $\dot{V}O_2$ and $\dot{V}CO_2$ kinetics in response to proportional step increases in work rate. *European Journal of Applied Physiology* 63: 94-100.

Zhang YY, Wasserman K, Sietsema KE, Barstow T, Mizumoto G, Sullivan CS. (1993). O_2 uptake kinetics in response to exercise: A measure of tissue anaerobiosis in heart failure. *Chest* 103: 735-741.