# OXYGEN UPTAKE DURING MIDDLE DISTANCE RUNNING

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# ABSTRACT

This thesis aimed to establish criteria for defining $\dot{V}O_{2max}$, and to investigate test-retest reliability, test duration, event specialism and pacing strategy as determinants of the % $\dot{V}O_{2max}$ attained during 400 and 800 m running.

Study I established criteria to define $\dot{V}O_{2max}$. Each participant (n = 8) completed four ramp tests. $\dot{V}O_2$ was determined using 15 and 45 s sampling periods. A $\dot{V}O_2$-plateau and a criterion $\dot{V}O_{2max}$ were identified using a modelling approach. For the 15 s data, two averaging methods and periods were used to define the highest $\dot{V}O_2$ attained ($\dot{V}O_{2peak}$) and the criterion validity and test-retest reliability of these were derived. A $\dot{V}O_2$-plateau was identified in all participants for both the 15 and the 45 s data. Bias between $\dot{V}O_{2peak}$ and the criterion $\dot{V}O_{2max}$ was less than 0.9 $ml.kg^{-1}.min^{-1}$. Test-retest variation in $\dot{V}O_{2peak}$ was less than ± 1 $ml.kg^{-1}.min^{-1}$ for 30 s averages for a $\dot{V}O_{2peak}$ of 70 $ml.kg^{-1}.min^{-1}$. It was concluded that deriving $\dot{V}O_{2peak}$ using a 30 s moving average is both valid and reliable for the determination of $\dot{V}O_{2max}$.

Study II investigated test-retest reliability and $\dot{V}O_{2max}$ as determinants of the % $\dot{V}O_{2max}$ attained during 800 m running. Each participant (n = 15) completed a ramp test and two 800 m runs. Participants were split into high and low $\dot{V}O_{2max}$ groups. $\dot{V}O_{2peak}$ was reliable in both groups but more so in the high $\dot{V}O_{2max}$ group (±2.3 vs. ± 3.5 $ml.kg^{-1}.min^{-1}$). There was a significant ($p = 0.001$) negative correlation ($r = -0.77$) between $\dot{V}O_{2max}$ and the % $\dot{V}O_{2max}$ attained. The % $\dot{V}O_{2max}$ attained by the low $\dot{V}O_{2max}$ group was significantly ($p < 0.001$) higher than for the high group (96.5 vs. 89.7%). It was concluded that $\dot{V}O_{2max}$ cannot be attained by aerobically fit runners during 800 m running and that the % $\dot{V}O_{2max}$ attained is negatively related to $\dot{V}O_{2max}$.

Study III investigated test duration and event specialism as determinants of the % $\dot{V}O_{2max}$ attained during 400 and 800 m running. Six 800 m specialists completed a ramp test, a 400 and an 800 m run. Six 400 m specialists completed a ramp test and a 400 m run. The % $\dot{V}O_{2max}$ attained was significantly ($p = 0.018$) higher for the 800 than for the 400 m run (89.1 vs. 85.7%). The % $\dot{V}O_{2max}$ attained was significantly ($p = 0.001$) higher for the 400 m specialists than for the 800 m specialists during the 400 m run (93.9 vs. 85.7%). It was concluded that there is a between-event (but within group) difference in the % $\dot{V}O_{2max}$ attained by 800 m specialists during 400 and 800 m running. However, there is also a between-group (but within event) difference in the % $\dot{V}O_{2max}$ attained between 400 and 800 m specialists during 400 m running.

Study IV investigated pacing strategy as a determinant of the % $\dot{V}O_{2max}$ attained during 800 m running. Participants (n = 8) completed a ramp test, constant speed accelerated start, and accelerated fast-start 800 m runs. The % $\dot{V}O_{2max}$ attained was significantly ($p = 0.048$) higher for the fast-start run compared to the constant one (92.5 vs. 89.3%). It was concluded that pacing strategy is an important determinant of the % $\dot{V}O_{2max}$ attained during 800 m running.

In conclusion, this thesis has shown that the determinants of the % $\dot{V}O_{2max}$ attained during 400 and 800 m running are more complex than previously reported. The % $\dot{V}O_{2max}$ attained varies within (i.e. as a function of aerobic fitness) and between 400 and 800 m running for 800 m specialists, between 400 and 800 m specialists for 400 m running, and in response to different pacing strategies during 800 m running. It was beyond the scope of this thesis to identify mechanisms that may explain these findings. However, there appears to be a potential link with differences in aerobic fitness between and within event specialists and how these differences may influence the $\dot{V}O_2$ response to severe intensity exercise.

## DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of the University of Gloucestershire and is original except where indicated by specific reference in the text. No part of the thesis has been submitted as part of any other academic award. The thesis has not been submitted to any other education institution in the United Kingdom or oversees.

**ANY VIEWS EXPRESSED IN THIS THESIS ARE THOSE OF THE AUTHOR AND IN NO WAY REPRESENT THOSE OF THE UNIVERSITY.**

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# *PART I*

# *STATEMENT OF THE PROBLEM AND REVIEW OF LITERATURE*

# CHAPTER 1

# INTRODUCTION

In 1913 the formation of the International Amateur Athletic Federation (IAAF) signalled the introduction of a rigorous system for measuring, verifying and recording world record performances (Schutz and Lui, 1998). It was the foundation for a rich source of accurate and precise time-distance data that were collected under constant and controlled conditions and recorded with a high resolution (0.01 s). As these data accumulated during the twentieth century a series of mathematical analyses materialized, modelling the relationship of past, and predicted future, performances with time (Blest, 1996; Chatterjee and Chatterjee, 1982; Deakin, 1967; Kennelly, 1926; Meade, 1916; Morton, 1984; Rumball and Coleman, 1970; Ryder et al., 1976; Schutz and Lui, 1993; Smith, 1988).

Modelling world running records was not simply restricted to analysing the relationships between record performances and time. Indeed, A. V. Hill (1925a) stated that "some of the most consistent physiological data available are contained, not in books on physiology, not even in books on medicine, but in the world's records for running different distances" (p 98). Thus, these data provoked an interest in modelling energy supply during running to explain the physiological basis for these records. In 1923 Hill and Lupton proposed the first model of middle-distance running based on two sources of energy supply: the maximum oxygen intake and the maximum oxygen debt.

Various authors (Di Prampero et al., 1993; Henry, 1954; Lloyd, 1966, 1967; Péronnet and Thibault, 1989; Sargent, 1926; Ward-Smith, 1985, 1999; Wood, 1999a) have since developed Hill and Lupton's (1923) original model, yet no additional sources of energy supply have been introduced. Indeed, if it is accepted that maximum oxygen uptake ($\dot{V}O_{2max}$) is synonymous with maximum oxygen intake and that the oxygen equivalent of the anaerobic capacity is synonymous with the maximum oxygen debt, it can be concluded that contemporary models (Di Prampero et al., 1993; Péronnet and Thibault, 1989; Ward-Smith, 1985, 1989; Wood, 1999a) are, at least conceptually, the same as

Hill and Lupton's (1923) traditional model. What has changed, however, is the way in which these sources of energy supply are modelled and, in turn, the assumptions that are made.

The models of middle-distance running performance each contain a set of parameters. Assumptions are then made about these parameters and values are ascribed to the parameters in order to assess the accuracy of the models. An important parameter common to the models is an asymptote for the $\dot{V}O_2$ attained during middle-distance running. Arguably the most critical, and most widely accepted, assumption underpinning this parameter is that the asymptote is the maximum oxygen uptake (i.e. $\dot{V}O_{2max}$) and that this asymptote will either be simply attained or that $\dot{V}O_2$ will rise towards it and be attained, providing the duration is sufficient, for all middle-distance running events (i.e. 400 to 3000 m) (Di Prampero et al., 1993; Henry, 1954; Hill and Lupton, 1923; Lloyd, 1966, 1967; Sargent, 1926; Ward-Smith, 1985).

Since middle-distance events are performed at an intensity that is considered to be in the severe intensity domain [i.e. above the 'fatigue threshold', which typically occurs halfway between the lactate threshold and $\dot{V}O_{2max}$ (Ward, 1999)], this assumption is in accordance with the view of many influential physiologists (Di Prampero and Ferretti, 1999; Gaesser and Poole, 1996; Ward, 1999; Whipp, 1994) that provided the exercise duration is sufficient, severe intensity exercise will always result in the achievement of $\dot{V}O_{2max}$ (Gaesser and Poole, 1996). The assumption is also supported by two recent studies (Hill and Ferguson, 1999; Williams et al., 1998) in which $\dot{V}O_{2max}$ was apparently attained during short exhaustive running bouts equivalent to middle-distance events.

However, two models (Péronnet and Thibault, 1989; Ward-Smith, 1999) assume that the asymptote parameter for the $\dot{V}O_2$ attained will be below $\dot{V}O_{2max}$ for the 3000 m event. Additionally, Wood (1999a) assumes that this asymptote parameter will be below $\dot{V}O_{2max}$ in the 400, 800 and 1500 m events and that it will only be $\dot{V}O_{2max}$ in the 3000 m event. These assumptions oppose the widely accepted view that $\dot{V}O_{2max}$ will be attained during all exercise bouts equivalent to middle-distance events. However, these assumptions receive support from two recent studies by Spencer et al. (1996) and

Spencer and Gastin (2001). These studies show that $\dot{V}O_2$ rises to an asymptote of 88 to 94% and 90 to 94% $\dot{V}O_{2max}$ during the 800 and 1500 m events, respectively. Furthermore, inspection of the Hill and Ferguson (1999) and the Williams et al. (1998) data, which were interpreted by the authors as providing support for the assumption that $\dot{V}O_{2max}$ is attained, reveals that the highest $\dot{V}O_2$ attained was in fact 5% lower for a run which lasted ~2 min than for one which lasted ~5 min.

Typically the values ascribed to the parameters in the models are based on data determined from constant speed running. Constant speed test protocols have been used with the motorised treadmill to simulate track running and the laboratory has been used to provide a controlled environment (e.g. Spencer et al., 1996). However, constant speed test protocols fail to simulate important elements of middle-distance track races and hence may compromise the ecological validity of the data on which the values ascribed to the parameters in the models are based. Importantly, the acceleration phase that occurs at the start of every track race, and represents a significant portion of the total duration for a middle-distance race, is ignored when such a protocol is used, as is the influence of pacing strategy.

The accuracy of the models has typically been assessed by comparing the predicted performance times from the models with World Record times for each of the middle-distance events (Di Prampero et al., 1993; Henry, 1954; Hill and Lupton, 1923; Péronnet and Thibault, 1989; Sargent, 1926; Ward-Smith, 1985, 1999). Since the assumptions underpinning the parameters in the models may cancel one another out, the models may yield accurate predictions despite each parameter being less meaningful when considered alone. Hence, the accuracy of the models' predictions does not guarantee that each parameter in the models is accurately represented or physiologically meaningful. For example, a model that assumes an asymptote below $\dot{V}O_{2max}$ for the $\dot{V}O_2$ attained following a rapid rise in $\dot{V}O_2$ during the 800 m event may yield a similar value for the total amount of $O_2$ used as a model that assumes a relatively slow rise, but that the asymptote for the $\dot{V}O_2$ attained is $\dot{V}O_{2max}$. Such a model would, therefore, yield an accurate prediction of performance, assuming that the other parameters are accurate. However, it would fail to accurately represent the rate of rise in $\dot{V}O_2$ and the $\dot{V}O_2$ attained.

It is important that these assumptions are addressed if models of middle-distance running performance are to be meaningfully applied. Practitioners use these models to determine which variables they should focus on when they conduct a physiological assessment of a middle-distance runner and which variables they should encourage such a runner to target in training. Researchers use them to ensure that the research they conduct has as its focus those factors that are most likely to exert a meaningful effect on performance in middle-distance running. To ensure that the application of these models is meaningful, it is imperative that the ecological validity of the data on which the values ascribed to the parameters in the models are based and the assumptions underpinning these parameters is addressed.

The aims of this thesis were:

1. to establish criteria for defining $\dot{V}O_{2max}$ both validly and reliably;
2. to determine the test-retest reliability in the highest $\dot{V}O_2$ attained during a simulated middle-distance run;
3. to investigate how the duration of the run affects the highest $\dot{V}O_2$ attained;
4. to investigate how event specialism affects the highest $\dot{V}O_2$ attained during a simulated middle-distance run;
5. to investigate how an acceleration phase and pacing strategy affects the highest $\dot{V}O_2$ attained during such a run.

Data showing that the asymptote for the $\dot{V}O_2$ attained is $\dot{V}O_{2max}$ during exercise bouts equivalent to middle-distance events would support the assumption common to most models of performance (Di Prampero et al., 1993; Henry, 1954; Hill and Lupton, 1923; Lloyd, 1966, 1967; Sargent, 1926; Ward-Smith, 1985). Alternatively, data showing that the asymptote for the $\dot{V}O_2$ attained is below $\dot{V}O_{2max}$ during bouts equivalent to the shorter middle-distance events would support the assumption in Wood's (1999a) model. In addition, if it could be demonstrated that the highest $\dot{V}O_2$ attained during a constant speed test protocol does not accurately reflect the highest $\dot{V}O_2$ attained during a protocol that simulates the speed profile of a middle-distance track race, the ecological validity of the data on which the values ascribed to the parameters in the models are based would be questioned. Alternatively, were the highest $\dot{V}O_2$ attained similar for both these protocols, the ecological validity of these data would be established.

There are four parts to this thesis. Part I reviews the literature on models of middle-distance running performance: it raises the assumptions underpinning the parameters in the models (chapter 2) and addresses the validity of these assumptions (chapter 3). Part II covers methodological considerations for the determination of $\dot{V}O_2$ (chapters 4 and 5), and includes a study (chapter 6) that addresses the first aim of the thesis. Part III investigates $\dot{V}O_2$ during middle-distance running and comprises three studies (chapters 7 to 9) that address the remaining aims (2 to 5) of the thesis. Finally, in Part IV, the findings are discussed (chapter 10) and recommendations are given for modelling energy supply during middle-distance running events (chapter 11).

# CHAPTER 2

# HISTORICAL PERSPECTIVES ON MODELLING THE ENERGETICS OF MIDDLE-DISTANCE RUNNING: RAISING THE ASSUMPTIONS

## 2.1 Modelling the energetics of running

### *2.1.1 Methods and formulae*

A common method of modelling running performance, which has been used throughout the twentieth century, is based on energy considerations (Di Prampero et al., 1993; Henry, 1954; Hill and Lupton, 1923; Lloyd, 1966, 1967; Péronnet and Thibault, 1989; Sargent, 1926; Ward-Smith, 1985, 1999; Wood, 1999a). The foundation for this method is the relationship that exists between the energy that is available, and supplied, to a runner and the related energy cost or requirement of the running bout: it is assumed that a balance can be established between the energy supplied and the energy cost, and that this balance can be used to predict performance. Models using this approach collectively assume that the energy supplied to a runner is based on two sets of parameters: the first set represents the energy available from a fixed store, which is synonymous with anaerobic metabolism, and the second set represents energy supplied at a rate, synonymous with aerobic metabolism.

However, these models differ in the way in which assumptions have been made about the parameter representing the energy cost of running: some assume a fixed value per metre travelled that is independent of speed (Di Prampero et al., 1993; Lloyd, 1966, 1967; Péronnet and Thibault, 1989; Ward-Smith, 1985, 1999) while others (Henry, 1954; Hill and Lupton, 1923; Sargent, 1926) assume a non-linear relationship between the energy cost and speed (i.e. the energy cost is dependent on speed). Additionally, different assumptions have been made about the effect of air resistance and accelerating the body from a stationary position, on the energy cost of running.

Since the parameter representing the energy cost of running allows predictions of performance to be made, it is an important part of the modelling process. However, it is beyond the scope of this thesis to review the assumptions associated with this parameter in addition to those associated with modelling energy supply. Rather, the focus of this thesis is on the parameters representing energy supply and the predicted performances associated with each model will be included only to illustrate the accuracy with which they make such predictions.

The models have been presented in the literature as mathematical formulae, but there has been no consistency in the form or presentation of these. Thus, the different forms of the mathematical expressions used to denote the relationship between the parameters representing energy supply in the models, at times, causes confusion. This makes it difficult to assess the different assumptions underpinning these parameters. Therefore, all formulae have been rearranged and presented in a consistent form in this chapter. In doing so, it is hoped that the development of the parameters in the models, and assumptions underpinning these parameters, will become clearer at the expense of being consistent with the way in which they have been presented in the literature.

### *2.1.2 Terminology*

Despite the models collectively using a set of parameters representing a fixed store of available energy and a set to represent a rate of energy supply, various terms have been used to denote these parameters. This inconsistency may also, therefore, cause confusion when comparing the parameters in the models. Early models (Henry, 1954; Hill and Lupton, 1923: Sargent, 1926) included the term oxygen intake to denote the rate at which the body uses oxygen (i.e. aerobic metabolism). They used this term, however, in a way that suggests that they were in fact referring to oxygen uptake ($\dot{V}O_2$), the term used by contemporary physiologists. Likewise, such models used the term oxygen debt to denote the total volume of oxygen used in the recovery from exercise in the belief that this reflected a store of anaerobically derived energy (i.e. anaerobic metabolism). This encapsulated the notion of a fixed store of available energy and, is conceptually, equivalent to the anaerobic capacity term used presently.

Moreover, the remaining models used a variety of terms to denote both the parameters representing the store of available energy and those representing the rate of energy supply. These models also differed in the measurement units associated with the parameters: some used kilocalories while others used oxygen equivalents. To overcome these problems, a single set of terms, and associated measurement units, will be used in this chapter to represent the parameters in the models (see section 2.1.3). The basis for these terms is similar to that in the models, defining a store (S), a rate (R), and the aerobic (Ae) and anaerobic (An) sources of energy supply.

*2.1.3 Terms*

The following terms have been adopted for this part of the thesis to denote the parameters in models of middle-distance running performance. All terms that are expressed relative to body mass are oxygen equivalents.

| | | |
|---|---|---|
| $D_{Fs_{An_{MAX}}}$ | Decline rate of $Fs_{An_{MAX}}$ with In T when T > $T_{R_{Ae_{MAX}}}$ | |
| $D_{FR_{Ae_{MAX}}}$ | Decline rate of $FR_{Ae_{MAX}}$ (ml.kg$^{-1}$.min$^{-1}$) with In T when T > $T_{R_{Ae_{MAX}}}$ | |
| $FR_{Ae_{MAX}}$ | Fraction of $R_{Ae_{MAX}}$ attained: fraction of $\dot{V}O_{2max}$ above resting attained | |
| $Fs_{An_{MAX}}$ | Fraction of $S_{An_{MAX}}$ used: fraction of the maximum anaerobic capacity used | |
| $R_{Ae}$ | Rate of aerobic energy supply above rest: $\dot{V}O_2$ above resting | (ml.kg$^{-1}$.min$^{-1}$) |
| $R_{Ae_{MAX}}$ | Maximum $R_{Ae}$: maximum $\dot{V}O_2$ above resting ($\dot{V}O_{2max}$) | (ml.kg$^{-1}$.min$^{-1}$) |
| $R_{Ae_{SS}}$ | Steady state $R_{Ae}$: steady state $\dot{V}O_2$ above resting | (ml.kg$^{-1}$.min$^{-1}$) |
| $R_{Ae}(t)$ | $R_{Ae}$ at t: $\dot{V}O_2$ above resting at t | (ml.kg$^{-1}$.min$^{-1}$) |
| $R_{TOT}$ | Average rate of total energy supply, above resting, over T | (ml.kg$^{-1}$.min$^{-1}$) |
| $S_{An}(T)$ | Store of anaerobic energy available for T: anaerobic capacity | (ml.kg$^{-1}$) |
| $S_{An_{MAX}}$ | Maximum store of $S_{An}(T)$: maximum anaerobic capacity | (ml.kg$^{-1}$) |
| T | Race duration | (min) |
| $T_{R_{Ae_{MAX}}}$ | Maximal race duration for which $R_{Ae_{MAX}}$ can be sustained | (min) |
| t | Time elapsed from the start of the race | (min) |
| $\tau_{Ae}$ | Time constant for the kinetics of $R_{Ae}$ at the race onset | (min) |
| $\tau_{An}$ | Time constant for the depletion of $S_{An}(T)$ | (min) |

## 2.2 The pioneering work of A. V. Hill and his colleagues

### *2.2.1 Background*

Throughout the 1920s Archibald Vivian Hill pioneered theories on the physiology of middle-distance running. Having been a prominent physiologist and a competent middle-distance runner, Hill was intrigued by the emerging world record performance data in athletics. In particular, he was interested in explaining "... the factors determining the variation of speed with distance" (1925b, p. 5323). He acknowledged the advantages of studying athletics: "the processes of athletics are simple and measurable" and "athletes themselves ... can be experimented on without danger and can repeat their performances exactly again and again" (Hill, 1927, p. 3). And perhaps equally important, he believed "that the study of athletes and athletics is 'amusing' " (Hill, 1927, p. 3).

In 1922 Hill began a series of studies on the physiology of severe intensity exercise with several colleagues, including H. Lupton, C. N. H. Long, and K. Furusawa (Furusawa et al., 1924; Hill et al., 1924a, b; Hill and Lupton, 1922, 1923). These studies provided the foundation for Hill's theories on the physiology of running and he presented and developed these theories in later lectures (Hill, 1925a, 1927, 1933). The theories were based on the concept of a maximum oxygen uptake ($\dot{V}O_{2max}$), which would be attained during middle-distance races, and a maximum oxygen debt. Hill and Lupton (1923) showed that as long as these are known for a given individual it is possible to calculate the total energy supply for any race distance between 0.25 and two miles (i.e. for any middle-distance event). In turn, they predicted the highest speed that this individual will be able to sustain for these event distances. Thus, effectively, they defined the first model of middle-distance running with two parameters representing energy supply: one representing an asymptote for the highest $\dot{V}O_2$ attained (equivalent to the contemporary concept of $\dot{V}O_{2max}$) and the second representing a store of energy derived from anaerobic metabolism (equivalent to the contemporary concept of anaerobic capacity).

### *2.2.2 The concept of an attainable $\dot{V}O_2$*

In their early studies Hill's group (Hill et al., 1924b; Hill and Lupton, 1922, 1923) determined the $\dot{V}O_2$ that could be attained during a series of constant speed runs around a circular grass track (84.5 m in circumference). The subjects carried a Douglas bag, together with the associated valves and taps, while they ran to allow the collection of expirate. This combined mass of ~ 5 kg (Sargent, 1926) would have increased the energy cost of running at a given speed, something which Hill and Lupton (1923) acknowledged.

Using this procedure, Hill and Lupton (1923) determined $\dot{V}O_2$ over a series of 30 s collection intervals from the onset of, and throughout, various constant speed runs. They showed that $\dot{V}O_2$ "rises rapidly from the start, reaching its final exercise value in 100 to 150 secs., and half its final value in about 25 secs" (p. 150) and that this final $\dot{V}O_2$ increased with an increase in the running speed. However, at the highest running speeds "the fact that the intake of oxygen has reached a constant value within 2½ min. represents nothing more than the fact that its maximum level has been attained" (p. 151). Hill and Lupton then suggested that "there is clearly some critical speed for each individual, below which there is a dynamic equilibrium ... above which, however, the maximum oxygen intake is inadequate" (p. 151) and that "However much the speed be increased beyond this limit, no further increase in oxygen intake can occur: the heart, lungs, circulation, and the diffusion of oxygen to the active muscle fibres have attained their maximum activity" (p. 156).

Hill and Lupton (1923) therefore proposed that there is a maximum $\dot{V}O_2$ (i.e. a $\dot{V}O_{2max}$). Hill et al. (1924b) tried to confirm this by determining $\dot{V}O_2$ across a range of running speeds for six subjects, three of whom were the authors of the paper. These data are important because at no other time did Hill's group present data on the relationship between $\dot{V}O_2$ and running speed for a range of speeds and a range of subjects. They fitted the entire set of data with a function that reached an asymptote at a $\dot{V}O_2$ of 4 $l.min^{-1}$. They scaled the data on two of their subjects (C.N.H.L. and H.L.), who had body masses of 68 and 58 kg respectively, "to the same body weight as Hill's before plotting" (p. 156) to allow these data to be compared with the corresponding data for Hill and the other three subjects (all of whom had a body mass of ~ 73 kg). They provided no details of how they actually did this scaling.

On the basis of these data, Hill et al. (1924b, pp. 156-157) concluded that "at high speeds ... the oxygen intake attains its maximum value, which in athletic individuals of about 73 kg ... is strikingly constant (in the case of running) at about 4 litres per minute. The oxygen intake fails to exceed this value, not because more oxygen is not required, but because the limiting capacity of the circulatory-respiratory system has been attained". They made no attempt to determine $\dot{V}O_2$ at speeds above 18 $km.h^{-1}$, partly because "greater speeds were not comfortable" on their small grass track, and partly because "much higher speeds could not be maintained long enough to allow a sufficient fore period and collection interval" (p. 157): they could not be maintained long enough for a steady state to be attained. They then added (p. 157) that "the form ... of the oxygen intake curve ..., approaching a constant level of 4 litres per minute, makes it obvious that no useful purpose would be served by investigating higher speeds in this way".

Hill's group did much more than present the idea of a $\dot{V}O_{2max}$. Indeed, they also speculated on what factors might limit this $\dot{V}O_{2max}$: "The chief determining factor ... in the oxygen intake is the rate of circulation of the blood" (Hill et al., 1924b, p. 165). They went so far as to calculate that a cardiac output of ~ 30 $l.min^{-1}$ would be required to support a $\dot{V}O_{2max}$ of 4 $l.min^{-1}$. Moreover, they proposed a method for quantifying how energy could be provided, in the absence of $O_2$ (i.e. the oxygen debt), above the critical speed that elicits $\dot{V}O_{2max}$.

### *2.2.3 The concept of an oxygen debt*

The concept of an oxygen debt was first introduced by Hill and Lupton (1922), and the same authors later outlined how this oxygen debt could be determined by monitoring the amount of oxygen used in the initial stages of recovery from a given exercise bout (Hill and Lupton, 1923). Hill et al. (1924a) and Furusawa et al. (1924) elaborated on the procedures involved, explaining that the oxygen debt should be calculated as the difference between the total volume of $O_2$ used during the first 30 min of recovery and that which would have been used during this period had the subject been at rest (i.e. the total volume of $O_2$ used, above resting, during the first 30 min of recovery).

The general assumption implicit in this approach is that, for a given exercise bout, the volume of $O_2$ taken up, above resting, during recovery represents the extent to which energy is derived from anaerobic metabolism during the exercise. Specifically, the assumption is that the amount of energy derived from anaerobic metabolism during exercise (expressed as an $O_2$ equivalent) and the amount of excess $O_2$ used during recovery are equal.

Hill's group never actually used the term 'anaerobic metabolism. However, they did propose that there is an upper limit to the oxygen debt that an individual can incur (i.e. a maximum oxygen debt). It seems reasonable to argue that their maximum oxygen debt was equivalent, conceptually at least, to a maximum store of anaerobically derived energy (i.e. an anaerobic capacity).

*2.2.4 The first physiological model of middle-distance running performance*

Hill and Lupton (1923) did calculations, using data that they had collected on Hill himself, to derive a model describing energy supply for race distances from 0.25 to 2 miles (400 to 3200 m). Though they never formally presented these calculations in a model, it is given by:

$$R_{TOT} = \frac{S_{An_{MAX}}}{T} + R_{Ae_{MAX}} \qquad (1)$$

where $R_{TOT}$ ($ml.kg^{-1}.min^{-1}$) is the average rate of energy supply, above resting, over T; $S_{An_{MAX}}$ ($ml.kg^{-1}$) is the maximum store of anaerobic energy available for T; T is the race duration (min); and $R_{Ae_{MAX}}$ ($ml\,O_2\,kg^{-1}.min^{-1}$) is the asymptote for the highest $\dot{V}O_2$ attained above resting (i.e. $\dot{V}O_{2max}$ above resting).

They ascribed values of 137 $ml.kg^{-1}$ to $S_{An_{MAX}}$ and 55 $ml.kg^{-1}.min^{-1}$ to $R_{Ae_{MAX}}$. They chose this value for $S_{An_{MAX}}$ simply because it was close to the highest oxygen debt value that they had observed at the time the paper was written. In a later paper (Hill et al., 1924a) they report a maximum oxygen debt of 150 $ml.kg^{-1}$ for Hill. In selecting a value for $R_{Ae_{MAX}}$ they considered the fact that the race times they used were achieved by Hill some 10 years prior to the experiments they reported. The highest $\dot{V}O_{2max}$ attained by Hill in their experiments was ~ 52 $ml.kg^{-1}.min^{-1}$, and the value they used in their calculations was 3 $ml.kg^{-1}.min^{-1}$ higher than this. They assumed, therefore, that Hill's $\dot{V}O_{2max}$ had declined since his best times were recorded. Furthermore, they assumed that $S_{An_{MAX}}$ and $R_{Ae_{MAX}}$ would be attained during all middle-distance event durations, and that $R_{Ae_{MAX}}$ would be attained immediately at the start of the exercise. Importantly, they assumed that the highest $\dot{V}O_2$ attained would be $\dot{V}O_{2max}$ (i.e. $R_{Ae_{MAX}}$) during all middle-distance events and that $\dot{V}O_{2max}$ would be attained immediately at the start of these events.

Hill and Lupton (1923) predicted the running speed that would be associated with $R_{TOT}$ for a range of middle-distance event durations. In doing so, they found that the speeds they obtained were lower than those that Hill had actually sustained. To resolve this, they suggested "that the respiration apparatus used in the experiments ... offered a definite, if small, hindrance to movement, and we may allow for this provisionally by assuming that ... the speed is reduced 15 per cent by the apparatus carried" (p. 159). It is apparent that carrying the respiratory apparatus would have affected the efficiency with which Hill could have run (see section 2.2.2) and their adjustment appears reasonable. However, they provided no rationale for why a value of 15% should be used.

For the range of middle-distance events that Hill and Lupton (1923) examined, the agreement between Hill's actual and predicted performance times is shown in table 2.1 (the predicted times shown here were subsequently corrected, as described above, to compensate for Hill carrying the respiratory apparatus). On the basis of these data, they concluded "that the maximum duration of an effort of given intensity is related *to the intensity in a manner depending simply upon the supply of oxygen, actual or potential* (their emphasis), i.e. upon the maximum rate of oxygen intake and the maximum oxygen debt of the subject in question" (p. 159).

**Table 2.1 Actual vs. predicted times for race distances from 0.25 to 2 miles (Hill and Lupton, 1923)**

| | Race Distance (miles) | | | | |
|---|---|---|---|---|---|
| | 0.25 | 0.33 | 0.50 | 1.00 | 2.00 |
| Actual (A) Time (s) | 53 | 77 | 123 | 285 | 630 |
| Predicted (P) Time (s) | 62 | 90 | 145 | 341 | 743 |
| A:P | 1.17 | 1.17 | 1.18 | 1.20 | 1.18 |

## 2.3 Modelling the rise in $\dot{V}O_2$ at the start of exercise: the developments of Sargent, Simonson, and Henry

### *2.3.1 The limitation of Hill and Lupton's (1923) model*

Hill (1925b) acknowledged that his assumption that $\dot{V}O_2$ rises to its maximum immediately at the onset of exercise was false: "for a more accurate calculation the gradual rise of the oxygen intake at the beginning of exercise can be taken into account" [p. 482 (footnote)]. In 1922 Hill and Lupton had determined $\dot{V}O_2$, using 30 s samples, at the onset of running "... to determine the rate at which the oxygen usage rises to its steady value ..." (p. xxxii). They observed that $\dot{V}O_2$ "rises exponentially from the start, reaching a steady value within two minutes, the total deficit at the beginning of exercise being compensated in the early stages of recovery" (p. xxxii). Therefore, Hill and Lupton (1922) knew, and possessed data which showed, that $\dot{V}O_2$ rises exponentially at the onset of running, but they neither used these data in their model of running performance nor expressed this relationship mathematically.

Hill and Lupton (1923) could, therefore, have included a parameter in their model to represent the rise in $\dot{V}O_2$ to its maximum. The fact that they acknowledged that this would be necessary for an accurate calculation of the rate of aerobic energy supply suggests that they chose to simplify their model. In 1926 Sargent published a report of an experiment in which he attempted to circumvent not only the problems associated with the assumption that the parameter representing the highest $\dot{V}O_2$ attained is reached immediately during running but also those associated with carrying the respiratory apparatus.

*2.3.2 Accounting for the rise in $\dot{V}O_2$ in the calculation of $R_{TOT}$*

Sargent tested one subject (N), a well-trained middle-distance runner, who completed a set distance (110 m) at a series of constant speeds. The subject did not carry any respiratory apparatus; rather, he held his breath while he ran. The mouthpiece was handed to him as soon as he stopped running, and his expirate was collected for the first 30 to 60 min of recovery. For each speed Sargent determined the $\dot{V}O_2$ and oxygen debt associated with the exercise; he then modelled $R_{TOT}$ in the same way as Hill's group [see equation (1)].

However, in doing so, Sargent accounted for the rise in $\dot{V}O_2$ at the onset of running. He determined the rate of rise in $\dot{V}O_2$, in the same way that Hill's group had previously done (see section 2.2.2), over varying successive time intervals from the start of exercise, assuming that the rate of this rise was the same for all race durations. These data were plotted ($\dot{V}O_2$ vs. the mid-point of the time interval) and Sargent derived a smoothed curve relating $\dot{V}O_2$ to time for the first three minutes of exercise. This curve was then used to calculate the rise in $\dot{V}O_2$ to the parameter representing the highest $\dot{V}O_2$ attained. Sargent (1926) assumed that this parameter would be $\dot{V}O_{2max}$ and he ascribed a value of 55 $ml.kg^{-1}.min^{-1}$ to it. However, no details were given to explain either how this rise in $\dot{V}O_2$ to its maximum was calculated or how the curve smoothing was done. In contrast to Hill and Lupton (1923), Sargent made use of this curve when he calculated $R_{TOT}$ for a range of middle-distance events.

Sargent revised Hill and Lupton's (1923) model of running performance to calculate N's $R_{TOT}$ for a range of race durations. He used the smoothed curve to account for the rise in $\dot{V}O_2$ at the onset of exercise and he ascribed a value of 55 $ml.kg^{-1}.min^{-1}$ to $R_{Ae_{MAX}}$, the $\dot{V}O_{2max}$ observed for N. He ascribed a value of 217 $ml.kg^{-1}$ for $S_{An_{MAX}}$, the maximum oxygen debt observed for N, and assumed that both $R_{Ae_{MAX}}$ and $S_{An_{MAX}}$ would be attained for all middle-distance events > 300 yds. Sargent then calculated $R_{TOT}$ for each race distance in the same way as Hill's group [see equation (1)]. These predicted times were then compared to N's actual (or estimated) performance times: the agreement between these, for the range of race distances examined, is shown in table 2.2.

**Table 2.2 Actual vs. predicted times for race distances from 0.17 to 2 miles (Sargent, 1926)**

| | Race Distance (miles) | | | | | |
|---|---|---|---|---|---|---|
| | 0.17 | 0.25 | 0.33 | 0.50 | 1.00 | 2.00 |
| Actual (A) Time (s) | 33 | 52 | 73 | 121 | 281 | 611 |
| Predicted (P) Time (s) | 34 | 51 | 75 | 122 | 280 | 610 |
| A:P | 1.03 | 0.98 | 1.03 | 1.00 | 1.00 | 1.00 |

Sargent successfully resolved the problems, encountered by Hill's group, associated with subjects carrying respiratory apparatus during running and the assumption that $\dot{V}O_{2max}$ is immediately attained at the onset of exercise. The agreement between N's calculated and actual times (table 2.2) confirms this and demonstrates the accuracy with which Sargent's model could predict middle-distance running performance. Since Sargent gave no details of how the rise in $\dot{V}O_2$ at the onset of exercise was calculated, his revised model cannot be expressed mathematically, and is limited in its application to his single subject. Therefore, despite the fact that Sargent (1926) accounted for the rise in $\dot{V}O_2$ at the onset of exercise, he failed to include a parameter to represent this rise. Sergeant's model was, therefore, essentially the same as Hill and Lupton's (1923) model, at least in its mathematical presentation. It was not until the work of Simonson (1927) that the relationship between the rise in $\dot{V}O_2$ and time at the start of exercise was first described mathematically.

### *2.3.3 Expressing the rise in $\dot{V}O_2$ as a mathematical function*

In 1927 Simonson hypothesised that, under conditions where the molecular $O_2$ supply is adequate and not limited by factors such as blood supply, the increase of $\dot{V}O_2$

proceeds in a very regular logarithmic curve, so that it may be expressed by a simple mathematical formula:

$$R_{Ae}(t) = R_{Ae_{SS}}\left(1 - e^{-t/\tau_{Ae}}\right) \tag{2}$$

where $R_{Ae}(t)$ ($ml.kg^{-1}.min^{-1}$) is the $\dot{V}O_2$ above resting at t, $R_{Ae_{SS}}$ ($ml.kg^{-1}.min^{-1}$) is the steady state $\dot{V}O_2$ above resting, $\tau_{Ae}$ is the time constant (min) for the kinetics of $\dot{V}O_2$, and t is the time (min) elapsed from the start of the race.

In 1951 Henry independently arrived at the same conclusion as Simonson (1927) and elaborated on the theoretical basis underpinning this exponential rise in $\dot{V}O_2$ at the start of exercise. Indeed, he predicted that $R_{Ae_{SS}}$ and $\tau_{Ae}$ are entirely independent mathematically and, hence, should be uncorrelated. Moreover, he suggested that $\tau_{Ae}$ should be independent of the exercise intensity while $R_{Ae_{SS}}$ should show a linear relation with exercise intensity up to the point where limitations of $O_2$ supply begin.

Henry (1951) did more than simply elaborate on the theoretical basis for the exponential rise in $\dot{V}O_2$ at the start of exercise. Indeed, he determined $\dot{V}O_2$ during the onset, and throughout, exercise at a moderate intensity on a cycle ergometer for 12 subjects to provide data to examine this theory. Henry derived semi-log plots of $\dot{V}O_2$ against time to determine the curve constants $R_{Ae_{SS}}$ and $\tau_{Ae}$, with the ordinate representing the $\dot{V}O_2$ 'deficiency' (i.e. the difference between the asymptotic $\dot{V}O_2$ and the actual $\dot{V}O_2$ for each minute). He then used these constants in equation (2) to calculate the $\dot{V}O_2$ curve at the onset of exercise, and plotted this together with the average $\dot{V}O_2$ data points determined experimentally from his 12 subjects (figure 1, curve A; Henry, 1951; p. 430). The agreement between the calculated curve and the experimental data points was excellent and was something that Henry found particularly convincing "since the formula for oxygen consumption has only 2 parameters and there are 6 experimental data points in the curved portion of the line" (Henry, 1951, p. 432).

Henry also used equation (2) to calculate theoretical curves for two other data sets: $\dot{V}O_2$ determined from a single subject during stepping exercise (taken from Berg, 1947) and $\dot{V}O_2$ determined from a single runner (taken from Hill et al., 1924a). These data also showed excellent agreement [figure 1, curves B and C; Henry (1951), p. 430] with their respective calculated curves.

Henry (1951) proposed, and confirmed with experimental data, that the rise in $\dot{V}O_2$ at the onset of exercise is an exponential function of time. In doing so, he assumed that the $\tau_{Ae}$ of this exponential rise in $\dot{V}O_2$ was 0.61 min (37 s) for the curve derived from the 12 subjects' data. In 1954 Henry incorporated this equation in a model of running performance.

*2.3.4 Incorporating the exponential rise in $\dot{V}O_2$ in a model of performance*

Henry (1954) developed Sargent's (1926) model of middle-distance running performance by including a mathematical term [equation (2)] for the exponential rise in $\dot{V}O_2$ at the start of exercise. He calculated $R_{TOT}$ for race distances from 200 to 3000 m based on the 1952 World Records times. While Henry never formally presented his model, it is clear that it was given by the following expression:

$$R_{TOT} = \frac{1}{T}\left[S_{An_{MAX}} + \int_0^T R_{Ae_{MAX}}\left(1 - e^{-t/\tau_{Ae}}\right)\right] \tag{3}$$

Like his predecessors, Henry assumed that the parameter representing the highest $\dot{V}O_2$ attained would be $\dot{V}O_{2max}$ (i.e. $R_{Ae_{MAX}}$). For this parameter Henry ascribed a value of 73 ml.kg$^{-1}$.min$^{-1}$ and for $S_{An_{MAX}}$ a maximum oxygen debt value of 240 ml.kg$^{-1}$. He simply assumed that these represented maximal values for a hypothetical 75 kg runner. Having included a parameter to represent the exponential rise in $\dot{V}O_2$ at the start of exercise, Henry gave no details of the value he ascribed to this parameter and it is not clear what value (or values) he used from the data that he gives. Consequently, it is clear that Henry assumed that $\dot{V}O_2$ would rise towards $\dot{V}O_{2max}$ and that $\dot{V}O_{2max}$ would be attained if the exercise duration was sufficient. Without knowing the value he ascribed to the parameter representing the time constant for this rise in $\dot{V}O_2$, it is impossible to determine the shortest event duration during which $\dot{V}O_{2max}$ would have been attained.

Henry's (1954) model was an important development in the history of modelling middle-distance running performance. However, he only addressed the assumption that Sargent (1926) had originally set out to challenge: that $\dot{V}O_{2max}$ is not immediately attained at the start of exercise. Consequently, despite the 31 years that had elapsed since Hill's group's model was first proposed, several assumptions underpinning the parameters in the models of middle-distance running performance remained unchallenged in 1954.

## 2.4 The concept of an anaerobic capacity: the developments of Lloyd, Ward-Smith, and Di Prampero et al.

### *2.4.1 The notion of a single 'anaerobic' energy store*

Hill's group's pioneering work on the physiological determinants of middle-distance running performance continued to influence physiologists into the 1960's. In 1966, B. B. Lloyd prefaced his Presidential Address to the Physiology Section of the British Association, on the energetics of running, with reference to Hill's group's work. He then went on to propose a model of performance, which principally challenged the assumptions underpinning 'anaerobic' energy supply. Lloyd revised his own model in 1967 and others (Di Prampero et al., 1993; Ward-Smith, 1985) went on to develop his work over the next 30 years. During this time, the focus of these studies centred on the parameters representing anaerobic energy supply and few developments were made in relation to the parameters representing aerobic energy supply during middle-distance running.

Lloyd (1966) proposed that the maximum energy available to a runner was determined by a set of parameters representing a rate of energy supply over the whole event duration, and by a set of parameters representing a fixed store. Like Hill, he used a financial analogy to describe this relationship as the store "corresponding with capital" and the rate "with income" (p. 517). In calculating this rate, he assumed that the highest $\dot{V}O_2$ attained parameter would not be $\dot{V}O_{2max}$ but rather a steady state $\dot{V}O_2$ ($R_{Ae_{SS}}$) that may be below $\dot{V}O_{2max}$. Furthermore, he assumed that this parameter would be attained after a short delay. By assuming this, Lloyd failed to consider Henry's (1951,

1954) exponential equation. This is surprising since Lloyd had made reference to Henry's 1954 paper throughout his address.

Lloyd's (1966) most important contribution, however, was the way in which he modelled the parameters representing the store of energy provision. He referred to this store as the oxygen debt and had clearly been influenced by Hill's group's work in doing so. However, the way in which he used the oxygen debt term was not consistent with Hill's group's reasoning: Lloyd did not use the oxygen debt to represent the excess $O_2$ taken in during recovery. Lloyd had therefore, effectively, described the notion of an 'anaerobic capacity' though, like Hill's group, he never used the term 'anaerobic'. It was given by:

$$S_{An}(T) = S_{An_{MAX}}\left(1 - e^{-T/\tau_{An}}\right) \quad (4)$$

where $S_{An}(T)$ ($ml.kg^{-1}$) is the store of anaerobic energy available over T and $\tau_{An}$ is the time constant (min) for the kinetics of $S_{An}(T)$ at the start of the race.

Hill's group, Sargent (1926), and Henry (1954) had assumed that $S_{An_{MAX}}$ could not be exhausted in short exercise durations and that several seconds were required to incur $S_{An_{MAX}}$. Whereas they did not include a parameter for this in their models, Lloyd's inclusion of the parameter representing the exponentially decreasing store did so.

To derive the physiological parameters for his model Lloyd applied an approach that was conceptually the same as a 'critical speed' model, based on the work of Scherrer and Monod (1960) (though he never referred to their work). The approach involved grouping the range of World Record event distances (50 yd to 623 miles) into six sets, for each of which he plotted the distance against performance time and fitted a straight line. The slope of this line represented $R_{Ae_{SS}}$, and the intercept represented $S_{An_{MAX}}$. For the set of data that included the range of middle-distance events (800 to 3000 m), $R_{Ae_{SS}}$ was 67 $ml.kg^{-1}.min^{-1}$. The $S_{An_{MAX}}$ was 29 $ml.kg^{-1}$ and $\tau_{An}$ was 0.42 min (25 s). Therefore, $S_{An_{MAX}}$ would equal $S_{An}(T)$ for event durations greater than 125 to 150 s.

Lloyd did not explicitly assume that $R_{Ae_{MAX}}$ would be attained. Rather, he assumed that a sustainable rate of energy supply ($R_{Ae_{SS}}$) would be attained for the range of race durations. Since $S_{An_{MAX}}$ would only be completely exhausted for race durations greater than 120 to 150 s, he assumed that it would be exhausted for the race distances of 1500 m and above (> 215.6 s), but not for the 800 m (105.1 s).

Lloyd (1966) failed to take account of the effect of air resistance on the parameter representing the energy cost of running and in his 1967 paper he resolved this by correcting his value ascribed to this parameter. As a result, the aforementioned values for $R_{Ae_{SS}}$ and $S_{An_{MAX}}$ were corrected to 76 ml.kg$^{-1}$.min$^{-1}$ and 50 ml.kg$^{-1}$, respectively. Additionally, $\tau_{An}$ was 0.28 min (17 s), meaning that $S_{An_{MAX}}$ would be exhausted by 102 s: it would be exhausted during race distances > 800m.

Lloyd's (1966, 1967) work was later developed by Ward-Smith (1985) who incorporated a parameter representing the exponential rise in $\dot{V}O_2$ at the onset of exercise, equivalent to that outlined by Henry (1951). Thus, he overcame the potential limitations of Lloyd's model. Additionally, though Hill's group, Sargent (1926), Henry (1954), and Lloyd (1966, 1967) had all encapsulated the idea of an anaerobic capacity in their models, and the term anaerobic capacity had been introduced in the 1960's (Margaria et al., 1966), Ward-Smith (1985) was the first to include this term in a model of running performance. Di Prampero et al. (1993) later presented a model that was essentially the same as Ward-Smith's. Their model contained the same parameters as Ward-Smith's but they ascribed different values to these parameters in order to assess the accuracy of the model.

### *2.4.2 The concept of an anaerobic capacity*

Ward-Smith's (1985) model was based on the same principles as that of his predecessors: a set of parameters representing a rate of aerobic energy supply and a set of parameters representing a store of available energy derived from anaerobic metabolism. However, he assumed that the parameter representing the highest $\dot{V}O_2$ attained would be $\dot{V}O_{2max}$, something that Lloyd (1966, 1967) did not explicitly assume. Ward-Smith also included a parameter representing the time constant for the exponential rise in $\dot{V}O_2$ at the onset of exercise and overcame the problems with Lloyd's (1966, 1967) models, in which he assumed that the parameter representing the highest $\dot{V}O_2$ attained would be reached after a short delay. Ward-Smith's (1985) model is given by:

$$R_{TOT} = \frac{1}{T}\left[S_{An_{MAX}}\left(1 - e^{-T/\tau_{An}}\right) + \int_0^T R_{Ae_{MAX}}\left(1 - e^{-t/\tau_{Ae}}\right)\right] \qquad (5)$$

For $R_{Ae_{MAX}}$ he ascribed a value of 67.5 $ml.kg^{-1}.min^{-1}$, $\tau_{An}$ and $\tau_{Ae}$ were both ascribed values of 0.5 min (30 s), and $S_{An_{MAX}}$ was ascribed a value of 81.3 $ml.kg^{-1}$. Thus, $S_{An_{MAX}}$ would be completely exhausted for event durations above 150 to 180 s. The $R_{Ae_{MAX}}$ parameter (i.e. $\dot{V}O_{2max}$) would not have been reached during 800 m running because the duration is insufficient. However, the important point here is that about 95 to 97% $\dot{V}O_{2max}$ would have been attained during 800 m running and that $\dot{V}O_2$ would be rising towards $\dot{V}O_{2max}$. This is different to assuming that $\dot{V}O_2$ would not be attained because it is rising towards an asymptote parameter that is below $\dot{V}O_{2max}$.

Ward-Smith predicted the performance times that would be attained by a hypothetical runner, with the above values, for the 100 to 10000 m events. He then compared these times with the actual average times attained by the medallists for the four Olympic games between 1960 and 1976. For the middle-distance events analysed, these times are presented in table 2.3.

**Table 2.3 Actual vs. predicted times for race distances from 400 to 1500 m (Ward-Smith, 1985)**

| | Race Distance (m) | | |
|---|---|---|---|
| | 400 | 800 | 1500 |
| Actual (A) Time (s) | 44.93 | 105.48 | 218.24 |
| Predicted (P) Time (s) | 44.50 | 104.15 | 221.49 |
| A:P | 1.01 | 1.01 | 0.99 |

Di Prampero et al. (1993) also referred to an 'anaerobic capacity' when they presented a model that specifically dealt with middle-distance running performance (800 to 5000 m events). This model is given by:

$$R_{TOT} = \frac{1}{T}\left[S_{An_{MAX}} + \int_0^T R_{Ae_{MAX}}\left(1 - e^{-t/\tau_{Ae}}\right)\right] \quad (6)$$

Di Prampero et al. (1993) did not include a parameter to represent the exponential decrease in $S_{An(T)}$: rather, they assumed that it would be exhausted during all middle-distance running events. Likewise, they assumed that $R_{Ae_{MAX}}$ would be attained during all these events. They then used three sets of values to test their model.

The first set was based on a hypothetical (75 kg) runner with a $R_{Ae_{MAX}}$ of 74 $ml.kg^{-1}.min^{-1}$. For the second set, they determined $\dot{V}O_{2max}$ in 16 'intermediate level' runners: $R_{Ae_{MAX}}$ of 60.2 ± 3.0 $ml.kg^{-1}.min^{-1}$ and 50.0 ± 5.2 $ml.kg^{-1}.min^{-1}$ for males and females, respectively. For the third set, they used data determined in a study by Lacour et al. (1990) on 27 elite runners: $R_{Ae_{MAX}}$ of 71.3 ± 4.5 $ml.kg^{-1}.min^{-1}$. For all these data, Di Prampero et al. (1993) ascribed values of 68 ml $O_2.kg^{-1}$ to $S_{An_{MAX}}$ and 0.17 min (10 s) to $\tau_{Ae}$. They predicted the times that could be achieved by the hypothetical runner and the 'real' runners on whom they had collected, or obtained, data. These times were then compared with the actual 1989 World Record times for the hypothetical runner and with the 'real' runners' actual seasonal best times. These comparisons are given in table 2.4.

**Table 2.4 Mean ratio of actual to predicted times, for three data sets, for race distances from 800 to 3000 m (Di Prampero et al., 1993)**

| Data Set | Race Distance (m) | | |
|---|---|---|---|
| | 800 | 1500 | 3000 |
| (1) Hypothetical Runner | 1.03 | 1.00 | 1.00 |
| (2) Di Prampero et al. (1993) | 1.16 | 1.04 | 1.03 |
| (3) Lacour et al. (1990) | 1.08 | 1.02 | 1.02 |

Table 2.4 shows that Di Prampero et al.'s (1993) model essentially overestimates performance and, more importantly that, the magnitude of this overestimation is greater for the shorter race distances. They suggested that their assumption that $S_{An_{MAX}}$ would be exhausted during the shorter distances may have been false and that these distances may be too short for its full exploitation. Something that Di Prampero et al. failed to consider, however, was that the highest $\dot{V}O_2$ attained may be below $\dot{V}O_{2max}$ during these shorter event durations and that they may, therefore, have overestimated the associated aerobic energy supply.

## 2.5 The notion of a fractional use of $\dot{V}O_{2max}$ during middle-distance running: the developments of Péronnet and Thibault, Ward-Smith, and Wood

### *2.5.1 Péronnet and Thibault's (1989) model*

In 1989 Péronnet and Thibault presented a model that developed the work of Ward-Smith (1985). However, they assumed that $S_{An_{MAX}}$ would only be attained for race durations longer than 120 to 150 s, yet shorter in duration than the maximal duration for which $R_{Ae_{MAX}}$ could be sustained ($T_{R_{Ae_{MAX}}}$). Indeed, they assumed that for event durations greater than $T_{R_{Ae_{MAX}}}$, the amount of energy available from anaerobic metabolism decreases progressively with increasing T. In doing so, they had been influenced by the work of Gollnick and Hermansen (1973) who proposed that $S_{An}(T)$ decreases with the natural logarithm of race duration when $T > T_{R_{Ae_{MAX}}}$.

Péronnet and Thibault's most important contribution, however, was the way in which they modelled $R_{Ae_{MAX}}$. They assumed that $R_{Ae_{MAX}}$ would only be attained for event durations less than $T_{R_{Ae_{MAX}}}$. On the basis of several studies (Costill and Fox, 1969; Londeree, 1986; Péronnet et al., 1987), they assumed that for event durations greater than $T_{R_{Ae_{MAX}}}$ only a fraction of $R_{Ae_{MAX}}$ would be attained, and that this fraction would decrease linearly with In T. Their model was given by:

$$R_{TOT} = \frac{1}{T}\left[S_{An}(T)\left(1-e^{-T/\tau_{An}}\right)+\int_0^T R_{Ae_{SS}}\left(1-e^{-t/\tau_{Ae}}\right)\right] \qquad (7)$$

where

$$R_{Ae_{SS}} = R_{Ae_{MAX}}(1 + D_{F_{R_{Ae_{MAX}}}}(\ln(T / T_{R_{Ae_{MAX}}})) \quad (8)$$

$$S_{An}(T) = S_{An_{MAX}}(1 + D_{F_{S_{An_{MAX}}}}(\ln(t / T_{R_{Ae_{MAX}}})) \quad (9)$$

where $D_{F_{R_{Ae_{MAX}}}}$ and $D_{F_{S_{An_{MAX}}}}$ are negative coefficients representing the decline of $F_{R_{Ae_{MAX}}}$ and $F_{S_{An_{MAX}}}$, respectively, as a function of In T.

On the basis of breath-by-breath data (Fox et al., 1980; Hagberg et al., 1978; Linnarsson, 1974), they ascribed values of 0.5 min (30 s) to $\tau_{Ae}$ and 80.1 ml.kg$^{-1}$.min$^{-1}$ to $R_{Ae_{MAX}}$. They also ascribed values of 0.3 min (20 s) to $\tau_{An}$, 79.3 ml.kg$^{-1}$ to $S_{An_{MAX}}$ and ~ 420 s (Costill and Fox, 1969; Londeree, 1986) to $T_{R_{Ae_{MAX}}}$.

This was the first model to explicitly assume that the highest $\dot{V}O_2$ attained would not be $\dot{V}O_{2max}$ for all middle-distance event durations. Rather, they assumed that the parameter representing the highest $\dot{V}O_2$ attained would be below $\dot{V}O_{2max}$ for the 3000 m event, which is greater than 420 s. Furthermore, their use of a high value for $\tau_{Ae}$ means that $\dot{V}O_{2max}$ would not be reached during the 800 m event. However, since the duration of the 3000 m event is very close to $T_{R_{Ae_{MAX}}}$ (452 s in Péronnet and Thibault's analysis) this effect is only conceptually important and has little physiological meaning. Indeed, Péronnet and Thibault's model predicts that 99.7% of $R_{Ae_{MAX}}$ will be attained during the 3000 m event. Péronnet and Thibault were also the first to assume that $S_{An_{MAX}}$ may not be totally exhausted during longer duration events. They assumed that it could only be completely exhausted for event durations greater than 120 to 150 s but less than 420 s (i.e. the 1500 m event). However, since the contribution of $S_{An_{MAX}}$ to $R_{TOT}$ would be relatively unimportant during event durations > 420 s this development was considered to be of little importance by some authors (Di Prampero et al., 1993). For assessing the predictive accuracy of the models this would be so, but for assessing the physiological importance of each energy supply term, and how they may interact, this would not be so.

Using equation (7), Péronnet and Thibault compared the predicted performance times for a hypothetical male runner with the actual 1987 World Record performance times for the 60 to 42195 m events. This comparison, for the 400 to 3000 m events, is presented in table 2.5.

**Table 2.5 Actual vs. predicted times for race distances from 400 to 3000 m (Péronnet and Thibault, 1989)**

| | Race Distance (m) | | | |
|---|---|---|---|---|
| | 400 | 800 | 1500 | 3000 |
| Actual (A) Time (s) | 44.1 | 101.7 | 209.5 | 452.1 |
| Predicted (P) Time (s) | 43.8 | 102.8 | 210.0 | 441.9 |
| A:P | 1.01 | 0.99 | 1.00 | 1.02 |

*2.5.2 Ward-Smith's (1999) model*

In 1999 Ward-Smith revised his previous model (Ward-Smith, 1985) to include the assumption that only a $F_{R_{Ae_{MAX}}}$ for event durations greater than 420 s and incorporated Péronnet and Thibault's (1989) term for this [equation (8)]. Otherwise, the terms in his model were identical to his previous 1985 model.

Ward-Smith (1999) revised some of the values used in his model: $S_{An_{MAX}}$ was 75.1 $ml.kg^{-1}$ and $R_{Ae_{MAX}}$ was 73.1 $ml.kg^{-1}.min^{-1}$. He then predicted times for a hypothetical runner and compared these with the actual 1997 World Record times for the 1500 to 10000 m events. This comparison for the 1500 and 3000 m events is given in table 2.6.

**Table 2.6 Actual vs. predicted times for race distances from 1500 to 3000 m (Ward-Smith, 1999)**

| Time | Race Distance (m) | |
|---|---|---|
| (s) | 1500 | 3000 |
| Actual (A) | 207.4 | 440.7 |
| Predicted (P) | 207.9 | 442.0 |
| Ratio of A to P | 1.00 | 1.00 |

Ward-Smith (1999) appeared to have improved the predictive capability of his model by assuming that the highest $\dot{V}O_2$ attained would be below $\dot{V}O_{2max}$ for event durations greater than 420 s. In particular, the agreement between the predicted and actual 1500 m performance times was better than in his 1985 paper. However, since this duration was less than 420 s, this agreement could not have been due to his revised model *per se*. Rather, it was likely due to the higher value for $R_{Ae_{MAX}}$ that he used (73.9 vs. 71.3 ml $O_2.kg^{-1}.min^{-1}$).

*2.5.3 Wood's (1999a) model*

Wood (1999a) developed the notion of a fractional use of $R_{Ae_{MAX}}$ during middle-distance events, based on data from Spencer et al. (1996) and incorporated this in a model of middle-distance running. In his model, Wood assumed that only a fraction of $R_{Ae_{MAX}}$ ($F_{R_{Ae_{MAX}}}$) could be attained for the 400 to 3000 m events, for a hypothetical middle-distance runner. Though the model was not formally presented, it calculated $R_{TOT}$ as:

$$R_{TOT} = \frac{1}{T}\left[F_{S_{AnMAX}} \times S_{AnMAX} + \int_0^T F_{R_{AeMAX}} \times R_{AeMAX}\left(1 - e^{-t/\tau_{Ae}}\right)\right] \quad (10)$$

where $F_{S_{An_{MAX}}}$ is the fraction of $S_{An_{MAX}}$ used.

Wood ascribed a set of typical values for a hypothetical runner: $R_{Ae_{MAX}}$ of 70 ml.kg$^{-1}$.min$^{-1}$ and $S_{An_{MAX}}$ of 72 ml.kg$^{-1}$. He also ascribed a set of values that were specific to each middle-distance event (see table 2.7). Wood's (1999a) model was, therefore, the first to assume that the parameter representing the highest $\dot{V}O_2$ attained would be below $\dot{V}O_{2max}$ for the shorter middle-distance events (400 to 1500 m). Indeed, he assumed that $\dot{V}O_2$ would rise towards an asymptote that is below $\dot{V}O_{2max}$ and that the extent to which this asymptote is below $\dot{V}O_{2max}$ will be dependant on event duration: the % $\dot{V}O_{2max}$ attained will decrease with event duration for a typical middle-distance runner. Furthermore, Wood (1999a) was the first to ascribe different values to the parameter representing the time constant for the rise in $\dot{V}O_2$ at the start of exercise, assuming that this parameter was dependant on event duration.

**Table 2.7 Values used to model the 400 - 3000 m events (Wood, 1999a)**

| Event (m) | $F_{S_{An_{MAX}}}$ | $F_{R_{Ae_{MAX}}}$ | $\tau$ (s) |
|---|---|---|---|
| 400 | 0.72 | 0.85 | 12.0 |
| 800 | 1.00 | 0.94 | 18.0 |
| 1500 | 1.00 | 0.98 | 17.5 |
| 3000 | 1.00 | 1.00 | 42.0 |

## 2.6 Raising the assumptions and their implications

### *2.6.1 The assumptions*

Since the first physiological model of middle-distance running was published by Hill and Lupton in 1923, no additional sources of energy supply have been introduced. Indeed, when the models are presented in a common form, and with common parameters, it is clear that they are all similar. What has changed is the way in which these parameters have been modelled and, in turn, the assumptions that have been made.

All of the models contain parameters that encapsulate the concept of an anaerobic capacity. Only the most recent models (Di Prampero et al., 1993; Péronnet and Thibault, 1989; Ward-Smith, 1985, 1999; Wood, 1999a), however, have made explicit reference to this. All models collectively assume that the anaerobic capacity will not be completely exhausted during the 400 m event (< 60 s). However, different assumptions are made about events of greater duration. Some (Di Prampero et al., 1993; Henry, 1954; Hill and Lupton, 1923; Lloyd, 1967; Sargent, 1926) assume that the anaerobic capacity will be exhausted for all durations > 100 s (i.e. ≥800 m event). Others (Ward-Smith, 1985, 1999) assume that it will be exhausted for event durations > 120 s (i.e. ≥ 1500 m event). In two models it is assumed that it will only be exhausted during the 1500 m event (Péronnet and Thibault, 1989; Wood, 1999a).

With the exception of Lloyd's (1967) model, it is assumed that $\dot{V}O_{2max}$ exists (i.e. $R_{Ae_{MAX}}$). In fact, it could be argued that, whilst Lloyd (1967) did not refer to $\dot{V}O_{2max}$, the value of 79 $ml.kg^{-1}.min^{-1}$ he used is typical for an elite runner. It is assumed in most models (Di Prampero et al., 1993; Henry, 1954; Hill and Lupton, 1923; Lloyd, 1967; Sargent, 1926; Ward-Smith, 1985) that this $\dot{V}O_{2max}$ will be the highest $\dot{V}O_2$ attainable during all middle-distance events. Moreover, whilst some (Péronnet and Thibault, 1989; Ward-Smith, 1999) assume that the highest $\dot{V}O_2$ attained will not be $\dot{V}O_{2max}$ in the 3000 m event, this is only conceptually important and has little physiological meaning. Finally, Wood (1999a) assumes that the highest $\dot{V}O_2$ attained will be below $\dot{V}O_{2max}$ in all but the 3000 m event.

The models that have included a parameter to represent the rise in $\dot{V}O_2$ at the start of exercise (Di Prampero et al., 1993; Henry, 1954; Péronnet and Thibault, 1989; Ward-Smith, 1985, 1999; Wood, 1999a) have assumed that this rise in $\dot{V}O_2$ is mono-exponential. Each of these models assumes that $\dot{V}O_2$ will rise towards the asymptote representing the highest $\dot{V}O_2$ attained. In three of these models (Péronnet and Thibault, 1989; Ward-Smith, 1985, 1999) the high value (30 s) ascribed to the parameter representing the time constant for the rise in $\dot{V}O_2$ means that $\dot{V}O_{2max}$ will not be reached during the 800 m event: only 95 to 97% $\dot{V}O_{2max}$ will be reached during this event. With the exception of Wood's (1999a) model, it has been assumed that the parameter representing this rise in $\dot{V}O_2$ is independent of exercise intensity: a single value has been ascribed to the parameter for all event durations.

All of the models have ascribed a single value to $\dot{V}O_{2max}$ and to the anaerobic capacity across all event durations: these values will not vary between runners specialising in different events. Finally, most of the values used in the models are based on data determined from constant speed running. It is, therefore, assumed that these data are ecologically valid: constant speed running, on which the models' predictions are mainly based, is assumed to reflect the pacing strategy used by middle-distance runners during 'actual' performances.

*2.6.2 The implications*

It is important that the assumptions underpinning the parameters, and the values ascribed to these parameters, are addressed if models of middle-distance running performance are to be meaningfully applied. It is insufficient to accept the models as valid on the grounds of their ability to accurately predict World Record performance times, which has been the typical approach for assessing their accuracy (Di Prampero et al., 1993; Henry, 1954; Péronnet and Thibault, 1989; Ward-Smith, 1985, 1999). The assumptions associated with each parameter may cancel one another out when the parameters are modelled and, hence, yield accurate predictions; yet each parameter may be less meaningful when considered alone. The accuracy of a model's predictions does not guarantee that each parameter is accurately represented or physiologically meaningful. For example, a model that assumes an asymptote below $\dot{V}O_{2max}$ for the highest $\dot{V}O_2$ attained following a rapid rise in $\dot{V}O_2$ during the 800 m event may yield a similar value for the total amount of $O_2$ used as a model that assumes a relatively slow rise, but that the asymptote for the highest $\dot{V}O_2$ attained is $\dot{V}O_{2max}$. Such a model would, therefore, yield an accurate prediction of performance, assuming that the other parameters are accurate. However, it would fail to accurately represent the rate of rise in $\dot{V}O_2$ and the $\dot{V}O_2$ attained.

# CHAPTER 3

# CONTEMPORARY PERSPECTIVES ON MODELLING THE ENERGETICS OF MIDDLE-DISTANCE RUNNING: ADDRESSING THE ASSUMPTIONS

## 3.1 The notion of an anaerobic capacity

### *3.1.1 Terminology*

Models of the energetics of middle-distance running have incorporated a parameter representing a fixed store of available anaerobically derived energy (i.e. $S_{AN_{MAX}}$). This is a maximum store since a single value, which is independent of event duration, has been ascribed to the parameters in the models. Different terms, which reflect those used in the wider scientific literature (Green, 1994), have been used in the models to describe this store. Likewise, different mechanisms, supporting this store, have been suggested by the proponents of the models. Despite these differences, the fixed store is consistent with the contemporary concept of an 'anaerobic capacity' ($C_{An}$): "the maximum amount of ATP re-synthesised via anaerobic metabolism (by the whole organism) during a specific type of short duration, maximal exercise" (Green, 1994, p 170).

Knowledge of the mechanisms supporting $C_{An}$ is important for applying the models: such knowledge may inform training strategies to target and develop, or racing strategies that maximise the effectiveness of, specific mechanisms. However, for the sole purpose of accurately modelling the energetics of running it is important that the maximum anaerobic capacity ($C_{An_{MAX}}$) and the relationship between available capacity and event duration is known. The use of the term $C_{An_{MAX}}$ is only of theoretical interest and has limited application to specific middle-distance event durations. Rather, it is the available $C_{An}$ that is the important parameter for specific events. However, the use of a single maximum value simplifies the process of modelling different race durations and removes the need to have several anaerobic capacities for specific event durations. However, it is important that the value ascribed to $C_{An_{MAX}}$ can potentially be elicited during running (i.e. it is mode specific) and is not a theoretical capacity, which can only be attained during other modes of exercise.

### *3.1.2 The maximum anaerobic capacity*

Hill and Lupton (1922) first introduced the concept of $C_{An_{MAX}}$ through their early work (Green, 1994), which developed methods for determining the oxygen debt ($O_{2\ debt}$) during running. This method assumed that the oxygen deficit (Krogh and Lindhard, 1920), which represents the delay in oxidative metabolism at the onset of exercise, would equal the amount of oxygen used in the recovery from this exercise (i.e. the $O_{2\ debt}$). However, since Hill and Lupton's ideas were initially devised, data have been presented that show the assumptions supporting the $O_{2\ debt}$ method to be incorrect. Christensen and Högberg (1950) first acknowledged that the $O_{2\ debt}$ "always ought to be greater than the deficit" (p 251) and showed that, during horizontal treadmill running at speeds between 10 and 15 $km.h^{-1}$, the oxygen deficit remained relatively constant at approximately half the value of the $O_{2\ debt}$. Henry (1954) was presumably unaware of these data when he used $O_{2\ debt}$ values to test his model.

Using a one-legged knee extensor model and direct methods for determining anaerobic energy production (Bangsbo, 1998), Bangsbo et al. (1990) showed that the anaerobic energy supply for $C_{An}$ during a high intensity exercise bout was much smaller than would be predicted on the basis of the $O_{2\ debt}$ method: the $O_2$ equivalent of $C_{An}$ represented only ~ 30% of that determined using the $O_{2\ debt}$ method. This confirmed that the $O_{2\ debt}$ method overestimates anaerobic metabolism during exercise (Green and Dawson, 1993) and demonstrated that the elevated oxygen uptake that is observed during recovery from severe exercise cannot be considered to represent the repayment of an $O_2$ deficit that was incurred during the exercise.

Contemporary physiologists have attempted to quantify the $C_{An_{MAX}}$ by determining the 'maximum accumulated oxygen deficit' (MAOD) (Medbø et al., 1988). This is the most promising method for determining the $C_{An_{MAX}}$ during whole body exercise despite having theoretical limitations (Green and Dawson, 1993). For treadmill running, this method typically involves a participant completing several bouts at various sub-$\dot{V}O_{2max}$ speeds and exhaustive bouts at supra-$\dot{V}O_{2max}$ speeds. A regression equation relating $\dot{V}O_2$ to speed is derived from the sub-$\dot{V}O_{2max}$ bouts and this equation is used to calculate theoretical $\dot{V}O_2$ values, which are equivalent to the rates of oxygen requirement, for the supra-$\dot{V}O_{2max}$ bouts (Medbø et al., 1988). The MAOD is then derived by calculating the total oxygen requirement and subtracting the actual amount of oxygen used for the duration of the bout.

There are three main conceptual problems with the MAOD method. Firstly, the oxygen requirement of the supra-$\dot{V}O_{2max}$ speed bouts must be extrapolated from a linear $\dot{V}O_2$-running speed relationship determined from the sub-$\dot{V}O_{2max}$ speed bouts: it is assumed that the relationship remains linear for supra-$\dot{V}O_{2max}$ speeds. For both cycling (Bearden and Moffatt, 2001; Green and Dawson, 1995;) and running (Bangsbo et al., 1993) this relationship has been shown to be non-linear above the anaerobic threshold. Thus, the oxygen requirement may be underestimated when extrapolated from the linear relationship determined at sub-$\dot{V}O_{2max}$ speeds. Consequently, the true oxygen deficit may be underestimated and, the extent of this underestimation may be a function of the chosen intensity for the supra-$\dot{V}O_{2max}$ speed running bouts (Bangsbo, 1998). Secondly, since the non-linearity in the $\dot{V}O_2$-running speed relationship is caused by an additional $\dot{V}O_2$, which is delayed in onset (Whipp and Wassermann, 1972), the $\dot{V}O_2$-running speed relationship is dependent on when $\dot{V}O_2$ is determined (Bangsbo, 1998) and the test protocol that is used (Green and Dawson, 1996). Thirdly, the MAOD method assumes that the total energy demand remains constant throughout the supra-$\dot{V}O_{2max}$ speed bout. However, it has been shown that this energy demand may vary during constant load exercise (Bangsbo, 1996).

Despite these conceptual problems, it is noteworthy that when the one-legged knee extensor exercise model has been studied, good agreement has been found between the AOD and the oxygen equivalent of the anaerobic ATP production as determined from changes in [ATP], [CP], [IMP], and [lactate]. With no alternative for quantifying the $C_{An_{MAX}}$ during running (Bangsbo, 1996), the MAOD method is widely accepted and is potentially useful for assessing the validity of the assumptions underpinning the parameter representing anaerobic metabolism in the models of middle-distance running performance, and the values ascribed to these parameters.

The contemporary models have ascribed similar values to $C_{An_{MAX}}$, expressed as oxygen equivalents: 68 $ml.kg^{-1}$ (Di Prampero et al., 1993), 79 $ml.kg^{-1}$ (Péronnet and Thibault, 1989), and 75 $ml.kg^{-1}$ (Ward-Smith, 1999). These agree with published MAOD values, albeit they most likely represent the upper range. Despite the limitations of MAOD (Green, 1995), the study of Olesen et al. (1994) reports a median MAOD of 59.9 $ml.kg^{-1}$ for 400 to 1500 m runners and Svedenhag et al. (1991) report a mean MAOD of 65 $ml.kg^{-1}$ for Swedish national team middle-distance runners.

### *3.1.3 The available anaerobic capacity*

While the models of the energetics of middle-distance running contain a set of parameters representing $C_{An_{MAX}}$ they vary in their assumptions about the availability of this parameter during the different events. It is assumed in all of the models that $C_{An_{MAX}}$ cannot be completely exhausted during the 400 m event. However, some (Di Prampero et al., 1993; Henry, 1954; Hill and Lupton, 1923; Lloyd, 1967; Sargent, 1926) assume that $C_{An_{MAX}}$ will be exhausted for the 800-3000 m events. Others (Ward-Smith, 1985, 1999) assume that it will be exhausted in the 1500 and 3000 m events or in the 1500 m event alone (Péronnet and Thibault, 1989; Wood, 1999a).

It has been argued that $C_{An}$ is independent of exercise duration during short exhaustive bouts longer than 30 s (Hermansen, 1969). If so, the $C_{An}$ would be completely exhausted during the 400 m event. It is unfortunate that studies that have determined AOD during middle-distance running events (Spencer et al., 1996; Spencer and Gastin, 2001) have used different specialist athletes to study the energetics of 400 and 800 m running: a comparison of AOD between the two events is not possible. However, Medbø et al. (1988) studied exhaustive treadmill running lasting from 15 s to 9 min and found that AOD increased with exercise duration for bouts lasting less than 2 min. The AOD was constant for all bouts lasting longer than 2 min and they interpreted this to mean that a maximum value had been attained for these bouts. These findings were confirmed in a further study by Medbø and Tabata (1989) and provide support for the assumption, regarding the 400 m event, in the models.

For the events that are longer in duration than the 400 m the situation is more complicated. The finding that MAOD can only be completely utilised for exercise durations greater than 2 min (Medbø et al., 1988; Medbø and Tabata, 1989) could be interpreted as lending support to the assumption that $C_{An_{MAX}}$ will not be exhausted in the 800 m event. However, AOD was determined during separate 1 min and 2 min runs and, while there was no increase in AOD after 2 min (i.e. for the 4 and 7 min runs), it is not clear how AOD would have changed for exercise durations between 1 and 2 min. Based on the relationship between the percentage of MAOD attained and duration (Medbø et al., 1988), MAOD would have been ~ 90% utilised after 90s of running. Therefore, it is likely that MAOD will be virtually, though not necessarily completely, utilised in the 800 m event. This is supported by the findings of Spencer et al. (1996), which showed that the mean AOD attained by a group of middle-distance trained runners was greater in the 1500 m (47.4 ± 6.9 $ml.kg^{-1}$) than in the 800 m event (44.9 ± 6.6 $ml.kg^{-1}$). If it is assumed that the 1500 m AOD value is maximal (i.e. MAOD), ~ 95% of MAOD was attained in the 800 m event.

The assumption that the $C_{An_{MAX}}$ parameter will be completely exhausted in the 1500 m event is supported by the work of Medbø's group (Medbø et al., 1988; Medbø and Tabata, 1989). Unfortunately, Spencer et al. (1996) did not determine AOD for event durations greater than the 1500 m so it is not clear whether the reported AOD value for this event is a maximum. For the 3000 m event Péronnet and Thibault (1989) and Wood (1999a) assume that $C_{An_{MAX}}$ will not be exhausted. Péronnet and Thibault (1989) based this assumption on the work of Gollnick and Hermansen (1973), suggesting that $C_{An_{MAX}}$ would not be exhausted for event durations greater than 420 s. Medbø et al (1988) determined AOD for a 7 min run and, while this was equivalent to the 2 min AOD value, these data are difficult to compare due to an increasing error in the determination of AOD: the error increased from 4 to 10% for the 2 and 7 min runs, respectively. Finally, while Karlsson (1971) has shown that the oxygen deficit is the same for exercise durations between 2 and 15 min, there are limited data available that examine the relationship between AOD and exercise duration either generally or specifically for durations < 2 min (i.e. the 400 and 800 m events).

Whether $C_{An}$ will be completely exhausted during the 3000 m event will have little impact on the predictive capability of the models since its contribution to the total energy supply would be relatively small. Furthermore, those who assume that $C_{An}$ is not exhausted in the 3000 m event assume that it is very nearly exhausted. While this has been the view of some authors (Di Prampero et al., 1993), it is important that this assumption is not disregarded so that the models parameters have physiological meaning and validity.

## 3.2 The concept of a maximum oxygen uptake

### *3.2.1 Background*

The work of Hill's group, while being the foundation to the first model of middle-distance running performance, has principally been associated with the concept of $\dot{V}O_{2max}$. The concept of $\dot{V}O_{2max}$ is central to models of middle-distance running performance as they assume that any factor that influences the rate at which an individual can take up and use $O_2$ will influence running performance. In recent years, Noakes (1988, 1997, 1998, 2000) has criticised this concept of $\dot{V}O_{2max}$, and particularly Hill's group's work, arguing that they failed to demonstrate the existence of $\dot{V}O_{2max}$. When Noakes delivered the J. B. Wolfe Memorial Lecture at the American College of Sports Medicine 1996 conference, he questioned some of the fundamental theories on which modern exercise physiology is based. He directed his questioning mainly at Hill's group's notion of a maximal $\dot{V}O_2$, developing what he had argued previously (Noakes, 1988). He challenged other physiologists to respond and Bassett and Howley (1997, 2000) accepted this challenge. They take an opposing stance, arguing that Hill's group did in fact demonstrate that a maximal $\dot{V}O_2$ could be attained.

Noakes (1988, 1997, 1998) has developed the argument that factors unrelated to $O_2$ supply might be important in determining the peak work rate that can be reached during progressive exercise. He challenges the theory that factors related to $O_2$ supply limit the $\dot{V}O_{2max}$ an individual can attain, arguing that whilst Hill's group proposed that the $\dot{V}O_2$-running speed relationship would plateau at high speeds, they did not demonstrate that such a plateau exists. His argument is twofold: on the one hand he raises methodological issues associated with determining a plateau in $\dot{V}O_2$; on the other, he challenges the theoretical basis for the physiological factors that are assumed to determine the incidence of this plateau.

### *3.2.2 Methodological problems with determining a plateau in $\dot{V}O_2$*

Noakes (1998) raises several methodological problems with Hill's group's work. First, Noakes criticises the way in which Hill et al. (1924b) scaled their data to allow a comparison between subjects of different body masses. While they provided no details of this scaling, it appeared to simply involve calculating the $\dot{V}O_2$ per kg of body mass (ml.kg$^{-1}$.min$^{-1}$) and multiplying this by 73 to obtain a value (in l.min$^{-1}$) representative of the $\dot{V}O_2$ that would be obtained by a 73 kg person. They concluded that "at high speeds ... the oxygen intake attains its maximum value, which in athletic individuals of about 73 kg ... is strikingly constant (in the case of running) at about 4 litres per minute" (Hill et al., 1924b, pp 156-157). Noakes (1998) criticised this, claiming that they failed to "explain ... whether that transformation influenced their conclusions" (p. 1383). However, the procedure is equivalent to expressing all $\dot{V}O_2$ data in ml.kg$^{-1}$.min$^{-1}$ and it is hard to conceive that, in doing so, they would have "influenced their conclusions" in any way.

Secondly, Noakes (1998) interprets Hill's group's scaling procedure to a $\dot{V}O_{2max}$ of 4 l.min$^{-1}$ to mean that they believed, not that $\dot{V}O_2$ would plateau at a value characteristic of the individual but rather, that it would not exceed ~ 4 l.min$^{-1}$ in any individual. However, Hill and Lupton (1922) had noted that whilst Hill (73 kg) who reached a maximum $\dot{V}O_2$ of 4.175 l.min$^{-1}$ during running was 'fairly fit he was not, and never had been, a 'first-class runner'. They suggested (p. xxxii) that a champion middle-distance runner would attain "considerably higher values (e.g. 5000 cc or more)".

Thirdly, Noakes (1998) suggests that Hill's group's data did not demonstrate the plateau phenomenon. He re-presented a graph of data (Hill et al., 1924b) determined from Hill himself, and for which Hill's group had made a concerted effort to demonstrate a $\dot{V}O_2$-plateau, and suggested these data were best described by a linear function. Bassett and Howley (1997) criticised Noakes re-interpretation of these data, claiming it was "biased towards the view that a plateau does not exist" (p. 592) and concluded that Hill et al.

(1924b) "clearly demonstrated the $\dot{V}O_2$ plateau" (p. 592). They focused on individual data from the Hill et al. (1924b) study, noting that "A. V. Hill did demonstrate a plateau in himself and also in subject J" (p. 592): a plateau was evident in two of the five subjects on whom $\dot{V}O_2$ data were presented for more than one speed.

Finally, Noakes (1998) has suggested that the variability in Hill et al.'s (1924b) data was considerable (data on Hill were collected over several days) and even if a $\dot{V}O_2$-plateau was present in the data on Hill it would be difficult to identify. Consequently, despite their efforts to demonstrate a $\dot{V}O_2$-plateau, the data they collected showed such high variability that a genuine plateau was dubious. If the Hill et al. (1924b) data were limited to those on Hill himself, Noakes would be correct in claiming that the data to show a plateau in the $\dot{V}O_2$-running speed relationship were lacking. However, data were also presented on the relationship between $\dot{V}O_2$ and running speed for four other subjects (S, W, CNHL, and J). Of these, a plateau in the $\dot{V}O_2$-running speed relationship was evident in only one subject. This subject (J) appears to have been able to run at a much higher speed than the others (> 15 $km.h^{-1}$).

It is clear that Hill's group failed to demonstrate that a plateau in the $\dot{V}O_2$-running speed relationship typically occurred in their subjects: only one of five subjects demonstrated a plateau, and in this subject the plateau was defined by only two data points. What is not clear, however, is why the work of Hill's group has had such a profound influence on so many exercise physiologists despite the fact that Hill's group presented no convincing data to support their theory. It can only be assumed that physiologists have been swayed by the authoritative nature of Hill's group's writing to the extent that they have felt it unnecessary to scrutinise the group's data.

Noakes (1998) criticisms are not restricted to Hill's group's methods and have also been directed at more recent studies that have attempted to establish whether a $\dot{V}O_2$-plateau exists. Indeed, he cites a study by Myers et al. (1990), who showed that there is considerable variability in the $\dot{V}O_2$ response to progressively increasing (ramp) work rate, to suggest that the plateau phenomenon may occur randomly during this type of exercise. Given this, and the fact that $\dot{V}O_{2max}$ is central to the parameters representing aerobic energy supply in the models of middle-distance running performance, some of the issues raised by Noakes are discussed in chapter 4 (section 4.2.3) and addressed in chapter 6.

### *3.2.3 Theoretical problems with the concept of a $\dot{V}O_{2max}$*

Hill and Lupton (1923) presented a theoretical argument to suggest that there should be a limit to the $\dot{V}O_2$ an individual can attain: "It is open to question whether the oxygen intake is limited by the heart or by the lungs. It is possible that, at the higher speeds of blood-flow, the blood is only imperfectly oxygenated in its rapid passage through the lungs; on the other hand, the limit may be placed simply by the sheer capacity of the heart" (p. 155). They did not determine arterial oxyhaemoglobin saturation or cardiac output ($\dot{Q}c$) in any of their studies, but they did perform some calculations which indicated that a $\dot{Q}c$ of between 28 and 38 $L.min^{-1}$ would be required to support a $\dot{V}O_2$ of 4.175 $L.min^{-1}$ (the highest value they observed in the course of their studies). On the basis that this $\dot{Q}c$ was much higher than anything that had been reported previously, they concluded that it is "impossible to be a good runner without possessing a powerful heart" (p. 154).

Implicit in Hill and Lupton's argument was the idea that the $\dot{V}O_2$ that can be attained during running is limited not by the rate at which the muscles can use $O_2$ but by the rate at which the cardiovascular/respiratory system can supply it. Indirect support for this idea came from some classic studies, conducted in the 1960s, which showed a) that $\dot{Q}c$ varied linearly with $\dot{V}O_2$ for both maximal and sub-maximal values of $\dot{V}O_2$ (Åstrand et al., 1964; Saltin et al., 1968) b) that among endurance athletes peak $\dot{Q}c$ varies with the highest $\dot{V}O_2$ attained and c) that these values for $\dot{V}O_2$ and $\dot{Q}c$ are much higher than those attained by sedentary individuals (Ekblom, 1969; Ekblom and Hermansen, 1968).

The above data were obtained during "whole body" exercise (running or cycling) and were interpreted as evidence that the $\dot{V}O_2$ that can be attained during such exercise was limited because $\dot{Q}c$ was limited. The notion that the lungs might limit the $\dot{V}O_2$ that can be attained received little attention despite the fact that marked arterial desaturation was reported to occur during 'maximal' exercise in some endurance athletes (Rowell et al., 1964). This was because other data were available which indicated that arterial $O_2$ saturation decreased little from rest to 'maximal' exercise in both sedentary (Åstrand et al., 1964; Mitchell et al., 1958; Saltin et al., 1968; Stringer et al., 1997) and highly trained (Ekblom and Hermansen, 1968) individuals. Subsequently, various studies were conducted in an attempt to demonstrate that the capacity of the skeletal muscle vasculature to dilate and receive blood flow is such that when at least two legs are involved in the exercise the heart is unable to supply the entire working muscle mass with a sufficient blood flow.

This argument, which has been presented in a series of publications by Saltin and associates (Saltin, 1986, 1988, 1990a, b; Saltin and Strange, 1992), suggests that for exercise involving a large muscle mass $\dot{V}O_2$ reaches a maximum because $\dot{Q}c$ reaches a maximum and the a-v $O_2$ difference does not increase sufficiently to compensate. Evidence to support this argument comes from studies of one-legged vs. two-legged cycling (Davies and Sargeant, 1974; Gleser, 1973; Klausen et al., 1982; Saltin et al., 1976; Stamford et al., 1978), from studies of one-legged dynamic knee extensor exercise (Andersen and Saltin, 1985; Richardson et al., 1993, 1995; Rowell et al., 1986), and from studies which have demonstrated that there is competition for blood flow between different muscle groups during whole body exercise (Harms et al., 1997; Secher et al., 1977).

This argument suggests that, when a progressive exercise test is performed, $\dot{Q}c$ and $\dot{V}O_2$ initially increase with work rate in an essentially linear fashion. However, if the exercise involves a large fraction of the individual's total muscle mass, there should be a time when $\dot{Q}c$ becomes limited and the $\dot{Q}c$-work rate relationship plateaus. From this time onwards, the blood flow that the working muscles demand will exceed that which the heart is able to supply, and hence vasoconstriction will have to occur in the active muscles so that blood pressure does not drop (Rowell, 1986). In theory, the extent of this vasoconstriction should increase in proportion to the active muscle mass. In practice, plasma noradrenaline levels during 'maximal' exercise increase as the active muscle mass increases, being highest in combined arm and leg exercise (Savard et al., 1989).

If $\dot{Q}c$ plateaus and vasoconstriction occurs in the active muscles, assuming that other vascular beds are already maximally constricted (Rowell, 1986), leg blood flow should also plateau. This is consistent with the work of Knight et al. (1992) and the view that $\dot{V}O_{2max}$ is set by peripheral diffusion limitation, secondary to a limited $O_2$ delivery rate (Hogan et al., 1989; Roca et al., 1989; Wagner, 1992, 1995, 1996). Given that leg blood flow plateaus, whether the $\dot{V}O_2$-work rate relationship plateaus in a progressive test will presumably depend on whether exercise is continued up to, and for a sufficient period beyond, the point at which such a diffusion limitation is reached. Whether the exercise can be continued beyond this point will depend on whether energy can be derived from anaerobic metabolism at a rate sufficient to support the increase in work rate. Hence, both $O_2$ delivery and anaerobic energy production must be involved in determining the peak work rate that can be reached on a progressive test.

Noakes (1988) has referred to this framework of interpreting data as the 'cardiovascular/anaerobic model' and has challenged its validity. He has repeatedly stressed (1988, 1997, 1998) that when a plateau in the $\dot{V}O_2$-work rate relationship is not observed in a progressive test it is impossible to be certain that the highest $\dot{V}O_2$ attained was limited by factors related to $O_2$ delivery to, or use by, skeletal muscle. In his 1988 paper he proposed an alternative model to interpret such data, suggesting that the peak work rate that can be attained in such a test might instead be limited by factors related to muscle contractility. The implication here was that any intervention that increased muscle contractility would also increase the peak work rate that could be attained, and thus the peak $\dot{V}O_2$ that could be reached, in a progressive exercise test.

In 1997 Noakes presented a different model. He suggested "skeletal muscle contractile function is regulated during exercise in both health and disease by a hierarchy of central and peripheral mechanisms, the goal of which is likely to prevent organ damage, including death" (Noakes, 1997, p. 581). To support his argument, he cited studies which show that when the ability to produce ATP is markedly reduced, either as a result of muscle ischemia (Spriet et al., 1987) or as a result of a disease of skeletal muscle metabolism such as phosphorylase deficiency (Lewis and Haller, 1986), skeletal muscle contractile function (and its rate of ATP use) is also reduced so that the decrease in [ATP] that occurs during exercise is not abnormally large. He went on to stress that progressive exercise at high altitude is terminated at a time when both $[La^-]_B$ (Green et al., 1989) and the integrated electromyographic activity of the active muscles (Kayser et al., 1994) are low relative to similar exercise performed at sea level, and that progressive exercise in heart failure patients, both before and after transplant, is terminated at a time when work rate, $\dot{V}O_2$, and $[La^-]_B$ levels are greatly reduced relative to those at which such exercise is terminated in normal subjects. Finally, he proposed that in healthy subjects (at sea level) skeletal muscle recruitment might be limited (i.e. the test might be terminated) once the maximal cardiac output has been reached in a progressive exercise test so that vasodilation does not occur to the point where a drop in blood pressure occurs.

Noakes' (1997) paper is important as it shows that there are situations in which factors other than those related to a limited $O_2$ supply, and the associated demand for anaerobic metabolism, might limit progressive exercise to exhaustion. Nevertheless, the explanation he gives for what might limit the peak work rate for a progressive test in which no plateau is observed is very similar to that which explains the occurrence of a $\dot{V}O_2$-plateau. In both cases, the maximal $\dot{Q}c$ is the primary determinant of the highest $\dot{V}O_2$ that can be attained during a progressive test. The 'cardiovascular/anaerobic' model would assume that exercise will continue for as long as anaerobic metabolism was able to supply ATP at a sufficient rate, with excessive vasodilation being prevented by sympathetically mediated vasoconstriction in the active muscles. Noakes' argument suggests that $\dot{V}O_2$ would not plateau, and that exercise would be terminated shortly after the maximal $\dot{Q}c$ is reached to prevent a drop in blood pressure.

In 1998 Noakes questioned the notion that there is a maximal $\dot{Q}c$. Starting from the premise that a plateau in $\dot{Q}c$ must be the result of a plateau in the $O_2$ supply to the myocardium, he went on to point out that whilst myocardial $O_2$ supply will only plateau if coronary blood flow plateaus, there is no logical reason to believe that coronary blood flow would plateau before $\dot{Q}c$. He proposed that instead skeletal muscle function might be regulated to prevent myocardial ischemia in such a way that neither $\dot{V}O_2$ nor $\dot{Q}c$ would plateau in a progressive test.

There are three problems with this most recent of Noakes' theories. The first is that it is not consistent with those studies (Mitchell et al., 1958; Stringer et al., 1997) that have shown that $\dot{Q}c$ does in fact plateau in the later stages of a progressive test. The second is that he is unaware of the study by Stenberg et al. (1966), which showed that during maximal exercise at an altitude of 4000 m blood pressure, stroke volume and cardiac output were similar to at sea level despite a reduction in $O_2$ saturation to 70%. Bergh et al. (2000) has argued that this is incompatible with the theory that the performance of the heart muscle is regulated to avoid ischemia. The third problem is that it fails to take account of the fact that $\dot{Q}c$ might plateau even if myocardial $O_2$ supply is completely adequate. Concerning the second problem, the obvious point is that, since "the heart ... cannot pump out what it does not receive" (Rowell, 1986, p.137), $\dot{Q}c$ will plateau if venous return plateaus. It has been shown that whilst the left ventricular ejection fraction typically increases from rest to moderate intensity exercise, little or no increase is observed when exercise intensity increases beyond that at which the lactate threshold occurs (Boucher et al., 1985; Clausell et al., 1993; Foster et al., 1995; Goodman et al., 1991). Furthermore, the ejection fraction typically reaches 70 to 80% (Di Bello et al., 1996; Clausell et al., 1993; Foster et al., 1995; Goodman et al., 1991) in young normal subjects during exercise at intensities close to that at which the highest $\dot{V}O_2$ is attained. It is unlikely, therefore, that the tendency for $\dot{Q}c$ to plateau in response to a plateau in the rate of venous return would be offset by an increase in the ejection fraction.

Noakes has made a significant contribution to the debate on the concept of $\dot{V}O_{2max}$. However, the available evidence suggests that $\dot{V}O_2$ does plateau over the closing stages of progressive exercise. The challenge for the exercise physiologist is identifying this plateau, particularly given the methodological issues surrounding the definition of $\dot{V}O_{2max}$ (see section 4.2.3).

## 3.3 The time constant for the rate of increase in $\dot{V}O_2$ at the onset of exercise

### *3.3.1 Severe exercise intensity domain*

The rate of increase in $\dot{V}O_2$ ($\dot{V}O_2$ kinetics) at the onset of exercise is dependent on the intensity of the exercise (Whipp et al., 1980). Typically, three domains are used to define exercise intensity: moderate, heavy, and severe. The severe intensity domain is of the greatest relevance to middle-distance running events since these events are typically performed in this domain. The severe domain is distinguished as being above the maximal lactate steady state (Gaesser and Poole, 1996). Poole et al. (1988) have shown that the highest work rate at which a steady state in $\dot{V}O_2$ can be attained coincides with the maximal lactate steady state and this work rate, termed the fatigue threshold (Gaesser and Poole, 1996) or critical power, has also been used to represent the lower limit of the severe intensity domain. The upper limit to this domain has not been firmly established. Hill and Ferguson (1999) define the upper limit of the severe intensity domain as the lowest intensity at which exhaustion occurs before $\dot{V}O_{2max}$ is attained. This is consistent with the view that exercise in the severe intensity domain will always result in the attainment of $\dot{V}O_{2max}$ if the duration is sufficient (Whipp, 1994).

The $\dot{V}O_2$ kinetics during severe intensity exercise can be described by three distinct phases. Phase 1 represents a transit delay of venous blood from the exercising muscle returning to the lung (Whipp, 1994). However, the exact mechanisms supporting this phase are unclear: $\dot{V}O_2$ has been shown to increase during this phase through an increase in cardiac output (Wasserman et al., 1974), but mechanisms other than cardiac output also influence $\dot{V}O_2$ kinetics during this phase (Casaburi et al., 1989). The phase 2 $\dot{V}O_2$ kinetics represent muscle oxygen uptake and further increases in pulmonary blood flow (Whipp, 1994). During moderate intensity exercise phase 2 kinetics project to a steady state in $\dot{V}O_2$ but during heavy and severe intensity exercise this is distorted: instead of $\dot{V}O_2$ reaching a steady state, a third phase that is delayed in onset materialises. The phase 3 $\dot{V}O_2$ kinetics has been termed the 'slow component of $\dot{V}O_2$' (Whipp and Wasserman, 1972) due to its delayed onset. This slow component starts approximately 80-100 s after the onset of exercise (Poole et al., 1994) and represents an excess $\dot{V}O_2$ that exceeds that predicted from a linear $\dot{V}O_2$-work rate relationship calculated from sub-$\dot{V}O_{2max}$ work rates.

### *3.3.2 Modelling $\dot{V}O_2$ kinetics during severe exercise*

The notion that $\dot{V}O_{2max}$ will be attained in the severe exercise intensity domain is consistent with the models that collectively assume, with the exception of Wood (1999a), that the highest $\dot{V}O_2$ attained will be $\dot{V}O_{2max}$ in all middle-distance events. However, the important consideration for the models is that the assumptions supporting the parameter representing the time constant for $\dot{V}O_2$ kinetics is accurate. This is particularly important since this parameter determines whether $\dot{V}O_{2max}$ is attained during all middle-distance event durations. Furthermore, there are relatively few studies investigating $\dot{V}O_2$ kinetics during severe intensity exercise and, of these, some have been published since the models of the energetics of middle-distance running were developed.

Modelling $\dot{V}O_2$ kinetics in this domain is problematic since the exercise duration may not be sufficient for the slow component to develop (Whipp, 1994) and the kinetics have typically been modelled as a mono-exponential function (Billat et al., 2000). Whether a slow component is manifest depends on the duration of the exercise. For severe intensity exercise lasting up to 2 to 3 minutes a mono-exponential model is appropriate but for longer durations a bi-exponential model is needed to properly characterise the $\dot{V}O_2$ response. This makes it difficult to model $\dot{V}O_2$ kinetics over the range of middle-distance events with a single approach and makes it difficult to compare the speed of $\dot{V}O_2$ kinetics across this range of events. However, the effect of a $\dot{V}O_2$ slow component is to slow the overall response. Models of middle-distance running performance assume a mono-exponential $\dot{V}O_2$ response. Such a response can be used to determine the total oxygen uptake but to account for the presence of a slow component in the longer event durations it is necessary to allow the effective time constant of this mono-exponential response to increase with increasing event duration.

There is also uncertainty as to whether the $\dot{V}O_2$ response should be referenced to $\dot{V}O_{2max}$ or the $\dot{V}O_2$ required. This is a further factor that makes it difficult to determine the real effect of event duration on the speed of the $\dot{V}O_2$ response. Nonetheless, $\dot{V}O_2$ kinetics appear to be intensity dependant within the severe domain. Hughson et al. (2000), using a model that used the $\dot{V}O_2$ required as the asymptote, showed that exercising at 125% $\dot{V}O_{2max}$ produced a faster $\tau$ (40 s) than exercising at 96% $\dot{V}O_{2max}$ (50 s). Williams (1997), using a model that used $\dot{V}O_{2max}$ as the asymptote, showed that a faster $\tau$ (32 s) occurred during exercise at 110% $\dot{V}O_{2max}$, than during exercise at 95% $\dot{V}O_{2max}$ ($\tau$ equalled 39 s). Finally, during middle-distance running events, Spencer et al. (1996) have shown that the percentage of $\dot{V}O_{2max}$ attained after 30 s of running was 69 and 59% for the 800 and 1500 m, respectively.

### 3.4 The idea that $\dot{V}O_{2max}$ is attained during event durations < 420 s

With the exception of Lloyd (1966, 1967) and Wood (1999a), the models of the energetics of middle-distance running performance assume that $\dot{V}O_{2max}$ will be attained in the range of middle-distance events. This assumption is supported by studies investigating $\dot{V}O_2$ kinetics during severe intensity exercise (see section 3.3) and studies that claim $\dot{V}O_{2max}$ is attained during short exhaustive exercise (Åstrand and Saltin, 1961; Hill and Ferguson, 1999; Williams, 1997).

Åstrand and Saltin (1961) studied cycle ergometer exercise and showed that the highest $\dot{V}O_2$ attained was lower for an exhaustive bout of cycling that lasted ~ 2 min than for one that lasted ~ 6 min. They mentioned this effect, but having claimed that the $\dot{V}O_2$ attained was only 2% higher for the longer bout, they dismissed it. A closer inspection of the individual data reveals, however, that in four of the five participants the difference between the highest and lowest values for the $\dot{V}O_2$ attained was 5%. The lowest $\dot{V}O_2$ was typically observed in the shortest bout (~ 2 min) and the highest was typically observed in the longest bout (~ 5-7 min).

Williams (1997) studied the $\dot{V}O_2$ response during short exhaustive running bouts lasting 120-300 s. The highest mean $\dot{V}O_2$ attained during the ~ 120 s run (3020 ml.min$^{-1}$) was 5% lower than that attained during the ~ 300 s run (3180 ml.min$^{-1}$) and the incremental test (3182 $ml.min^{-1}$). Hill and Ferguson (1999) also studied the $\dot{V}O_2$ attained during short exhaustive running bouts. The highest $\dot{V}O_2$ attained was 5% lower for a run which lasted ~ 2 min than one which lasted ~ 5 min, despite the authors claiming that $\dot{V}O_2$ reached $\dot{V}O_{2max}$. This finding is consistent with that of Williams (1997) and suggests that $\dot{V}O_{2max}$ was not attained during the shorter run. It is interesting to note that in both these studies, the aerobic fitness of the runners was low (mean $\dot{V}O_{2max}$ < 55 $ml.kg^{-1}.min^{-1}$).

Spencer et al. (1996) investigated the $\dot{V}O_2$ attained during constant speed 400, 800 and 1500 m race pace running, using specialist sprinters for the 400 m and middle-distance runners for both the 800 and the 1500 m. This study showed that $\dot{V}O_2$ reached a plateau at ~ 90 and ~ 94% $\dot{V}O_{2max}$ in the 800 and 1500 m runs, respectively. These findings provide support for the notion that the highest $\dot{V}O_2$ attained during middle-distance running may be below $\dot{V}O_{2max}$ during the shorter middle-distance events. In the same study, the $\dot{V}O_2$ response to a 400 m run was determined for the group of sprinters. The $\dot{V}O_2$ response to this run reached a plateau at ~ 98% of $\dot{V}O_{2max}$ after 35 s. The aerobic fitness of these sprinters was much lower than the middle distance runners [$\dot{V}O_{2max}$ (mean ± SEM): 53 ± 3 vs. 65 ± 2 $ml.kg^{-1}.min^{-1}$].

Spencer and Gastin (2001) extended the Spencer et al. (1996) study to include an extra running event (200 m) and a specialist sample of athletes for each of the events. Furthermore, each race pace run was customised to reflect the athlete's race pace strategies: they were free-range non-constant pace runs. The findings were similar to the Spencer et al. (1996) study for the 800 and 1500 m events: the $\dot{V}O_2$ attained reached a plateau at ~ 88 and ~ 94% $\dot{V}O_{2max}$ for the 800 and 1500 m runs, respectively. The $\dot{V}O_2$ response to the 400 m run was, however, different: the $\dot{V}O_2$ attained reached a plateau at ~ 89% of $\dot{V}O_{2max}$. The aerobic capability of these sprinters was higher than those previously studied in the 1996 paper (59 ± 3 vs. 53 ± 3 $ml.kg^{-1}.min^{-1}$).

It is noteworthy that Spencer et al. (1996) and Spencer and Gastin (2001) showed that in aerobically fit runners $\dot{V}O_2$ plateaus below $\dot{V}O_{2max}$. In contrast, studies that have investigated a similar exercise duration have shown that $\dot{V}O_{2max}$ may be attained.

Similarly, in the Spencer et al. (1996) and Spencer and Gastin (2001) studies, the sprint specialists, with lower aerobic fitness than the 800 and 1500 m specialists, were able to attain a higher % $\dot{V}O_{2max}$ than the other specialists in their specialist event. The highest $\dot{V}O_2$ attained during middle-distance running may, therefore, be related to $\dot{V}O_{2max}$.

### 3.5 The ecological validity of constant speed running

Several studies have investigated the effect of various strategies, including pacing (Foster et al., 1993a), free-range exercise (Foster et al., 1997), and simulated competition (Foster et al., 1993b), on cycling performance. Similar studies have also been conducted for running. The most relevant of these to modelling the energetics of performance are the simulated competition experimental designs since performance in competitions is what the models of the energetics of middle-distance running ultimately attempt to predict.

Most of the values ascribed to parameters in the models of middle-distance running performance are based on data determined from constant speed running. This has presumably been done because limited data are available on the pacing strategies used in middle-distance running events and on the physiological responses to such strategies. Nonetheless, some authors have investigated the $\dot{V}O_2$ response to different pacing strategies used in short duration (~ 4 min) exhaustive running.

Léger and Ferguson (1974) studied two different pacing strategies (fast-medium-very slow and slow-medium-slow) during an exhaustive ~ 200 s run. These strategies were chosen because they were considered to reflect those used in competitions at the time of the study. After ~ 140 s the $\dot{V}O_2$ attained was 4% less for the fast (4.16 $l.min^{-1}$) than for the slow start strategy (4.33 $l.min^{-1}$). At the end of the runs (~ 212 s) this difference in the $\dot{V}O_2$ attained had reduced to just 2% and there was little difference in the total amount of $O_2$ used during both pacing strategies (13.28 vs. 13.32 L). Since a control (constant pace) condition was not included in the experimental design it is not possible to assess the implications of these findings for the assumptions supporting the energetic models. However, one important finding that arises from this study is that the highest percentage of $\dot{V}O_{2max}$ attained was 90%, lending further support to the notion that in aerobically fit middle-distance runners $\dot{V}O_{2max}$ cannot be attained during severe intensity exercise.

Ariyoshi et al. (1979a) investigated three different pacing strategies (fast-slow, slow-fast, and constant) during an exhaustive run. The time to exhaustion was significantly longer for the fast start strategy than for the others: the fast start strategy yielded a time to exhaustion that was 17% longer than for the constant pace run (99 s vs. 82 s). The amount of $O_2$ used during the runs was similar for both the fast start (12.5 L) and constant pace (12.4 L) strategies. This implies that the differences in time to exhaustion may have been caused by the effect of the pacing strategies on the anaerobic energy contribution to the fast start run. The oxygen debt following the runs was 15% lower for the fast start compared to the constant pace strategy (4.4 vs. 5.2 L). Unfortunately, due to the limitations with this method (see section 3.1) it is difficult to draw any inferences about the potential interaction between aerobic and anaerobic energy contributions from these data.

Ariyoshi et al. (1979b) replicated their previous study but this time they focused on the $\dot{V}O_2$ response. Although the total $O_2$ used during the exhaustive runs was similar for the three pacing strategies, the rate of increase in $\dot{V}O_2$ was faster for the fast start than the other two strategies. Blood lactate levels reached a peak after 2-4 min and this peak was significantly lower for the fast start than the other pacing strategies. Finally, the $\dot{V}O_2$ attained, which clearly reached a plateau, was only ~ 90% of $\dot{V}O_{2max}$. This provides further support for the argument that only a percentage of $\dot{V}O_{2max}$ may be attained by aerobically fit middle-distance runners.

### 3.6 The use of assumed values for the models parameters

The energetic models have typically ascribed a single set of values, representative of a typical runner, to their parameters. While these values are in accordance with published data, the models assume that the values are independent of race duration. That is, it is assumed that middle-distance runners all share the same physiological characteristics, regardless of which event they specialise in. While most studies have focused on the differences in physiological characteristics between middle- and long-distance runners (e.g. Svedenhag and Sjödin, 1994), some data are available on the differences among different middle-distance specialists.

Svedenhag and Sjödin (1984) have shown that $\dot{V}O_{2max}$ differs among athletes who specialise in specific middle-distance events: 63.7 ml.kg$^{-1}$.min$^{-1}$, 400 m; 68.8 ml.kg$^{-1}$.min$^{-1}$, 800 m; 71.9 ml.kg$^{-1}$.min$^{-1}$, 800 –1500 m; and 75.0 ml.kg$^{-1}$.min$^{-1}$, 1500-5000 m. Furthermore, other physiological characteristics such as the fractional utilisation of $\dot{V}O_{2max}$ were also shown to be different between the event specialists. When running economy at 20 km.h$^{-1}$ was expressed as a percentage of $\dot{V}O_{2max}$ this factional utilisation of $\dot{V}O_{2max}$ decreased with increasing race duration: 94.1%, 800 m; 92.4%, 800-1500 m; and 87.9%, 1500-5000m.

## 3.7 Addressing the assumptions and their implications

### *3.7.1 The assumptions*

The early models (Hill and Lupton, 1923; Henry, 1954; Sargent, 1926) collectively assumed that the oxygen debt method accurately represented $C_{An}$. However, research has shown that this assumption is false (see section 3.1) and these early models would have overestimated the contribution of anaerobic metabolism to the energetics of middle-distance running. Since the early models used the oxygen debt to determine the oxygen requirement of running, the models would have also overestimated the true oxygen requirement, particularly for high speeds. This explains why these early models were still able to predict race times with a reasonable degree of accuracy despite overestimating the $C_{An_{MAX}}$ and the total energetic requirement. The more recent models (i.e. post Henry, 1954) have encapsulated the assumption, supported by contemporary physiologists, of a $C_{An_{MAX}}$ and the values used in these models agree with those published in the literature. Current research on the relationship between the fraction of $C_{An_{MAX}}$ that is available and exercise duration (see section 3.1) suggests that the assumption that $C_{An_{MAX}}$ will be exhausted in the 800 m event is false. Consequently,

$C_{An_{MAX}}$ may be overestimated in the models of Di Prampero et al. (1993) and Lloyd (1967).

Challenges to the concept of $\dot{V}O_{2max}$ (see section 3.2) have largely been based on speculation and are largely conjectural: there has been no convincing evidence to suggest that the assumptions supporting the concept of $\dot{V}O_{2max}$ are false. With the exception of Wood (1999a), all of the models have assumed that $\dot{V}O_{2max}$ will be attained during all middle-distance events. However, there is evidence to suggest that this assumption, though consistent with the commonly held view that $\dot{V}O_{2max}$ will always be attained during severe intensity exercise provided the duration is sufficient, is invalid (see section 3.4). That is, $\dot{V}O_{2max}$ may not be attained during middle-distance events, particularly the 800 m, and the percentage of $\dot{V}O_{2max}$ attained may be a function of event duration: the percentage of $\dot{V}O_{2max}$ attained may increase with increasing event duration. This is not due to fatigue terminating the exercise before $\dot{V}O_{2max}$ is attained. Rather, it seems that $\dot{V}O_2$ may plateau below $\dot{V}O_{2max}$. Consequently, with the exception of Wood (1999a), the models may overestimate the contribution of aerobic metabolism to the total energetics of middle-distance running. This overestimation may be greater for the shorter events (i.e. 400 and 800 m) than for the longer ones (i.e. 3000 m).

The process of modelling $\dot{V}O_2$ kinetics during severe intensity exercise has important implications for the mono-exponential functions used in the contemporary models (see section 3.3). With the exception of Wood (1999a), the models that have included a parameter to account for the $\dot{V}O_2$ kinetics at the onset of running have assumed a mono-exponential function referenced to $\dot{V}O_{2max}$ as the asymptote. Also with the exception of Wood's (1999a) model, a single $\tau$, which is independent of exercise intensity, has been ascribed to this parameter. These values for $\tau$ have typically been either fast or slow: Di Prampero et al. (1993) assume 10 s whereas Péronnet and Thibault (1989) and Ward-Smith (1999) assume 30 s. It is conceptually important that the correct asymptote, whether it be $\dot{V}O_{2max}$ or the $\dot{V}O_2$ required, or some other value, is referenced in the models and that an appropriate $\tau$ for this asymptotic reference point is used. There is also evidence to suggest that $\dot{V}O_2$ kinetics are intensity dependent within the severe intensity domain, regardless of the asymptotic value that is used in the modelling process, and that using a single $\tau$ in the models is invalid. Since $\tau$ will become slower with increasing event duration, the models using a single value for $\tau$ that is representative of the $\dot{V}O_2$ kinetics for 800 m running for example, will overestimate and underestimate the aerobic and anaerobic contribution, respectively, to the energetics of 1500 and 3000 m running. Likewise, the models using a slower $\tau$ representative of the $\dot{V}O_2$ kinetics during 3000 m running for example, will underestimate and overestimate the aerobic and anaerobic contribution, respectively, to the energetics of 800 and 1500 m running.

There are data available (see section 3.5) which suggest that physiological responses may differ between simulated competition and constant speed running. This is important because most of the values used in the models are based on data determined from constant speed running, yet the models are used predict competitive track performances. The amount of $O_2$ used during running appears to be independent of the pacing strategy used, yet $\dot{V}O_2$ kinetics appear to be quicker for a fast-start than for a constant pace strategy

Finally, each model has assumed a set of values for the physiological parameters, which is typical of a middle-distance athlete. Unfortunately, this approach assumes that the physiological characteristics of middle-distance runners are similar across the range of events. There are data available (see section 3.6) that show this assumption to be false: different event specialists have different physiological characteristics. Therefore, at best, the models will be valid only for a given event. Even this will only be the case if the chosen values are representative of a specialist in this event.

### *3.7.2 The implications*

To ensure that the application of the models is meaningful, it is imperative that the validity of the models and their associated assumptions is addressed. While the problems associated with accurately determining $C_{An}$ (see section 3.1) restrict the potential to test the assumptions associated with this component of the energetics of middle-distance running, the assumptions associated with the aerobic component can be readily tested.

If it could be shown that $\dot{V}O_{2max}$ is attained during middle-distance events the assumption common to most models of performance (Di Prampero et al., 1993; Henry, 1954; Hill and Lupton, 1923; Lloyd, 1966, 1967; Sargent, 1926; Ward-Smith, 1985, 1999) would be upheld. Alternatively, data showing that $\dot{V}O_{2max}$ is not attained would support the assumption in Wood's (1999a) model and would suggest that the aerobic contribution to middle-distance running has been overestimated in the past, especially for the shorter events. Such data would also have wider implications for the demarcation and characterisation of the severe intensity exercise domain.

Finally, if it could be demonstrated that the highest $\dot{V}O_2$ attained during constant speed running does not accurately reflect the highest $\dot{V}O_2$ attained during simulated competition, the ecological validity of the data on which most of the values ascribed to the parameters in the models are based would be questioned. Alternatively, were the highest $\dot{V}O_2$ attained similar for both these strategies, the ecological validity of the data would be established.

# *PART II*

# *METHODOLOGICAL CONSIDERATIONS*

# CHAPTER 4

# ERGOMETRIC CONSIDERATIONS FOR THE ASSESSMENT OF GAS EXCHANGE INDICES

## 4.1 Motorised treadmill running

### *4.1.1 Background*

Since the models of the energetics of middle-distance running are typically applied to track running, it could be argued that the assessment of $\dot{V}O_2$ during middle-distance running events should be evaluated in this situation. While portable equipment is available and has the potential to determine $\dot{V}O_2$ during track running, the running track does not offer a controlled environment for experimental research. It is difficult to accurately measure and control running speed on the track and attempting to control environmental conditions is troublesome. An alternative approach is to simulate track running using an ergometer (motorised treadmill). If this is done successfully the assessment of $\dot{V}O_2$ will be applicable to track running. A motorised treadmill approach was taken in this thesis; the following sections describe the motorised treadmill (MT) and test protocols used for the determination of gas exchange indices.

### *4.1.2 The motorised treadmill as an ergometer*

It is typically assumed that running mechanics are similar during over-ground and MT running. However, some studies have shown mechanical differences to exist between these two modes of running (Dal Monte et al., 1973; Elliot and Blanksby, 1976; Nelson et al., 1972; Sykes, 1975). In particular, Williams (1985) has suggested that mechanical differences are observed for running speeds above 18 $km.h^{-1}$. Mechanical differences between over-ground and MT running are therefore important considerations for simulating middle-distance running events on the MT, as these events are typically performed at speeds well above 18 $km.h^{-1}$.

Van Ingen Schenau (1980) has used a theoretical approach to show that the mechanics of MT and over-ground running are essentially the same provided the MT speed is constant. He suggested that particular MT specifications were required to achieve this constant speed assumption: the ability to absorb maximal load opposing the mat surface and a feedback mechanism with a sufficiently short response time to prevent changes in speed. Van Ingen Schenau (1980) also suggested that the construction of the MT must be such that the runners' perceptual information during MT running is close to that received during over-ground running. If these specifications are satisfied, the only mechanical difference between MT and over-ground running will be air resistance (Van Ingen Schenau, 1980).

Nigg et al. (1995) have suggested that the different types of MT used in research may explain the observed sources of variation between MT and over-ground running. These authors suggested that the larger MT, designed for research and high-performance testing, fulfil the specifications discussed above to a greater extent than smaller MT, designed for fitness-related testing. The MT used in this thesis is the former type and satisfies these specifications and the assumption of constant speed. This is in contrast to latter MT type, which typically consists of a rubber conveyor belt running over a wooden bed and around two rollers. This design is more likely to cause deviations in MT speed due to friction causing the rubber belt to expand and lose tension between the rollers. In addition, the size of the mat surface, and the safety functions, on the MT used in this thesis should have ensured that the runners felt safe and that their perceptions of running on this MT were equivalent to over-ground running.

In this thesis all exercise tests were performed on a Woodway Ergo ELG 70 motorised treadmill (Woodway, Weil and Rhein, Germany). The running mat surface (2 m x 0.7 m) consists of 104 transverse rubber slats fitted on a set of continuous toothed belts, which engage in deflection rollers, at the front and back of the MT. These deflection rollers prevent the mat from slipping and the front roller engages in the drive motor. The continuous belts are reinforced with steel wire to hold the slats together and prevent the mat from slipping laterally.

Two rails and 200 ball bearings support the running mat. This reduces friction, which is important for preventing the mat from decelerating on foot-strike, and distributes load evenly across the running mat. The friction is such that the MT can be used without the drive motor by simply pushing the treadmill to get it started.

A Syncron-servo-motor drives the MT, receiving load output from the deflection rollers and the roller guides to adjust the torque to compensate for any deviations in the speed of the mat as a result of foot-striking. This drive motor, therefore, is constantly updated with information on the forces and moments that are applied to the running mat to maintain a constant speed. The MT has an incline range of 0 – 30% and a speed range of 0 – 40 $km.h^{-1}$ with a resolution of 0.1% and 0.01 $km.h^{-1}$ when computer-interfaced, respectively. Due to the high speeds that can be attained on this MT, a safety harness (worn around the waist) was used for all tests. This harness was adjusted to the participant's height so that it did not impede running mechanics and, when activated in the event of a stumble or fall, it immediately stopped the power supply to the MT. This safety mechanism was in addition to a further three emergency stop buttons.

The MT was interfaced to a computer and was always operated in this way. This allowed warm-ups and test protocols to be programmed, thus removing the need for manual operation of the MT and ensuring the precision of test protocols. The software was capable of storing 100 stages for a given test protocol. This was sufficient for all protocols used in this thesis.

### *4.1.3 Calibration of the motorised treadmill*

Throughout this thesis the MT was only used on the flat (0% gradient). This was checked with a spirit level, and if necessary adjusted, before each experimental study. It was also important that the actual MT speed agreed with the displayed MT speed and that this actual speed was constant. The actual MT speed can be derived from measuring the running mat surface and recording the time for a given number of revolutions of the mat (Consolazio et al., 1963). Though this may be a practical and relatively accurate method, providing a large number of revolutions are timed, it is difficult to use this method at high speeds. This difficulty can be overcome by using a simple electrical circuit (Ricci, 1979) to time the number of belt revolutions. However, this method is also limited because it does not allow the assumption of constant speed to be fully assessed: it determines variability in speed between, but not within, complete belt revolutions.

The approach taken in this thesis was to use an electrical circuit to time four measured sections (~ 0.45 m) of the MT belt at a range of speeds. Belt speed was then derived (distance/time, in $m.s^{-1}$) and converted to $km.h^{-1}$ (by multiplying by 3.6). This was done for the speeds likely to be encountered during middle-distance running events (21 to 25 $km.h^{-1}$), with and without a runner (body mass of 75 kg) on the MT belt. This approach, therefore, gave an independent calculation of belt speed to compare to the displayed speed on the MT.. While the MT cannot be easily adjusted to calibrate any bias in actual (belt) speed versus the displayed speed, the MT was regularly serviced by Woodway technical engineers. This involved adjusting the motor to accurately receive the load feedback loop from the deflection rollers and roller guides to maintain a constant belt speed. Table 4.1 shows the agreement between the displayed MT speed (i.e. the nominal speed) and the actual belt speed for the upper range of speeds over which the MT was used in this thesis.

**Table 4.1 95% Limits of Agreement (Bland and Altman, 1986) for displayed vs. actual MT belt speed**

| | Limits of Agreement between displayed and actual belt speed ($km.h^{-1}$)* | |
|---|---|---|
| Displayed Speed ($km.h^{-1}$) | Without runner | With runner |
| 21 | 0.00 ± 0.05 | 0.00 ± 0.17 |
| 22 | 0.01 ± 0.07 | 0.01 ± 0.17 |
| 23 | 0.00 ± 0.06 | 0.00 ± 0.18 |
| 24 | 0.01 ± 0.07 | 0.01 ± 0.20 |
| 25 | 0.00 ± 0.07 | 0.00 ± 0.24 |

* Limits of agreement are presented as the mean difference (bias) ± 1.96 x the SD of the differences.

Table 4.1 shows that the bias was always less than 0.01 $km.h^{-1}$: the displayed speed is accurate. The random variation of the difference between the displayed and the actual belt speed was reasonably constant across the range of speeds when no load was applied to the MT belt (without a runner). However, when a load was applied to the MT belt (with a runner) this random variation increased for speeds greater than 23 $km.h^{-1}$. This random variation is acceptable for the purpose of this thesis, given that ± 0.2 $km.h^{-1}$ is likely to be the worst-case scenario (i.e. high speeds), that it is unlikely to have an impact on the determination of $\dot{V}O_2$, and that the random variation is difficult to interpret given that there are no comparable data for other types of MT.

### *4.1.4 Facial Cooling*

The air resistance encountered running outdoors provides facial and body cooling. This is important for cooling the body and reducing thermoregulatory stress. Since no air resistance is encountered during MT running, convective heat loss will be absent. This may cause thermoregulatory stress, which may affect the ecological validity of physiological responses determined during MT running. For all exercise tests in this thesis, three electronic fans passed ambient air over the runner's body. Two of these fans were floor mounted and one was mounted overhead. Although a valid simulation of air movement would require an air speed equivalent to the running speed for each exercise test, this is not permissible with the above fans. The air speed emitted from these fans and encountered on the runner's body ranged from ~ 11 to ~ 15 $km.h^{-1}$ from the legs to the head, respectively.

## 4.2 Test protocols to assess $\dot{V}O_{2max}$

### *4.2.1 Terminology*

Following the work of A. V. Hill and his colleagues (see section 2.2), $\dot{V}O_{2max}$ during running has traditionally been defined as a plateau in $\dot{V}O_2$ with increasing running speed. However, confusion among physiologists surrounds the definition of $\dot{V}O_{2max}$ and whether $\dot{V}O_{2max}$ has been attained during a progressive test. It has been suggested that the term $\dot{V}O_{2max}$ should only be used for situations in which a $\dot{V}O_2$-plateau is observed; in situations where no $\dot{V}O_2$-plateau is observed the term peak $\dot{V}O_2$ ($\dot{V}O_{2peak}$), the highest $\dot{V}O_2$ observed, should be used (Armstrong and Welsman, 1994; Davis, 1995). The term $\dot{V}O_{2peak}$ is used by some authors (Barnett et al., 1996; Barstow et al., 1996; Gastin and Lawson, 1994a, b; Green et al., 1996; Londeree et al., 1997) to define the highest $\dot{V}O_2$ attained in a progressive test regardless of whether a $\dot{V}O_2$-

plateau has been observed. Equally, the term $\dot{V}O_{2max}$ is often used to describe this highest $\dot{V}O_2$ attained in a progressive test regardless of whether a $\dot{V}O_2$-plateau has transpired. Whether the use of the terms $\dot{V}O_{2max}$ or $\dot{V}O_{2\,peak}$ reflects a conscious belief among those who use them that the highest $\dot{V}O_2$ attained in a progressive test, despite the absence of a $\dot{V}O_2$-plateau, is a maximal $\dot{V}O_2$, is unknown. In study I (chapter 6) these issues are addressed and a method, with associated terminology, to define $\dot{V}O_{2max}$ is established for use throughout the remainder of this thesis.

*4.2.2 Test protocols: speed ramped test*

Exercise testing guidelines typically recommend that exercise protocols should be individualised for the participants being tested and for the purpose of the test (Myers and Bellin, 2000). Unfortunately, this is often overlooked and test protocols are frequently selected based on familiarity, convenience, or tradition (Myers and Bellin, 2000). For the purpose of this thesis, the important considerations for the use of a suitable test protocol to assess $\dot{V}O_{2max}$ were that the incidence of a plateau in $\dot{V}O_2$ was high, $\dot{V}O_{2max}$ was equivalent to that which could be attained in middle-distance track running events, and the protocol did not place excessive time demands on the participants.

Many protocols have been, and are, used to assess $\dot{V}O_{2max}$. The two most common types are incremental protocols, where work rate increases in a 'step' pattern with time, and ramped protocols, where work rate increases as a continuous linear function of time. For both types of protocol, work rate can be manipulated during running by increasing the speed or the gradient. However, it has been suggested that some people may lack the necessary skill to run at the speeds required to elicit $\dot{V}O_{2max}$ on a level MT (Taylor et al., 1955). Taylor et al. (1955) argued that "raising the grade, with the speed held constant, is the most satisfactory method of increasing work load with the motor driven treadmill to attain a maximal oxygen uptake" (p.75) and recommended that a constant speed grade incremented protocol should be used for the assessment of $\dot{V}O_{2max}$

Indeed, such a protocol has been used by a variety of researchers for the assessment of $\dot{V}O_{2max}$ in middle-distance and long-distance runners (Boileau et al., 1982; Conley and Krahenbuhl, 1980; Costill, 1970; Daniels and Daniels, 1992; Foster et al., 1978; Morgan et al., 1989; Saltin and Åstrand, 1967; Spencer et al., 1996; Svedenhag and Sjödin, 1984). Moreover, published guidelines for the assessment of $\dot{V}O_{2max}$ during MT running recommend that this protocol is used, regardless of whether the athletes being assessed are trained runners or athletes who specialise in sports other than running (Bird and Davison, 1997; McConnell, 1988; Thoden, 1991).

Ramped protocols were introduced over 20 years ago (Whipp et al., 1981). At the time it was suggested that the incidence of a $\dot{V}O_2$-plateau might be higher for a ramped than for an incremental protocol. Whipp et al. (1981) compared a ramped protocol with two incremental protocols during cycling. They reported that "a plateau in $\dot{V}O_2$ was typically discerned from the ramp test, whereas this was often not the case with the ... incremental tests" (p.219) but they presented no data to support this statement. Such ramped protocols have typically been used during cycling, presumably with the emergence of electronically-braked cycle ergometers permitting work rate to be pre-programmed. Likewise, the more recent emergence of computer interfaced MTs has allowed ramped protocols to be easily pre-programmed.

Draper et al. (1998) compared $\dot{V}O_{2max}$ assessed during three ramped protocols on a MT: increasing speed (1.2 $km.h^{-1}$ per min) at a 0% gradient, increasing gradient (1% per min) at a constant (individually determined) speed, and increasing speed (1.2 $km.h^{-1}$ per min) at a 5% gradient. The incidence of a $\dot{V}O_2$-plateau was 92% for the increasing speed protocol at a 0% gradient and 100% for the other two protocols. Values for $\dot{V}O_{2max}$ were lower for the increasing speed protocol at a 0% gradient than for the other two protocols. Draper et al. (1998) suggested that these differences in $\dot{V}O_{2max}$ might reflect differences in the muscle mass recruited. This is consistent with the finding that a greater muscle mass is recruited during uphill running than during running on the flat (Sloniger et al., 1997), allowing a higher $\dot{V}O_{2max}$ to be attained.

Several important points emerge from the Draper et al. (1998) study. First, the incidence of a $\dot{V}O_2$-plateau is high (92%) for a speed ramped protocol at a 0% gradient.

Furthermore, this incidence is higher than that reported elsewhere in the literature for incremental protocols (Duncan et al., 1997; Rivera-Brown et al., 1994; Sheehan et al., 1987). Second, the high incidence of a $\dot{V}O_2$-plateau suggests that the runners attained $\dot{V}O_{2max}$ and were not limited by cadence, as suggested by Taylor et al. (1955). Thirdly, if the $\dot{V}O_2$ attained on a speed ramped protocol is to be compared to the $\dot{V}O_2$ attained during a simulated middle-distance event on the MT, both must be done on a 0% gradient. This is to ensure that the $\dot{V}O_{2max}$ attained on a speed ramped protocol at a 0% gradient on the MT will be equivalent to the $\dot{V}O_{2max}$ that could potentially be attained during track running: the same muscle mass is recruited during the speed ramped protocol as during track running.

The protocol used in this thesis was a speed ramped protocol (0.16 $km.h^{-1}$ per 5 s) at a 0% gradient. It has been suggested (Buchfuhrer et al., 1983) that 10 ± 2 min is the optimal duration for a progressive test used to determine $\dot{V}O_{2max}$. The starting speed was therefore set for each participant so that the test lasted for ~ 10 min. This was done by assuming that the peak speed attained on the test would be equivalent to the participant's average speed for the 800 m event and subtracting 12 $km.h^{-1}$ from this estimated peak speed (0.16 $km.h^{-1}$ per 5 s equates to 1.2 $km.h^{-1}$ per min) to determine the start speed.

### *4.2.3 Criteria for defining $\dot{V}O_{2max}$*

Taylor et al.'s (1955) study was the first in which a systematic approach to defining a $\dot{V}O_2$-plateau was taken. They established confidence limits for the expected increase in $\dot{V}O_2$ between incremental stages ($\Delta\dot{V}O_2$) and reported that the mean ± SD $\Delta\dot{V}O_2$ associated with a gradient increase of 2.5% was 4.18 ± 1.07 $ml.kg^{-1}.min^{-1}$, ranging from 2.2 to 5.9 $ml.kg^{-1}.min^{-1}$. They proposed that a $\dot{V}O_2$-plateau could be confirmed if a $\Delta\dot{V}O_2$ of less than 2.1 $ml.kg^{-1}.min^{-1}$ was observed between two consecutive incremental stages.

The Taylor et al. (1955) study was the first to emphasise that the random variation in $\dot{V}O_2$ data may obscure the identification of a plateau. Implicit in their approach was the idea that an increase in $\dot{V}O_2$ might be observed between consecutive incremental stages when the true $\Delta\dot{V}O_2$ is zero. Therefore, it is not appropriate to consider that a plateau has only occurred when $\dot{V}O_2$ shows no change or a decrease in response to an increase in work rate.

Since the publication of the Taylor et al. (1955) paper several different approaches using a criterion $\Delta\dot{V}O_2$ have been used to define a $\dot{V}O_2$-plateau. The criterion that has been commonly used is that of a $\Delta\dot{V}O_2$ less than the lower 95% confidence limit for the $\Delta\dot{V}O_2$ determined from sub-$\dot{V}O_{2\,peak}$ data for the group of participants (Mitchell et al., 1958; Niemelä et al., 1980; Sheehan et al., 1987) or for individuals (Rowland and Cunningham, 1992). A modification of this approach (Holthoer, 1996) involves deriving a linear regression equation relating $\dot{V}O_2$ to work rate for sub-$\dot{V}O_{2\,peak}$ intensities and calculating a predicted $\dot{V}O_2$ for the work rate corresponding to the final sampling interval. A $\dot{V}O_2$-plateau would be defined as an actual observed $\dot{V}O_2$ for the final sampling interval of less than the lower 95% confidence limit of the predicted $\dot{V}O_2$ (Draper et al., 1998).

An alternative approach has been taken by Wood (1999b) who identified the occurrence of a $\dot{V}O_2$-plateau by fitting a linear model and a plateau model to the $\dot{V}O_2$ vs. time data from a progressive ramp test. This approach assumes that $\dot{V}O_2$ either increases as a linear function of time throughout the test (linear model) or increases as a linear function initially and then plateaus in the closing stages (plateau model). The linear model was defined by a single equation ($y = a_1x + b_1$) and the two-segment plateau model by two equations: an initial linear segment ($y = a_2x + b_2$) and a final horizontal segment ($y = c$). Standard least squares regression techniques were used to derive the best-fit linear model and the best fit plateau model and the goodness of fit was evaluated by calculating the standard error of estimate (SEE). A plateau was deemed to have occurred when the SEE was lower for the plateau than for the linear model.

Other criteria that have been used to identify a $\dot{V}O_2$-plateau include a $\Delta\dot{V}O_2$ less than the mean sub-$\dot{V}O_{2\,peak}$ $\Delta\dot{V}O_2$ (Freedson et al., 1986) or some fraction of this mean $\Delta\dot{V}O_2$ (Cumming and Friesen, 1967). Alternatively, some researchers have used an 'absolute plateau', defined as no increase or a decrease in $\dot{V}O_2$ despite an increase in work rate (Clark and McConnell, 1986; Froelicher et al., 1974; Mayhew and Gross, 1975). Many researchers (Armstrong et al., 1996; Boileau et al., 1977; Cunningham et al., 1977; Davies et al., 1984; Rivera-Brown, et al., 1992; Rowland, 1993; Sidney and Shephard, 1977) have also carelessly applied Taylor et al.'s (1955) $\Delta\dot{V}O_2$ criterion value of 2.1 $ml.kg^{-1}.min^{-1}$ which would only be in circumstances where the sub-maximal $\Delta\dot{V}O_2$ is likely to differ from that reported by Taylor et al. (1955).

There is a clear rationale for using the criterion of a $\Delta\dot{V}O_2$ less than the lower 95% confidence limit for the sub-$\dot{V}O_{2peak}$ $\Delta\dot{V}O_2$, the modification of this approach (Holthoer, 1996), and the modelling approach taken by Wood (1999b), for determining whether a $\dot{V}O_2$-plateau has occurred. There is no obvious rationale for the use of the other approaches. It could be argued, therefore, that whilst many studies have presented data on the incidence of a $\dot{V}O_2$-plateau, the extent to which these data reflect the true incidence of such a plateau is questionable.

## 4.3 Test protocols to assess the lactate threshold

### *4.3.1 Test protocols*

Throughout this thesis the V-slope method was used to identify the lactate threshold (LT) using gas exchange data determined from the speed ramped test (see section 4.2.2). However, the ramp rate that is ideal for determining $\dot{V}O_{2max}$ is not necessarily ideal for determining the LT. Whipp et al. (1987) have argued that the ability to discern a break point in $\dot{V}CO_2$ relative to that of $\dot{V}O_2$ during progressive exercise depends on the effects of $CO_2$ storage. Factors that cause a rapid loading of $CO_2$ into the body stores in the early stages of a progressive test have the potential to impair valid discrimination of the LT. Such factors include a very rapid ramp rate (Ward and Whipp, 1992) and participants hyperventilating immediately prior to the exercise bout (Ozcelik et al., 1999).

The speed ramped test protocol was primarily selected for the determination of $\dot{V}O_{2max}$ and the rapid ramp rate was not ideal for the application of the V-Slope method.

However, the LT was only used as a control variable (i.e. to determine warm-up intensities) and was of secondary importance to the determination of $\dot{V}O_{2max}$. To satisfy the recommendations for determining the LT using the V-slope method, an additional ramp test, with a slower ramp rate, would have been required. This would have placed excessive time commitments on the participants and was considered to be unnecessary. Strict criteria were however used to determine whether the break point in $\dot{V}CO_2$ was genuine or 'pseudo'. Hyperventilation of the participants prior to a test is difficult to eliminate and at best can only be minimised by relaxing the participants.

### *4.3.2 Criteria for defining the lactate threshold*

The V-slope method (Beaver et al., 1986) identifies the LT as the $\dot{V}O_2$ at the point when the slope of the relationship between $\dot{V}O_2$ and $\dot{V}CO_2$ changes during a progressive test. The rationale for this approach is that there will be an increase in arterial lactate concentration and a corresponding decrease in the concentration of arterial bicarbonate, the major buffer of lactic acid, at the LT. Consequently, this increase in bicarbonate concentration results in a proportionate increase in $CO_2$ output at the lungs. This increase during a progressive test, relative to $\dot{V}O_2$, signals the point at which arterial blood lactate begins to increase (Ozcelik et al., 1999): the $\dot{V}CO_2$ - $\dot{V}O_2$ relationship shows an increased slope at this point.

In this thesis the $\dot{V}CO_2$ - $\dot{V}O_2$ relationship was modelled using least squares piecewise linear regression (Vieth, 1989). The first minute of the test and the portion over which a plateau in $\dot{V}O_2$ was evident was excluded from the analysis. The remaining data were divided into two segments, each of which was fitted by a simple linear model. All possible solutions were evaluated for this approach. That is, initially the first two data points were included in the first segment and the remainder were allocated to the second. Then the first three points were included in the first segment and the remainder were allocated to the second, and so on. This procedure continued until the last two points were allocated to the second segment. Each data point was included in either the first or the second segment; no data points were common to both. Each of the solutions was evaluated to assess whether the slope of the first segment was between 0.7 and 1.0; from those solutions that satisfied this criterion, the best-fit model (the solution for which the residual sum of squares was lowest) was selected. The intersection of these two segments was taken as the LT and was expressed as the corresponding $\dot{V}O_2$.

Published data to date show that the V-slope method is an accurate and precise approach to detecting the point at which blood lactate appearance exceeds its removal (Koike et al., 1990; Wasserman et al., 1990; Wasserman et al., 1994b). Criteria (Ward and Whipp, 1992) were used to check whether a true or 'pseudo' LT was detected. First, when expressed as a fraction of $\dot{V}O_{2max}$, the LT should be > 49% for normal adults (Davis et al., 1979; Jones et al., 1985; Orr et al., 1982); a 'pseudo-threshold' is characterised by an unusually low fraction of $\dot{V}O_{2max}$ which is < 49% (Hansen et al., 1984; Ozcelik et al., 1999). Second, the slope of the first sub-threshold segment should be between 0.95 and 1.00 (Beaver and Wasserman, 1992; Wasserman et al., 1994a); a 'pseudo-threshold' has an unusually low value of < 0.7 (Ozcelik et al., 1999). Low values for the slope of this first segment may also be apparent for subjects who are glycogen depleted (Cooper et al., 1992). The respiratory exchange ratio (RER) during unloaded cycling or at rest will also be low for these subjects. Hence, the ratio of this RER to the slope of the first linear segment may be used as a discriminatory index when the validity of the LT is questionable (Beaver and Wasserman, 1992). In studies that have demonstrated a valid LT, this ratio has been consistently < 1 (Beaver and Wasserman, 1992; Cooper et al., 1992; Ozcelik et al., 1999; Ward and Whipp, 1992); in studies in which 'pseudo-threshold' has been apparent, it has been > 1 (Ozcelik et al., 1999; Ward and Whipp, 1992). Throughout this thesis, a pseudo threshold was deemed to have occurred if one of the above criterions was not met.

# CHAPTER 5

# CONSIDERATIONS FOR THE DETERMINATION OF RESPIRATORY GAS EXCHANGE

## 5.1 Accuracy and precision

### *5.1.1 Background*

The focus of this thesis is the assessment of oxygen uptake ($\dot{V}O_2$) during exercise bouts equivalent to the duration of middle-distance running events. The key variable is therefore $\dot{V}O_2$, though carbon dioxide output ($\dot{V}CO_2$) is also important for the indirect determination of the lactate threshold (V-Slope method: see section 4.3.3). Oxygen uptake and $\dot{V}CO_2$ are not, technically, measurements, rather they are calculations based on a number of component variables. The Douglas bag method is the gold standard method for determining these variables, against which other methods are evaluated (Davies, 1995). It is a gold standard because few assumptions are made in the determination of the component variables and the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$. The key requirement is, therefore, to be able to determine each of these component variables, and therefore $\dot{V}O_2$ and $\dot{V}CO_2$, with a high degree of accuracy and precision.

Accuracy and precision are defined as the extent to which measured values agree with the actual (or expected) values and the extent to which these measured values agree with one another, respectively (Challis, 1997; Topping, 1972). To illustrate this an analogy can be drawn between the accuracy and precision of measurements and the accuracy and precision of rifle shooting. Imagine a rifle fixed to a rigid support and aimed at a target. If successive firing yields a tightly grouped set of shots, the rifle might be said to be precise, even if its accuracy is poor [i.e. even if the group of shots lie some distance from the intended (or expected) centre of the target].

With respect to accuracy, the difference between the actual value and the measured value is typically referred to as a systematic error (bias) or systematic uncertainty (Challis, 1997). On the other hand, for precision, the difference between repeated measured values is typically referred to as a random error or random uncertainty

(Challis, 1997). While the terms error and uncertainty are often used interchangeably (Challis, 1997), they do not refer to the same phenomena.

An 'error' is a mistake and in the case of a systematic difference between the measured and the actual value this is the appropriate term to use. These differences arise from the measurement instrument and may be constant in magnitude or vary in some regular (predictable) way. They should therefore be eliminated, or corrected for, with careful calibration procedures, and failure to do so is a mistake. In the above analogy, failing to adjust the sight of the rifle for a downhill aim would be an error of this type and would affect the accuracy of the shots.

The difference between repeated measured values is not an error but an 'uncertainty'. Such differences may arise from a lack of uniformity in the instruments used, small changes in other factors that influence the measurement, or variability of the experimenter. Uncertainties are, therefore, disordered in their incidence and variable in their magnitude. The random nature of the differences between repeated measured values means that they can not be eliminated; they can at best, only be estimated as a likely range of uncertainty in the measured value (by calculating confidence intervals). In the above analogy, the effect of environmental factors such as a variable crosswind, or the variability of the performer, would be uncertainties of this kind and would affect the precision of the shots. Throughout this thesis, the terms error and uncertainty will be used separately to describe systematic differences between the measured and the actual value and differences between repeated measured values, respectively.

Experimenters must strive for both accuracy and precision in their measurements. Without accurate measurements, the generalisation and comparison of findings beyond the laboratory in question is difficult. Without precision of measurement the chance of detecting 'real' changes in the measured value, in response to an intervention, is limited. This chapter describes the Douglas bag method used to determine $\dot{V}O_2$ and $\dot{V}CO_2$ in the studies reported in this thesis. A novel approach has been taken with this method to examine its potential for continuous short collections of expirate. Therefore, this chapter also examines the errors and uncertainties in the determination of $\dot{V}O_2$ and $\dot{V}CO_2$ that arise from using this Douglas bag method. "The descriptions are given in considerable detail, as attention to small matters of detail is often of much importance" (Haldane, 1912, Preface).

## 5.2 Calculations involved in the determination of $\dot{V}O_2$ and $\dot{V}CO_2$

### *5.2.1 Background*

The basic calculation of $\dot{V}O_2$ is:

$$\dot{V}O_2 = \dot{V}_I \times F_IO_2 - \dot{V}_E \times F_EO_2 \tag{1}$$

where $\dot{V}_I$ and $\dot{V}_E$ are the rate at which air is inspired and expired respectively, and $F_IO_2$ and $F_EO_2$ are the fractions of oxygen in the inspired and expired air, respectively.

The basic calculation of $\dot{V}CO_2$ is:

$$\dot{V}CO_2 = \dot{V}_E \times F_ECO_2 - \dot{V}_I \times F_ICO_2 \tag{2}$$

where $F_ECO_2$ and $F_ICO_2$ are the fractions of carbon dioxide in the expired and inspired air, respectively.

The volume of a gas varies depending on its temperature (Charles Law), pressure (Boyle's Law), and content of water vapour. Further calculations to standardise $\dot{V}_I$ and $\dot{V}_E$ are therefore necessary in order that comparisons can be made between data collected in different circumstances. Volumes of expirate are measured at *a*mbient *t*emperature and *p*ressure *s*aturated (ATPS), where ambient temperature and pressure are the temperature of the expirate and the pressure acting on it at the time the volume is measured. Since the typical ambient temperature for a physiology laboratory (15-25°) is below body temperature (~ 37°), expirate will be fully saturated with water at this ambient temperature. By convention, gas volumes, though measured at ATPS, are reported as the equivalent volume that would be obtained were the measurement made under *s*tandardised conditions (STPD): a *t*emperature of 0°C (273 K), a *p*ressure of 760 mmHg (sea level), and *dry* (no water vapour content). Gas volumes, at standard temperature (ST), can be calculated (from ATPS) as follows:

$$V_{(ST)} = V_{(ATPS)} \times \frac{273^{\circ}}{T_{EXP}} \tag{3}$$

where 273° is the absolute temperature (in Kelvin), and $T_{EXP}$ is the temperature of the expirate (in Kelvin) at the time the expirate is measured.

To correct a gas volume (ATPS) to standard pressure dry (SPD) the following calculation is used:

$$V_{(SPD)} = V_{(ATPS)} \times \frac{(P_B - P_{H_2O})}{760} \tag{4}$$

where $P_B$ is the pressure acting on the expirate (in mmHg) at the time its volume is measured, and $P_{H_2O}$ is the saturated vapour pressure of water associated with a given value for $T_{EXP}$.

These standard correction factors [equations (3) and (4)] can then be combined into one expression to correct a gas volume measured at ambient temperature and pressure, saturated (ATPS) to an STPD volume :

$$V_{(STPD)} = V_{(ATPS)} \times \frac{273 \times (P_B - P_{H_2O})}{T_{EXP} \times 760} \tag{5}$$

The accuracy and precision with which $\dot{V}O_2$ can be calculated using equations (1) and (5) will be affected by the accuracy and precision with which the variables $\dot{V}_{I(ATPS)}$, $\dot{V}_{E(ATPS)}$, $P_B$, $T_{EXP}$, $F_IO_2$, and $F_EO_2$ can be determined. Likewise, the accuracy and precision with which $\dot{V}CO_2$ can be calculated using equations (2) and (5) will be affected by the accuracy and precision with which the variables $\dot{V}_{I(ATPS)}$, $\dot{V}_{E(ATPS)}$, $P_B$, $T_{EXP}$, $F_ICO_2$, and $F_ECO_2$ can be determined. The following sections focus on these issues and outline the procedures and equipment used to determine the above variables.

## 5.3 Procedures involved in the determination of $\dot{V}O_2$ and $\dot{V}CO_2$

### *5.3.1 Determination of $\dot{V}_I$*

When the Douglas bag method is used to determine $\dot{V}O_2$ and $\dot{V}CO_2$, $\dot{V}_I$ is not typically measured. Instead, $\dot{V}_I$ is calculated from $\dot{V}_E$. The assumption on which this calculation is based is that nitrogen ($N_2$) is metabolically inert, such that the volume of $N_2$ expired and the volume of $N_2$ inspired are equal. This can be represented by the following equation:

$$\dot{V}_I \times F_IN_2 = \dot{V}_E \times F_EN_2 \quad (6)$$

where $F_IN_2$ and $F_EN_2$ are the fractions of $N_2$ in inspired and expired air, respectively. Equation (6) can then be rearranged to calculate $\dot{V}_I$ from $\dot{V}_E$:

$$\dot{V}_I = \dot{V}_E \times \frac{F_EN_2}{F_IN_2} \quad (7)$$

Neither $F_IN_2$ nor $F_EN_2$ are typically measured when the Douglas bag method is used. Alternatively, it is assumed that inspired air is composed only of $O_2$, $CO_2$, and $N_2$, and an expression for $F_IN_2$ that involves $F_IO_2$ and $F_ICO_2$, both of which are typically measured or estimated, can be used:

$$F_IN_2 = 1 - F_IO_2 - F_ICO_2 \quad (8)$$

This assumption is valid because the trace gases (i.e., argon, neon, helium etc) that comprise ~ 0.93% of inspired air are metabolically inert and can, therefore, be combined with $N_2$. Similarly, if it is assumed that expired air is composed only of $O_2$, $CO_2$, and $N_2$, an expression for $F_EN_2$ that involves $F_EO_2$ and $F_ECO_2$, both of which are typically measured, can be used:

$$F_EN_2 = 1 - F_EO_2 - F_ECO_2 \quad (9)$$

Substituting equations (8) and (9) into equation (7) yields an expression that can be used to calculate $\dot{V}_I$:

$$\dot{V}_I = \dot{V}_E \times \frac{(1 - F_EO_2 - F_ECO_2)}{(1 - F_IO_2 - F_ICO_2)} \tag{10}$$

Substituting for $\dot{V}_I$ in equation (1) gives

$$\dot{V}O_2 = \dot{V}_E \times \frac{(1 - F_EO_2 - F_ECO_2)}{(1 - F_IO_2 - F_ICO_2)} \times F_IO_2 - \dot{V}_E \times F_EO_2,$$

and rearranging gives

$$\dot{V}O_2 = \dot{V}_E \times \left( \frac{(1 - F_EO_2 - F_ECO_2)}{(1 - F_IO_2 - F_ICO_2)} \times F_IO_2 - F_EO_2 \right) \tag{11}$$

The equality of inspired and expired volumes of $N_2$ during respiration was first demonstrated by Lavoisier in 1775 (Cissik & Johnson, 1972a). Its incorporation as equation (7) in the determination of $\dot{V}O_2$ has been attributed to J. S. Haldane (1912) by some physiologists (Cissik & Johnson, 1972a; Dudka et al., 1971), and equation (7) is commonly referred to as the 'Haldane transformation'. However, others (Otis, 1964; Poole and Whipp, 1988) believe this procedure was first presented by Geppert and Zuntz (1888). In recognition of the fact that the $N_2$ correction factor may properly belong to Geppert and Zuntz (1888) it will be referred to as the $N_2$ correction factor hereafter. The $N_2$ and gas volume correction factors [equations (11) and (5), respectively] can be combined to yield the following equation for the determination of $\dot{V}O_{2\,(STPD)}$:

$$\dot{V}O_{2\,(STPD)} = \dot{V}_{E\,(ATPS)} \times \frac{273 \times (P_B - P_{H_2O})}{T_{EXP} \times 760} \times \left( \frac{(1 - F_EO_2 - F_ECO_2)}{(1 - F_IO_2 - F_ICO_2)} \times F_IO_2 - F_EO_2 \right) \tag{12}$$

The $N_2$ correction factor could also be used to derive $\dot{V}_I$ from $\dot{V}_E$ in the calculation of $\dot{V}CO_2$. However, for this calculation it is typically assumed that $\dot{V}_E$ and $\dot{V}_I$ are equal

(Lamarra & Whipp, 1995). The error in $\dot{V}CO_2$ associated with this assumption is equal to $F_ICO_2 \times (\dot{V}_E - \dot{V}_I)$. For a $\dot{V}O_2$ of 4 $L.min^{-1}$, $\dot{V}CO_2$ of 5 $L.min^{-1}$, and $\dot{V}_E$ of 110 $L.min^{-1}$, the true $\dot{V}_I$ would equal 109.1 $L.min^{-1}$ ($\dot{V}_I = \dot{V}_E - \dot{V}CO_2 + \dot{V}O_2$) and the error introduced in the calculation of $\dot{V}CO_2$ would be equal to $F_ICO_2 \times (110 - 109.1)$. For the range of $F_ICO_2$ measured in the laboratory (see section 5.3.5) the error in the calculation of $\dot{V}CO_2$ would range from 0.00036 to 0.00099 $L.min^{-1}$, or 0.00007-0.0002%. Consequently, $\dot{V}CO_2$ can be calculated as:

$$\dot{V}CO_2 = \dot{V}_E \times (F_ECO_2 - F_ICO_2) \qquad (13)$$

Equations (13) and (5) can be combined to yield the following equation for the determination of $\dot{V}CO_2$:

$$\dot{V}CO_{2\,(STPD)} = \dot{V}_{E\,(ATPS)} \times \frac{273 \times (P_B - P_{H_2O})}{T_{EXP} \times 760} \times (F_ECO_2 - F_ICO_2) \qquad (14)$$

The accuracy and precision with which $\dot{V}_I$ can be determined, using equation (10), will depend on the validity of the assumption that there is no disparity between the inspired and expired volume of $N_2$ (assuming that $\dot{V}_E$, $F_EO_2$, $F_ECO_2$, $F_IO_2$, and $F_ICO_2$ can be determined accurately and precisely).

Since Lavoisier's proposition of $N_2$ equality during respiration the hypothesis has been alternately confirmed and refuted. Dudka et al. (1971) conducted 36 resting and 35 exercise experiments on four subjects and reported a mean $N_2$ retention of 27 $ml.min^{-1}$ at rest, and a mean $N_2$ elimination of 132 $ml.min^{-1}$ during exercise. The uncorrected $\dot{V}O_2$ (i.e. the value derived from measured values for $\dot{V}_I$ and $\dot{V}_E$) at rest and during exercise was 12% and 8% less, respectively, than the corrected $\dot{V}O_2$ (i.e. the value derived using the $N_2$ correction factor). Cissik et al. (1972a) reported $N_2$ retention (38 $ml.min^{-1}$) in resting fasted subjects, and $N_2$ elimination of 44, 84, and 128 $ml.min^{-1}$ in resting subjects after 22, 34, and 61 g protein meals, respectively. The uncorrected $\dot{V}O_2$ was 11% greater, in fasting subjects, than the corrected $\dot{V}O_2$. In a further study, Cissik et al. (1972b) demonstrated $N_2$ elimination of 217 ml.min$^{-1}$ in exercising subjects in the post-absorptive state, and of 319, 409, and 509 ml.min$^{-1}$ following 21, 35, and 61 g protein meals, respectively. The uncorrected $\dot{V}O_2$ was up to 31% less than the corrected $\dot{V}O_2$. They concluded that published values of $\dot{V}O_2$ determined using the $N_2$ correction factor might be substantially in error.

The work of Cissik's group was challenged in a phase of research (1972-1976) that revived support for the original $N_2$ equality hypothesis. Initially, in response to the Cissik et al. (1972a) study, Farhi (1972) cited evidence of $N_2$ in mixed venous blood and gaseous $N_2$ in solution in blood to suggest that the cardiovascular system could not supply the observed uptake of $N_2$ at the rate of 36 ml.min$^{-1}$ in fasting subjects. Wagner et al. (1973) conducted 72 determinations of $\dot{V}O_2$ at rest and during exercise on 10 subjects in a post-absorptive state: the corrected $\dot{V}O_2$ was 1.1% greater using assumed $F_IO_2$ and $F_ICO_2$ values (20.93% and 0.03%, respectively), and 0.5% greater using measured $F_IO_2$ and $F_ICO_2$ values (20.91% and 0.03%, respectively), than the uncorrected $\dot{V}O_2$. Fox and Bowers (1973) conducted 20 determinations of $F_IN_2$ and $F_EN_2$ at rest in five fasted subjects. They reported no difference between the uncorrected and the corrected $\dot{V}O_2$ (290 ± 50 ml.min$^{-1}$ vs. 288 ± 48 m).

Wilmore and Costill (1973) determined $\dot{V}O_2$ using the $N_2$ correction factor and direct methods during three exercise intensities in six subjects. The corrected $\dot{V}O_2$ was 32 ± 20 ml.min$^{-1}$ greater than the uncorrected $\dot{V}O_2$ but the error in $\dot{V}O_2$ decreased from 1.8% (6.4 km.h$^{-1}$) to 0.8% (12.1 km.h$^{-1}$) across the three exercise intensities. Finally, Musch and Brooks (1976) reported no $N_2$ retention or $N_2$ production at rest but a retention of 106 ml.min$^{-1}$ during exercise. In this study, the corrected $\dot{V}O_2$ was 1.8% less than the uncorrected $\dot{V}O_2$ during exercise.

These more recent studies support Lavoisier's original hypothesis and the use of the $N_2$ correction factor in the determination of $\dot{V}O_2$. If $N_2$ retention or production does occur in respiration its magnitude appears to be independent of exercise intensity.

Importantly for this thesis, the magnitude is small enough to have little effect on calculations of $\dot{V}O_2$ during heavy or severe intensity exercise where minute ventilation is high. The conflicting findings by Dudka et al. (1972) and Cissik's group, where light exercise and resting metabolism were studied, suggest that errors associated with the use of the $N_2$ correction factor may be substantial if minute ventilation is small.

### *5.3.2 Determination of $\dot{V}_{E\,(ATPS)}$*

#### 5.3.2.1 Calculation of $V_{E\,(ATPS)}$

When the Douglas bag method is used, $\dot{V}_{E\,(ATPS)}$ is not technically measured but is calculated. For a given Douglas bag, the volume of expirate collected in the bag is divided by the time of the collection period ( $\dot{V}_{E\,(ATPS)} = V_{E\,(ATPS)}$ / collection period) to yield the average rate of ventilation. The accuracy and precision with which $\dot{V}_{E\,(ATPS)}$ can be determined will, therefore, be affected by the accuracy and precision with which $V_{E\,(ATPS)}$ can be collected in the Douglas bag and $V_{E\,(ATPS)}$ can be measured.

#### 5.3.2.2 Collection of $V_{E\,(ATPS)}$

Subjects wore a nose clip and a flanged rubber mouthpiece of their choice (Collins, Massachusetts, USA; Hans Rudolph Inc., Kansas, USA). They breathed through a low-resistance valve box (Jakeman and Davies, 1979), the expired side of which was connected to a 1.2 m length (34.2 mm internal diameter) of falconia tubing (Hans Rudolph Inc., Kansas, USA). The falconia tubing was connected to a transparent plastic cylinder, within which was fixed a rubber diaphragm. The plastic cylinder was connected to a two-way master valve (Hans Rudolph Inc., Kansas, USA) that was mounted on a tripod approximately 1.3 m above the ground.

Douglas bags (Cranlea and Co., Birmingham, UK) were connected to the master valve to allow continuous sampling of expirate (Figure 5.1). Each 150 L bag was fitted with a two-way bag valve (Type 343, Georg Fischer, Switzerland) so that whilst the bags were connected to the master valve the subject's expirate could be collected (bag valve open), or the bags could be sealed and exchanged for another bag (bag valve closed). The bags were arranged on an overhead rail so that the bags could be orientated above the master valve during collections and quickly removed after collections.

The procedure for continuous bag collections was as follows:

1) Bag 1 and bag 2 were connected to the exposed ports on the master valve while both bag valves were closed;

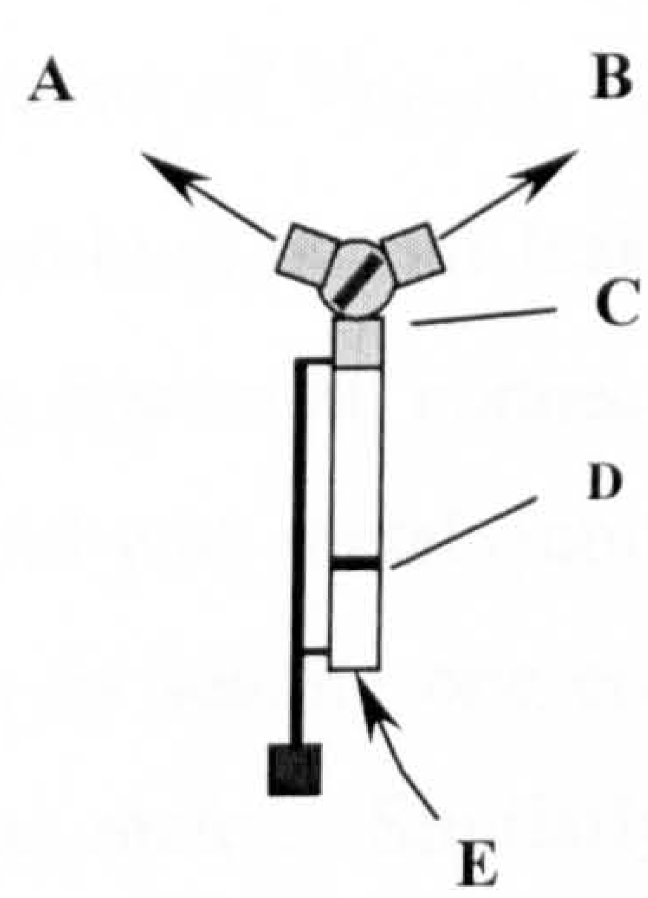
2) The master valve was opened to bag 2 and the subject's expirate was vented through to the laboratory;

3) The bag valve on bag 1 was opened and the master valve was turned to bag 1 to initiate the collection of expirate in this bag;

4) The bag valve on bag 2 was opened and the master valve was turned to bag 2 to terminate collection in bag 1 and initiate collection in bag 2;

5) The bag valve on bag 1 was closed and the bag was removed; bag 3 was attached to the master valve and the bag valve was opened;

6) The master valve was turned to bag 3 to terminate collection in bag 2 and initiate collection in bag 3. The bag valve on bag 2 was closed and the bag was removed, and so on.




| | |
|---|---|
| A | Odd Numbered Douglas Bags |
| B | Even Numbered Douglas Bags |
| C | Master Valve |
| D | Rubber Diaphragm |
| E | Falconia From The Subject |

**Figure 5.1 Schematic of the master valve system used for continuous collections of expirate.**

To ensure accurate and precise collections of $V_{E\,(ATPS)}$, a whole number of breaths was always collected. To identify the end of expiration (to initiate and terminate a collection period) the experimenter observed the rubber diaphragm located in the plastic cylinder (see figure 5.1).

The falconia tubing between the subject and the master valve was always flushed with expirate (for ~ 60 s) before bag 1 was opened to the master valve to ensure that the initial collection was expirate and not ambient air. However, each time the bags were removed from the master valve thereafter, all valves were exposed to ambient air (for ~ 5 s). It was not possible to both flush these valves with expirate and make continuous collections. The initial collection of expirate in each bag (excluding bag 1) would therefore have been ambient air, or a mixture of ambient air and expirate. The total exposed dead-space volume, between the master valve and the bag valve, was 50 ml. The response kinetics of the entire gas analysis system (see section 5.3.6.1.1) were not rapid enough to allow the $O_2$ and $CO_2$ fractions in this dead-space to be determined between bag changes. It was assumed, therefore, that the 50 ml dead space contained ambient air. The contaminating effect of this dead space was corrected for in the determination of expired gas fractions (see section 5.3.6.2.2).

The accurate and precise collection of $V_{E\,(ATPS)}$ is dependent on the assumption that all valves, Douglas bags, and plumbing do not leak (Lamarra and Whipp, 1995). In an attempt to prevent leaks in the system all connections, such as those between the bags and the bag valves, were secured with metal (jubilee) clips. The entire system was also consistently checked for leaks by sealing one end of the plumbing and attempting to extract air through the dry gas meter. Similarly, the bags and the bag valves were checked for leaks by evacuating the bag and attempting to extract air through the dry gas meter.

### 5.3.2.3 Timing of $V_{E\,(ATPS)}$

Each Douglas bag collection period was manually timed with a stopwatch (Fastime; Cranlea and Co., Birmingham, U.K.). This stopwatch was capable of recording up to 100 split times with a resolution of 0.01 s. Collection periods were timed continuously and recalled after completion of the data collection. The stopwatch was started at the initiation of the first collection period; thereafter, the split-time was taken each time the master valve was turned, until the end of the final collection when the watch was stopped.

### 5.3.2.4 Measurement of $V_{E\,(ATPS)}$

The volume of expirate ( $V_{E\,(ATPS)}$ ) in each Douglas bag was measured by evacuating its contents through a dry gas meter (Harvard Apparatus Ltd., Edenbridge, U.K.). Hart et al. (1992) and Hart and Withers (1996) have shown that the principle on which dry gas meters operate may produce alinearity in the volumes measured depending on where the gas is passed in the expansion range of the bellows. These authors further suggested that a volume of at least 25 L must be passed through the dry gas meter per measurement to ensure an alinearity-induced error of < 1% (based on a maximal absolute error of 0.25 L). Collection periods < 30 s may contain small volumes (< 25 L) so it was important to assess the accuracy and precision of the Harvard dry gas meter across the full range of volumes.

An attempt was made to replicate the situation in which $V_E$ would be collected and measured using the Douglas bag method. A 3 L precision syringe (Hans Rudolph Inc., Kansas, USA) was used to pump known volumes ($V_s$, ranging from 3 to 150 L, in 3 L increments) of room air into a Douglas bag, via a valve-box and falconia tubing, which was subsequently evacuated through the dry gas meter. The air from the Douglas bag was pulled through the meter by a vacuum pump connected, via corrugated tubing, to the outlet side and the meter volume ($V_M$) was noted for each $V_s$. In this situation an analogy can be drawn between room air being pumped by the syringe and expirate being exhaled into a Douglas bag. The $V_s$ represents the expirate actually exhaled in a given time (which would be collected in a Douglas bag) and $V_M$ represents the expirate that would be evacuated from the Douglas bag through the dry gas meter.

Hart and Withers (1996) suggest that when a rapid syringe bolus is executed through a valve-box the gas in the connected tubing temporarily keeps moving due to its momentum after flow through the valve-box has stopped. A brief negative pressure in the tubing may briefly open the inspiratory diaphragm and, therefore, draw in a volume of gas in addition to that delivered by the syringe. Sealing the inspiratory side of the valve-box during each expiratory syringe bolus would control such an effect. However, the effect would also be present during respiration, when a valve-box and falconia tubing are used. It should not, therefore, be controlled when the accuracy and precision of the measurement of $V_{E(ATPS)}$ are evaluated. The above procedure yielded 50 data pairs ($V_M$ vs. $V_s$) which were used to derive a linear regression equation relating $V_s$ to $V_M$. A typical set of data is given in figure 5.2.

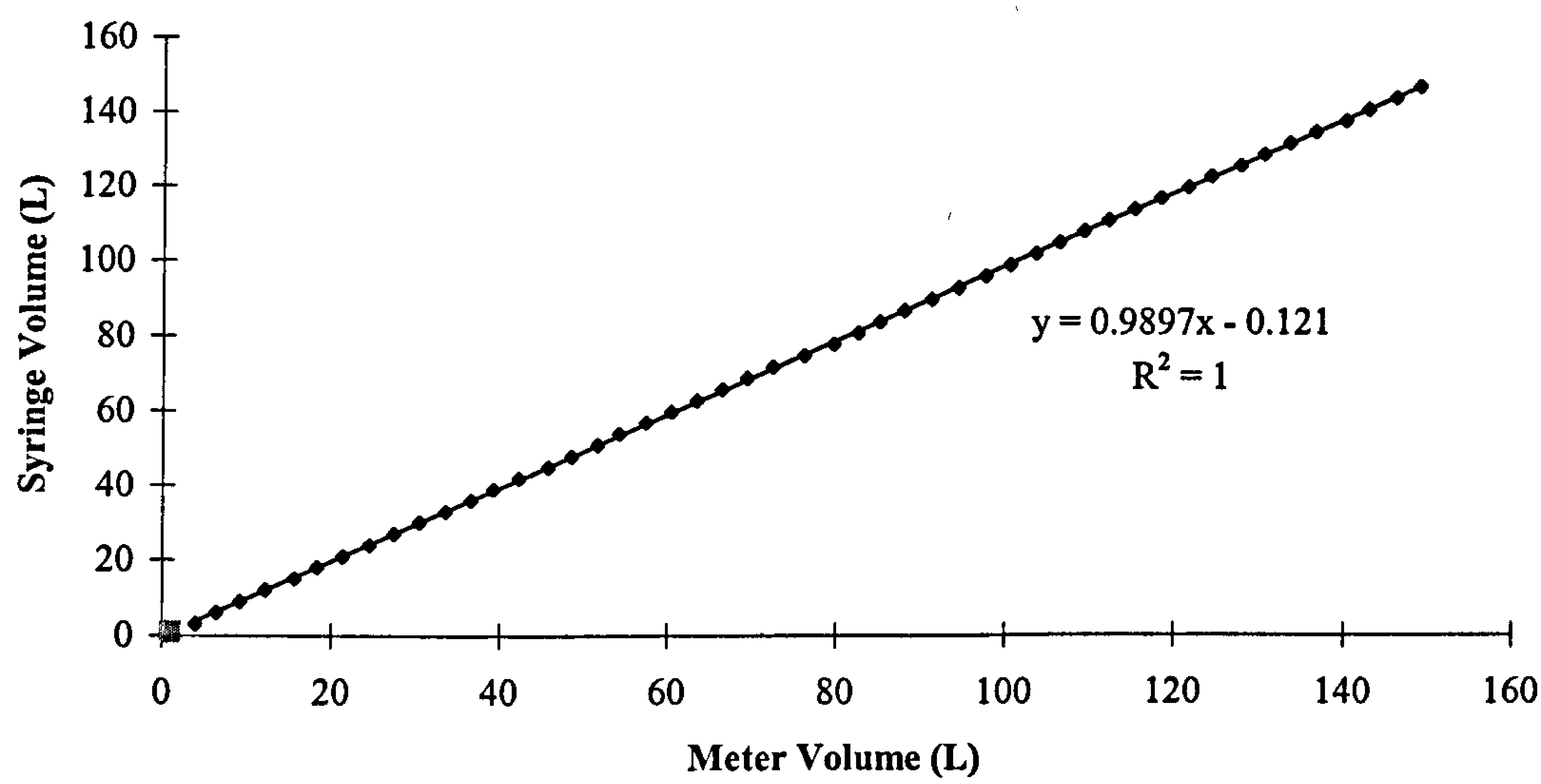



**Figure 5.2 The volume measured by the dry gas meter versus that delivered by the syringe.**

Figure 5.2 shows that the relationship between the volume delivered by the syringe and that measured by the dry gas meter is linear and that the intercept of this relationship is very close to zero. The absolute value of the intercept was always less than 0.2 L. For each study the above procedure was performed and the regression equation was used to derive a corrected meter volume (the predicted syringe volume) for the values used in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$. The $V_M$ was multiplied by the slope of the regression equation, and the intercept was added, to obtain the corrected $V_E$. If this corrected $V_E$ differs from the volume of expirate that is actually exhaled an uncertainty will be introduced in the determination of $\dot{V}O_2$ and $\dot{V}CO_2$. This uncertainty will be proportional to the difference between the corrected $V_E$ [(slope × $V_M$ + intercept)] and that which is actually exhaled ($V_S$).

In figure 5.3 the data presented in figure 5.2 are presented again, but this time the difference between $V_S$ and the corrected $V_E$ [(slope × $V_M$ + intercept)] is plotted as a function of $V_S$. This is equivalent to plotting the uncertainty in the corrected $V_E$ as a function of the 'actual' $V_E$ (equivalent to the $V_S$).

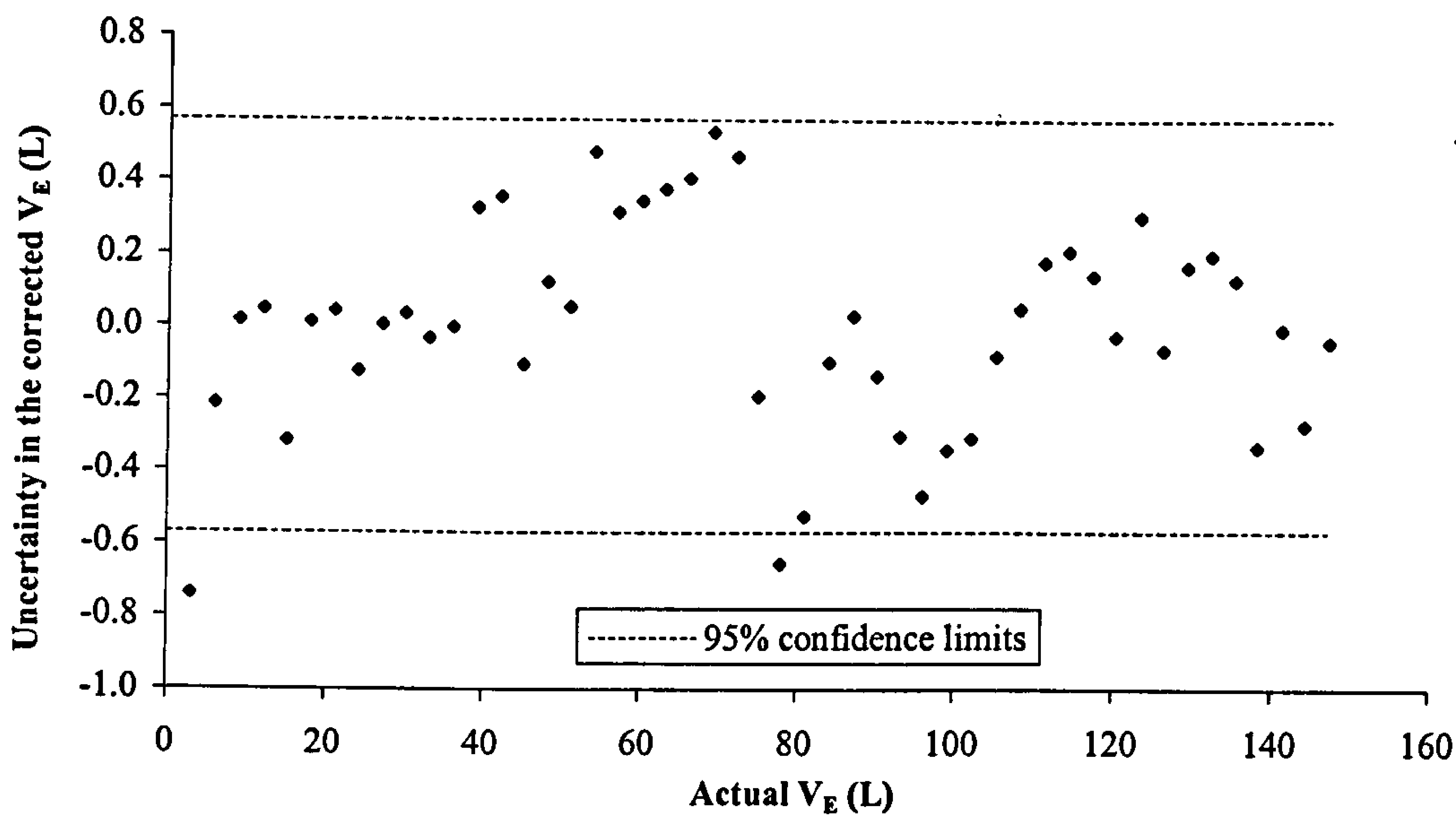



**Figure 5.3 Estimated uncertainty in the corrected $V_E$ as a function of the actual $V_E$ ($V_S$).**

Figure 5.3 shows the residuals for the regression equation presented in figure 5.2. The standard deviation of the differences between $V_S$ and the corrected $V_E$ is 0.29 L, and the 95% confidence interval is –0.57 to + 0.57 L (figure 5.3). This interval is equivalent to the 95% confidence interval for the uncertainty in the corrected $V_E$.

From figure 5.3 it can be seen that the uncertainty in the corrected $V_E$ is independent of the 'actual' $V_E$. Consequently, when it is expressed as a percentage of the 'actual' $V_E$, this uncertainty, and therefore the uncertainty in $\dot{V}O_2$ and $\dot{V}CO_2$, will decrease as exercise intensity increases for a given collection period. Similarly, for a given exercise intensity the uncertainty in $\dot{V}O_2$ and $\dot{V}CO_2$ will decrease as the collection period increases. To illustrate the impact of this uncertainty on $\dot{V}O_2$ and $\dot{V}CO_2$ a typical set of data were compiled to yield values that might realistically be obtained for exercise of a moderate, heavy and severe intensity (table 5.1). Equation (12) was used to calculate $\dot{V}O_2$, whilst $\dot{V}CO_2$ was calculated using equation (14). For these calculations, it was assumed that $T_{(EXP)}$ was 293 K (20°), $P_B$ was 760 mmHg, and $P_{H_2O}$ was 17.4 mmHg at the time the volume measurement was made. $F_IO_2$ and $F_ICO_2$ were assumed to be 0.20915 and 0.0007, respectively (see section 5.3.5). Using the data and calculations on which table 5.1 was compiled, the uncertainty incurred in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$ for a ± 0.57 L uncertainty in the corrected $V_E$ was determined (table 5.2).

**Table 5.1 Variables used to calculate $\dot{V}O_2$ and $\dot{V}CO_2$ for 3 levels of exercise intensity.**

| Exercise Intensity | $F_EO_2$ | $F_ECO_2$ | $V_{E\,(ATPS)}$ ($L.min^{-1}$) | $V_{E\,(STPD)}$ ($L.min^{-1}$) | $\dot{V}O_2$ ($L.min^{-1}$) | $\dot{V}CO_2$ ($L.min^{-1}$) |
|---|---|---|---|---|---|---|
| Moderate | 0.150 | 0.050 | 44.0 | 40.0 | 2.472 | 1.973 |
| Heavy | 0.165 | 0.041 | 87.9 | 80.0 | 3.616 | 3.226 |
| Severe | 0.180 | 0.032 | 175.8 | 160.0 | 4.574 | 5.008 |

**Table 5.2 Effect of a ± 0.57 L uncertainty in the corrected $V_E$ on the % uncertainty incurred in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$ at three levels of exercise intensity and for four collection periods.**

| | % Uncertainty in $\dot{V}O_2$ | | | | % Uncertainty in $\dot{V}CO_2$ | | | |
|---|---|---|---|---|---|---|---|---|
| | Collection Period (s) | | | | Collection Period (s) | | | |
| Exercise Intensity | 15 | 30 | 45 | 60 | 15 | 30 | 45 | 60 |
| Moderate | ± 5.19 | ± 2.59 | ± 1.73 | ± 1.30 | ± 5.19 | ± 2.59 | ± 1.73 | ± 1.30 |
| Heavy | ± 2.59 | ± 1.30 | ± 0.86 | ± 0.65 | ± 2.59 | ± 1.30 | ± 0.86 | ± 0.65 |
| Severe | ± 1.30 | ± 0.65 | ± 0.43 | ± 0.32 | ± 1.30 | ± 0.65 | ± 0.43 | ± 0.32 |

Before $V_E$ is measured a sample of expirate is drawn from the Douglas bag for the analysis of expired gases (see section 5.3.6.1). It is important that this sample volume can be quantified, and added to the corrected $V_E$, for the accurate and precise determination of $\dot{V}_E$. A flow control device regulated the flow of expirate from the Douglas bag through the gas analysis system (see section 5.3.6.1) so provided this sample period is timed the sample volume could be calculated. The displayed flow was set at 2 $L.min^{-1}$ and the sample period was always 1 min (see section 5.3.6.1.1). However, if this displayed flow differed from the actual flow an error and an uncertainty would be introduced in the measurement of $V_E$. To examine this, the 'actual' flow-rate of the gas analysis system was calculated by repeatedly filling a Douglas bag with known volumes ($V_s$) and timing the evacuation of these through the gas analysis system.

The 'actual' mean flow-rate was 1.3 $L.min^{-1}$ when the displayed flow was set at 2 $L.min^{-1}$. This would introduce an error of 0.7 L in the measurement of $V_E$ and, thus, in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$. To eliminate this the 'actual' flow of 1.3 $L.min^{-1}$ was used for all sample volume calculations. The standard deviation of the mean flow was ± 0.03 $L.min^{-1}$. This yielded 95% confidence limits of ± 0.07 $L.min^{-1}$ and would introduce a small uncertainty in the measurement of $V_E$ and the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$. This is illustrated in table 5.3 using the data and calculations used to compile table 5.1

**Table 5.3 Effect of a ± 0.07 $L.min^{-1}$ uncertainty in sample volume on the % uncertainty in $\dot{V}O_2$ and $\dot{V}CO_2$ at three levels of exercise intensity and for four collection periods.**

| | % Error in $\dot{V}O_2$ | | | | % Error in $\dot{V}CO_2$ | | | |
|---|---|---|---|---|---|---|---|---|
| | Collection Period (s) | | | | Collection Period (s) | | | |
| Exercise Intensity | 15 | 30 | 45 | 60 | 15 | 30 | 45 | 60 |
| Moderate | ± 0.64 | ± 0.32 | ± 0.21 | ± 0.16 | ± 0.64 | ± 0.32 | ± 0.21 | ± 0.16 |
| Heavy | ± 0.32 | ± 0.16 | ± 0.11 | ± 0.08 | ± 0.32 | ± 0.16 | ± 0.11 | ± 0.08 |
| Severe | ± 0.16 | ± 0.08 | ± 0.05 | ± 0.04 | ± 0.16 | ± 0.08 | ± 0.05 | ± 0.04 |

The timing of the sample volume evacuation was considered to have little impact on errors in $V_E$ since a timing error of 2 s during a 60 s sample would not affect the calculated sample volume (to 1 decimal place).

### *5.3.3 Measurement of $P_B$*

Barometric pressure ($P_B$) was measured, using a Fortin mercury barometer (F.D. and Co Ltd, Watford, U.K.), immediately after the last Douglas bag had been evacuated. This barometer is equipped with a vernier scale, and has a resolution of 0.05 mmHg. The laboratory was situated 75 m above sea level (determined from ordinance survey maps) and the $P_B$ was, therefore, calibrated to this height using the following equation (WMO, 1996):

$$P_{B_{SL}} = P_{B_{LAB}}(H/29.27T_{ATM}) \tag{15}$$

Which can be rearranged to give $P_{B_{LAB}}$ as follows

$$P_{B_{LAB}} = P_{BSL}/(H/29.27T_{LAB}) \tag{16}$$

where $P_{B_{SL}}$ is the $P_B$ at sea-level, $P_{B_{LAB}}$ is the $P_B$ for the laboratory (and both pressures are in hPa where 1 mm Hg = 1.33 hPa), H is the laboratory elevation in metres, and $T_{ATM}$ is the atmospheric (outside) temperature in Kelvin.

Measurements of $P_B$ were always taken to the nearest 0.05 mmHg and equation (16) was used regularly to check the accuracy of the barometer. The error in the measurement of $P_B$ associated with the use of the above barometer and calibration procedure is likely to be small (< 1 mmHg). The uncertainty in the measurement of $P_B$ associated with setting the ivory pointer in contact with the mercury column or reading the vernier scale is also likely to be small (< ±0.2 mmHg).

The % error in the calculation of $\dot{V}_{E\,(STPD)}$ from $\dot{V}_{E\,(ATPS)}$ that would be associated with an error of 1 mmHg in the measurement of $P_B$ is equal to $1/(P_B - P_{H_2O})$ and will be directly reflected in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$. For the typical values used to calculate $\dot{V}O_2$ and $\dot{V}CO_2$ in table 5.1, a 1 mmHg error in the measurement of $P_B$ would introduce an error of 0.13% [1/(760-17.4)] in the calculation of $\dot{V}_{E\,(STPD)}$ from $\dot{V}_{E\,(ATPS)}$ and thus in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$. Similarly, an uncertainty of ± 0.2 mmHg in the measurement of $P_B$ would induce a ± 0.03% uncertainty [± 0.2/(760-17.4)] in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$.

### *5.3.4 Measurement of $T_{(EXP)}$*

In the standardisation of gas volumes from ATPS to STPD it is the $T_{(EXP)}$ at the time the volume measurement is made that should be used. This was achieved by placing a thermistor probe (Hanna Instruments NS920; RS Components, Corby, UK), with a resolution of 0.1 °C, in the inlet port of the dry gas meter. This thermistor was factory calibrated to give a maximum error of 0.2 °C and this is also likely to be the upper limit for the uncertainty associated with temperature measurements. The % error in the calculation of $\dot{V}_{E\,(STPD)}$ from $\dot{V}_{E\,(ATPS)}$ that would be associated with an error or uncertainty of 0.2 °C in the measurement of $T_{(EXP)}$ is equal to $T_{(EXP)}/(T_{(EXP)} + 0.2) - 1$, and, again, will be directly reflected in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$. For the typical values used to calculate $\dot{V}O_2$ and $\dot{V}CO_2$ in table 5.1, an error or uncertainty of 0.2 °C in the measurement of $T_{(EXP)}$ would introduce a maximum error of – 0.07% [293/(293 + 0.2) – 1] in the calculation of $\dot{V}_{E\,(STPD)}$ from $\dot{V}_{E\,(ATPS)}$ and thus in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$.

The measured value for $T_{(EXP)}$ is also used to calculate $P_{H_2O}$ in the standardisation of $\dot{V}_{E\,(ATPS)}$ to $\dot{V}_{E\,(STPD)}$. An error or uncertainty in $T_{(EXP)}$ may therefore propagate an error or uncertainty in the calculation of $P_{H_2O}$. The relationship between temperature and $P_{H_2O}$ is non-linear (Hall & Brouillard, 1985) but over the temperature range likely to be encountered in the laboratory (15-20 °C) this relationship can be approximately represented by a linear function with a slope of 1. A 0.2 °C error or uncertainty in $T_{(EXP)}$ would induce an error or uncertainty of ~ 0.2 mmHg in the calculated $P_{H_2O}$. The percentage error or uncertainty in the calculation of $\dot{V}_{E\,(STPD)}$ from $\dot{V}_{E\,(ATPS)}$ that would be associated with this error or uncertainty in the calculated $P_{H_2O}$ is equal to – 0.2/($P_B$ – $P_{H_2O}$). For the typical values used to calculate $\dot{V}O_2$ and $\dot{V}CO_2$ in table 5.1, an error or uncertainty of 0.2 mmHg in the calculation of $P_{H_2O}$ would introduce an error or uncertainty of – 0.03% [- 0.2/(760 – 17.4)] in the calculation of $\dot{V}_{E\,(STPD)}$ from $\dot{V}_{E\,(ATPS)}$, and thus in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$.

For a given error or uncertainty in the measurement of $T_{(EXP)}$, the error and uncertainty introduced in the calculation of $\dot{V}_{E\,(STPD)}$ through using incorrect values for $P_{H_2O}$ and $T_{(EXP)}$ are both in the same direction. Nonetheless, the error incurred in the calculated $\dot{V}_{E\,(STPD)}$, and therefore in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$, will be ≤ 0.10% provided the error in $T_{(EXP)}$ is ≤ 0.2°C. Similarly, the uncertainty in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$ will be ≤ ± 0.10% provided the uncertainty in $T_{(EXP)}$ is ≤ ± 0.2°C.

*5.3.5 Measurement of $F_IO_2$ and $F_ICO_2$*

When the Douglas bag method is used to determine $\dot{V}O_2$ and $\dot{V}CO_2$ in normoxic conditions $F_IO_2$ and $F_ICO_2$ are rarely measured. Instead, many physiologists assume that $F_IO_2$ is 0.2093 and $F_ICO_2$ is 0.0003 (Davis, 1995; McArdle et al., 1996; Powers and Howley, 1997) and these values are used in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$. Equation (12), for the determination of $\dot{V}O_2$, can be rearranged to give the following calculation:

$$\dot{V}O_{2\,(STPD)} = \dot{V}_{E\,(ATPS)} \times \frac{273 \times (P_B - P_{H_2O})}{T_{EXP} \times 760} \times \left( \frac{F_IO_2}{(1 - F_IO_2 - F_ICO_2)} \times (1 - F_EO_2 - F_ECO_2) - F_EO_2 \right) \quad (17)$$

Inserting the above assumed $F_IO_2$ and $F_ICO_2$ values gives a value of 0.2648 for the inspired ratio [$F_IO_2$/(1-$F_IO_2$-$F_ICO_2$)].

Precise measurements of the atmospheric $O_2$ fraction since 1915 have been in the range of 0.20945 to 0.20952 (Machta and Hughes, 1970) and recent data suggest that a realistic current value for the $CO_2$ fraction would be ~ 0.00036 (Keeling et al., 1995).

It is not clear why the 0.2093 and 0.0003 values for $F_IO_2$ and $F_ICO_2$, respectively, have been so widely adopted in the physiological literature. However, it is plausible that they arose from Haldane's investigations of mine air at the start of the twentieth century and have been assumed to be constant over time (Haldane, 1912). Nonetheless, it is unlikely that $F_IO_2$ and $F_ICO_2$ will reflect atmospheric (outside) air when the inspirate is room air. This is because the extent to which the composition of room air differs from atmospheric air might depend on factors such as how many subjects are exercising and how well ventilated the laboratory is. It is likely, therefore, that the $CO_2$ fraction will be higher and the $O_2$ fraction will be lower for room air than for atmospheric air and that these fractions will vary both between laboratories and between exercise tests.

To investigate this, measurements of $F_IO_2$ and $F_ICO_2$ were made during 38 tests, all of which were conducted in the same laboratory with one window open (~ 0.5 m). None of these tests involved more than one subject exercising at the same time and there were typically two experimenters present. For each test, the $O_2$ and $CO_2$ fractions of the laboratory room air were recorded at 2 min intervals and these data were averaged to yield mean values for $F_IO_2$ and $F_ICO_2$, respectively. These measurements were made by placing a sampling tube within 0.5 m of the exercising subject's mouth. This tube was connected to the gas analysis system (see section 5.3.6.1) which was calibrated (see section 5.3.6.1.2) prior to each exercise test. Following each test outside air was immediately sampled to ensure that the readings on the $O_2$ and $CO_2$ gas analysers were restored to atmospheric air values. This was the case for each of the 38 exercise tests.

For the 38 tests the mean (95% confidence limits) of the measured values was 0.20915 (± 0.00035) for $F_IO_2$ and 0.0007 (± 0.0003) for $F_ICO_2$. The corresponding value for the inspired ratio was 0.2647 (± 0.0005). As the mean value for the inspired ratio was 0.2647, an error would be incurred if the assumed value of 0.2648 was used in the calculation of $\dot{V}O_2$ (table 5.4). If the mean inspired ratio (0.2647) was used in the calculation of $\dot{V}O_2$, in place of the assumed 0.2648 inspired ratio, this error would be removed but an uncertainty would remain. Since the $N_2$ correction factor is not used in the calculation of $\dot{V}CO_2$ only an error or uncertainty in the $F_ICO_2$ term in equation

(14) will introduce an error or uncertainty in $\dot{V}CO_2$. Furthermore, because errors or uncertainties are independent of the determination of $\dot{V}_{E(ATPS)}$, the associated errors or uncertainties in $\dot{V}O_2$ and $\dot{V}CO_2$ will not be affected by the collection period. The above effects are shown in table 5.4, which was compiled using the calculations and on which table 5.1 is based.

**Table 5.4 Effect of an error or uncertainty in the $F_IO_2/(1-F_IO_2-F_ICO_2)$ ratio and $F_ICO_2$ on errors or uncertainties in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$ respectively, at three levels of exercise intensity.**

| | % Error | | % Uncertainty | |
|---|---|---|---|---|
| | $\dot{V}O_2$ | $\dot{V}CO_2$ | $\dot{V}O_2$ | $\dot{V}CO_2$ |
| Exercise Intensity | $F_IO_2/(1-F_IO_2-F_ICO_2)$ .2647 vs .2648 | $F_ICO_2$ · .0007 vs .0003 | $F_IO_2/(1-F_IO_2-F_ICO_2)$ .2647 ± .0005 | $F_ICO_2$ · .0007 ± .0003 |
| Moderate | 0.13 | 0.81 | ± 0.65 | ± 0.61 |
| Heavy | 0.18 | 0.99 | ± 0.88 | ± 0.74 |
| Severe | 0.28 | 1.28 | ± 1.38 | ±0.96 |

These errors in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$ could be eliminated by measuring the $O_2$ and $CO_2$ fractions in the laboratory room air for a large number of tests to derive mean inspired values. However, the uncertainty that arises from the inter-test variation in $F_IO_2$ and $F_ICO_2$ can only be eliminated if these are measured during every test. Consequently, to eliminate this uncertainty, inspired gas fractions were measured for every test and used in all calculations of $\dot{V}O_2$ [equation (17)] and $\dot{V}CO_2$ [equation (14)] throughout this thesis.

### *5.3.6 Determination of $F_EO_2$ and $F_ECO_2$*

#### 5.3.6.1 Sensitivity of $\dot{V}O_2$ and $\dot{V}CO_2$ to errors in $F_EO_2$ and $F_ECO_2$

Accurate and precise gas analysis equipment and procedures are paramount for the determination of expired gas fractions. This is because errors in the determination of expired gas fractions, and particularly errors in the determination of $F_EO_2$, can have harmful effects on the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$. The effect of a 1% increase in $F_EO_2$ and $F_ECO_2$ on the calculated values for $\dot{V}O_2$ and $\dot{V}CO_2$, respectively, shown in Table 5.5, illustrates this. This table has been compiled using the calculations and data used to compile table 5.1.

**Table 5.5 Effect of a 1% increase in $F_EO_2$ and $F_ECO_2$ on the error incurred in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$ respectively, at three levels of exercise intensity.**

| | 1 % Increase in $F_EO_2$ | | 1% Increase in $F_ECO_2$ | |
|---|---|---|---|---|
| Exercise Intensity | % Error in $\dot{V}O_2$ | % Error in $\dot{V}CO_2$ | % Error in $\dot{V}O_2$ | % Error in $\dot{V}CO_2$ |
| Moderate | -3.07 | 0.00 | -0.21 | +1.01 |
| Heavy | -4.61 | 0.00 | -0.24 | +1.01 |
| Severe | -7.94 | 0.00 | -0.30 | +1.01 |

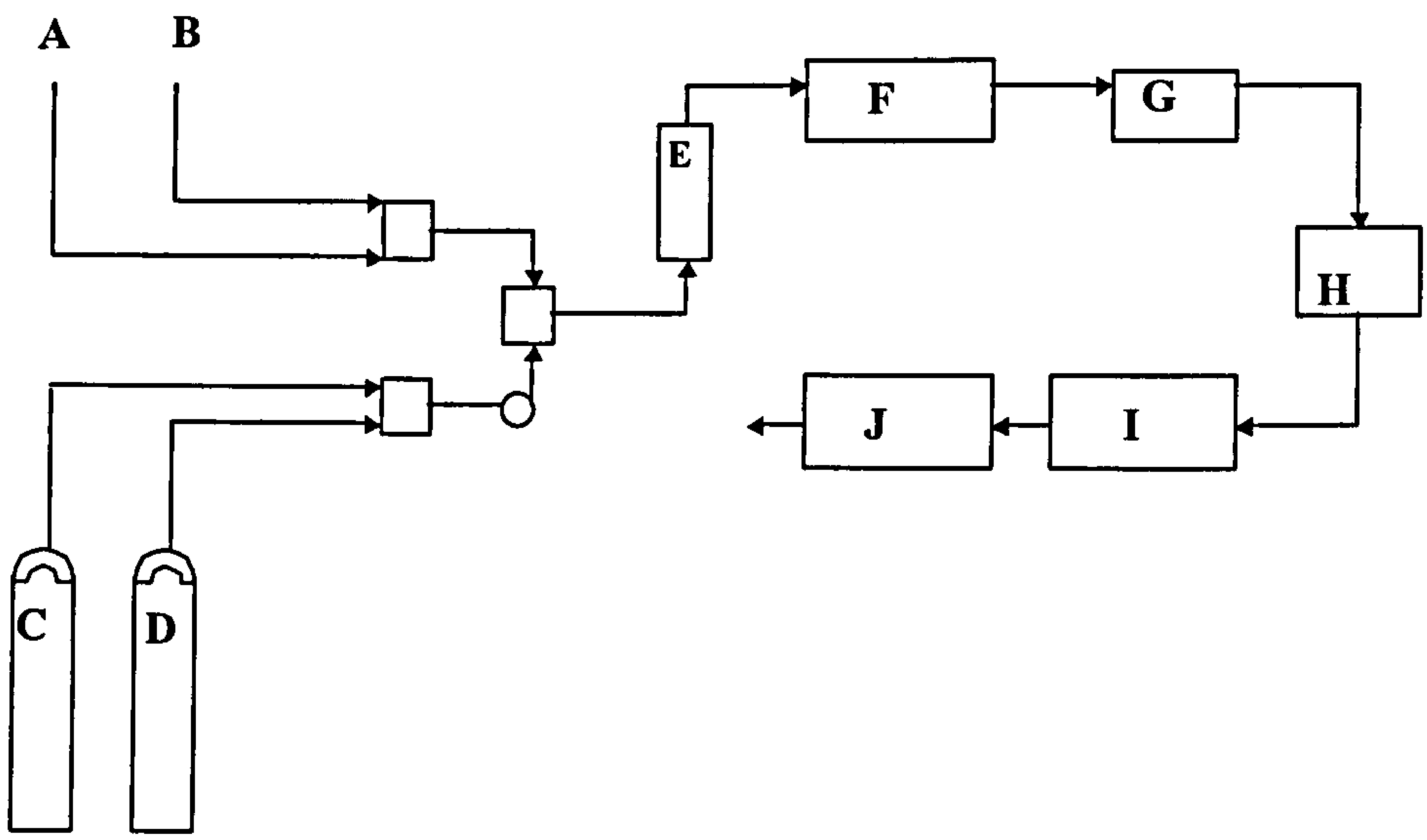
Table 5.5 clearly demonstrates that a small error in the determination of $F_EO_2$ will translate into a large error in the calculation of $\dot{V}O_2$. This is because the $F_EO_2$ variable is used twice in the calculation of $\dot{V}O_2$ and the error incurred at the first stage of the calculation is in the same direction as that which is introduced at the second stage [(1-$F_EO_2$ - $F_ECO_2$) $-F_EO_2$, see equation (17)]. In the calculation of $\dot{V}CO_2$ no variable is used twice so this amplification effect does not occur.

The data in table 5.5 suggest that the calculation of $\dot{V}O_2$ is highly sensitive to errors in the determination of $F_EO_2$ and $F_ECO_2$, particularly when $F_EO_2$ is high and $F_ECO_2$ is low, such as is typically seen during severe exercise. Consequently, for the accurate determination of $\dot{V}O_2$ in this exercise intensity domain accurate and precise measurements of expired gas fractions are paramount. Though $F_ECO_2$ is considered of secondary importance in the determination of $\dot{V}O_2$, many of the factors that affect the accuracy and precision with which $F_EO_2$ can be determined will also affect the accuracy and precision with which $F_ECO_2$ can be determined.

The accuracy and precision with which $F_EO_2$ and $F_ECO_2$ can be determined will largely depend on two factors. First, it will depend on the accuracy and precision with which the fractional concentrations of $O_2$ and $CO_2$ in the sample of expirate can be measured. Second, it will depend on the extent to which the composition of the sample of expirate passed through the analysers reflects that of the actual expirate collected from the subject. Issues surrounding the control of water vapour in the gas analysis system and the calibration of $O_2$ and $CO_2$ analysers are related to the first factor. Issues surrounding the fact that a plastic Douglas bag may never be completely evacuated and the possibility that the expirate collected may become contaminated, with residual air present in the bag, are related to the second factor. The gas analysis system described below has consequently been developed to ensure that the measurement of expired gas fractions can be achieved with a high degree of accuracy and precision. The following sections describe the equipment and procedures that were used to derive values for $F_EO_2$ and $F_ECO_2$.

5.3.6.2 Measurement of $O_2$ and $CO_2$ fractions in expirate

The system used to analyse samples of expirate for the fractions of $O_2$ and $CO_2$ is shown in figure 5.4. The three-way valves shown in this figure are electronically controlled solenoid valves (124N Burkert Contromatic Ltd; RS Components, Bristol, U.K.). These valves were controlled to ensure that only one of the four gases (zero cylinder, span cylinder, outside air, expirate) could be sampled at any given time.




| | | | |
|---|---|---|---|
| A | Sample To Outside Air | G | Nafian Tubing |
| B | Sample To Douglas Bag | H | Condenser |
| C | Zero Gas Cylinder | I | $CO_2$ Analyser |
| D | Span Gas Cylinder | J | $O_2$ Analyser |
| E | Flow Control Device | □ | Three-way Valve |
| F | Pump | O | Vent For Excess Pressure |

**Figure 5.4 Schematic of the gas analysis system used to analyse samples of expirate for the fractions of $O_2$ and $CO_2$.**

The concentrations of $O_2$ and $CO_2$ in expirate were measured using a paramagnetic $O_2$ analyser (static cell) and an infrared $CO_2$ analyser (series 1440; Servomex plc, Crowborough, U.K.). The $O_2$ analyser was calibrated using reference gases and outside air; the $CO_2$ analyser was calibrated using reference gases only (see section 5.3.6.1.2). The reference gases used for calibration were stored under pressure (200 bar) and it was important that the gas analysers were not exposed to these high pressures. A vent for excess pressure and a flow control device (GT/GTV Gapmeter; CT Platon Limited, Hampshire, U.K.) were therefore placed before the analysers in the gas analysis circuit. The flow to the gas analysers was controlled at 1.3 $L.min^{-1}$ (see section 5.3.2.3) and the pressure regulators (Legris; Airco Pneumatics Ltd, Cheltenham, U.K.) on the cylinders, in which the reference gases were stored, were set to ensure that the rate at which these gases were released was 1.5 L.min$^{-1}$. The excess gases were expelled through the vent. In addition to the calculation of the sample volume (5.3.2.3), it was important that expirate, outside air, and each of the reference gas mixtures entered the analysers at the same flow rate because, for a given concentration of $O_2$ or $CO_2$ in a gas mixture, the reading obtained on a partial pressure analyser is proportional to the rate at which this sample passes through the analysers.

Both the $O_2$ and $CO_2$ analysers measure the partial pressure generated by the specified gas and not the absolute concentration of this gas. In this type of analyser water vapour acts as a diluent, such that if a sample of expirate (which is saturated with water vapour at room temperature) was analysed wet and the same sample was then dried and re-analysed, the analysers would give a higher reading for the gas fractions for the dry expirate than for the wet expirate (Beaver, 1973; Norton and Wilmore, 1975). It was therefore important to give consideration to the control of water vapour content in the gases entering the analysers.

The $O_2$ analyser was calibrated using both outside air and reference gas cylinders. Outside air is partially saturated, with its water vapour content proportional to the ambient temperature and the relative humidity. The reference gases are dry and expirate is fully saturated at normal room temperature. Norton and Wilmore (1975) highlighted that when a dry (cylinder) gas mixture is sampled after moist gases (such as expirate), the dry gas mixture will collect moisture from the plumbing, between the cylinder and the analyser, and thus will become partially humidified before it reaches the analyser. They suggest that the concentration read by the analyser will gradually increase to the nominal (dry) value as this moisture is carried away and the calibration mixture entering the analyser becomes increasingly drier. It follows, therefore, that the opposite effect might occur when a moist gas mixture (expirate) is sampled after a dry gas. In this situation some of the water vapour in the moist gas might condense in the dry plumbing and on the dry valves. Were this to occur, some water vapour would be lost and the measured concentrations of $O_2$ and $CO_2$ would continue to decrease as the water vapour content of the moist gas entering the analysers slowly increases.

All the gases that were analysed, whether they were calibration gases, outside air, or expirate, were passed through a condenser (Buhler PKE3; Paterson Instruments, Leighton Buzzard, UK) on their way to the analysers to ensure that their water vapour content was at a low and constant level (see figure 5.4). This condenser consists of an aluminium core, the temperature of which is maintained within 5 ± 0.1 °C by an electrical cooling unit. At this temperature the saturated vapour pressure of water is 6.47 ± 0.05 mmHg. When expirate is passed through this condenser prior to analysis the water vapour content of the sample that enters the analysers should be controlled within a narrow range. However, since the cylinders of reference gases are dry, and the water vapour pressure of water in outside air will, on some days, be less than 6.5 mmHg (see Appendix II), it was important that all gases enter the analysers with the same water vapour content as expirate. This was achieved by saturating the reference gases and outside air with water vapour by passing them through a length of Nafian tubing (MH Series Humidier; Perma Pure Inc, New Jersey, USA.) before entering the condenser. This tubing was submerged in water and is selectively permeable to water vapour (see figure 5.4).

5.3.6.1.1 Response time for the gas analysers

The full response time was determined for each analyser by sampling expirate at regular intervals using the system shown in figure 5.4. The determined response times, therefore, represent the response time for this system as a whole. For each analyser, the measured response time will reflect the time required to wash out the dead space of this system and the response kinetics of the analysers. In table 5.6 the values given for each time point are mean values for 10 measurements of $F_EO_2$ or $F_ECO_2$.

**Table 5.6 Response times for the $O_2$ and $CO_2$ gas analysers**

| Time from start of sampling (s) | Measured $O_2$ fraction (mean ± SD) | Measured $CO_2$ fraction (mean ± SD) |
|---|---|---|
| 20 | 0.1973 ± .0064 | 0.0406 ± .00043 |
| 30 | 0.1668 ± .0024 | 0.0413 ± .00003 |
| 40 | 0.1661 ± .0010 | 0.0413 ± .00003 |
| 50 | 0.1658 ± .0001 | 0.0413 ± .00003 |
| 60 | 0.1658 ± .0001 | 0.0413 ± .00003 |

These results show that a stable reading was obtained on the $O_2$ analyser after 50 s and on the $CO_2$ analyser after 30 s. The quicker response time of the $CO_2$ analyser is due to the fact that any samples passed through the gas analysis system (see figure 5.4) pass through the $CO_2$ analyser before reaching the $O_2$ analyser. Throughout this thesis, all gases (expirate, calibration gases and gas mixtures) were sampled for 60 s. Readings were noted in the last 5 s of this period, by which time stable values had always been reached on both analysers.

5.3.6.1.2 Calibration of gas analysers

A two point calibration (zero and span) was available for both the $O_2$ and the $CO_2$ analyser. In each case, adjusting the zero setting was equivalent to altering the intercept of a linear function relating the analyser reading to the output from the sample cell. Adjusting the span was equivalent to altering the slope of this relationship. For both analysers, the zero setting was adjusted to ensure that the reading on the analyser was zero when a cylinder of $N_2$ was passed through the analyser (the zero gas in figure 5.4). For the $O_2$ analyser the span setting was adjusted to ensure that the reading on the analyser was 0.2095 when outside air was passed through the analyser. For the $CO_2$ analyser the span setting was adjusted to ensure that the reading on the analyser was

0.0400 when a sample from a gravimetrically prepared cylinder of a reference gas mixture (0.1600 $O_2$, 0.0400 $CO_2$, balance $N_2$: the span gas in figure 5.4) was passed through the analyser.

Arieli et al. (1999) have shown that infrared $CO_2$ analysers respond differently, depending on whether the background gas (present in a gas mixture) is $N_2$ or $O_2$. The implication of their findings is that if the $N_2/O_2$ ratio is different in the calibration span gas mixture to that of the measured gas mixture an error will be incurred in the measured $CO_2$ fraction. This error increases relative to increases in both the $CO_2$ and $O_2$ fraction in the calibration gas mixture (Arieli et al., 1999). Calibration gas mixtures should therefore be carefully selected to contain a $CO_2$ fraction close to the highest $CO_2$ fractions likely to be measured, and the lowest $O_2$ fraction which satisfies the linearity check on the $O_2$ analyser. For the calibration gas mixture used in the above procedure, the error in measured $CO_2$ fractions will be less than 0.00001, but of unknown direction, as a result of the background gas effect.

The calibration procedure adopted was as follows:

1. The zero adjustment was made for both analysers;

2. The span adjustment was made for the $O_2$ analyser;

3. The span adjustment was made for the $CO_2$ analyser.

This procedure allowed the linearity of the $O_2$ analyser to be checked each time the analysers were calibrated by comparing the reading obtained on this analyser at stage 3 with the nominal concentration of $O_2$ in the reference span gas cylinder.

Some authors appear sceptical of the precision with which gas mixtures in cylinders can be prepared (Howley et al., 1995). These authors recommend the concentrations of $O_2$ and $CO_2$ in reference gas mixtures used for the calibration of manometric analysers are measured using volumetric techniques such as those developed by Haldane (1912) and later modified by Lloyd (1958), and Scholander (1947).

For the Lloyd-Haldane technique, with five repeat analyses, Abdul-Rasool et al. (1981) report a SD of ± 0.0002 and ± 0.0006 for gas mixtures with low (< 0.2000) and high (> 0.4000) $O_2$ fractions, respectively. Consolazio et al. (1963) suggest that an operator should be considered unreliable if duplicate analyses of expired air do not agree within ± 0.0004 for $O_2$ and ± 0.0003 for $CO_2$, respectively. For gas analysis using the Scholander technique, Collins et al. (1977) reports a SD of ± 0.00012 for $O_2$ and of ± 0.00006 for $CO_2$ for 36 repeat analyses of fresh outside air. Hermansen (1973) reports a SD for 10 repeat analyses of the same gas mixture (0.158 $O_2$, 0.062 $CO_2$) of ± 0.0003 for $O_2$ and ± 0.0002 for $CO_2$.

The precision of these volumetric techniques is similar, but for both methods the precision is lower than the precision of the $O_2$ fraction in fresh outside air and the precision with which gas mixtures can be prepared gravimetrically. Recent data from the meteorological literature show that the $O_2$ fraction in fresh outside (atmospheric) air is relatively constant, varying by ~ 0.00002, within a year (Keeling and Shertz, 1992). The precision of the gravimetrically prepared gas mixtures used in the above calibration procedure is reported to be within ± 0.0001 of the actual nominal gas fraction (BOC Gases, New Jersey, U.S.A). In particular, the precision of the $O_2$ analyser calibration procedure will be extremely high because the reference gas mixture cylinder is only used to check the linearity of the $O_2$ analyser and is not a calibration gas mixture *per se*. This analyser was, therefore, considered to be calibrated when it read within ± 0.0001 of the nominal $O_2$ fraction in the reference gas mixture cylinder during the linearity check.

5.3.6.1.3 Accuracy and precision of measured $F_EO_2$ and $F_ECO_2$

The above section implies that the error in the measurement of $O_2$ and $CO_2$ fractions, as a result of the calibration procedure used for the system shown in figure 5.4, is unlikely to exceed 0 .0001 and 0.00011, respectively. To determine the precision with which the fractions of $O_2$ and $CO_2$ in expirate can be determined with the system shown in figure 5.4, 10 repeat analyses were performed on two different samples of expirate. For the first sample, the mean (± SD) was 0.1644 ± 0.00005 for $O_2$ and

0.0427 ± 0.00005 for $CO_2$. For the second sample, the mean (± SD) was 0.1796 ± 0.00005 for $O_2$ and 0.0309 ± 0.00004 for $CO_2$. These data yielded ~ 95% confidence limits of ± 0.0001 for both the $O_2$ and $CO_2$ fractions. It seems reasonable to conclude, therefore, that the uncertainty in the measured fractions of $O_2$ and $CO_2$ in expirate is unlikely to exceed ± 0.0001.

Table 5.7 shows the impact of a ± 0.0001 uncertainty in the measurement of both $F_EO_2$ and $F_ECO_2$ on the uncertainty incurred in $\dot{V}O_2$ and $\dot{V}CO_2$. This table has been compiled using the calculations and data used to compile table 5.1.

**Table 5.7 Effect of a ± 0.0001 uncertainty in both $F_EO_2$ and in $F_ECO_2$ on the uncertainty incurred in $\dot{V}O_2$ and $\dot{V}CO_2$, at three levels of exercise intensity.**

| | ± .0001 Uncertainty in $F_EO_2$ and in $F_ECO_2$ | |
|---|---|---|
| Exercise Intensity | % Uncertainty in $\dot{V}O_2$ | % Uncertainty in $\dot{V}CO_2$ |
| Moderate | ±0.25 | ±0.20 |
| Heavy | ±0.34 | ±0.25 |
| Severe | ±0.53 | ±0.32 |

The calculation of $\dot{V}O_2$ is sensitive to an uncertainty in both $F_EO_2$ and $F_ECO_2$. Hence the uncertainty in $\dot{V}O_2$ reported in table 5.7 is a worst-case scenario for an uncertainty of ± 0.0001 in both $F_EO_2$ and $F_ECO_2$. The errors in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$, as a result of an ~ 0.0001 error in the calibration of the gas analysers, would be of a similar magnitude to the uncertainties reported in table 5.7.

5.3.6.2 Contamination of $O_2$ and $CO_2$ fractions in expirate

As discussed previously (section 5.3.6), a possible source of error with the Douglas bag method may arise from the contamination of the bag volume with ambient air. This has been suggested to occur when an evacuated Douglas bag creates a partial vacuum and, by suction, draws in a small volume of ambient air through the bag valve (Welch and Pedersen, 1981). The impact of this contamination with ambient (normoxic) air will be greatest when the inspirate is a hyperoxic mixture. Indeed, in such a situation, contamination with only 100 to 200 ml of ambient air could induce an error of 75% in the calculated $\dot{V}O_2$ (Welch and Pedersen, 1981).

A further source of contamination may arise from the Douglas bag itself, as it is unlikely that a polythene Douglas bag could ever be evacuated fully. Any residual mixture that is present in the bag before the collection of expirate begins will mix with the expirate and the measured expired fractions will reflect this. This effect is summarised by the following equation:

$$F_{MEAS} = (F_{RES} \times V_{RES} + F_{ACT} \times V_E)/(V_E + V_{RES}) \qquad (18)$$

where $F_{MEAS}$ is the measured fraction of $O_2$ or $CO_2$, $F_{RES}$ is the fraction of $O_2$ or $CO_2$ in the residual mixture, $F_{ACT}$ is the actual fraction of $O_2$ or $CO_2$ in the expirate, $V_{RES}$ is the volume that is present in the Douglas bag before any expirate is collected, and $V_E$ is the volume of expirate collected (ATPD).

From equation (18) it follows that the measured fraction of $O_2$ or $CO_2$ will only equal the actual fraction if the $V_{RES}$ is zero or the composition of this $V_{RES}$ is the same as that of the expirate. Rearranging equation (18) to yield an expression for the error in the measured fraction of $O_2$ or $CO_2$ ($F_{MEAS} - F_{ACT}$) leads to the conclusion that the error in the measured gas fraction depends on just two factors: the ratio of $V_{RES}$ to the $V_E$ and the extent to which the composition of the residual mixture differs from that of the expirate:

$$F_{MEAS} - F_{ACT} = V_{RES}/V_E \times (F_{RES} - F_{MEAS}) \qquad (19)$$

The only study in which the influence of $V_{RES}$ contamination has been considered is that of Prieur et al. (1998) who report a mean $V_{RES}$ of 644 ml for polythene Douglas bags. The capacity of these bags was not specified, but given that contamination with only 100 to 200 ml of ambient air could induce an error of 75% in the calculated $\dot{V}O_2$ when the inspirate is a hyperoxic mixture (Welch and Pedersen, 1981), a $V_{RES}$ of ~ 600 ml could pose major problems for studies in which the Douglas bag method is used to determine $\dot{V}O_2$ in hyperoxia. However, the effect of $V_{RES}$ contamination is not confined to situations in which the inspirate is a hyperoxic mixture. The contamination Welch and Pedersen (1981) describe, in which ambient air enters the Douglas bag after it has been evacuated, has no effect on the determination of $\dot{V}O_2$ when the inspired mixture and the contaminating mixture are the same because the measured expired volume includes this contaminating volume. Residual volume contamination, on the other hand, has the potential to influence the determination of $\dot{V}O_2$ not just when the inspirate is a hyperoxic or a hypoxic mixture but also when the inspirate is normoxic (ambient air) because the $V_{RES}$ is not included in the measured expired volume. In fact, as equation (19) shows, the only situation in which $V_{RES}$ contamination will have no effect on the measured gas fractions (and thus on the calculated $\dot{V}O_2$) is when the composition of the residual mixture is identical to that of the expirate.

It was decided that rather than attempting to minimise the effect of $V_{RES}$ contamination, it might be possible to correct for this effect if the size of $V_{RES}$ could be determined. The following sections describe how $V_{RES}$ was quantified and, its contaminating effect, corrected for.

#### 5.3.6.2.1 Quantification of $V_{RES}$

The approach adopted in this thesis involved adding a small volume of ambient air to an evacuated Douglas bag and measuring the changes in the $O_2$ and $CO_2$ fractions that occurred when the added air mixed with the residual mixture. Expirate (50-60 L) was collected in a pre-evacuated Douglas bag from a subject who was cycling at a moderate intensity (to ensure that there was a marked difference between the fractions of $O_2$ and $CO_2$ in the expirate and those in ambient air). The contents of the bag were mixed and the fractions of $O_2$ and $CO_2$ were measured. The Douglas bag was evacuated again and a 3 L precision syringe was used to deliver a known volume of ambient air, the $O_2$ and $CO_2$ fractions of which had been measured, to the evacuated bag. The contents of the bag were mixed and the fractions of $O_2$ and $CO_2$ were measured once more. The equipment and procedures used in this approach have been described in previous sections.

It follows from equation (18) that the $O_2$ or $CO_2$ fraction measured at the final stage of the process ($F_{MIX}$) should be a function of $V_{RES}$, the syringe volume ($V_S$), the fraction of $O_2$ or $CO_2$ in the ambient air delivered to the bag ($F_{AIR}$), and the fraction of $O_2$ or $CO_2$ in the expirate collected during the moderate intensity cycling ($F_{EXP}$):

$$F_{MIX} = (F_{EXP} \times V_{RES} + F_{AIR} \times V_S)/(V_S + V_{RES}) \qquad (20)$$

The following expression for $V_{RES}$ can then be derived by rearranging equation (20):

$$V_{RES} = V_S \times (F_{AIR} - F_{MIX})/(F_{MIX} - F_{EXP}) \qquad (21)$$

As both the $O_2$ and $CO_2$ fractions were measured, two versions of equation (21) were used (one for $O_2$ and one for $CO_2$) and two values of $V_{RES}$ were calculated. The mean of the two values was used as the representative value for $V_{RES}$. Because the gas analysers (see section 5.3.6.1) were calibrated to measure gas fractions relative to the total volume of a dry gas mixture, the $V_S$ in equation (21) was expressed as the equivalent dry volume (ATPD) as follows:

$$V_{S\,(ATPD)} = V_{S\,(ATP)} \times (P_B - P_{H_2O})/P_B$$

$V_{RES}$ was determined for a total of 12 Douglas bags: four times each for eight of these bags (inter-bag data) and eight times each for the remaining four bags (intra-bag data). It was suspected that there might be between-bag variation in $V_{RES}$, depending, for example, on how the bags hang when empty. It was of interest therefore to evaluate the variability in $V_{RES}$ for different bags relative to that for repeat determinations on the same bag. The intra-bag data were separated into four data sets, each of which contained eight values for repeat determinations of $V_{RES}$ on the same bag. The inter-bag data were separated into four data sets, each of which contained eight values for $V_{RES}$

that were determined on eight different bags. For each data set both the mean $V_{RES}$ and the SD about this mean were calculated.

The $V_{RES}$ value obtained was 0.12 ± 0.012 L for the inter-bag analysis and 0.12 ± 0.016 L for the intra-bag analysis. These data do not support the notion that $V_{RES}$ varies systematically for different Douglas bags. Instead, they suggest that a common $V_{RES}$ can be assumed for all bags. The uncertainty in $V_{RES}$ associated with this assumption, expressed as 95% confidence limits, would be ± 0.024 L. The uncertainty in $V_{RES}$ for a given bag is unlikely to exceed ± 0.031 L (95% confidence limits).

5.3.6.2.2 Correcting for the effect of $V_{RES}$ contamination

Throughout this thesis all Douglas bags were flushed with room air immediately prior to use. The aim was to ensure that the composition of the residual air was essentially the same as that of the room air (determined from the measurement of $F_IO_2$ and $F_ICO_2$, see section 5.3.5). Corrected values for $F_EO_2$ and $F_ECO_2$ were calculated for each sample, assuming that the expirate that entered the analysers was contaminated with 0.17 L of room air [this includes the 0.12 L $V_{RES}$ and the 0.05 L volume in the master valve which was assumed to be exposed to room air during each bag change (see section 5.3.2.1)]. These corrected values [equation (22)] were then used for the determination of $\dot{V}O_2$ and $\dot{V}CO_2$, respectively. The corrected value ($F_{CORR}$) was derived as follows:

$$F_{CORR} = (F_{MEAS} + 0.17/V_E) \times (F_{MEAS} - F_{AIR}) \quad (22)$$

and as both the measured $O_2$ and $CO_2$ fractions were corrected, two versions of equation (22) were used (one for $O_2$ and one for $CO_2$).

Provided the actual $V_{RES}$ and master valve volume combined is always 0.17 L, $F_{CORR}$ should be equivalent to the actual gas fraction. For a given error in $V_{RES}$, the error incurred in the calculated value for $F_{CORR}$ is a function of both $V_E$ and $F_{MEAS}$. For both $F_EO_2$ and $F_ECO_2$, the error incurred in the calculated value will be highest when $V_E$ is small. For $F_EO_2$, this error will be highest when the $F_{MEAS}$ for $O_2$ is low. For $F_ECO_2$, the error will be highest when $F_{MEAS}$ for $CO_2$ is high. For a given exercise intensity $V_E$

will increase and the variation incurred in $F_{CORR}$ as a result of variation in $V_{RES}$ will decrease, as the sampling period increases. Similarly, for a given sampling period, $V_E$ will increase as exercise intensity increases. However, $F_EO_2$ tends to increase and $F_ECO_2$ tends to decrease. Hence the variation incurred in $F_{CORR}$ for $O_2$ and $F_{CORR}$ for $CO_2$ as a result of variation in $V_{RES}$ decreases markedly as exercise intensity increases.

Table 5.8 shows data on the uncertainty that would be incurred in $\dot{V}O_2$ and $\dot{V}CO_2$ as a result of the ± 0.031 L uncertainty in $V_{RES}$. This table was compiled using the calculations and data used to compile table 5.1. In all cases it was assumed that the $O_2$ and $CO_2$ fractions in the residual mixture were .2093 and .0007, respectively.

**Table 5.8 Effect of a ± 0.031 L uncertainty in $V_{RES}$ on the uncertainty incurred in $\dot{V}O_2$ and $\dot{V}CO_2$ at three levels of exercise intensity and for four collection periods.**

| | % Uncertainty in $\dot{V}O_2$ | | | | % Uncertainty in $\dot{V}CO_2$ | | | |
|---|---|---|---|---|---|---|---|---|
| | Collection Period (s) | | | | Collection Period (s) | | | |
| Exercise Intensity | 15 | 30 | 45 | 60 | 15 | 30 | 45 | 60 |
| Moderate | ± 0.28 | ± 0.14 | ± 0.09 | ± 0.07 | ± 0.28 | ± 0.14 | ± 0.09 | ± 0.07 |
| Heavy | ± 0.10 | ± 0.07 | ± 0.05 | ± 0.04 | ± 0.10 | ± 0.07 | ± 0.05 | ± 0.04 |
| Severe | ± 0.07 | ± 0.04 | ± 0.02 | ± 0.01 | ± 0.07 | ± 0.04 | ± 0.02 | ± 0.01 |

Assuming that the actual $V_{RES}$ is 0.12 L (and the 0.05 L master valve volume is contaminated with room air only), the error in $\dot{V}O_2$ and $\dot{V}CO_2$ will be zero for any sampling period and any exercise intensity. The uncertainty (table 5.8) in $\dot{V}O_2$ or $\dot{V}CO_2$, associated with this assumption, is extremely small and will decrease as either exercise intensity or sampling period increases.

## 5.4 Accuracy and precision of the derived data for $\dot{V}O_2$ and $\dot{V}CO_2$

### *5.4.1 Background*

In section 5.3 data were presented on the errors and uncertainties that might realistically be incurred in $\dot{V}O_2$ and $\dot{V}CO_2$ for a variety of sampling periods and exercise intensities, assuming incorrect values for a given variable were used in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$. This approach is useful in that it can provide some insight into which factors are likely to exert the greatest influence on the accuracy and precision with which $\dot{V}O_2$ and $\dot{V}CO_2$ can be determined. However, it does not allow an estimate to be made of the overall accuracy and precision of the derived $\dot{V}O_2$ and $\dot{V}CO_2$ data.

Estimating the total accuracy of $\dot{V}O_2$ and $\dot{V}CO_2$ is of interest to ensure that these data are comparable with the findings of other laboratories (assuming that these other laboratories are concerned with the accuracy of their measurements). Estimating the total precision of $\dot{V}O_2$ and $\dot{V}CO_2$ provides an indication of the technological day-to-day variability in repeated determinations when these are partitioned into biological and technological components. Finally, estimating the total precision of $\dot{V}O_2$ and $\dot{V}CO_2$ allows one to assess whether changes in these values, in response to an intervention, are due to the intervention itself or to the technological/biological variability.

The following sections provide estimates of the total error (accuracy) and the total uncertainty (precision) in the calculated values for $\dot{V}O_2$ and $\dot{V}CO_2$ when the procedures outlined in the preceding sections are followed.

### *5.4.2 Accuracy of the derived data for $\dot{V}O_2$ and $\dot{V}CO_2$: the effect of errors*

As far as errors in the determination of $\dot{V}O_2$ and $\dot{V}CO_2$ are concerned, the situation is relatively straightforward. There may be an error of 0.1 mmHg error in the measurement of $P_B$ (see section 5.3.3), a 0.2 °C error in the measurement of $T_{(EXP)}$ and consequently a 0.2 mmHg error in the calculation of $P_{H_2O}$ (see section 5.3.4), and an error of 0.0001 and 0.00011 in the measurement of $F_EO_2$ and $F_ECO_2$, respectively (see section 5.3.6.1.2). The worst-case scenario for the total error in the calculation of $\dot{V}O_2$ or $\dot{V}CO_2$ would be if these errors were present in each of the variables at the same time in a direction (+ or -) that maximised the error in the calculated value. For the calculation of $\dot{V}O_2$ this scenario would arise if all the above errors were in a negative direction, with the exception of the error in $P_B$. For $\dot{V}CO_2$ the worst case scenario would arise if all the above errors were also in a negative direction, with the exception of the error in $P_B$ and the error in $F_ECO_2$ (and excluding $F_EO_2$). These worst case scenarios for the total error in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$ are presented in table 5.9. This table was compiled using the calculations and data used to compile table 5.1.

**Table 5.9 Total error incurred in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$ at three levels of exercise intensity and for four collection periods.**

| | Total % error in $\dot{V}O_2$ | | | | Total % error in $\dot{V}CO_2$ | | | |
|---|---|---|---|---|---|---|---|---|
| | Collection Period (s) | | | | Collection Period (s) | | | |
| Exercise Intensity | 15 | 30 | 45 | 60 | 15 | 30 | 45 | 60 |
| Moderate | 0.50 | 0.50 | 0.50 | 0.50 | 0.51 | 0.48 | 0.47 | 0.47 |
| Heavy | 0.59 | 0.59 | 0.59 | 0.59 | 0.56 | 0.53 | 0.52 | 0.52 |
| Severe | 0.78 | 0.78 | 0.78 | 0.78 | 0.64 | 0.61 | 0.60 | 0.60 |

### *5.4.3 Precision of the derived data for $\dot{V}O_2$ and $\dot{V}CO_2$: the effect of uncertainties*

As far as uncertainties are concerned, the situation is more complicated than it is for errors. It is possible to estimate the total uncertainty that would be incurred in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$ for the situation in which the direction of the individual uncertainties involved in each calculation is such that the total uncertainty in the calculated value is maximal. However, this estimation is likely to be an overestimation of the total uncertainty that might realistically be incurred because in practice some of the above uncertainties would cancel. Formulae are available that allow an estimate to be made of the total uncertainty that would be incurred in the dependent variable for the situation in which one variable is a function of several independent variables (Challis, 1997; Topping, 1972). The requirements are that an estimate of the uncertainty that would be present is available for each of the independent variables and that the dependent variable can be expressed algebraically as a function of the independent variables. For a function of the form $P = f(X_1, X_2, \ldots, X_4)$, the formula is:

$$\delta P = \sqrt{\sum_{i=1}^{n}\left[\frac{\delta P}{\delta X_i} X_i\right]^2} \tag{23}$$

There will be an uncertainty of ± 0.57 L in the corrected $V_E$ measurement (see section 5.3.2.3) and a ± 0.07 $L.min^{-1}$ uncertainty in the calculation of the sample volume lost during the measurement of expired gas fractions (see section 5.3.2.3). Additionally, there will be an uncertainty of ± 0.2 mmHg in the measurement of $P_B$ (see section 5.3.3), a ± 0.2 °C uncertainty in the measurement of $T_{(EXP)}$, and consequently a ± 0.2 mmHg uncertainty in the calculation of $P_{H_2O}$ (see section 5.3.4). However, an important assumption underpinning the above approach to estimating the propagation of uncertainties is that the uncertainties in the independent variables are independent of each other. This is not the case with $T_{(EXP)}$ because a given uncertainty in $T_{(EXP)}$ will introduce uncertainties in $P_{H_2O}$ and, thus in the determination of $V_{E(STPD)}$ from $V_{E(ATPS)}$, as well as in the determination of $V_{E(STPS)}$ from $V_{E(ATPS)}$. The combined effect, for an uncertainty of ± 0.2 °C in $T_{(EXP)}$, is that an uncertainty of 0.10% will be incurred in the calculated $\dot{V}O_2$ and $\dot{V}CO_2$ (see section 5.3.4). A similar effect can be obtained, however, by assuming that the uncertainty in $T_{(EXP)}$ is ± 0.3 °C and ignoring the effect that this uncertainty would have on $P_{H_2O}$. This is what was done when equation (23) was used to estimate the total uncertainty in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$.

The effect of the ± 0.024 L uncertainty in the size of $V_{RES}$ (see section 5.3.6.2) was quantified in terms of the effect that this variation would have on the corrected values for expired gas fractions. This uncertainty, which is equivalent to the difference between $F_{ACT}$ and $F_{CORR}$, was calculated for each exercise intensity and each sampling period, and for both $F_EO_2$ and $F_ECO_2$. Finally, a ± 0.0001 uncertainty in the measurement of $F_EO_2$ and $F_ECO_2$ (5.3.6.1) was also included in the above estimation of the total uncertainty.

All of the above uncertainties will affect the precision with which $\dot{V}O_2$ can be determined. The precision with which $\dot{V}CO_2$ can be determined will be affected by each of the above uncertainties with the exception of uncertainties in the determination of $F_EO_2$. The total uncertainty in $\dot{V}O_2$ and $\dot{V}CO_2$ was calculated using equation (23) with equations (17) and (14), respectively. The total uncertainty in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$ is shown in table 5.10. This table was compiled using the calculations and data used to compile table 5.1.

**Table 5.10 Total uncertainty incurred in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$ at three levels of exercise intensity and for four collection periods.**

| | Total % uncertainty in $\dot{V}O_2$ | | | | Total % uncertainty in $\dot{V}CO_2$ | | | |
|---|---|---|---|---|---|---|---|---|
| | Collection Period (s) | | | | Collection Period (s) | | | |
| Exercise Intensity | 15 | 30 | 45 | 60 | 15 | 30 | 45 | 60 |
| Moderate | 6.0 | 3.3 | 2.4 | 2.0 | 6.2 | 3.5 | 2.6 | 2.1 |
| Heavy | 3.2 | 1.8 | 1.4 | 1.1 | 3.4 | 1.9 | 1.4 | 1.2 |
| Severe | 1.9 | 1.2 | 0.9 | 0.8 | 1.8 | 1.1 | 0.8 | 0.7 |

Two important conclusions can be drawn from the data presented in this chapter. First, since it has been shown that the error in the calculated $\dot{V}O_2$ will always be $< 0.9\%$ it can be concluded that the procedures adopted in this thesis allow $\dot{V}O_2$ to be determined accurately across a wide range of exercise intensities and, in particular, for short sampling periods. Second, it can be concluded that whilst the uncertainty in the calculated $\dot{V}O_2$ is likely to be very small when a long sampling period is used or severe intensity exercise is studied, this uncertainty or variability will increase as the sampling period decreases. Furthermore, the possibility that the variability in $\dot{V}O_2$ may decrease as exercise intensity increases suggests that short sampling periods should only be used during severe intensity exercise, where the two determinants of variability (sampling period vs. exercise intensity) may partly counter each other. These conclusions are important for establishing criteria to define $\dot{V}O_{2max}$ and are investigated further in Study I (Chapter 6).

# CHAPTER 6

# STUDY I: ESTABLISHING CRITERIA TO DEFINE $\dot{V}O_{2max}$

## 6.1 Background

### *6.1.1 Identifying the issues*

The notion of $\dot{V}O_{2max}$ was originally conceived at the start of the twentieth century (see section 2.2.2) and since this time there has been some confusion among physiologists over the definition of $\dot{V}O_{2max}$ and whether a true $\dot{V}O_{2max}$ has been attained during exercise (see section 4.2). Since the concept of $\dot{V}O_{2max}$, and whether it is attained during middle-distance running, is central to this thesis, it is essential that $\dot{V}O_{2max}$ can be quantified both validly and reliably.

This study addressed some of the issues raised in chapters 4 and 5. The focus was on establishing criteria for defining $\dot{V}O_{2max}$ (see section 4.2.3) and assessing the reliability and criterion validity of the off-line Douglas bag system used in this thesis (see chapter 5) to determine $\dot{V}O_{2max}$. The important considerations for this study were that:

1. criteria for defining $\dot{V}O_{2max}$ can undeniably demonstrate the true incidence of a plateau in $\dot{V}O_2$ during progressive exercise to exhaustion;
2. a method for quantifying the value of such a $\dot{V}O_2$ plateau (i.e. $\dot{V}O_{2max}$) can be established;
3. this quantification method can be used to determine the highest $\dot{V}O_2$ attained during exercise protocols (e.g. constant intensity square-wave exercise) other than those typically used to determine $\dot{V}O_{2max}$ (e.g. progressive exercise);
4. this quantification method is both valid and reliable.

### *6.1.2 Criteria for defining $\dot{V}O_{2max}$*

Traditionally, $\dot{V}O_{2max}$ during running has been defined as a plateau in $\dot{V}O_2$ with increasing running speed (see section 2.2.2). If this definition is adopted, the process of determining $\dot{V}O_{2max}$ can be split into two clear stages. First, a $\dot{V}O_2$-plateau must be demonstrated during progressive exercise if the experimenter is to be confident that $\dot{V}O_{2max}$ has been attained. Second, if a $\dot{V}O_2$-plateau is identified, a value for this plateau (i.e. the criterion $\dot{V}O_{2max}$) must be derived.

There are several approaches that could be taken to determine whether a $\dot{V}O_2$-plateau occurs during a progressive test, thus satisfying the first of these stages (see section 4.2.3). Confidence interval based approaches have been the most common method. These approaches attempt to identify whether the observed $\dot{V}O_2$ values during the closing stages of a progressive test depart from the linear $\dot{V}O_2$-work rate relationship. These observed $\dot{V}O_2$ values must be less than a criterion lower confidence limit for the predicted $\dot{V}O_2$ for a plateau to be identified. Such approaches are, however, limited to identifying the point at which the $\dot{V}O_2$-work rate relationship begins to plateau. They do not identify an asymptotic $\dot{V}O_2$ value (Howley et al., 1995).

The mathematical modelling approach (Wood, 1999b) discussed in chapter 4 (see section 4.2.3) allows a $\dot{V}O_2$-plateau to be identified and a $\dot{V}O_2$ value for this plateau to be derived (the criterion $\dot{V}O_{2max}$). It therefore satisfies the two stages for defining $\dot{V}O_{2max}$. This approach could be used for individual participants both to identify a plateau in $\dot{V}O_2$ and to derive the value of this plateau. However, this would only be the case if all participants were to demonstrate a $\dot{V}O_2$-plateau. Alternatively, providing the majority of participants demonstrate a $\dot{V}O_2$-plateau, the highest $\dot{V}O_2$ observed (i.e. $\dot{V}O_{2peak}$) could be used to represent the criterion $\dot{V}O_{2max}$ on the basis that it is likely to be a maximal $\dot{V}O_2$.

For this thesis, the drawback of solely using the modelling approach proposed by Wood (1999b) to define $\dot{V}O_{2max}$ is that it cannot easily be applied to a range of exercise protocols: it is constrained to those protocols where a linear $\dot{V}O_2$-work rate relationship followed by a plateau in $\dot{V}O_2$ is expected. However, this modelling approach could be used to identify whether $\dot{V}O_2$ typically plateaus in the participants studied during progressive exercise. If there is a high incidence of a $\dot{V}O_2$-plateau, the experimenter can be confident that $\dot{V}O_{2max}$ has typically been attained for the test protocol and procedures used. A $\dot{V}O_{2\,peak}$ value, representing the highest $\dot{V}O_2$ attained during the progressive test, could then be used to define $\dot{V}O_{2max}$. If this $\dot{V}O_{2\,peak}$ value agrees with the criterion $\dot{V}O_{2max}$ from the model for those participants demonstrating a $\dot{V}O_2$-plateau, the experimenter can be confident that the method of using $\dot{V}O_{2\,peak}$ to define $\dot{V}O_{2max}$ has criterion validity. Furthermore, this $\dot{V}O_{2\,peak}$ method could be readily used during middle-distance running to determine the highest $\dot{V}O_2$ attained.

### *6.1.3 Variability in $\dot{V}O_2$: effect of sampling period*

It is possible that a $\dot{V}O_2$-plateau is something that may occur very late in a ramp test. It is also possible that the duration of this plateau will vary between individuals. When the aim is to maximise the incidence of a $\dot{V}O_2$-plateau, a short sampling period should be used so that the plateau can be identified, even if it occurs late in the test. The logic of this suggestion is apparent when a scenario in which a true $\dot{V}O_2$-plateau occurs over the last 60 s of a ramp test is considered. Two data points would identify the plateau if 30 s sampling periods were used and the first of these was initiated at the onset of the plateau (i.e. 60 s before the end of the test). However, at least three data points would identify the plateau if 15 s sampling periods were used, regardless of when the first of these was initiated.

It has been suggested previously (see chapter 5) that the variability in $\dot{V}O_2$ is likely to increase as the sampling period decreases. This suggestion was made on the basis of an analysis of the technical uncertainty that might realistically be incurred in the determination of $\dot{V}O_2$ and how this uncertainty might be affected by sampling period. This suggestion is also in agreement with the work of Myers et al. (1990) who determined $\dot{V}O_2$ on-line during exercise that elicited a $\dot{V}O_2$ equivalent to ~ 50% $\dot{V}O_{2\,peak}$ and, having averaged the breath-by-breath data over various periods (from 5 to 60 s), showed that the variability in $\dot{V}O_2$ increased as the sampling period decreased.

This notion of the variability in $\dot{V}O_2$ decreasing with an increase in sampling period raises a potential contradiction between the two stages for establishing criteria to define $\dot{V}O_{2max}$. The effect of sampling period on the variability in $\dot{V}O_2$ causes a conflict between the need to use a relatively short sampling period to identify a plateau in $\dot{V}O_2$ and the need to use a relatively long sampling period to ensure that the presence of a plateau is not obscured by excessive variability in the $\dot{V}O_2$ data. In addition, the variability in $\dot{V}O_2$ associated with using a relatively short sampling period to increase the chance of identifying a plateau may affect the criterion validity and reliability of the value used to represent this $\dot{V}O_2$-plateau.

It is possible that if $\dot{V}O_{2\,peak}$ were used to represent $\dot{V}O_{2max}$, this value may increase in response to a decrease in sampling period as a result of the associated variability in $\dot{V}O_2$. Gomes et al. (1997) compared $\dot{V}O_{2peak}$ values derived from raw breath-by-breath data with those determined by averaging these data over 5, 15, 20, 30, or 60 s periods. The peak $\dot{V}O_2$ increased as the averaging period decreased ($\dot{V}O_{2peak}$ was 5% higher for the 5 than for the 60 s period) but there were no statistically significant differences in $\dot{V}O_{2peak}$ among the various sampling/averaging periods.

The issues identified above could be partially resolved by using a relatively short sampling period (e.g. 15 s) to allow a plateau in $\dot{V}O_2$ to be identified and then averaging the data over a longer period (e.g. 30 s) to derive a $\dot{V}O_{2peak}$ value to represent this plateau value (i.e. $\dot{V}O_{2max}$). This approach would potentially increase the chance of detecting a short plateau (e.g. 45 s) occurring late in a progressive test in comparison to using a longer sampling period. The subsequent use of a longer averaging period would potentially ensure that the variability in $\dot{V}O_{2peak}$ is reduced in comparison to the 15 s raw data used to identify the $\dot{V}O_2$-plateau. The use of averaging periods longer than 15 s could also be applied to 15 s raw $\dot{V}O_2$ data determined during middle-distance running to identify the highest $\dot{V}O_2$ attained. The key consideration here is that the averaging period should be short enough to enable the highest $\dot{V}O_2$ attained to be validly quantified, since the duration of such runs may be < 120 s (i.e. the 400 and 800 m), but long enough to ensure that the variability in $\dot{V}O_2$ is controlled.

*6.1.4 Variability in $\dot{V}O_2$: effect of exercise intensity*

It was suggested previously (see chapter 5) that the variability in $\dot{V}O_2$ might decrease as exercise intensity increases. Once again, this suggestion was made on the basis of an analysis of the technical uncertainty that might realistically be incurred in the determination of $\dot{V}O_2$ and how this uncertainty might be affected by exercise intensity. This notion agrees with a similar analysis done by Wood (1999b) but it conflicts with the work of Lamarra et al. (1987) who showed that the standard deviation for raw breath-by-breath data, was the same for unloaded (0 W) and moderate intensity (100 W) cycling. However, the highest exercise intensity studied by Lamarra et al. was moderate and this exercise intensity domain was the lowest considered in the analysis presented in chapter 5. It is conceivable that variability in $\dot{V}O_2$ does decrease as exercise intensity increases but that this effect is only apparent at higher exercise intensities (i.e. in the heavy or severe intensity domains).

If the variability in $\dot{V}O_2$ does decrease with increasing exercise intensity, the variability in $\dot{V}O_2$ for a given sampling period will decrease throughout a progressive exercise test. Therefore, the variability associated with a relatively short sampling period (i.e. 15 s) used towards the end of a progressive test may be such that a plateau in $\dot{V}O_2$ is not obscured by excessive variability. That is, the intensity-effect may counterbalance the sampling-effect. This would resolve the potential problem of excessive variability associated with short sampling periods obscuring the identification of a plateau in $\dot{V}O_2$. Consequently, the approach of using a short sampling period (i.e. 15 s) to identify a plateau in $\dot{V}O_2$ and a longer averaging period (e.g. 30 s) to derive a $\dot{V}O_{2peak}$ to represent this $\dot{V}O_2$-plateau value (i.e. the criterion $\dot{V}O_{2max}$) could satisfy the two stages for establishing criteria to define $\dot{V}O_{2max}$ (see section 6.1.1), providing this approach can be shown to be both valid and reliable.

In the present study, the criterion validity and test-retest reliability of the above approach to defining $\dot{V}O_{2max}$ was evaluated in accordance with the first aim of this thesis by assessing the:

1. incidence of a plateau in raw $\dot{V}O_2$ data determined from 15 and 45 s sampling periods, using the modelling approach proposed by Wood (1999b);
2. agreement between $\dot{V}O_{2peak}$ values determined from various averaging periods of the 15 s raw data and the plateau $\dot{V}O_2$ value (i.e. the criterion $\dot{V}O_{2max}$) derived from the model (Wood, 1999b);
3. agreement between repeat determinations of $\dot{V}O_{2peak}$ based on the 15 and 45 s raw data and various averaging periods of the 15 s raw data.

## 6.2 Methods

### *6.2.1 Participants*

Eight male trained runners (age 26.3 ± 4.9 yr; height 1.80 ± 0.08 m; mass 72.0 ± 7.6 kg) volunteered to participate. All were well habituated with laboratory procedures in general and with motorised treadmill running in particular. Each participant was in regular running training at the time of the study.

### *6.2.2 Preliminary tests*

All participants initially completed a progressive ramp test (0.16 $km.h^{-1}$ per 5 s) on a level motorised treadmill (see section 4.2.2 for a more detailed description of this ramp test). This test allowed an appropriate starting speed to be selected for future tests to ensure that exhaustion would be reached in ~ 10 min (Buchfuhrer et al., 1983) for each participant (see section 4.2.2 for more detail of this process). The $\dot{V}O_2$ at which the lactate threshold occurred was determined by means of the V-slope method (Beaver et al., 1986) for each participant (see section 4.3.3). The corresponding speed for this $\dot{V}O_2$ was then determined from each participant's $\dot{V}O_2$-running speed relationship.

### *6.2.3 Experimental design*

Following the preliminary test, each participant completed a further four ramp tests (0.16 $km.h^{-1}$ per 5 s) on a level motorised treadmill. Participants were encouraged to continue running for as long as possible. For two of the tests a nominal 15 s sampling period was used and for the other two tests a nominal 45 s sampling period was used to determine $\dot{V}O_2$:

1. test A: 15 s sampling period;
2. test B: 15 s sampling period;
3. test C: 45 s sampling period;
4. test D: 45 s sampling period.

The preliminary test described above was always completed first, but thereafter the eight participants completed tests A-D in a random order. Two participants were allocated to each sequence within a 4 × 4 Latin Square to control for order and carryover effects. Each participant completed their own sequence of tests at the same time of day. All five tests (i.e. preliminary and tests A-D) were completed within 14 days, with at least 48 hours between each test. Each of the four tests (A-D) was preceded by a 5 min warm-up at 10% below the speed corresponding to each participant's lactate threshold (see section 6.2.2) to control for the effects of prior exercise on the determination of $\dot{V}O_2$ (Gerbino et al., 1996).

### *6.2.4 Data collection*

The off-line Douglas bag system described in chapter 5 was used to determine all gas exchange variables. The sampling periods were nominally 15 and 45 s. A whole number of breaths was always collected, so typically the actual period was not identical to the intended nominal one (i.e. 15 or 45 s). Every effort was made to ensure that the actual was as close to the nominal sampling period as possible. For the 15 s sampling period, the actual period was usually between 15 and 20 s, and on no occasion was it less than 15 s. For the 45 s nominal sampling period, the actual period was between 40 and 50 s.

### *6.2.5 Treatment of data*

#### 6.2.5.1 Defining a $\dot{V}O_2$-plateau

For each test (A-D), $\dot{V}O_2$ data from the first 90 s were excluded from the analysis of the incidence of a $\dot{V}O_2$-plateau to account for the initial lag in the $\dot{V}O_2$ response to exercise. The remaining data were fitted with two different models. The first was a linear model ($y = a_1x + b_1$) and the second was a two segment plateau model (Wood, 1999b): the first segment was a linear function ($y = a_2 x + b_2$) and the second was a horizontal line ($y = c$). The independent variable was running speed ($km.h^{-1}$) and the dependent variable was $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$).

Model fitting was done using standard piecewise least squares regression (Vieth, 1989). For the plateau model, all possible groupings were evaluated. Initially, the first two data points were included in the first segment of the model and the remainder were allocated to the second segment. Then, the first three data points were included in the first segment and the remainder were allocated to the second segment, and so on. This procedure was continued until the last two data points were allocated to the second segment and the remainder were allocated to the first segment.

Each data point was included in either the first or the second segment: no data points were common to both. The residual sum of squares (RSS) was calculated for each grouping and the grouping that yielded the lowest RSS was selected. Goodness of fit was evaluated by means of the standard error of estimate (SEE): $\sqrt{RSS/df}$, where df (degrees of freedom) is equal to the total number of data points minus the number of parameters (Vieth, 1989). There were two parameters ($a_1$ and $b_1$) for the linear model and three for the plateau model ($a_2$, $b_2$, and c).

In those cases in which the SEE was lower for the plateau model than for the linear model, a plateau in the $\dot{V}O_2$-running speed relationship was deemed to have occurred. When such a $\dot{V}O_2$-plateau was identified, the $\dot{V}O_2$ for this plateau was derived from the value of the horizontal line ($y = c$) that defines the second segment of the plateau model. The duration of the $\dot{V}O_2$-plateau was calculated by solving the two equations ($y = a_2 x + b_2$ and $y = c$) to yield a set of coordinates (running speed, $\dot{V}O_2$) for the intercept between the two segments. The time corresponding to this intercept was then derived and subtracted from the end test time to yield the plateau duration.

6.2.5.2 Defining $\dot{V}O_{2max}$

For each set of raw $\dot{V}O_2$ data [i.e. 15$s_{RAW}$ (test A and B) and 45$s_{RAW}$ (tests C and D)] $\dot{V}O_{2peak}$ was noted. For each set of 15$s_{RAW}$ data (i.e. tests A and B), four sets of averaged data were derived and $\dot{V}O_{2peak}$ was calculated from these:

1. 30 s standard (30$s_{STAN}$): [i.e. sample (1 + 2)/2, (3 + 4)/2 ...];
2. 30 s moving (30$s_{MOVE}$): [i.e. sample (1 + 2)/2, (2 + 3)/2 ...];
3. 45 s standard (45$s_{STAN}$): [i.e. sample (1 + 2 + 3)/3, (4 + 5 + 6)/3 ...];
4. 45 s moving (45$s_{MOVE}$): [i.e. sample (1 + 2 + 3)/3, (2 + 3 + 4)/3 ...].

The averaging always started with the final 15 s sample from the end of the test and worked back towards the start. A 60 s averaging period was not considered here because it would not be practical for determining $\dot{V}O_{2peak}$ during middle-distance running. Therefore, for each set of 15$s_{RAW}$ data (tests A and B), five $\dot{V}O_{2peak}$ values were derived: 15$s_{RAW}$, 30$s_{STAN}$, 30$s_{MOVE}$, 45$s_{STAN}$, and 45$s_{MOVE}$. Additionally, $\dot{V}O_{2peak}$ was derived for each set of 45$s_{RAW}$ data (tests C and D).

*6.2.6 Statistical analysis*

6.2.6.1 General

All tests were analysed at an alpha level of 0.05 and all data are presented as mean ± SD unless otherwise stated. Individual data can be found in Appendix I, together with full results for each of the tests described below.

6.2.6.2 Criterion validity of $\dot{V}O_{2peak}$

For each participant a mean $\dot{V}O_{2peak}$ value was calculated from the two tests [(A + B)/2] for each of the five sampling/averaging periods (described in section 6.2.5.2) based on the 15$s_{RAW}$ data. This was also done for the 45$s_{RAW}$ $\dot{V}O_{2peak}$ data [(C + D)/2].

Similarly, for each participant a mean criterion $\dot{V}O_2$-plateau value from the second segment of the plateau model, determined from the $15s_{RAW}$ data, was calculated [(A + B)/2]. In total, this gave six data sets: the criterion $\dot{V}O_2$-plateau value from the model vs. the $\dot{V}O_{2peak}$ derived from the $15s_{RAW}$, $30s_{STAN}$, $30s_{MOVE}$, $45s_{STAN}$, $45s_{MOVE}$, and $45s_{RAW}$ data.

It was assumed that the plateau model based on $15s_{RAW}$ data will yield the greatest incidence of a $\dot{V}O_2$-plateau, that the value of this plateau will therefore be the true criterion $\dot{V}O_{2max}$, and that the agreement between this criterion value and the various $\dot{V}O_{2peak}$ values will represent the bias (i.e. criterion validity) associated with using the sampling/averaging periods to define $\dot{V}O_{2max}$. Bias was assumed to be a constant function of $\dot{V}O_{2max}$ and was calculated as the mean difference between each of the six data sets.

6.2.6.3 Test-retest reliability of $\dot{V}O_{2peak}$

The difference between repeat determinations of $\dot{V}O_{2peak}$ (e.g. test A - test B and test C - test D) was derived for each participant and for each of the six sampling/averaging periods described in section 6.2.5.2. The bias in these test-retest determinations of $\dot{V}O_{2peak}$ was calculated as the mean difference as described in section 6.2.6.2.

To investigate heteroscedasticity, the absolute test-retest differences were plotted as a function of the mean $\dot{V}O_{2peak}$ for each of the six sets of paired data. A positive slope for such a plot indicates positive heteroscedasticity (i.e. an increase in the magnitude of the differences with an increase in the mean), whereas a negative slope indicates negative heteroscedasticity (i.e. a decrease in the magnitude of the differences with an increase in the mean). For determining test-retest reliability using 95% limits of agreement (LOA), a log-transformation is appropriate for positive heteroscedasticity; however for negative heteroscedasticity, a regression based approach is required (Bland and Altman, 1999). The slopes for the plots in this study were all negative, indicating negative heteroscedasticity. Hence regression based 95% LOA were used. These regression based 95% LOA were derived by regressing the absolute differences (R) on the mean $\dot{V}O_{2peak}$ (A) to get:

$$R = a_4A + b_4 \quad (1)$$

The SD of R is then obtained by multiplying the predicted values by $\sqrt{\pi/2}$ (Bland and Altman, 1999). The 95% LOA for the reliability of $\dot{V}O_{2peak}$ are then given by:

$$95\%\ LOA = \pm 1.96\sqrt{\pi/2}\,R \quad (2)$$

## 6.3 Results

### *6.3.1 Defining a $\dot{V}O_2$-plateau*

Table 6.1 gives data on the SEE and the incidence of a $\dot{V}O_2$-plateau for the $15s_{RAW}$ and $45s_{RAW}$ data. In addition, the plateau duration and the value of this plateau (i.e. $\dot{V}O_{2max}$) derived from the plateau model are given. In determining the incidence of a $\dot{V}O_2$-plateau, it was assumed that a plateau had occurred if the SEE was lower for the plateau than for the linear model.

**Table 6.1 SEE for the linear and the plateau model and the incidence of a $\dot{V}O_2$-plateau for the four sets of raw data (n = 8).**

| Test | SEE – linear ($ml.kg^{-1}.min^{-1}$) | SEE – plateau ($ml.kg^{-1}.min^{-1}$) | Incidence (%) | Duration (s) | $\dot{V}O_{2max}$ ($ml.kg^{-1}.min^{-1}$) |
|---|---|---|---|---|---|
| A - $15s_{RAW}$ | 1.54 ± 0.61 | 1.00 ± 0.25 | 100 | 81.7 ± 41.5 | 62.5 ± 5.6 |
| B - $15s_{RAW}$ | 1.61 ± 0.38 | 1.06 ± 0.19 | 100 | 82.7 ± 24.3 | 62.2 ± 5.4 |
| C - $45s_{RAW}$ | 1.48 ± 0.52 | 0.85 ± 0.30 | 75 | 73.0 ± 32.7 | 62.5 ± 5.8 |
| D - $45s_{RAW}$ | 1.28 ± 0.56 | 0.91 ± 0.35 | 88 | 61.9 ± 28.7 | 62.5 ± 5.6 |

For the $15s_{RAW}$ data the SEE was lower for the plateau than for the linear model in all cases. For the $45s_{RAW}$ data there were two cases in test C, and one in test D, where the SEE was lower for the linear than for the plateau model. The $\dot{V}O_2$-plateau values were similar across all data sets. Data from a representative participant for the plateau model based on $15s_{RAW}$ data are given in Figure 6.1.

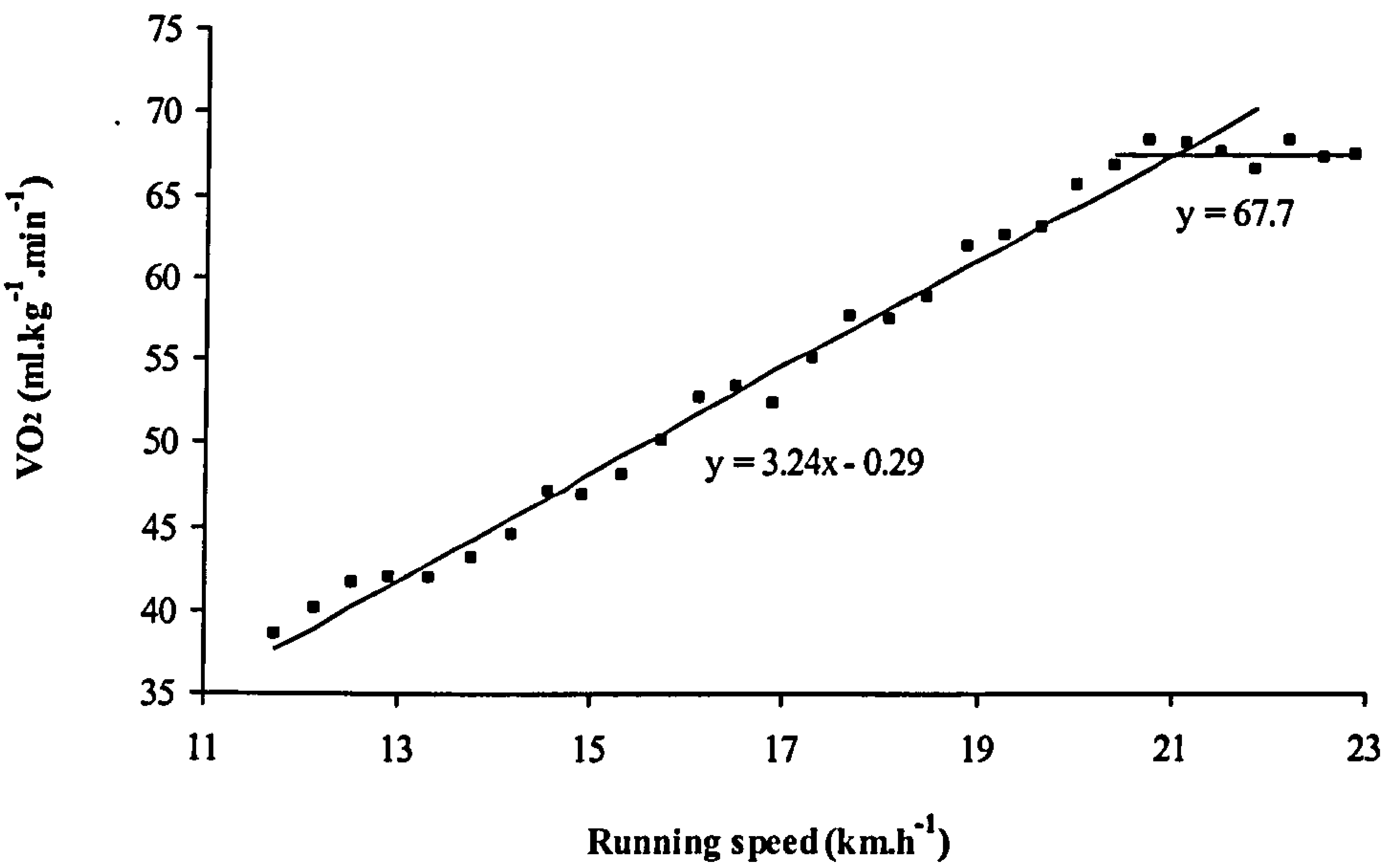



**Figure 6.1 Data from a representative participant showing $\dot{V}O_2$ determined from $15s_{RAW}$ sampling periods as a function of running speed.**

### *6.3.2 Defining $\dot{V}O_{2max}$*

#### 6.3.2.1 Criterion validity of $\dot{V}O_{2max}$

Figure 6.2 gives data on the agreement between the mean $\dot{V}O_2$ value derived from the second segment of the plateau model (i.e. the criterion $\dot{V}O_{2max}$) from test A and B, and the mean $\dot{V}O_{2peak}$ values derived from the $15s_{RAW}$ [(A + B)/2)], the $45s_{RAW}$ [(C + D)/2)], and each of the four averaging periods based on the $15s_{RAW}$ data (see section 6.2.6.2). The bias between $\dot{V}O_{2max}$ derived from the plateau model and $\dot{V}O_{2peak}$ derived using each of the six sampling/averaging periods was calculated as the mean difference (see section 6.2.6.2). This represents the bias in the particular approach to using $\dot{V}O_{2peak}$ to define $\dot{V}O_{2max}$. Given that a plateau in $\dot{V}O_2$ was observed in all participants when a 15 s sampling period was used with the modelling approach, it is assumed that the plateau model based on $15s_{RAW}$ data represents the true or actual $\dot{V}O_{2max}$. Therefore, this criterion plateau model value was considered to be the 'gold standard' approach to defining $\dot{V}O_{2max}$ against which the approach of defining $\dot{V}O_{2max}$ as the $\dot{V}O_{2peak}$ observed for a particular averaging technique and period should be evaluated.

The bias in $\dot{V}O_{2peak}$ determined from each of the four averaged sets of $15s_{RAW}$ data, and the $15s_{RAW}$ and $45s_{RAW}$ data themselves, is given in table 6.2. The mean ± SD $\dot{V}O_{2peak}$ values, for each of the sampling/averaging periods, are also given.

**Table 6.2 Bias in $\dot{V}O_{2peak}$ derived from six sampling/averaging periods.**

| | Averaging or sampling period (s) | | | | | |
|---|---|---|---|---|---|---|
| | $15s_{RAW}$ | $45s_{RAW}$ | $30s_{STAN}$ | $30s_{MOVE}$ | $45s_{STAN}$ | $45s_{MOVE}$ |
| Bias in $\dot{V}O_{2peak}$ ($ml.kg^{-1}.min^{-1}$) | 0.98 | 0.86 | 0.80 | 0.88 | 0.68 | 0.73 |
| Mean ± SD $\dot{V}O_{2peak}$ ($ml.kg^{-1}.min^{-1}$) | 63.4 ± 5.4 | 63.0 ± 5.4 | 63.0 ± 5.4 | 63.0 ± 5.5 | 62.7 ± 5.4 | 62.8 ± 5.4 |

Table 6.2 shows that the bias in $\dot{V}O_{2peak}$ was positive (i.e. $\dot{V}O_{2peak}$ overestimated the criterion $\dot{V}O_{2max}$ derived from the plateau model) and that the magnitude of this bias decreased with an increase in sampling/averaging period. For a given averaging period, the two averaging methods gave similar bias in $\dot{V}O_{2peak}$, within 0.1 $ml.kg^{-1}.min^{-1}$. Table 6.2 also shows that the mean ± SD $\dot{V}O_{2peak}$ values were similar across all of the sampling/averaging periods.

6.3.2.2 Test-retest reliability of $\dot{V}O_{2max}$

The bias between repeat tests (A and B for the $15s_{RAW}$ and averaged data, and C and D for the $45s_{RAW}$ data) was calculated as the mean difference between repeat tests (see section 6.2.6.2). This bias was always ≤ 0.35 $ml.kg^{-1}.min^{-1}$. Regression based 95% LOA were calculated using equation (2) in section 6.2.6.3 to give the test-retest reliability (i.e. the random variation) of $\dot{V}O_{2peak}$. Plots of the absolute test-retest differences against the mean $\dot{V}O_{2peak}$ are shown in Figure 6.2. The limits for the test-retest reliability (i.e. the random variation in $\dot{V}O_{2peak}$) are given in table 6.3 for the range of $\dot{V}O_{2peak}$ values likely to be encountered in this thesis. The random variation decreased as a negative function of $\dot{V}O_{2peak}$ (i.e. the data showed negative heteroscedasticity) and was greatest for the $15s_{RAW}$ data and lowest for the $45s_{RAW}$ data for the range of $\dot{V}O_{2peak}$ values considered.

**Table 6.3 Test-retest reliability of $\dot{V}O_{2peak}$ for six sampling/averaging periods.**

| | Test-retest reliability of $\dot{V}O_{2peak}$ ($ml.kg^{-1}.min^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| $\dot{V}O_{2peak}$ ($ml.kg^{-1}.min^{-1}$) | $15s_{RAW}$ | $45s_{RAW}$ | $30s_{STAN}$ | $30s_{MOVE}$ | $45s_{STAN}$ | $45s_{MOVE}$ |
| 55 | ± 3.02 | ± 1.78 | ± 3.69 | ± 3.63 | ± 3.56 | ± 3.29 |
| 60 | ± 2.53 | ± 1.42 | ± 2.69 | ± 2.76 | ± 2.80 | ± 2.72 |
| 65 | ± 2.04 | ± 1.06 | ± 1.69 | ± 1.88 | ± 2.04 | ± 2.14 |
| 70 | ± 1.55 | ± 0.70 | ± 0.69 | ± 1.00 | ± 1.28 | ± 1.56 |

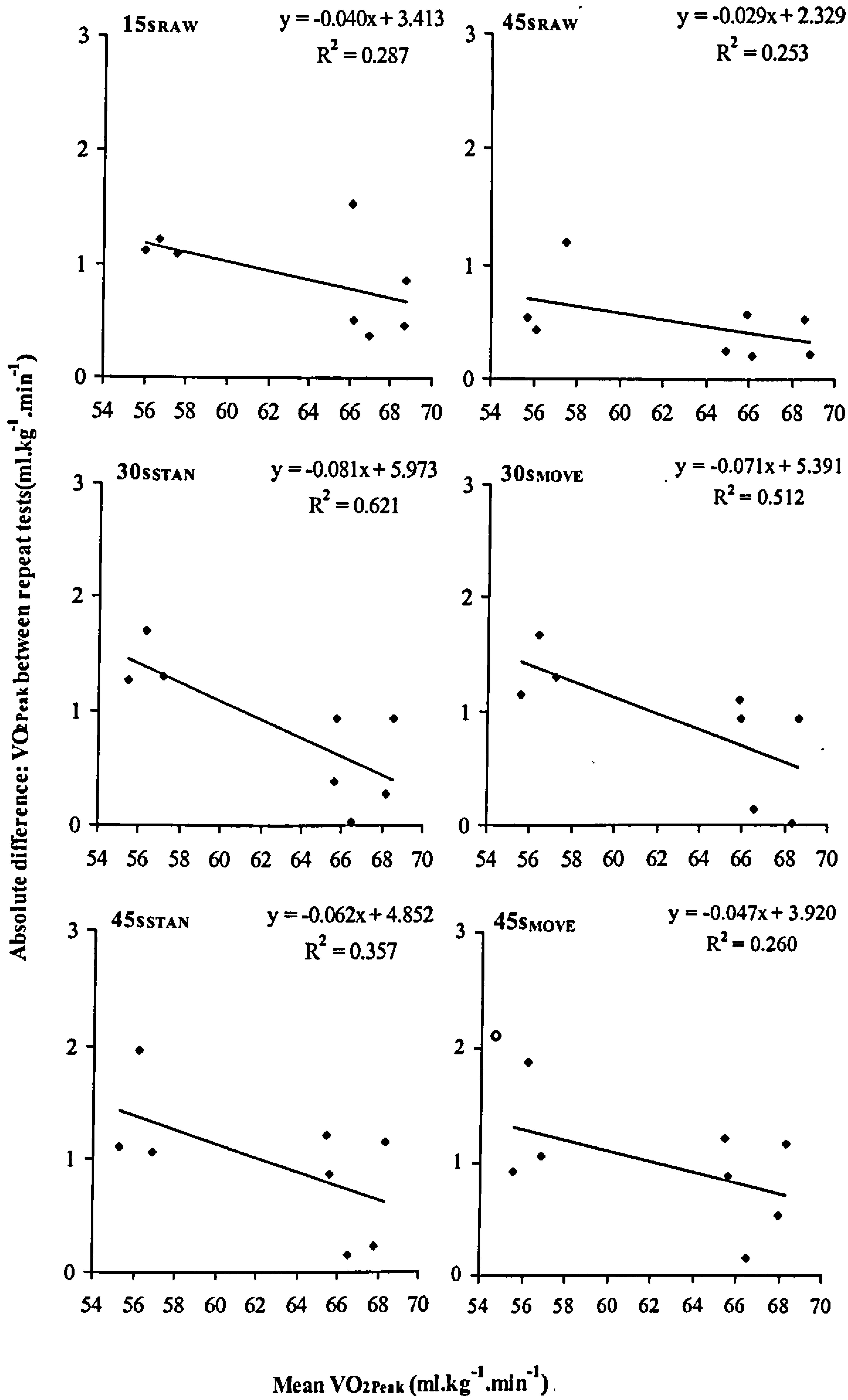



**Figure 6.2 Relationship between the absolute differences in $\dot{V}O_{2peak}$, derived from repeat tests, and the mean $\dot{V}O_{2peak}$ for six sampling/averaging periods.**

## 6.4 Discussion

### *6.4.1 Defining a $\dot{V}O_2$-plateau*

The results of the present study suggest that in trained runners the $\dot{V}O_2$-running speed relationship does plateau over the closing stages of a ramp test. A $\dot{V}O_2$-plateau was evident in all participants, and in repeat tests, when a 15 s sampling period was used in conjunction with the modelling approach of Wood (1999b). This is in contrast to the lower incidence ($\leq$88%) seen when a longer 45 s sampling period was used. The use of this modelling approach, therefore, satisfies the first stage of establishing criteria to define $\dot{V}O_{2max}$: it identifies whether the $\dot{V}O_2$-running speed relationship plateaus for the majority of individuals during progressive exercise. Furthermore, if 15 s sampling periods are used to derive the $\dot{V}O_2$ data on which the modelling is based, the incidence of identifying a $\dot{V}O_2$-plateau will be relatively higher than if longer sampling periods are used.

The modelling approach to defining a plateau assumes that $\dot{V}O_2$ either increases as a linear function of running speed throughout the ramp test or increases as a linear function initially and then plateaus in the closing stages of the test. When the $15s_{RAW}$ $\dot{V}O_2$ data were modelled, at least 26 data points were typically included in the model. Were the $\dot{V}O_2$-running speed relationship linear, each of these data points would vary randomly around a straight line. The goodness of fit would only be better for the plateau model if the final few data points varied in such a way that they were generally lower than would be predicted from a linear $\dot{V}O_2$-running speed relationship. For example, the plateau model would be the best fit model for a set of data in which all data points except the last fit a straight line, provided the final point falls well below this line. The chance of this randomly occurring, and a spurious plateau being identified, when 26 or more data points are available and the $\dot{V}O_2$-running speed relationship is linear, is, however, small.

For the $15s_{RAW}$ data, the duration of the $\dot{V}O_2$-plateau ranged from 33 to 165 s across the two tests. Together with the mean ± SD plateau duration of 82.2 ± 32.8 s for the two tests, these data suggest that when a plateau is evident in a ramp test it generally occurs within the last 1-2 min of the test. The relatively higher incidence of a $\dot{V}O_2$-plateau for the 15s$_{RAW}$ compared to the 45s$_{RAW}$ data suggests that the greater density of data for the final 1-2 min of the test, when 15 s sampling periods are used, allows a greater chance of a plateau being identified (assuming one exists). This suggestion is logical as the greater density of data over the closing stages of the test would increase the chance of the final data points falling well below the straight line of the linear model.

The high incidence of a $\dot{V}O_2$-plateau for the 15 s samples also suggests that the relatively high variability associated with short sampling periods did not obscure the identification of a plateau. This is important because the variability associated with short sampling periods potentially causes a conflict between the first stage (defining a $\dot{V}O_2$-plateau) and the second stage (assigning a value to this plateau) of establishing criteria to define $\dot{V}O_{2max}$. It is possible that the increased variability in $\dot{V}O_2$ with a decrease in sampling period (highlighted by the lower 95% LOA for the reliability of 45s$_{RAW}$ than 15s$_{RAW}$ $\dot{V}O_{2peak}$ data) is counterbalanced by a decreased variability in $\dot{V}O_2$ at high exercise intensities close to $\dot{V}O_{2max}$. This latter point is loosely supported by the decreased variability in $\dot{V}O_{2peak}$ between repeat tests as a function of the size of $\dot{V}O_{2peak}$ (see section 6.4.3). This potential counterbalancing effect, coupled with the greater density of data points for the final 1-2 min of the test, should ensure that the use of 15 s sampling periods will allow a $\dot{V}O_2$-plateau to be identified whenever one lasting at least 30 s exists. Therefore, short (e.g. 15 s) sampling periods should be used to determine $\dot{V}O_2$ over the closing stages of a progressive test when the primary aim is to identify a plateau.

The findings of the present study also lend support to the use of speed ramped tests on a level motorised treadmill to determine $\dot{V}O_{2max}$ in runners. The high incidence of a $\dot{V}O_2$-plateau in the present study for this type of ramp test on a level treadmill, even when 45 s sampling periods are used to determine $\dot{V}O_2$ (81% incidence of a plateau across the two repeat tests), is in agreement with the high (92%) incidence of a $\dot{V}O_2$-plateau reported by Draper et al. (1998) for a similar test protocol. Furthermore, this incidence is higher than has been reported elsewhere in the literature for incremental protocols (Duncan et al., 1997; Rivera-Brown et al., 1994; Sheehan et al., 1987). Finally, the present study suggests that the runners attained $\dot{V}O_{2max}$, and were not limited by cadence, as has been suggested by Taylor et al. (1955).

### 6.4.2 *Defining $\dot{V}O_{2max}$*

Since a $\dot{V}O_2$-plateau was identified in all participants when a 15 s sampling period was used to determine $\dot{V}O_2$, the results of the present study suggest that the $\dot{V}O_2$ value associated with this plateau is likely to be maximal (i.e. $\dot{V}O_{2max}$) for level treadmill running. The use of 15 s sampling periods in conjunction with the modelling approach satisfies the first stage of establishing criteria to define $\dot{V}O_{2max}$: a $\dot{V}O_2$-plateau was identified in all participants and the experimenter can be confident that this plateau value is a true $\dot{V}O_{2max}$. Deriving the value of this plateau is the second stage of establishing criteria to define $\dot{V}O_{2max}$ and it is important that this derivation is both valid and reliable. Furthermore, for the purpose of this thesis, it is important that the method used to associate a $\dot{V}O_2$ value with the plateau identified during a progressive ramp test can also be used to identify the highest $\dot{V}O_2$ attained during simulated middle-distance running events on the motorised treadmill.

#### 6.4.2.1 Criterion validity of $\dot{V}O_{2max}$

The results of the present study show that $\dot{V}O_{2peak}$ values derived from averages of raw data determined from 15 s sampling periods provide a valid representation of the criterion $\dot{V}O_{2max}$ (i.e. that derived from the plateau model). Indeed, when a moving average approach was used, $\dot{V}O_{2peak}$ was within 0.9 ml.kg$^{-1}$.min$^{-1}$ of the criterion $\dot{V}O_{2max}$. The criterion $\dot{V}O_{2max}$ based on $15s_{RAW}$ data was considered to be the true value since a $\dot{V}O_2$-plateau was evident in all participants using this approach and it is, therefore, likely that this value was maximal. Furthermore, the $\dot{V}O_{2max}$ values derived from the plateau model based on $15s_{RAW}$ data (62.5 ± 5.6 and 62.2 ± 5.4 ml.kg$^{-1}$.min$^{-1}$, for tests A and B respectively) were very similar to those based on the $45s_{RAW}$ data (62.5 ± 5.8 and 62.5 ± 5.6 ml.kg$^{-1}$.min$^{-1}$, for tests C and D respectively).

The bias in $\dot{V}O_{2peak}$ decreased from 0.98 to 0.73 ml.kg$^{-1}$.min$^{-1}$ as the averaging period increased between the 15s$_{RAW}$ and 45s$_{MOVE}$ $\dot{V}O_{2peak}$ data. While this effect is very small it may be explained by the fact that the variability in $\dot{V}O_{2peak}$ derived from the averaged data would have decreased with an increase in the averaging period. Therefore, some of the variability in the 15s$_{RAW}$ data may have been smoothed as the averaging period used to determine $\dot{V}O_{2peak}$ increased. The bias in $\dot{V}O_{2peak}$ was positive: $\dot{V}O_{2peak}$ consistently overestimated the criterion $\dot{V}O_{2max}$. This is logical because $\dot{V}O_{2peak}$ is an average of two or three data points whereas the criterion $\dot{V}O_{2max}$ could have been averaged over as many as six data points. Therefore, the variability in the $\dot{V}O_{2peak}$ values would have been greater than in the criterion $\dot{V}O_{2max}$ values.

The mean $\dot{V}O_{2peak}$ values (from repeat test data) for each of the six sampling/averaging periods were very similar (see table 6.2). This finding is similar to that reported by Gomes et al. (1997) who reported no statistically significant differences in $\dot{V}O_{2peak}$ among 5 to 60 s averages of raw breath-by-breath data. Gomes et al. reported a 5% difference in $\dot{V}O_{2peak}$ between the 5 and 60 s averages. In the present study, the 15s$_{RAW}$ $\dot{V}O_{2peak}$ (63.4 ml.kg$^{-1}$.min$^{-1}$) was 1% greater than the 45s$_{STAN}$ (62.7 ml.kg$^{-1}$.min$^{-1}$).

6.4.2.2 Test-retest reliability of $\dot{V}O_{2max}$

The bias in repeat determinations of $\dot{V}O_{2peak}$ was considered to be constant and was very small (< 0.35 ml.kg$^{-1}$.min$^{-1}$). This confirms that the experimental design and, in particular, the Latin Square effectively controlled for any order or carryover effects. The random test-retest variation in $\dot{V}O_{2peak}$ decreased through the process of averaging the 15s$_{RAW}$ data. For a $\dot{V}O_{2peak}$ of 70 ml.kg$^{-1}$.min$^{-1}$, the variation was ± 1.55 and ± 1.00 ml.kg$^{-1}$.min$^{-1}$ for the 15s$_{RAW}$ and 30s$_{MOVE}$ data, respectively. The random variation was similar for the 30s$_{MOVE}$ and 30s$_{STAN}$ averaging methods and the 30s$_{MOVE}$ is, therefore, preferable.

The decrease in random variation in $\dot{V}O_{2peak}$ with an increase in sampling period supports the suggestion made in chapter 5 that the technical uncertainty in $\dot{V}O_2$ will decrease with an increasing sampling period. This is mainly due to the uncertainty in the measurement of the volume of expirate (± 0.57 L) causing greater variability in $\dot{V}O_2$ when this volume is small (i.e. when the sampling period is short). Therefore, the averaging of the 15s$_{RAW}$ data may have smoothed some of these uncertainties in the derived $\dot{V}O_{2peak}$ values. This finding also supports that of Myers et al. (1990) who report a decrease in the SD for repeat determinations of $\dot{V}O_2$ from 1.7 to 1.4 ml.kg$^{-1}$.min$^{-1}$ (95% LOA of ± 3.3 and ± 2.7 ml.kg$^{-1}$.min$^{-1}$) for 15 and 30 s averages of breath-by-breath data, respectively, during exercise at a $\dot{V}O_2$ equivalent to ~ 23.5 ml.kg$^{-1}$.min$^{-1}$. While this agreement appears to be much better than that reported in the present study, it should be noted that Myers et al. (1990) studied variability within a single test, where biological and technical variability would presumably be very small, as opposed to the between-test variability studied here. Since the $\dot{V}O_2$ equivalent of the exercise intensity studied by these authors was also very low, it would be meaningless to extrapolate the regression based 95% LOA (based on $\dot{V}O_2$ values of 55 to 68 ml.kg$^{-1}$.min$^{-1}$) reported here to enable a comparison with the Myers et al. study.

The effect of the uncertainty in the measurement of the volume of expirate may also help to explain why the random variation in $\dot{V}O_{2peak}$ decreased as a function of $\dot{V}O_{2peak}$. Just as an increase in sampling period will increase the volume of expirate collected and reduce the impact of the associated uncertainty in measuring this volume, a similar effect will occur when exercise intensity increases. Indeed, while all participants were exercising at the same relative exercise intensity towards the end of the ramp test (i.e. the speed corresponding to $\dot{V}O_{2peak}$), those exercising at the higher absolute exercise intensities (i.e. those with the higher $\dot{V}O_{2peak}$) may have a relatively larger volume of expirate collected for a given sampling period. In turn, this would reduce the impact of the uncertainty in the measurement of the volume of expirate.

### 6.4.3 Establishing criteria to define $\dot{V}O_{2max}$

The findings of the present study suggest that using 15 s sampling periods to determine $\dot{V}O_2$ during progressive exercise satisfies the two key stages for defining $\dot{V}O_{2max}$. First, the incidence of a $\dot{V}O_2$-plateau is high (100%) when a 15 s sampling period is used to determine $\dot{V}O_2$ with the modelling approach of Wood (1999b). Second, when these 15 s data are smoothed using a $30s_{MOVE}$ averaging approach and $\dot{V}O_{2peak}$ is derived from these averaged data, $\dot{V}O_{2peak}$ is within 0.9 $ml.kg^{-1}.min^{-1}$ of the criterion $\dot{V}O_{2max}$ value and can, therefore, be considered to be maximal. This $\dot{V}O_{2peak}$ value will also be reliable, with 95% LOA ranging from ± 2.76 to ± 1.00 $ml.kg^{-1}.min^{-1}$ for $\dot{V}O_{2peak}$ values from 60 to 70 $ml.kg^{-1}.min^{-1}$ when the $30s_{MOVE}$ averaging approach is used. Finally, the $30s_{MOVE}$ averaging approach used here to define $\dot{V}O_{2max}$ could be used during middle-distance running to identify the highest $\dot{V}O_2$ attained. This would ensure that the variability in $\dot{V}O_2$ associated with the sampling/averaging period is the same for the test used to determine $\dot{V}O_{2max}$ and that used to derive $\dot{V}O_{2peak}$ during constant speed running.

The term $\dot{V}O_{2max}$ will only be used in the rest of this thesis to define the value determined from a progressive test, using the approach described above. This ensures that the term is consistent with the traditional definition of $\dot{V}O_{2max}$ (i.e. that a plateau in $\dot{V}O_2$ is observed) and that the value ascribed to this plateau closely agrees with the criterion $\dot{V}O_{2max}$ (to within 0.9 $ml.kg^{-1}.min^{-1}$). The term $\dot{V}O_{2peak}$ will only be used from this point onwards to define the highest $\dot{V}O_2$ attained during middle-distance running.

# *PART III*

# *OXYGEN UPTAKE DURING MIDDLE-DISTANCE RUNNING*

# CHAPTER 7

# STUDY II: TEST-RETEST RELIABILITY AND $\dot{V}O_{2max}$ AS DETERMINANTS OF PEAK $\dot{V}O_2$ DURING 800 M RUNNING

## 7.1 Background

### *7.1.1 Identifying the issues*

A critical assumption in the majority of models of middle-distance running is that the parameter representing the asymptote for the highest $\dot{V}O_2$ attained will be $\dot{V}O_{2max}$ for all events. That is, it is assumed that $\dot{V}O_2$ will rise towards $\dot{V}O_{2max}$, with $\dot{V}O_{2max}$ being attained provided the duration is sufficient (see chapter 2). This is consistent with the view of many influential physiologists (Di Prampero and Ferretti, 1999; Gaesser and Poole, 1996; Ward, 1999; Whipp, 1994) who believe that $\dot{V}O_{2max}$ will be attained during such running events as they are performed at intensities considered to be in the severe intensity domain [i.e. above the 'fatigue threshold', which typically occurs halfway between the lactate threshold and $\dot{V}O_{2max}$ (Ward, 1999)].

The findings of several studies contradict this belief, showing that $\dot{V}O_{2max}$ is not attained during short (~ 2 min) exhaustive exercise equivalent to 800 m running (Ariyoshi et al., 1979b; Åstrand and Saltin, 1961; Hill and Ferguson, 1999; Léger and Ferguson, 1974; Spencer and Gastin, 2001; Spencer et al., 1996; Williams, 1997). In particular, Spencer et al. (1996) showed that the highest $\dot{V}O_2$ attained during 800 m running reached an asymptote below $\dot{V}O_{2max}$ (i.e. that $\dot{V}O_2$ was not rising towards an asymptote equal to $\dot{V}O_{2max}$). Physiologists, including the authors of the above studies, have consistently overlooked such findings. This is presumably because the attainment of $\dot{V}O_{2max}$ was not the focus of the above studies. To date, no study has been designed specifically to establish whether $\dot{V}O_{2max}$ is attained during the 800 m running event.

To address the second aim of this thesis, this study drew on the findings from study I to investigate whether $\dot{V}O_{2max}$ is attained during the 800 m middle-distance running event. If it could be shown that $\dot{V}O_2$ reaches an asymptote that is below $\dot{V}O_{2max}$ during 800 m running, the assumption common to most models of middle-distance running performance (Di Prampero et al., 1993; Henry, 1954; Hill and Lupton, 1923; Lloyd, 1966, 1967; Sargent, 1926; Ward-Smith, 1985, 1999) that the asymptote will be $\dot{V}O_{2max}$ would be refuted. Alternatively, if it could be shown that $\dot{V}O_2$ reaches an asymptote that is $\dot{V}O_{2max}$ during 800 m running, this assumption would be upheld. The important considerations for this second study were that:

1. the $\dot{V}O_{2max}$ determined from a progressive ramp test must theoretically be attainable during constant speed 800 m running: this $\dot{V}O_{2max}$ must not be biased high due to the protocol and procedures used to determine $\dot{V}O_{2max}$;

2. the $\dot{V}O_2$ in the closing stages of the constant speed run must be shown to plateau at a value lower than $\dot{V}O_{2max}$ to be confident that $\dot{V}O_{2max}$ is not, or could not have been, attained;

3. the potential phenomenon of $\dot{V}O_{2max}$ not being attained during the 800 m run must be repeatable and not explained by variability in the determination of $\dot{V}O_2$ during this run.

### *7.1.2 $\dot{V}O_2$ attained during short duration exhaustive running*

Of the studies showing that $\dot{V}O_{2max}$ is not attained during short duration exhaustive exercise (Ariyoshi et al., 1979b; Åstrand and Saltin, 1961; Hill and Ferguson, 1999; Léger and Ferguson, 1974; Spencer and Gastin, 2001; Spencer et al., 1996; Williams, 1997) three have focused on both constant speed running and durations representative of the 800 m event (Hill and Ferguson, 1999; Spencer et al., 1996; Williams, 1997). Hill and Ferguson (1999) showed that $\dot{V}O_{2peak}$ was 5% lower for a run lasting ~ 120 s than for one lasting ~ 300 s. This finding is consistent with that of Williams (1997) who also studied the $\dot{V}O_2$ response to short exhaustive running bouts lasting ~ 120-300 s: the $\dot{V}O_{2peak}$ for the ~ 120 s run (3020 $ml.min^{-1}$) was 5% lower than both that for the ~ 300 s run (3180 $ml.min^{-1}$) and $\dot{V}O_{2max}$ determined from an incremental test (3182 $ml.min^{-1}$). Collectively, the findings from these studies (Hill and Ferguson, 1999; Williams, 1997) suggest that $\dot{V}O_{2max}$ was not attained during the ~ 120 s run which is equivalent to 800 m running.

It could be argued that $\dot{V}O_{2max}$ was not attained in these studies because the exercise duration was not sufficient. Williams (1997) report a time constant of 30 s for the rate of rise in $\dot{V}O_2$ at the onset of exercise. Therefore, $\dot{V}O_{2max}$ would have been virtually attained (i.e. 97% $\dot{V}O_{2max}$) after ~ 120 s if $\dot{V}O_2$ was rising towards $\dot{V}O_{2max}$ or above.

Spencer et al. (1996) were the first to actually acknowledge that $\dot{V}O_{2max}$ is not attained during 800 m running. These authors determined $\dot{V}O_2$ breath-by-breath in specialist middle-distance runners (i.e. 800 and 1500 m specialists) during constant speed 800 m race pace running to exhaustion. This study showed that $\dot{V}O_2$ reached a plateau at ~ 90 % $\dot{V}O_{2max}$ after ~ 90 s for this 800 m run. Since $\dot{V}O_2$ reached an asymptote below $\dot{V}O_{2max}$, the Spencer et al. (1996) study suggests that $\dot{V}O_{2max}$ was not attained because $\dot{V}O_2$ was rising towards an asymptote below $\dot{V}O_{2max}$. However, there are several problems with the experimental design of this study that cast doubt over whether the % $\dot{V}O_{2max}$ attained was an artefact of the test protocols and procedures used to determine $\dot{V}O_2$.

First, $\dot{V}O_{2max}$ determined from a constant speed increasing gradient test protocol was used as the reference for the $\dot{V}O_{2peak}$ derived from the 800 m run. Given that the 800 m run was performed on a level treadmill, this was inappropriate. A greater muscle mass is recruited during uphill running than during running on the flat (Sloniger et al., 1997) and this may allow a higher $\dot{V}O_{2max}$ to be attained. Therefore, the $\dot{V}O_{2max}$ reference point in the Spencer et al. (1996) study would have overestimated the actual $\dot{V}O_{2max}$ that could be attained during level treadmill running (i.e. the $\dot{V}O_{2max}$ that could potentially be attained during 800 m running). In turn, the % $\dot{V}O_{2max}$ attained (i.e. ~ 90%) would have been an underestimate of the true percentage.

Second, data were presented as 10 s averages for the 800 m run. Given the relatively poor test-retest reliability of $\dot{V}O_{2peak}$ determined from short sampling/averaging periods (see section 6.3.2.2), the $\dot{V}O_{2peak}$ for the 800 m run may have been biased high. In turn, the % $\dot{V}O_{2max}$ attained may have been overestimated. When the potential overestimation of $\dot{V}O_{2max}$ is coupled with the potential overestimation of $\dot{V}O_{2peak}$, the exact value at which $\dot{V}O_2$ plateaued below $\dot{V}O_{2max}$ in the Spencer et al. (1996) study is not clear.

In the present study, the above issues with the Spencer et al. (1996) experimental design were resolved as part of a concerted effort to establish whether $\dot{V}O_{2max}$ is attained during 800 m running. This was done by assessing:

1. $\dot{V}O_{2max}$ in accordance with the approach established in study I and for a progressive ramp test on a level motorised treadmill;
2. both $\dot{V}O_{2peak}$ during 800 m running and $\dot{V}O_{2max}$ using the same $30s_{MOVE}$ averaging method;
3. the test-retest reliability of $\dot{V}O_{2peak}$ during 800 m running;
4. the role of $\dot{V}O_{2max}$ as a determinant of $\dot{V}O_{2peak}$ for 800 m running.

## 7.2 Methods

### *7.2.1 Participants*

Fifteen male middle-distance runners (age 23.3 ± 3.8 yr; height 1.80 ± 0.10 m; mass 76.9 ± 10.6 kg) volunteered to participate. Of these, seven had a mean personal best time of 112.1 ± 3.5 s for the 800 m, which is within 11% of the World Record (101.11 s) set by Wilson Kipketer on 24/08/97 in Köln. The remaining eight runners had never run within 20% of this World Record (i.e. none had run faster than 121 s). All were well habituated with laboratory procedures in general and with motorised treadmill running in particular. Each participant was in regular running training at the time of the study.

### *7.2.2 Preliminary tests*

All participants initially completed a ramp test (0.16 $km.h^{-1}$ per 5 s) on a level motorised treadmill (see section 4.2.2 for a more detailed description of this ramp test) and a constant speed 800 m run, also on a level treadmill. The ramp test allowed an appropriate starting speed to be selected for future ramp tests to ensure that exhaustion would be reached in ~ 10 min (Buchfuhrer et al., 1983) for each participant (see section

4.2.2 for more detail of this process). The $\dot{V}O_2$ at which the lactate threshold occurred was determined by means of the V-slope method (Beaver et al., 1986) for each participant (see section 4.3.3). The corresponding speed for this $\dot{V}O_2$ was then determined from each participant's $\dot{V}O_2$-running speed relationship.

The speed for the 800 m run was determined from each participant's seasonal best time for the 800 m event. The time to exhaustion for this constant speed run was then compared to the participant's seasonal best time. If the two times differed markedly, the speed was adjusted accordingly for all future tests. The motorised treadmill was set at the constant speed and the experimenter initiated a 10 s countdown when the participant was ready to start the test. The participant stood astride the motorised treadmill belt and at the start of the countdown used the support rails to suspend their body above the belt while they developed cadence in their legs. The test officially started, and the first collection of expirate was initiated, when the participant released the support rails and started running on the treadmill belt.

### *7.2.3 Experimental design*

Each participant completed one ramp test (0.16 km.h$^{-1}$ per 5 s) and two constant speed 800 m runs, all on a level motorised treadmill. The speed for both these 800 m runs was based on the findings from the preliminary test: the actual or adjusted speed corresponding to each runner's seasonal best performance time for the 800 m was used (see section 7.2.2). Participants were encouraged to continue running for as long as possible in all tests.

The preliminary tests described above were always completed first, but thereafter the fifteen participants completed the three tests (i.e. the ramp test and the two constant speed 800 m runs) in a random order. Five participants were allocated to each sequence within a 3 × 3 Latin Square to control for order and carryover effects. Each participant completed his own sequence of tests at the same time of day. All tests (i.e. the preliminary tests, ramp test, and the two constant speed 800 m runs) were completed within 14 days, with at least 48 hours between testing sessions. Each of the tests (excluding the preliminary tests) was preceded by a 5 min warm-up at 10% below the speed corresponding to each participant's lactate threshold (see section 7.2.2) to control for the effects of prior exercise on the determination of $\dot{V}O_2$ (Gerbino et al., 1996).

### *7.2.4 Data collection*

The off-line Douglas bag system described in chapter 5 was used to determine all gas exchange variables. The sampling period was nominally 15 s over approximately the final 4 min of the ramp test and throughout the 800 m run. A whole number of breaths was always collected, so typically the actual period was not identical to the nominal period. Every effort was made to ensure that the actual was as close to the nominal sampling period as possible. For the 15 s sampling periods, the actual period was usually between 15 and 20 s, and on no occasion was it less than 15 s.

### *7.2.5 Treatment of data*

#### 7.2.5.1 Defining $\dot{V}O_{2max}$

For the ramp test, a plateau in $\dot{V}O_2$ was modelled using the approach described in section 6.2.5.1. A 30 s moving average ($30s_{MOVE}$) was used to determine the value of this plateau (i.e. $\dot{V}O_{2max}$) (see section 6.4.3). The averaging always started with the final 15 s sampling period and moved back towards the start of the test. This $\dot{V}O_{2max}$ value was used as the reference point for the $\dot{V}O_{2peak}$ attained during the 800 m runs.

#### 7.2.5.2 Defining $\dot{V}O_{2peak}$

For the 800 m runs, a 30 s moving average ($30s_{MOVE}$) was used to identify the highest $\dot{V}O_2$ attained (i.e. $\dot{V}O_{2peak}$). The averaging always started with the final 15 s sampling period and moved back towards the start of the test (see section 6.2.5.2).

### *7.2.6 Statistical analysis*

#### 7.2.6.1 General

All tests were analysed at an alpha level of 0.05 and all data are presented as mean ± SD unless otherwise stated. Individual data can be found in Appendix II, together with full results for each of the tests described below.

7.2.6.2 Test-retest reliability as a determinant of $\dot{V}O_{2peak}$

The estimated bias in $\dot{V}O_{2peak}$ between the two runs was assumed to be constant and was determined in the same way as for study I (see section 6.2.6.2). The test-retest reliability of $\dot{V}O_{2peak}$ was then evaluated using regression based 95% LOA in accordance with the procedures outlined in section 6.2.6.3.

7.2.6.3 $\dot{V}O_{2max}$ as a determinant of $\dot{V}O_{2peak}$

To address the common assumption that the parameter in the models of middle-distance running performance representing the asymptote for the highest $\dot{V}O_2$ attained will be $\dot{V}O_{2max}$, it was important to assess two questions: a) does $\dot{V}O_2$ plateau during 800 m running? and b) is the highest $\dot{V}O_2$ attained during 800 m running below $\dot{V}O_{2max}$?. To address the first question, a paired samples t-test was used to assess whether there was a difference between each of the two data points that were averaged (i.e. $30s_{MOVE}$) to define $\dot{V}O_{2peak}$. If the two data points were not significantly different it could be argued that $\dot{V}O_2$ had reached a plateau and was not still rising. To address the second question, the $\dot{V}O_{2peak}$ attained during the 800 m runs was expressed as a percentage of the reference $\dot{V}O_{2max}$ value determined from the ramp test (section 7.2.5.1) to give the $\%\dot{V}O_{2max}$ attained during 800 m running. This would indicate whether the highest $\dot{V}O_2$ attained is below $\dot{V}O_{2max}$ and, coupled with the identification of a plateau in $\dot{V}O_2$, would suggest that $\dot{V}O_2$ reached an asymptote below $\dot{V}O_{2max}$.

The role of $\dot{V}O_{2max}$ as a determinant of $\dot{V}O_{2peak}$ was assessed in two ways. First, the 15 runners were separated into two groups of seven (i.e. high and low $\dot{V}O_{2max}$) using a median-split (i.e. ranks 1-7 and 9-15) and an independent samples t-test was used to assess if there was a difference between the two groups in the $\%\dot{V}O_{2max}$ attained during 800 m running. Second, Pearson's Correlation was used to evaluate for all 15 runners the strength of the relationship between $\dot{V}O_{2max}$ and the $\%\dot{V}O_{2max}$ attained during 800 m running. In both these analyses, each participant's mean $\%\dot{V}O_{2max}$ attained (from the repeat tests) was used.

## 7.3 Results

### *7.3.1 Defining $\dot{V}O_{2max}$*

It was assumed that a plateau in $\dot{V}O_2$ had occurred if the SEE was lower for the plateau than for the linear model (see section 6.2.5.1). The SEE was lower for the plateau than for the linear model in all participants (1.42 ± 1.03 vs. 1.81 ± 1.01 ml.kg$^{-1}$.min$^{-1}$). Therefore, a $\dot{V}O_2$-plateau was evident in all participants. The value for this $\dot{V}O_{2max}$, derived using the 30s$_{MOVE}$ averaging approach, was 58.9 ± 7.1 ml.kg$^{-1}$.min$^{-1}$ for the 15 runners. For the low and high $\dot{V}O_{2max}$ groups it was 52.4 ± 1.8 and 65.7 ± 3.0 ml.kg$^{-1}$.min$^{-1}$, respectively. The peak speed attained on the ramp test was 20.5 ± 2.3 km.h$^{-1}$. The mean speed for the 800 m constant speed runs was 21.6 ± 2.7 km.h$^{-1}$.

### *7.3.2 Test-retest reliability as a determinant of $\dot{V}O_{2peak}$*

The bias in $\dot{V}O_{2peak}$ between the 800 m runs (i.e. the mean difference ) was 1.2 ml.kg$^{-1}$.min$^{-1}$. Regression based 95% LOA were calculated using equation (2) in section 6.2.6.3 to evaluate the test-retest reliability of this $\dot{V}O_{2peak}$. The plot of the absolute test-retest differences against the mean $\dot{V}O_{2peak}$ is shown in Figure 7.1.

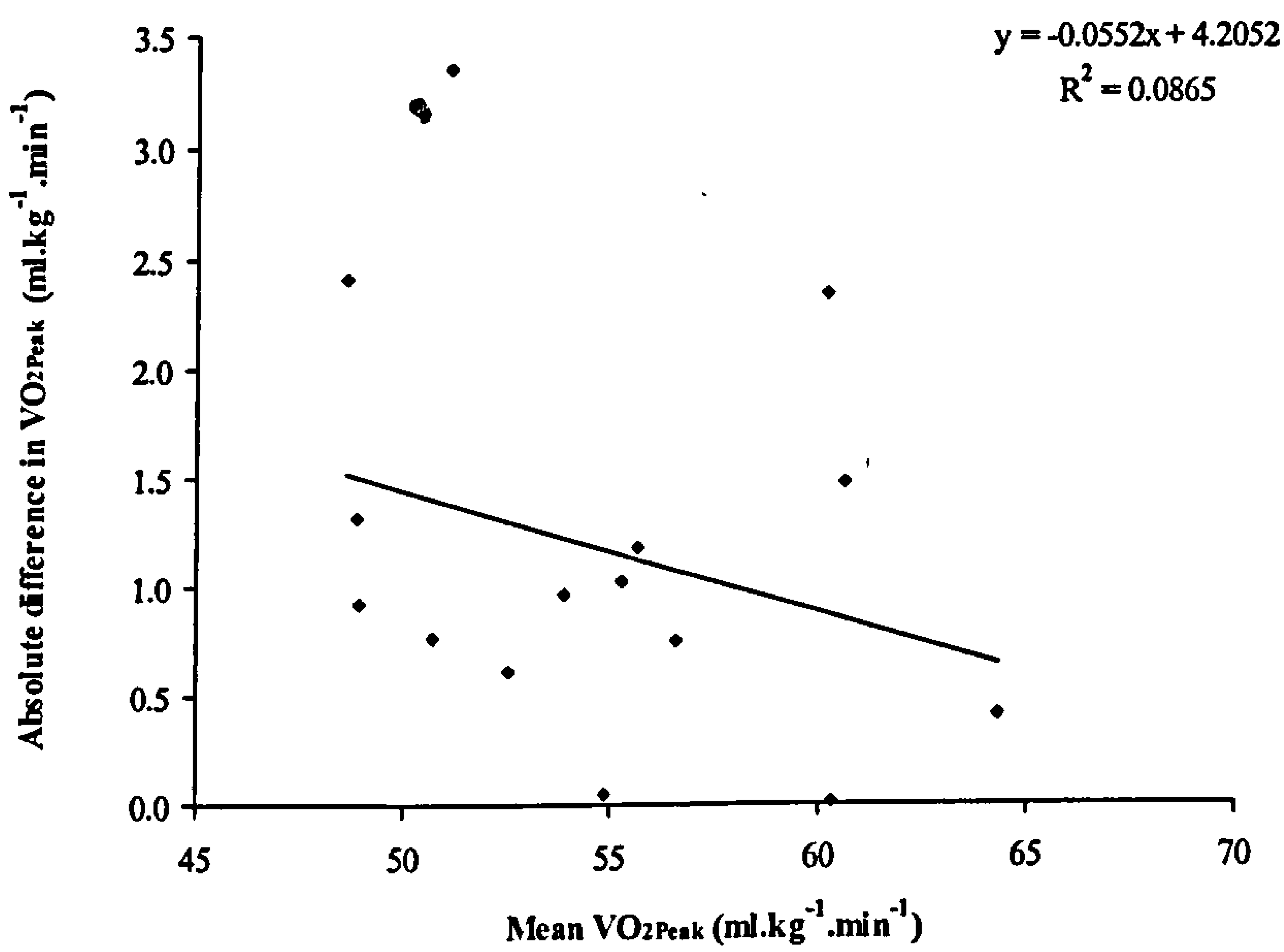



**Figure 7.1 Relationship between the absolute differences in $\dot{V}O_{2peak}$ and the mean $\dot{V}O_{2peak}$ for the two 800 m constant speed runs.**

The test-retest reliability for a $\dot{V}O_{2peak}$ of 50.6 ml.kg$^{-1}$.min$^{-1}$ (the mean $\dot{V}O_{2peak}$ for the low $\dot{V}O_{2max}$ group) was ± 3.5 ml.kg$^{-1}$.min$^{-1}$. The test-retest reliability for a $\dot{V}O_{2peak}$ of 59.0 ml.kg$^{-1}$.min$^{-1}$ (the mean $\dot{V}O_{2peak}$ for the high $\dot{V}O_{2max}$ group) was ± 2.3 ml.kg$^{-1}$.min$^{-1}$.

### *7.3.3 $\dot{V}O_{2max}$ as a determinant of $\dot{V}O_{2peak}$*

The $\dot{V}O_{2peak}$ for the 800 m runs was 54.8 ± 4.9 ml.kg$^{-1}$.min$^{-1}$ for the 15 runners. For the low and high $\dot{V}O_{2max}$ groups it was 50.6 ± 2.0 and 59.0 ± 3.3 ml.kg$^{-1}$.min$^{-1}$, respectively. For the low $\dot{V}O_{2max}$ group, there was no significant difference (mean difference of 0.70 ± 1.44 ml.kg$^{-1}$.min$^{-1}$, p = 0.092) between the two $\dot{V}O_2$ values used to determine $\dot{V}O_{2peak}$. For the high $\dot{V}O_{2max}$ group, there was also no significant difference (mean difference of 0.04 ± 0.60 ml.kg$^{-1}$.min$^{-1}$, p = 0.800) between the two $\dot{V}O_2$ values used to determine $\dot{V}O_{2peak}$.

Figures 7.2 and 7.3 show data from representative participants from the low and high $\dot{V}O_{2max}$ groups, respectively. In Figure 7.2 the $\dot{V}O_{2peak}$ is 51.3 ml.kg$^{-1}$.min$^{-1}$ and $\dot{V}O_{2max}$ is 52.1 ml.kg$^{-1}$.min$^{-1}$, yielding a % $\dot{V}O_{2max}$ attained of 98.5%. In Figure 7.3 the $\dot{V}O_{2peak}$ is 55.9 ml.kg$^{-1}$.min$^{-1}$ and $\dot{V}O_{2max}$ is 64.8 ml.kg$^{-1}$.min$^{-1}$, yielding a % $\dot{V}O_{2max}$ attained of 86.2%.

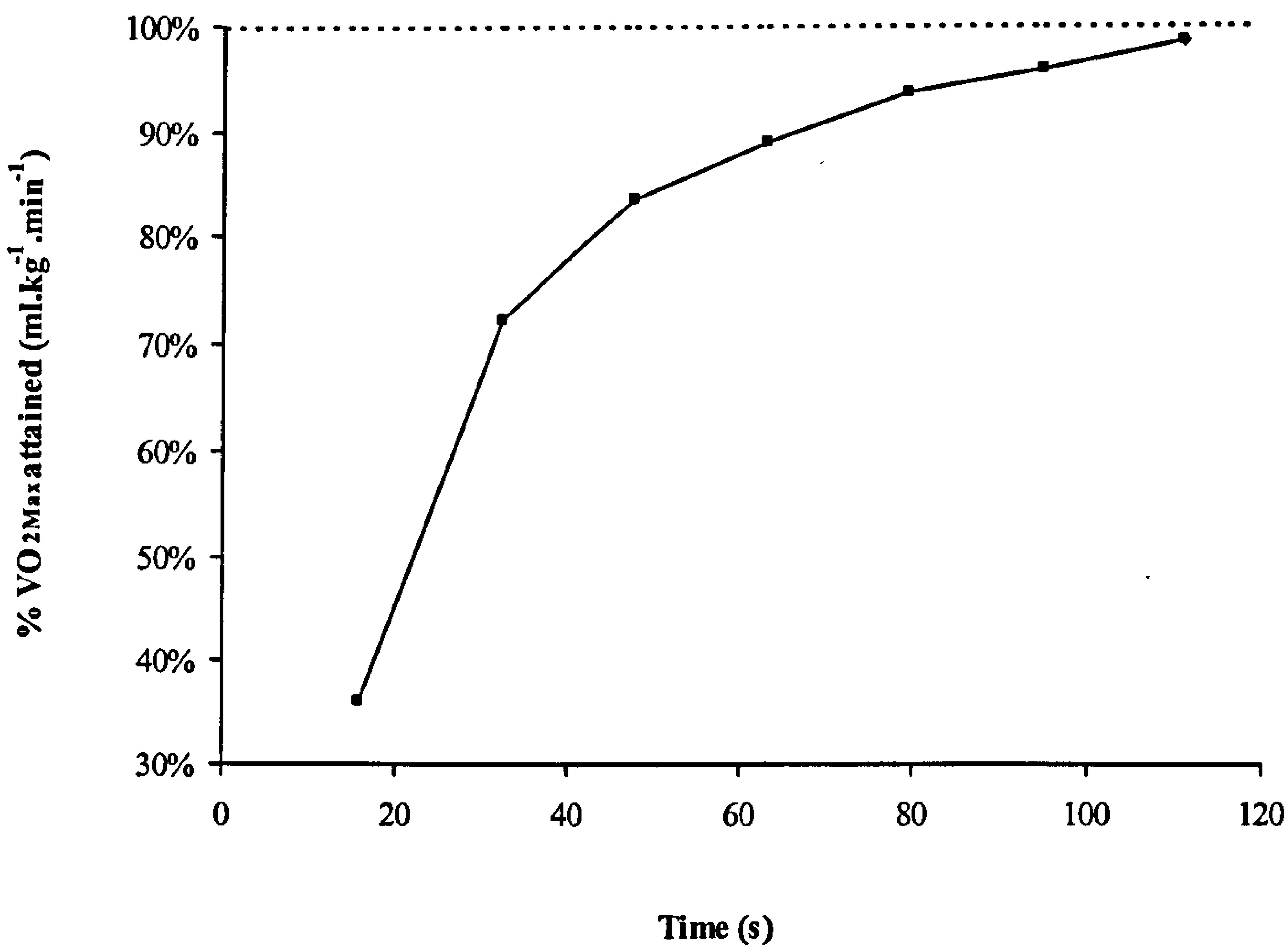



**Figure 7.2 Data from a representative participant from the low $\dot{V}O_{2max}$ group showing the % $\dot{V}O_{2max}$ attained during a constant speed 800 m run.**

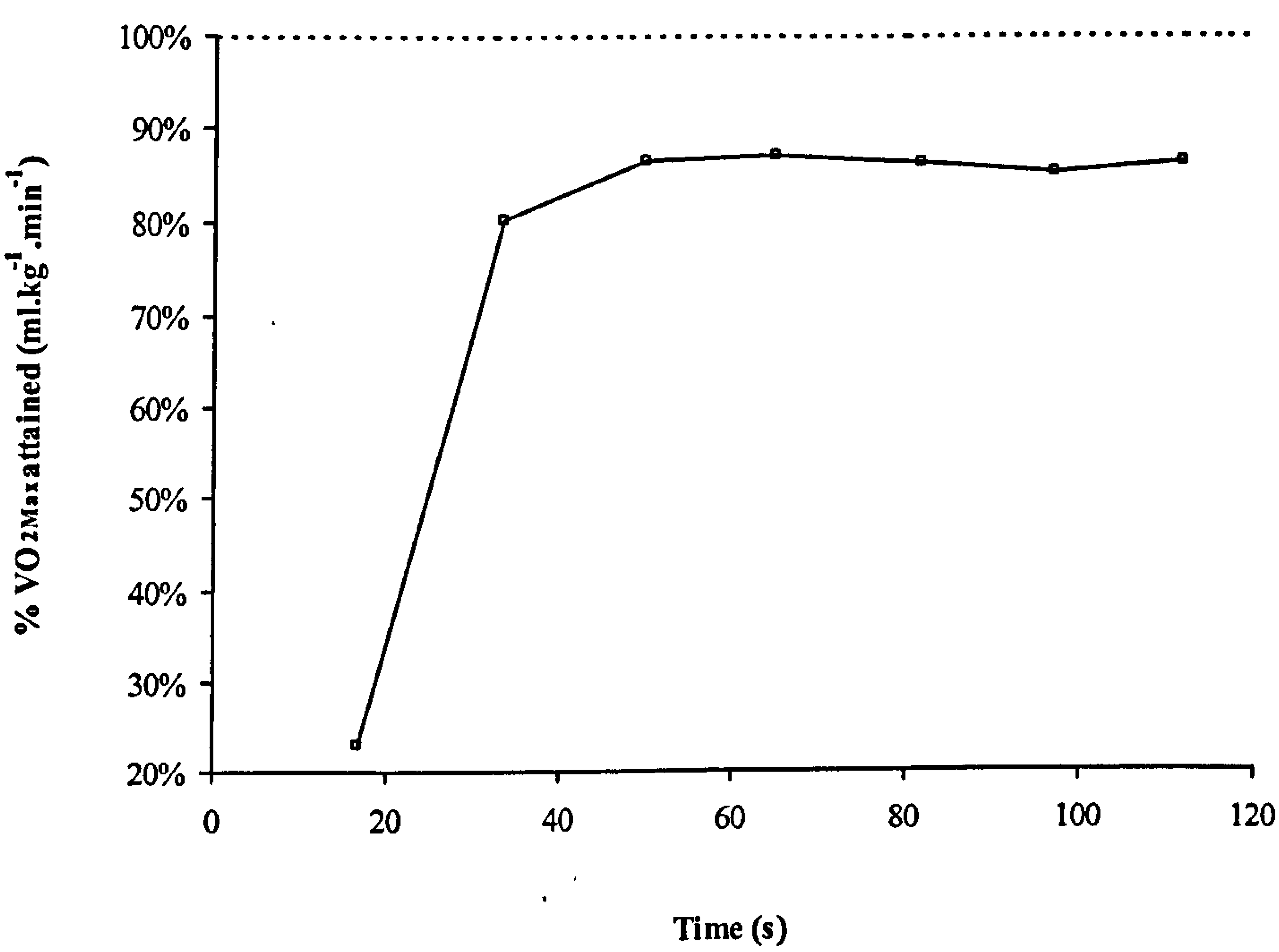



**Figure 7.3 Data from a representative participant from the high $\dot{V}O_{2max}$ group showing the % $\dot{V}O_{2max}$ attained during a constant speed 800 m run.**

Figure 7.4 shows the group (mean) $\dot{V}O_2$ response to the 800 m run for the low and high $\dot{V}O_{2max}$ groups. For the low $\dot{V}O_{2max}$ group (filled squares), the $\dot{V}O_{2peak}$ is 50.6 $ml.kg^{-1}.min^{-1}$ and $\dot{V}O_{2max}$ is 52.4 $ml.kg^{-1}.min^{-1}$, yielding a % $\dot{V}O_{2max}$ attained of 96.5%. For the high $\dot{V}O_{2max}$ group (unfilled squares), the $\dot{V}O_{2peak}$ is 59.0 $ml.kg^{-1}.min^{-1}$ and $\dot{V}O_{2max}$ is 65.7 $ml.kg^{-1}.min^{-1}$, yielding a % $\dot{V}O_{2max}$ attained of 89.7%.

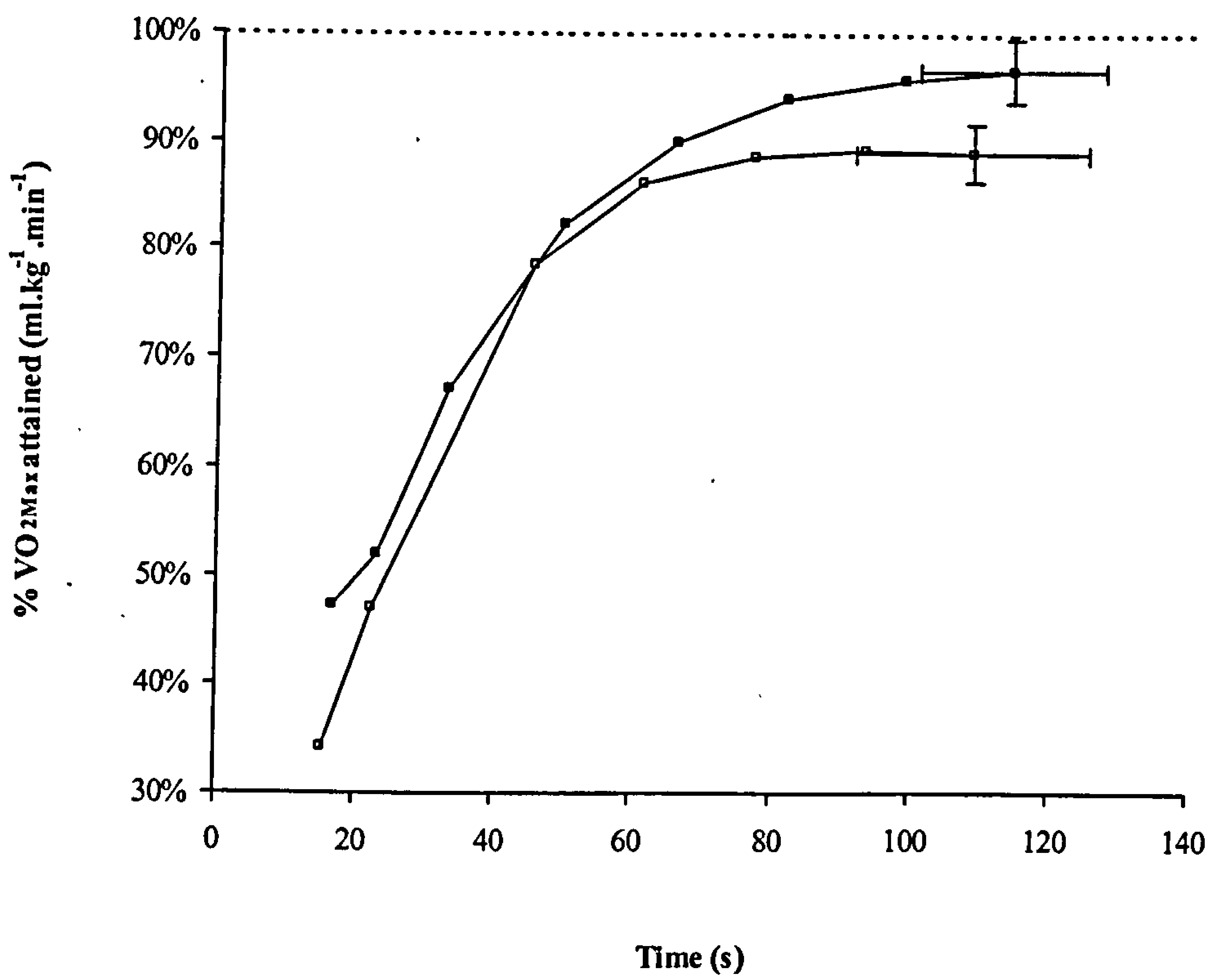



**Figure 7.4 Mean data for the low (■) and high (□) $\dot{V}O_{2max}$ groups showing the % $\dot{V}O_{2max}$ attained during the constant speed 800 m runs. For clarity error bars (representing one SD) have been omitted from all but the final data points.**

The relationship between $\dot{V}O_{2max}$ and % $\dot{V}O_{2max}$ attained for all 15 runners is given in Figure 7.5. This relationship was strong (- 0.77) and significant ($p = 0.001$). Using the regression equation from Figure 7.5 to estimate the $\dot{V}O_{2max}$ for which a given percentage of $\dot{V}O_{2max}$ will be attained during 800 m running suggests that 100, 95 and 90 % $\dot{V}O_{2max}$ will be attained with $\dot{V}O_{2max}$ values of 45, 55 and 66 $ml.kg^{-1}.min^{-1}$, respectively. This suggests that, typically, $\dot{V}O_{2max}$ will only be attained during 800 m running in individuals with a $\dot{V}O_{2max}$ $\leq$45 ml.kg$^{-1}$.min$^{-1}$.

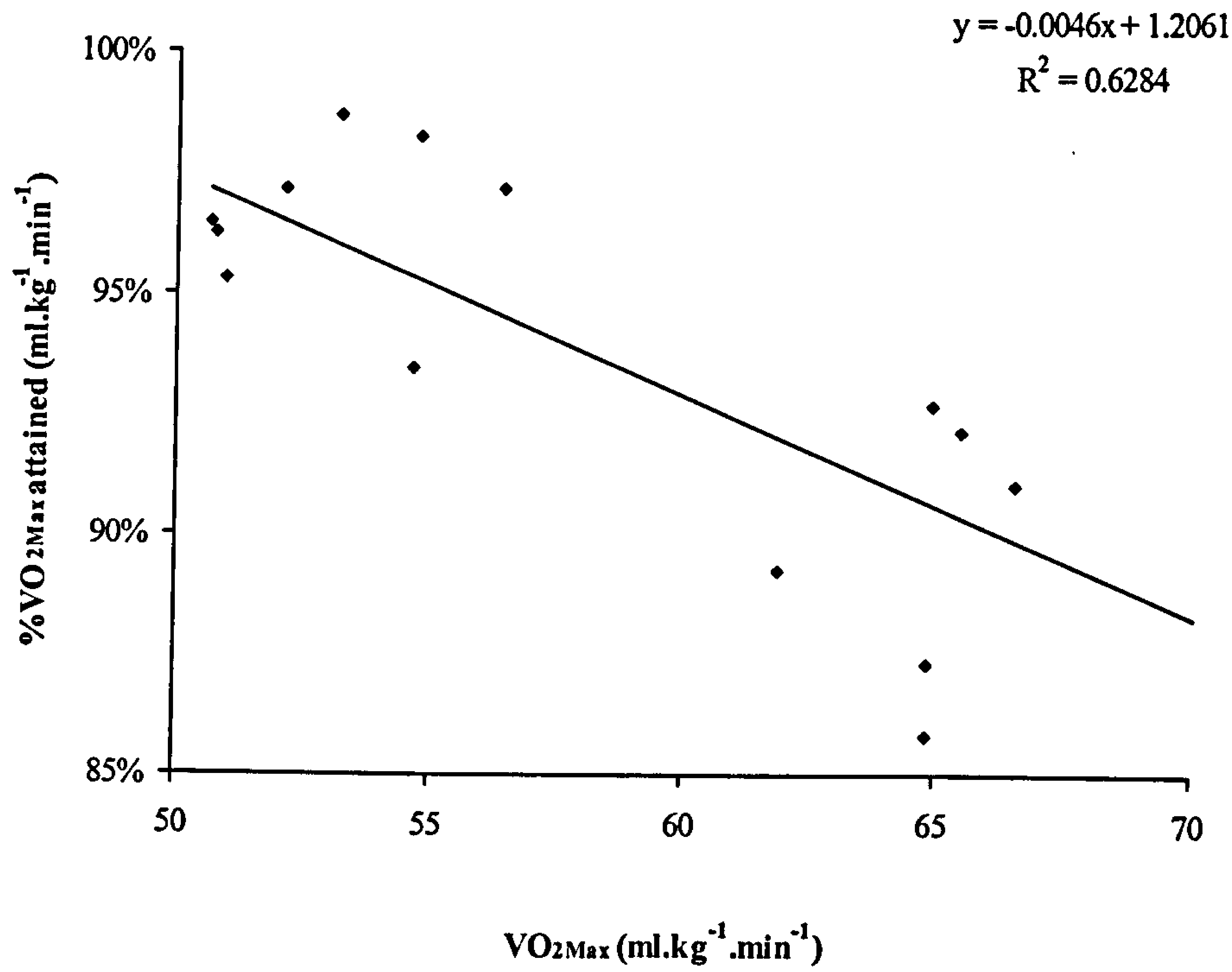



**Figure 7.5 Relationship between $\dot{V}O_{2max}$ and % $\dot{V}O_{2max}$ attained during constant speed 800 m running (n = 15 - two data points overlap since twp participants had the same $\dot{V}O_{2max}$ and % $\dot{V}O_{2max}$ attained: see table AII.1 and AII.2).**

## 7.4 Discussion

### *7.4.1 Test-retest reliability and $\dot{V}O_{2max}$ as determinants of $\dot{V}O_{2peak}$*

The present study is the first to show that the % $\dot{V}O_{2max}$ attained during constant speed 800 m running is inversely related to $\dot{V}O_{2max}$. As $\dot{V}O_{2max}$ increases the % $\dot{V}O_{2max}$ that can be attained during constant speed 800 m running decreases ($r = -0.77$, $p = 0.001$). Additionally, when the regression equation defining this within-event relationship (i.e. Figure 7.5) is used to predict the $\dot{V}O_{2max}$ that can be attained during constant speed 800 m running, it becomes clear that only runners with a low $\dot{V}O_{2max}$ (< 45 ml.kg$^{-1}$.min$^{-1}$)

will be able to reach $\dot{V}O_{2max}$ during this event. The significant difference in the $\%\dot{V}O_{2max}$ attained between the low and high $\dot{V}O_{2max}$ groups lends further support to the notion that there is a negative within-event relationship between $\dot{V}O_{2max}$ and the $\%\dot{V}O_{2max}$ attained during 800 m running.

In middle-distance runners with a low $\dot{V}O_{2max}$ (i.e. the low $\dot{V}O_{2max}$ group; $\dot{V}O_{2max}$ of $52.4 \pm 1.8$ ml.kg$^{-1}$.min$^{-1}$), the $\%\dot{V}O_{2max}$ attained averaged 96.5% (range = 93.4 to 98.7%. The finding that there was no significant difference between the two $\dot{V}O_2$ data points averaged to determine $\dot{V}O_{2peak}$ during the 800 m run suggests that $\dot{V}O_2$ plateaued. However, this statistical analysis is not entirely convincing given that the mean difference was $0.70 \pm 1.44$ ml.kg$^{-1}$.min$^{-1}$ and the p value was 0.092 for the low $\dot{V}O_{2max}$ group. It may be that $\dot{V}O_2$ plateaued in some individuals because $\dot{V}O_{2max}$ had been attained, while in others it was still tending towards $\dot{V}O_{2max}$.

In middle-distance runners with a high $\dot{V}O_{2max}$ (i.e. the high $\dot{V}O_{2max}$ group; $\dot{V}O_{2max}$ of $65.7 \pm 3.0$ ml.kg$^{-1}$.min$^{-1}$), the $\%\dot{V}O_{2max}$ attained averaged 89.7% (range = 85.8 to 92.7%). This finding is in agreement with that of Spencer et al. (1996) who showed that ~ 90% $\dot{V}O_{2max}$ is attained in middle-distance runners with a similar $\dot{V}O_{2max}$ (~ 65 ml.kg$^{-1}$.min$^{-1}$). This suggests that the Spencer et al. (1996) study did not overestimate the $\%\dot{V}O_{2max}$ attained during 800 m running in event specialist with a high $\dot{V}O_{2max}$.

The test-retest reliability of $\dot{V}O_{2peak}$ was generally good and showed that the phenomenon of $\dot{V}O_{2max}$ not being attained is repeatable, at least for the high $\dot{V}O_{2max}$ group. The reliability, however, was better in the high $\dot{V}O_{2max}$ group.

The findings of the present study are convincing for several reasons. First, the fact that all participants showed a $\dot{V}O_2$-plateau during the ramp test suggests that $\dot{V}O_{2max}$ was attained in this test. More importantly, since this $\dot{V}O_{2max}$ was determined from a ramp test on a level motorised treadmill, it should potentially have been attainable during 800 m constant speed running also on a level treadmill. Second, the peak speed attained during the ramp test ($20.5 \pm 2.3$ km.h$^{-1}$) was similar to the speed of the constant speed 800 m runs ($21.6 \pm 2.7$ km.h$^{-1}$) for all the runners. This suggests that cadence did not prevent these runners from attaining their $\dot{V}O_{2max}$ during the 800 m runs. Third, Figure 7.4 clearly shows that the $\dot{V}O_2$ response in the runners with a high $\dot{V}O_{2max}$ plateaued (beneath $\dot{V}O_{2max}$) after 70 s. This is confirmed by the fact that there was no significant difference between the two $\dot{V}O_2$ data points that were averaged to derive the $\dot{V}O_{2peak}$ for the 800 m runs. Fourth, the fact that the averaging approach used to define $\dot{V}O_{2max}$ from the ramp test and $\dot{V}O_{2peak}$ from the 800 m runs was the same (i.e. the $30s_{MOVE}$ average) suggests that the variability in $\dot{V}O_2$ associated with these two $\dot{V}O_2$ values would have been similar. The effect of the absolute exercise intensity (i.e. that the variability in $\dot{V}O_2$ decreases with an increase in $\dot{V}O_2$) on the variability in $\dot{V}O_2$ would not have been controlled by the experimental design. However, this effect would have been reflected in the regression based 95% LOA for the test-retest reliability of $\dot{V}O_{2peak}$ during 800 m running.

### *7.4.2 Implications for models of middle-distance running performance*

The findings of the present study suggest that the assumption that the parameter representing the asymptote for the highest $\dot{V}O_2$ attained will be $\dot{V}O_{2max}$, in the majority of models of middle-distance running (Di Prampero et al., 1993; Henry, 1954; Hill and Lupton, 1923; Lloyd, 1966, 1967; Sargent, 1926; Ward-Smith, 1985, 1999) during 800 m running, is false. The fact that $\dot{V}O_2$ plateaued below $\dot{V}O_{2max}$ at ~ 90% $\dot{V}O_{2max}$ in the high $\dot{V}O_{2max}$ group confirms this and demonstrates that $\dot{V}O_2$ was not rising towards an asymptote equal to $\dot{V}O_{2max}$. This supports the assumption in Wood's (1999a) model that the asymptote for the highest $\dot{V}O_2$ attained during 800 m running will be below $\dot{V}O_{2max}$. The implication is that the majority of models overestimate the aerobic energy contribution to 800 m running. This overestimation will be greater for those authors that have ascribed relatively higher values to the asymptote parameter (i.e. $\dot{V}O_{2max}$) in order to test their models. For example, Di Prampero et al. (1993) use a $\dot{V}O_{2max}$ value of 74 $ml.kg^{-1}.min^{-1}$ for a 75 kg hypothetical runner. Based on the negative within-event relationship between $\dot{V}O_{2max}$ and the % $\dot{V}O_{2max}$ attained reported here for 800 m running, the % $\dot{V}O_{2max}$ attained for such a runner would be 86%. The effect of this on the model is equivalent to assuming that $\dot{V}O_{2max}$ is attained and using a $\dot{V}O_{2max}$ value of ~ 64.5 $ml.kg^{-1}.min^{-1}$ for the hypothetical runner.

Since models of middle-distance running performance can accurately predict performance by overestimating the aerobic energy contribution to 800 m running, other components of the models must be in error. This suggests, therefore, that the application of the majority of models to 800 m running is meaningless. Since Wood's (1999a) model has the greatest potential to accurately represent middle-distance running performance, the impact of the present study on his model is explored in more detail in Chapter 10. To assess the full impact of the findings from the present study on Wood's (1999a) model, it is important to further explore two potential determinants of the $\%\dot{V}O_{2max}$ attained during middle-distance running. First, does the $\%\dot{V}O_{2max}$ attained vary with event duration in a given group of runners? If so, specific values should be ascribed to the parameter representing the asymptote for the highest $\dot{V}O_2$ attained for each middle-distance event. Second, do event specialists attain the same $\%\dot{V}O_{2max}$ as non-specialists during a given event? This will inform whether it is appropriate for a set of data based on a hypothetical runner, with a given set of characteristics, to be used to evaluate a model across a range of events. These questions were the focus of study III.

# CHAPTER 8

# STUDY III: TEST DURATION AND EVENT SPECIALISM AS DETERMINANTS OF PEAK $\dot{V}O_2$ DURING 400 AND 800 M RUNNING

## 8.1 Background

### *8.1.1 Identifying the issues*

The models of middle-distance running performance have typically ascribed a single set of values (representative of a typical runner) to their parameters in order to assess the accuracy of their predictions. While these values are in accordance with published data (see section 3.6.1), the use of a single set of values assumes that these values are independent of event duration. That is, it is assumed that athletes who specialise in different middle-distance events will share the same physiological characteristics. Study II showed that there is a negative within-event relationship between $\dot{V}O_{2max}$ and the %$\dot{V}O_{2max}$ attained during 800 m running. This finding makes the majority of models of middle-distance running performance meaningless since they assume that the parameter representing the asymptote for the highest $\dot{V}O_2$ attained will be $\dot{V}O_{2max}$ for all events. However, the findings from study II support the assumption in Wood's (1999a) model that this parameter will be below $\dot{V}O_{2max}$ for the 800 m event. Wood (1999a) did not include a negative within-event relationship between $\dot{V}O_{2max}$ and the %$\dot{V}O_{2max}$ attained for the parameter representing the asymptote below $\dot{V}O_{2max}$ in his model (though this could be readily done). However, the fact that he ascribed different values to this parameter for each event suggests that he assumed there would be a between-event difference in the %$\dot{V}O_{2max}$ attained. In order to assess the validity of Wood's (1999a) model, it is important to determine if there is a between-event (but within group) or between-group (but within event) difference in the %$\dot{V}O_{2max}$ attained during middle-distance running.

To address the third aim of the thesis, this study developed the findings whether there is a between-event (but within group) difference in the %$\dot{V}O_{2max}$ attained during middle-distance running. In addition, to address the fourth aim, this study investigated whether there is: a) a between-group difference in $\dot{V}O_{2max}$ and b) a between-group (but within event) difference in the % $\dot{V}O_{2max}$ attained. If it could be shown that event duration is a determinant of the % $\dot{V}O_{2max}$ attained for a given group of runners, a between-event (but within group) difference would be established, supporting the assumption in Wood's (1999s) model. Alternatively, if it could be shown that event specialism is a determinant of the % $\dot{V}O_{2max}$ attained in a given event, a between-group (but within event) difference in the % $\dot{V}O_{2max}$ attained would be established and specific values may need to be ascribed to the parameters in Wood's (1999a) model for each event.

This study is in two parts. Part A investigates event duration as a determinant of the % $\dot{V}O_{2max}$ attained during middle-distance running, assuming that the runners' event specialism is not a determinant of the % $\dot{V}O_{2max}$ attained. Part B investigates whether the assumption that event specialism is not a determinant of the % $\dot{V}O_{2max}$ attained for a given event is valid. The important considerations for this study were that:

1. criteria developed in studies I and II to define the % $\dot{V}O_{2max}$ attained in middle-distance running can be applied to different events and specialist middle-distance runners;
2. the middle-distance events selected are such that the characteristics of the middle-distance runners (i.e. the event specialists) are likely to be different.

*8.1.2 Test duration as a determinant of $\dot{V}O_{2peak}$ (Part A)*

Åstrand and Saltin (1961) studied cycle ergometer exercise and showed that the highest $\dot{V}O_2$ attained was lower for an exhaustive bout of cycling that lasted ~ 120 s than for one that lasted ~ 360 s. They mentioned this effect, but having claimed that the $\dot{V}O_2$ attained was only 2% higher for the longer bout, they dismissed it. A closer inspection of the individual data reveals, however, that in four of the five participants the difference between the highest and lowest values for the $\dot{V}O_2$ attained was 5%. The lowest $\dot{V}O_2$ was typically observed in the shortest bout (~ 120 s) and the highest was typically observed in the longest bout (~ 360 s). Williams (1997) showed that the highest $\dot{V}O_2$ attained during a ~ 120 s run (3020 $ml.min^{-1}$) was 5% lower than that attained during a ~ 300 s run (3180 $ml.min^{-1}$). Similarly, Hill and Ferguson (1999) showed that the highest $\dot{V}O_2$ attained was 5% lower for a run which lasted ~ 120 s than one which lasted ~ 300 s. However, it is not clear from these studies whether the $\% \dot{V}O_{2max}$ attained decreases with test duration because the asymptote for the highest $\dot{V}O_2$ attained decreases with event duration or because the exercise duration is not sufficient for $\dot{V}O_2$ to rise to, and attain, $\dot{V}O_{2max}$.

Spencer et al. (1996) investigated the $\dot{V}O_2$ attained during constant speed 800 and 1500 m running using 800 and 1500 m event specialists for both the 800 and the 1500 m runs. This study showed that $\dot{V}O_2$ reached a plateau at ~ 90 and ~ 94% $\dot{V}O_{2max}$ for the 800 and 1500 m runs, respectively. The findings provide further support for the notion that the $\% \dot{V}O_{2max}$ attained during middle-distance running decreases as test duration decreases in a given group of runners. More importantly, the fact that $\dot{V}O_2$ reached an asymptote below $\dot{V}O_{2max}$, and that this asymptote was lower for the 800 than the 1500 m event, suggests that the asymptote for the highest $\dot{V}O_2$ attained will decrease with a decrease in event duration, at least for the 800 and 1500 m events.

### *8.1.3 Event specialism as a determinant of $\dot{V}O_{2peak}$ (Part B)*

Spencer et al. (1996) also investigated the $\dot{V}O_2$ attained during constant speed 400 m running using 200 and 400 m event specialists. For these runners, the $\dot{V}O_2$ response reached a plateau at ~ 98% $\dot{V}O_{2max}$ after 35 s. The aerobic fitness of these 200 and 400 m event specialists was lower than that of the 800 and 1500 m event specialists (a mean $\dot{V}O_{2max}$ of 53 $ml.kg^{-1}.min^{-1}$ versus 65 $ml.kg^{-1}.min^{-1}$). This study suggests that event specialism may be a determinant of the $\% \dot{V}O_{2max}$ attained during 400 m running. Since the $\% \dot{V}O_{2max}$ attained by the 800 and 1500 m specialists decreased with a decrease in event duration (i.e. 94% $\dot{V}O_{2max}$ for the 1500 m compared to 90% $\dot{V}O_{2max}$ for the 800 m), it would be expected that these runners would have attained < 90 $\% \dot{V}O_{2max}$ for the 400 m run. The $\% \dot{V}O_{2max}$ attained during 400 m running by the 200 and 400 m specialists (i.e. ~ 98% $\dot{V}O_{2max}$) is therefore greater than would be expected for 800 and 1500 m specialists. However, since the 800 and 1500 m specialists did not perform the 400 m run and the 200 and 400 m event specialists performed neither the 800 nor the 1500 m run, it is not clear how event specialism affects the $\% \dot{V}O_{2max}$ attained during middle-distance running.

Svedenhag and Sjödin (1984) have shown that $\dot{V}O_{2max}$ differs between athletes who specialise in specific middle-distance events. Runners who specialise in the 400 m event typically have a lower $\dot{V}O_{2max}$ (63.7 $ml.kg^{-1}.min^{-1}$) than those who specialise in the 800 m only (68.8 $ml.kg^{-1}.min^{-1}$) or the 800 and 1500 m (71.9 $ml.kg^{-1}.min^{-1}$). If there is a between-event (but within group) difference in the $\%\dot{V}O_{2max}$ attained during middle-distance running, it will be apparent between event specialists with the largest difference in $\dot{V}O_{2max}$. The above data suggest that a between-group difference in $\dot{V}O_{2max}$, and hence a between-event (but within group) difference in the $\%\dot{V}O_{2max}$ attained, is likely to be apparent in the 400 m event among 400 and 800/1500 m specialists. Furthermore, it is typical for runners to specialise in a combination of the 800, 1500 and 3000 m events. It is less typical for runners to specialise in the 400 m event in combination with any of the 800 to 3000 m events or even the 100 and 200 m events. The 400 m event specialists are, therefore, a relatively clearly defined group of runners. It is debatable whether the 400 m event should be considered to be a true middle-distance event. Nonetheless, the models of middle-distance running performance have all been applied to this event along with the 800, 1500 and 3000 m.

The previously identified limitation of the Spencer et al. (1996) study must be resolved to establish whether during 400 and 800 m running: a) a relationship exists between the $\%\dot{V}O_{2max}$ attained and event duration for a given group of runners [between-event (but within group) difference in the $\%\dot{V}O_{2max}$ attained] and b) event specialism is a determinant of the $\%\dot{V}O_{2max}$ attained for a given event [between-group (but within event) difference in the $\%\dot{V}O_{2max}$ attained]. In the present study, the above issues were investigated in two parts. This was done by assessing the:

1. $\%\dot{V}O_{2max}$ attained during 400 and 800 m level treadmill running by 800 m event specialists (part A)in accordance with the approach established in study II ;

2. $\%\dot{V}O_{2max}$ attained during 400 m level treadmill running by 400 m event specialists (part B);

3. $\%\dot{V}O_{2max}$ attained during 400 m running by 400 m event specialists (part B) in comparison to that attained by the 800 m event specialists (part A).

# PART 8A

# STUDY IIIA: TEST DURATION AS A DETERMINANT OF PEAK $\dot{V}O_2$

## 8.2A Methods

### *8.2.1A Participants*

Six male middle-distance runners (age 24.8 ± 3.2 yr; height 1.79 ± 0.07 m; mass 68.3 ± 4.9 kg) volunteered to participate. These runners had a mean personal best time of 111.8 ± 3.7 s for the 800 m, which is within 11% of the World Record (101.11 s). All were well habituated with laboratory procedures in general and with motorised treadmill running in particular. Each participant was in regular running training at the time of the study.

### *8.2.2A Preliminary tests*

All participants initially completed a ramp test (0.16 $km.h^{-1}$ per 5 s) (see section 4.2.2 for a more detailed description of this ramp test) and constant speed 400 and 800 m runs on a level motorised treadmill. The ramp test allowed an appropriate starting speed to be selected for future ramp tests to ensure that exhaustion would be reached in ~ 10 min (Buchfuhrer et al., 1983) for each participant (see section 4.2.2 for more detail of this process). The $\dot{V}O_2$ at which the lactate threshold occurred was determined by means of the V-slope method (Beaver et al., 1986) for each participant (see section 4.3.3). The corresponding speed for this $\dot{V}O_2$ was then determined from each participant's $\dot{V}O_2$-running speed relationship. The speed for the 800 m run was determined from each participant's seasonal best time for the 800 m event. The speed for the 400 m run was either determined from each participant's seasonal best time (for those who had competed in a 400 m) or estimated based on each participant's most recent 400 m performance time. The time to exhaustion for the 400 or 800 m constant speed run was then compared to the participant's seasonal best time or most recent time. If the two times differed markedly, the speed was adjusted accordingly for the subsequent test. The three preliminary tests (i.e. the ramp test, and the 400 and 800 m constant speed runs) were performed over two sessions. Typically, the ramp test and the 400 m run were completed in one session and the 800 m run in the other. The procedure for the constant speed runs was the same as in study II (see section 7.2.2).

*8.2.3A Experimental design*

Each participant completed one ramp test (0.16 $km.h^{-1}$ per 5 s), a 400 and an 800 m constant speed run, all on a level motorised treadmill. The speeds for the 400 and 800 m runs were based on the findings from the preliminary tests: the actual or adjusted speed corresponding to each runner's seasonal best or most recent performance time for the 400 and 800 m events were used (see section 8.2.2A). Participants were encouraged to continue running for as long as possible in all tests.

The preliminary tests described above were always completed first, but thereafter the six participants completed the three tests (i.e. the ramp test and the 400 and 800 m constant speed runs) in a random order. Two participants were allocated to each sequence within a 3 × 3 Latin Square to control for order and carryover effects. Each participant completed his own sequence of tests at the same time of day. All five test sessions (i.e. the two preliminary test sessions, the ramp test, and the 400 and 800 m constant speed runs) were completed within 14 days, with at least 48 hours between each session. Each of the tests (excluding the preliminary tests) was preceded by a 5 min warm-up at 10% below the speed corresponding to the participant's lactate threshold (see section 8.2.2A) to control for the effects of prior exercise on the determination of $\dot{V}O_2$ (Gerbino et al., 1996).

*8.2.4A Data collection*

The off-line Douglas bag system described in chapter 5 was used to determine all gas exchange variables. The sampling period was nominally 15 s over approximately the final 4 min of the ramp test and throughout the 400 and 800 m runs. A whole number of breaths was always collected, so typically the actual period was not identical to the nominal period. Every effort was made to ensure that the actual was as close to the nominal sampling period as possible. For the 15 s sampling periods, the actual period was usually between 15 and 20 s, and on no occasion was it less than 15 s.

### *8.2.5A Treatment of data*

#### 8.2.5.1A Defining $\dot{V}O_{2max}$

For the ramp test, a plateau in $\dot{V}O_2$ was modelled using the approach described in section 6.2.5.1. A 30 s moving average ($30s_{MOVE}$) was used to determine the value of this plateau (i.e. $\dot{V}O_{2max}$: see section 6.4.3). The averaging always started with the final 15 s sampling period and moved back towards the start of the test. This $\dot{V}O_{2max}$ was used as the reference point for the $\dot{V}O_{2peak}$ attained during the 400 and 800 m runs.

#### 8.2.5.2A Defining $\dot{V}O_{2peak}$

For the 400 and 800 m runs, a 30 s moving average ($30s_{MOVE}$) was used to identify the highest $\dot{V}O_2$ attained (i.e. $\dot{V}O_{2peak}$). The averaging always started with the final 15 s sampling period and moved back towards the start of the test.

### *8.2.6A Statistical analysis*

#### 8.2.6.1A General

All tests were analysed at an alpha level of 0.05 and all data are presented as mean ± SD unless otherwise stated. Individual data can be found in Appendix III, together with full results for each of the tests described below.

#### 8.2.6.2A Test duration as a determinant of $\dot{V}O_{2peak}$

The $\dot{V}O_{2peak}$ attained during the 400 and 800 m constant speed runs was expressed as a percentage of the reference $\dot{V}O_{2max}$ value determined from the ramp test (section 8.2.5.1A) to give the $\%\dot{V}O_{2max}$ attained during the 400 and 800 m runs, respectively. A paired samples t-test was used to assess if the $\%\dot{V}O_{2max}$ attained differed between the 400 and 800 m runs.

## 8.3A Results

### *8.3.1A Defining $\dot{V}O_{2max}$*

It was assumed that a plateau in $\dot{V}O_2$ had occurred if the SEE was lower for the plateau than for the linear model (see section 6.2.5.1). The SEE was lower for the plateau than for the linear model in all participants (0.88 ± 0.27 vs. 1.15 ± 0.45 $ml.kg^{-1}.min^{-1}$). Therefore, a $\dot{V}O_2$-plateau was evident in all participants. The value for this $\dot{V}O_{2max}$, derived using the $30s_{MOVE}$ averaging approach, was 69.3 ± 4.5 $ml.kg^{-1}.min^{-1}$. The peak speed attained on the ramp test was 22.3 ± 0.8 $km.h^{-1}$. The speed of the 400 and 800 m runs was 25.8 ± 1.2 $km.h^{-1}$ and 24.3 ± 0.8 $km.h^{-1}$, respectively.

### *8.3.2A Test duration as a determinant of $\dot{V}O_{2peak}$*

The test duration was 55.8 ± 2.3 s and 108.4 ± 21.2 s for the 400 and 800 m runs, respectively. Figure 8.1A shows the % $\dot{V}O_{2max}$ attained in the 400 and 800 m runs by a representative participant. Here, the $\dot{V}O_{2peak}$ is 65.4 $ml.kg^{-1}.min^{-1}$ and 70.5 $ml.kg^{-1}.min^{-1}$ for the 400 and 800 m runs, respectively; $\dot{V}O_{2max}$ determined from the ramp test is 75.7 $ml.kg^{-1}.min^{-1}$. These data yield a % $\dot{V}O_{2max}$ attained of 87.6 and 93.6% for the 400 and 800 m runs, respectively.

The mean $\dot{V}O_{2peak}$ for the group during the 400 and 800 m constant speed runs was 59.4 ± 4.4 $ml.kg^{-1}.min^{-1}$ and 61.7 ± 5.4 $ml.kg^{-1}.min^{-1}$, respectively; the mean $\dot{V}O_{2max}$ determined from the ramp test was 69.3 ± 4.5 $ml.kg^{-1}.min^{-1}$. The mean % $\dot{V}O_{2max}$ attained was 85.7 ± 3% and 89.1 ± 5% for the 400 and 800 m runs, respectively. In Figure 8.2A, the mean $\dot{V}O_2$ response, expressed as a percentage of $\dot{V}O_{2max}$, is given for both the 400 and the 800 m runs. There was a significant difference ($p = 0.018$) in the % $\dot{V}O_{2max}$ attained between the 400 and 800 m runs.

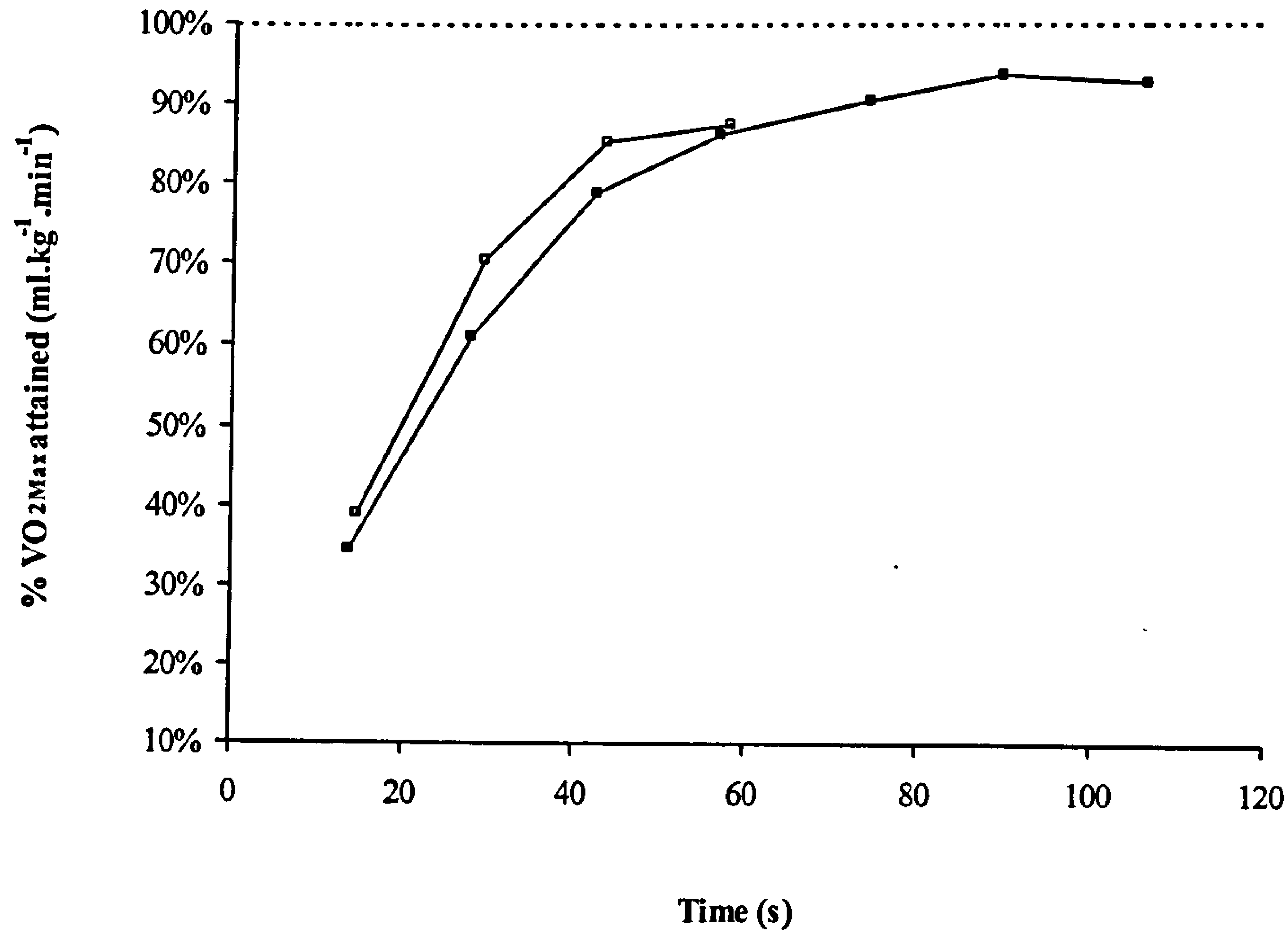



**Figure 8.1A Data from a representative participant showing the % $\dot{V}O_{2max}$ attained during the 400 m (□) and 800 m (■) constant speed runs.**

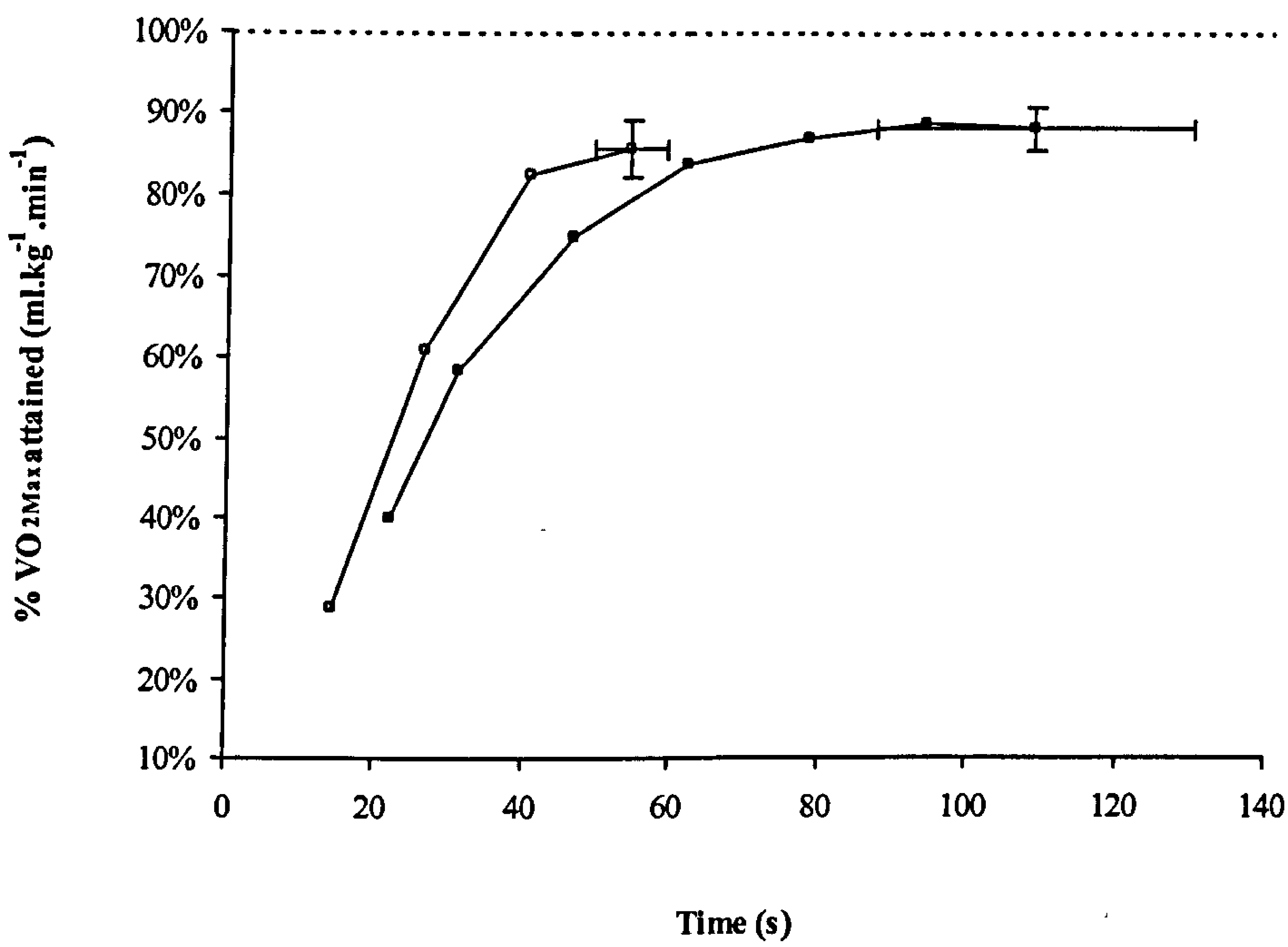



**Figure 8.2A Group data showing the % $\dot{V}O_{2max}$ attained during the constant speed 400 m (□) and 800 m (■) runs. For clarity error bars (representing one SD) have been omitted from all but the final data points.**

## 8.4A Discussion

### *8.4.1A Test duration as a determinant of $\dot{V}O_{2peak}$*

The results of the present study reinforce those of study II, showing that $\dot{V}O_{2max}$ cannot be attained during 800 m constant speed running. The 800 m event specialists studied here attained only 89% $\dot{V}O_{2max}$ during the 800 m run. This % $\dot{V}O_{2max}$ attained is similar to that reported in study II (i.e. 90% $\dot{V}O_{2max}$) for a comparable group of 800 m runners (i.e. the high $\dot{V}O_{2max}$ group). The 800 m event specialists studied here also failed to attain $\dot{V}O_{2max}$ during constant speed 400 m running. However, the fact that the % $\dot{V}O_{2max}$ attained decreased (from 89 to 86%) with a decrease in test duration (from 108 to 56 s), and was significantly different for these two runs, suggests that there is a between-event (but within group) difference in the % $\dot{V}O_{2max}$ attained. This finding lends further support to those of Spencer et al. (1996) who showed that the % $\dot{V}O_{2max}$ attained by 800 and 1500 m event specialists during 1500 and 800 m running was ~ 94 and ~ 90% $\dot{V}O_{2max}$, respectively.

Spencer et al. (1996) also showed that ~ 98% $\dot{V}O_{2max}$ was attained during 400 m running by 200 and 400 m event specialists. However, since the 800 and 1500 m event specialists did not perform a 400 m run, the between-event (but within group) difference in the % $\dot{V}O_{2max}$ attained during 400 to 1500 m running was not fully explored. The findings of the present study suggest that if the 800 and 1500 m event specialists from the Spencer et al. (1996) study had performed a 400 m run, the % $\dot{V}O_{2max}$ attained would have been lower than 90%. The fact that a similar group of 800 m specialists, with a similar $\dot{V}O_{2max}$ (65 vs. 69 $ml.kg^{-1}.min^{-1}$), attained 86% $\dot{V}O_{2max}$ during 400 m running in the present study therefore completes the partial relationship between event duration and the % $\dot{V}O_{2max}$ attained during 400 to 1500 m running established by Spencer et al. (1996).

### *8.4.2A Implications for models of middle-distance running performance*

The findings of the present study extend those of study II to provide further evidence to refute the assumption in the majority of models of middle-distance running performance that the asymptote representing the highest $\dot{V}O_2$ attained will be $\dot{V}O_{2max}$ during both the 400 and the 800 m events. Furthermore, the between-event (but within group) difference in the % $\dot{V}O_{2max}$ attained shown here suggests that the majority of models would have increasingly overestimated the aerobic energy supply for the shorter middle-distance events. That is, as the event duration increases the % $\dot{V}O_{2max}$ attained will tend towards 100% and, hence, the assumption that the asymptote parameter is equal to $\dot{V}O_{2max}$. Additionally, if there is a within-event relationship between $\dot{V}O_{2max}$ and the % $\dot{V}O_{2max}$ attained for the 400 m event, similar to that found in study II for the 800 m event, the high values (~ 75 $ml.kg^{-1}.min^{-1}$) ascribed to the $\dot{V}O_{2max}$ asymptote parameter in the majority of models are likely to magnify the overestimation of aerobic energy supply for the shorter events.

For Wood's (1999a) model, the between-event (but within group) difference in the % $\dot{V}O_{2max}$ attained shown here supports his assumption that the parameter representing the asymptote for the highest $\dot{V}O_2$ attained will be below $\dot{V}O_{2max}$ and will decrease with event duration. Indeed, the findings of the present study, in association with those of Spencer et al. (1996), would suggest that the % $\dot{V}O_{2max}$ attained during middle-distance running increases as a linear function of event duration. That is, the % $\dot{V}O_{2max}$ attained by a similar group of event specialists with a similar $\dot{V}O_{2max}$ will be approximately 86, 90 and 94% for the 400, 800 and 1500 m events, respectively. If there is a within-event relationship between $\dot{V}O_{2max}$ and the % $\dot{V}O_{2max}$ attained, similar to that shown in study II for the 800 m event, this would need to be considered for each event in Wood's (1999a) model to ensure that the model can be applied to event specialists of varying standards.

The values ascribed to the parameters in Wood's model are based on the assumption that the relationship between the % $\dot{V}O_{2max}$ attained and event duration [between-event (but within group) difference in the % $\dot{V}O_{2max}$ attained] is independent of event specialism. Therefore, it is important to investigate whether there is a between-group (but within event) difference in the % $\dot{V}O_{2max}$ attained for a given event. Part B investigates this by determining the % $\dot{V}O_{2max}$ attained by 400 m event specialists during 400 m running. This % $\dot{V}O_{2max}$ attained is then compared to that attained by the 800 m event specialists reported here.

## PART 8B

## STUDY IIIB: EVENT SPECIALISM AS A DETERMINANT OF PEAK $\dot{V}O_2$

### 8.2B Methods

*8.2.1B Participants*

Six male 400 m event specialist runners (age 21.3 ± 1.5 yr; height 1.78 ± 0.07 m; mass 74.5 ± 7.3 kg) volunteered to participate. These runners had a mean personal best time of 50.6 ± 0.7 s for the 400 m, which is within 18% of the World Record (43.2 s) set by Michael Johnson on 26/08/99 in Seville. All were well habituated with laboratory procedures in general and with motorised treadmill running in particular. Each participant was in regular running training at the time of the study.

*8.2.2B Preliminary tests*

All participants initially completed a ramp test (0.16 $km.h^{-1}$ per 5 s) (see section 4.2.2 for a more detailed description of this ramp test) and a constant speed 400 m run on a level motorised treadmill. The purpose of these preliminary tests was the same as for Part A (see section 8.2.2A). The speed for the 400 m run was determined from each participant's seasonal best time for the 400 m event. The time to exhaustion for this constant speed run was then compared to the participant's seasonal best time. If the two times differed markedly, the speed was adjusted accordingly for the subsequent test. The procedure for the constant speed run was the same as in part A and study II (see sections 8.2.2A and 7.2.2).

*8.2.3B Experimental design*

Each participant completed one ramp test (0.16 $km.h^{-1}$ per 5 s) and a 400 m constant speed run, on a level motorised treadmill. The speed for the 400 m run was based on the findings from the preliminary test: the actual or adjusted speed corresponding to each runners seasonal best performance time for the 400 m was used (see section 8.2.2B). Participants were encouraged to continue running for as long as possible in both tests.

The preliminary test described above was always completed first, but thereafter the participants completed the two tests (i.e. the ramp test and the constant speed 400 m run) in a counterbalanced order. Three participants completed the ramp test followed by the 400 m run and the other three completed the 400 m run followed by the ramp test to control for order and carryover effects. Each participant completed his own sequence of tests at the same time of day. All three test sessions (i.e. the preliminary test, the ramp test, and the constant speed 400 m run) were completed within 14 days, with at least 48 hours between each test. Each of the tests (excluding the preliminary tests) was preceded by a 5 min warm-up at 10% below the speed corresponding to the participant's lactate threshold (see section 8.2.2A and 8.2.2B) to control for the effects of prior exercise on the determination of $\dot{V}O_2$ (Gerbino et al., 1996).

*8.2.4B Data collection*

The off-line Douglas bag system described in chapter 5 was used to determine all gas exchange variables. The sampling procedure was the same as for Part A (see section 8.2.4A).

*8.2.5B Treatment of data*

8.2.5.1B Defining $\dot{V}O_{2max}$

For the ramp test, $\dot{V}O_{2max}$ was defined using the approach described in section 8.2.5.1A. This $\dot{V}O_{2max}$ was used as the reference point for the $\dot{V}O_{2peak}$ attained during the 400 m run.

8.2.5.2B Defining $\dot{V}O_{2peak}$

For the constant speed 400 m run, $\dot{V}O_{2peak}$ was defined using the approach described in section 8.2.5.2A.

*8.2.6B Statistical analysis*

8.2.6.1B General

All tests were analysed at an alpha level of 0.05 and all data are presented as mean ± SD unless otherwise stated. Individual data can be found in Appendix III, together with full results for each of the tests described below.

8.2.6.2B Event specialism as a determinant of $\dot{V}O_{2peak}$

The $\dot{V}O_{2peak}$ attained during the 400 m run was expressed as a percentage of the reference $\dot{V}O_{2max}$ value determined from the ramp test (section 8.2.5.1B) to give the $\%\dot{V}O_{2max}$ attained during 400 m running. An independent samples t-test was used to assess if there was a difference between this $\%\dot{V}O_{2max}$ attained by the 400 m event specialists and that attained by the 800 m event specialists in Part A.

**8.3B Results**

*8.3.1B Defining $\dot{V}O_{2max}$*

The SEE was lower for the plateau than for the linear model in all participants (0.88 ± 0.28 vs. 1.38 ± 0.28 ml.kg$^{-1}$.min$^{-1}$). Therefore, a $\dot{V}O_2$-plateau was evident in all participants. The value for this $\dot{V}O_{2max}$, derived using the 30s$_{MOVE}$ averaging approach, was 56.2 ± 4.7 ml.kg$^{-1}$.min$^{-1}$ (69.3 ± 4.5 ml.kg$^{-1}$.min$^{-1}$ for the 800 m event specialists in Part A). The peak speed attained on the ramp test was 19.0 ± 1.4 km.h$^{-1}$ (22.3 ± 0.8 km.h$^{-1}$ for the 800 m event specialists in Part A). This compared to a speed of 26.1 ± 1.1 km.h$^{-1}$ for the 400 m run (25.8 ± 1.2 km.h$^{-1}$ for the 800 m event specialists in Part A).

*8.3.2B Event specialism as a determinant of $\dot{V}O_{2peak}$*

The test duration was 55.1 ± 4.2 s for the 400 m run (55.8 ± 2.3 s for the 800 m event specialists in Part A). Figure 8.1B shows the $\%\dot{V}O_{2max}$ attained in the 400 m run by representative 400 and 800 m event specialists. Here, the $\dot{V}O_{2peak}$ is 51.8 ml.kg$^{-1}$.min$^{-1}$ and 55.4 ml.kg$^{-1}$.min$^{-1}$ for the 400 and 800 m event specialists, respectively; whilst $\dot{V}O_{2max}$ determined from the ramp test is 55.7 ml.kg$^{-1}$.min$^{-1}$ and 65.6 ml.kg$^{-1}$.min$^{-1}$ for the 400 and 800 m event specialists, respectively. These data yield a $\%\dot{V}O_{2max}$ attained of 93.0 and 84.5% for the 400 and 800 m event specialists, respectively.

The mean $\dot{V}O_{2peak}$ for the 400 and 800 m event specialist groups during the 400 m constant speed run was 52.8 ± 4.6 ml.kg$^{-1}$.min$^{-1}$ and 59.4 ± 4.4 ml.kg$^{-1}$.min$^{-1}$, respectively; the mean $\dot{V}O_{2max}$ determined from the ramp test was 56.7 ± 4.2 $ml.kg^{-1}.min^{-1}$ and 69.3 ± 4.5 $ml.kg^{-1}.min^{-1}$ for the 400 and 800 m event specialists, respectively. The mean % $\dot{V}O_{2max}$ attained was 93.9 ± 2% and 85.7 ± 3% for the 400 and 800 m event specialists, respectively. In Figure 8.2B, the mean $\dot{V}O_2$ response during the 400 m run, expressed as a percentage of $\dot{V}O_{2max}$, is given for the 400 and the 800 m event specialist groups. There was a significant difference ($p = 0.001$) in the % $\dot{V}O_{2max}$ attained during the 400 m run between the 400 and 800 m event specialists.

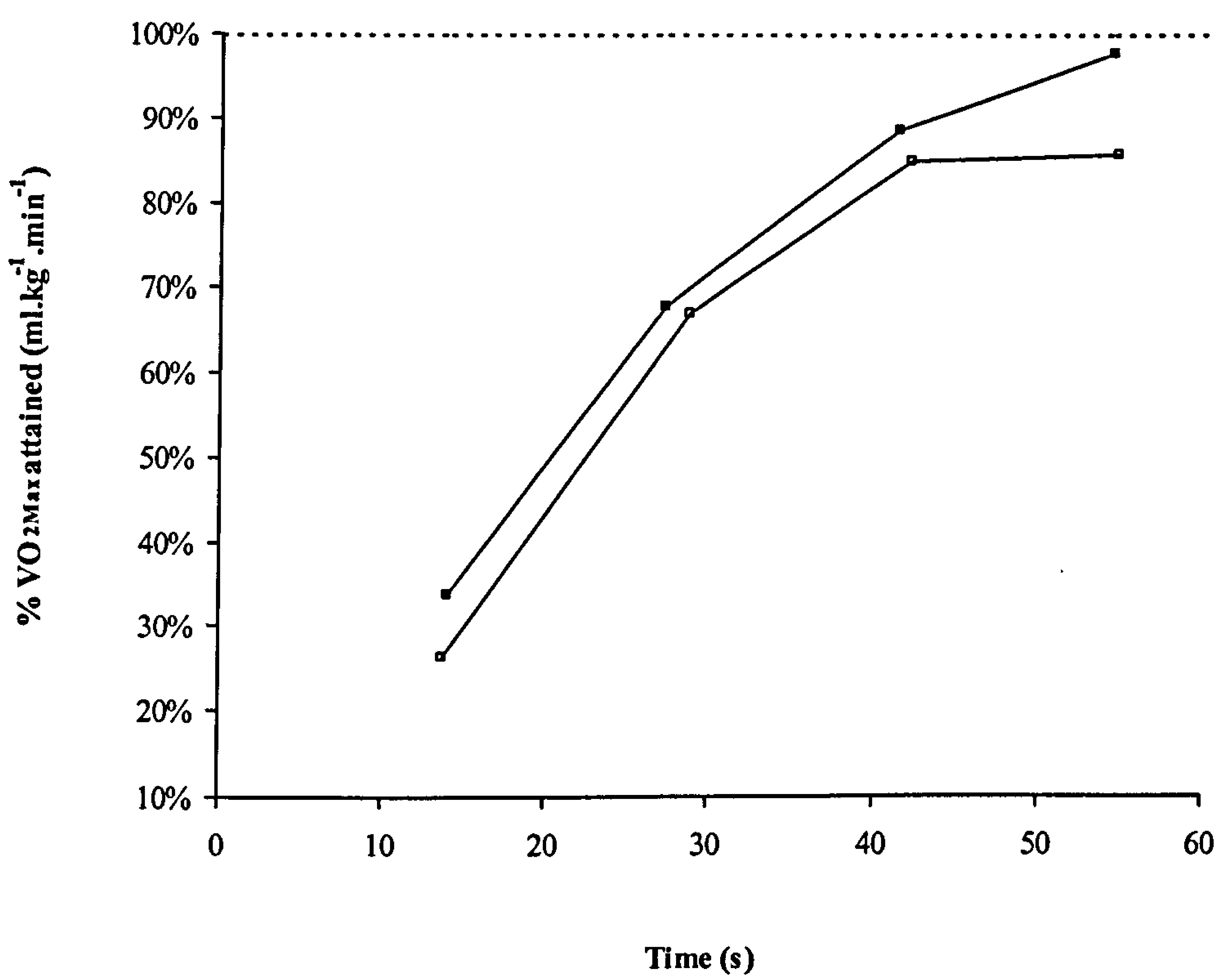



**Figure 8.1B Data from representative 400 m (■) and 800 m (□) event specialists showing the % $\dot{V}O_{2max}$ attained during the constant speed 400 m run.**

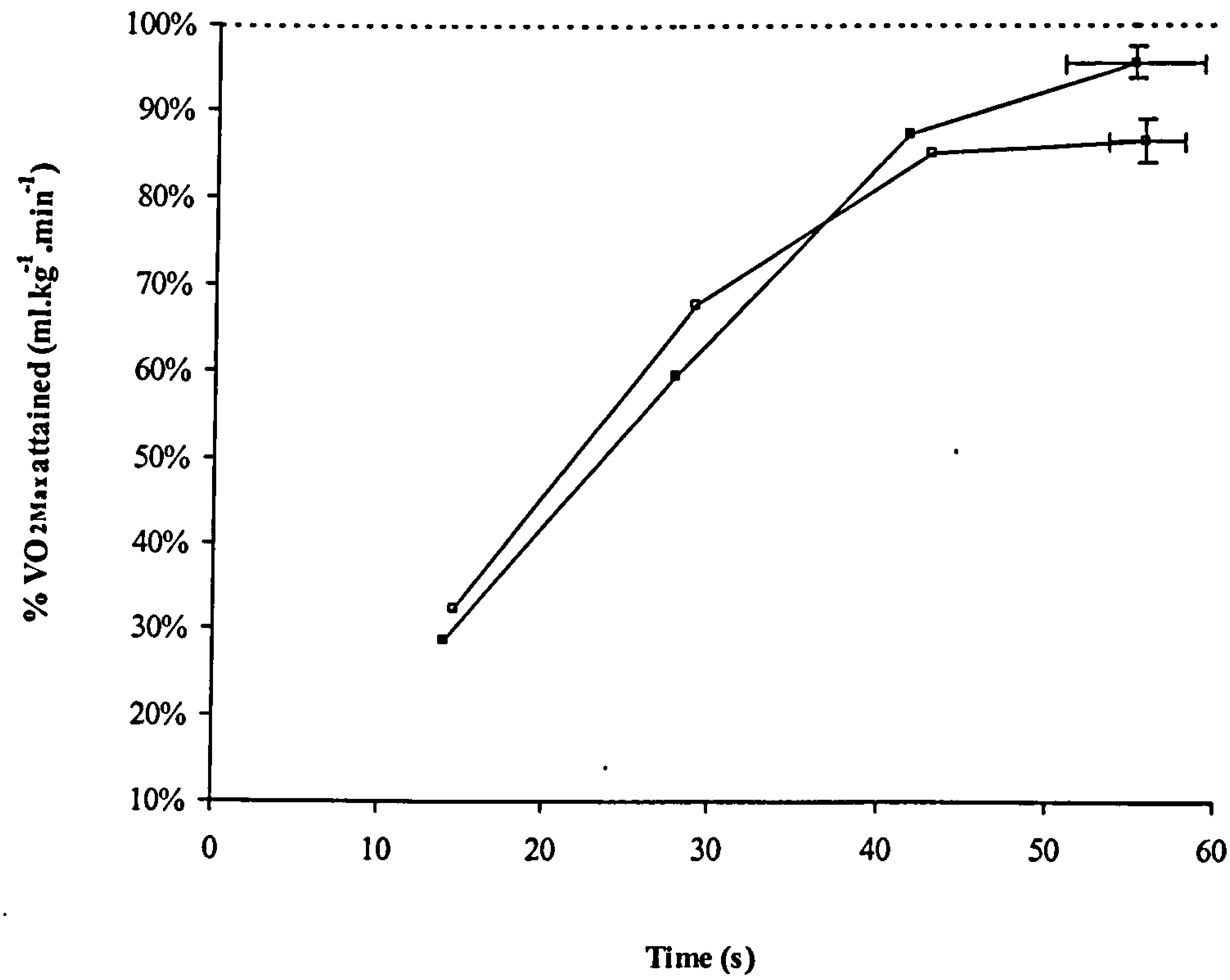



**Figure 8.2B Group data for 400 m (■) and 800 m (□) event specialists showing the % $\dot{V}O_{2max}$ attained during the constant speed 400 m run. For clarity error bars (representing one SD) have been omitted from all but the final data points.**

## 8.4B Discussion

### *8.4.1B Event specialism as a determinant of $\dot{V}O_{2peak}$*

In part A it was assumed that the set of characteristics of middle-distance runners, and in particular $\dot{V}O_{2max}$, is common to both the 400 and 800 m events. This assumption is consistent with that of Wood (1999a) where a common set of values are ascribed to the parameters in the model, and assumed to be independent of event specialism, for the 400 to 3000 m events. Using this approach, it was shown that there is a between-event (but within group) difference in the % $\dot{V}O_{2max}$ attained during 400 and 800 m running. This finding was combined with those of Spencer et al. (1996), to suggest that the

$\%\dot{V}O_{2max}$ attained during 400 to 1500 m running is likely to decrease with an increase in event duration, for a group of runners with a $\dot{V}O_{2max}$ of ~ 65-69 $ml.kg^{-1}.min^{-1}$.

The results of the present study refute the assumption that a common set of values can be ascribed to the parameters in the models for all middle-distance events. Indeed, there is a between-group difference in $\dot{V}O_{2max}$ among 400 and 800 m event specialists (57 vs. 69 $ml.kg^{-1}.min^{-1}$ for the 400 and 800 m event specialists, respectively). Furthermore, since the $\dot{V}O_{2max}$ attained during 400 m constant speed running by the 400 m event specialists studied here (94%) is significantly higher than was attained by the 800 m event specialists (86%), there is a between-group (but within event) difference in the $\%\dot{V}O_{2max}$ during 400 m running. Therefore, it is inappropriate to assume that $\dot{V}O_{2max}$ and the $\%\dot{V}O_{2max}$ attained during 400 m constant speed running will be the same for 400 m event specialists as for other event specialists.

The approach taken in this thesis to benchmark the standard of the event specialists has been to express personal best times relative to the World Record for a given event specialism. This objective approach is useful for highlighting the standard of event specialists on an international level and allowing a comparison between different event specialists. Given this, it could be argued that the 400 and 800 m event specialist groups studied here were not comparable since the 400 m event specialists had only run within 18% of the 400 m World Record whereas the 800 m event specialists had run within 11% of the 800 m World Record. It is important that the standard of these groups is comparable so that the difference in the $\%\dot{V}O_{2max}$ attained during 400 m running between the two groups can confidently be assumed to be a group effect and not the standard of the groups themselves. This latter point is reflected in the findings of study II, where 800 m event specialists who had never run within 20% of the 800 m World Record attained a higher $\%\dot{V}O_{2max}$ than specialists who had run within 11% of the 800 m World Record (96.5 vs. 92.6%).

For the 400 m event specialists, benchmarking their standard relative to Michael Johnson's World Record of 43.18 s is misleading for a comparison with other event specialists as the 400 m World Record is relatively more challenging than the 800 m Record. In 2003, 64 athletes in the World ran within 5% of the 800 m World Record

(101.11), with the fastest (Wilfred Bungei: 102.52 s) being within 1%. In comparison, in 2003 only 42 athletes in the World ran within 5% of the 400 m World Record, with the fastest (Tyree Washington: 44.33 s) being within 3%. Furthermore, when British runners alone are considered, only 37 athletes in history have run within 5% of the 800 m World Record whereas 19 athletes have run within 5% of the 400 m World Record. When the standard of the event specialists studied here is considered at a national level, the 400 and 800 m event specialists' personal best times are within 11 and 14% of the British Records (101.73, Sebastian Coe and 44.36, Iwan Thomas), respectively. Therefore, the standard of the event specialist groups is reasonably comparable, at least on a British national level.

The present study showed that 94% $\dot{V}O_{2max}$ can be attained during constant speed 400 m running by 400 m event specialists with a $\dot{V}O_{2max}$ of 57 $ml.kg^{-1}.min^{-1}$. In contrast, Spencer et al. (1996) showed that ~ 98% $\dot{V}O_{2max}$ is attained during constant speed 400 m running by 200 and 400 m event specialists with a $\dot{V}O_{2max}$ of 53 $ml.kg^{-1}.min^{-1}$. However, limitations in the methods used in the Spencer et al. (1996) study to determine the % $\dot{V}O_{2max}$ attained (see section 7.1.2) may have resulted in these values being overestimated. Alternatively, the fact that the $\dot{V}O_{2max}$ of the event specialists in the Spencer et al. (1996) study was lower than for the event specialists studied here, there may be a within-event relationship between $\dot{V}O_{2max}$ and the % $\dot{V}O_{2max}$ attained during 400 m running, similar to that shown in study II for 800 m running.

It is not clear whether the difference in the % $\dot{V}O_{2max}$ attained during 400 m running between 400 and 800 m specialists is due to the difference in $\dot{V}O_{2max}$ itself or some other difference in the characteristics of the 400 and 800 m specialist groups. There may be a within-event relationship between $\dot{V}O_{2max}$ and the % $\dot{V}O_{2max}$ attained during 400 m running for 400 m specialists. However, it is likely that $\dot{V}O_{2max}$ will always be lower for 400 m than for 800 m specialists. Indeed, Svedenhag and Sjödin (1984) have shown that 400 m event specialists typically have a lower $\dot{V}O_{2max}$ (63.7 $ml.kg^{-1}.min^{-1}$) than those specialising in the 800 m event (68.8 $ml.kg^{-1}.min^{-1}$). Furthermore, the 400 m specialists studied here, and by Spencer et al. (1996), all had lower $\dot{V}O_{2max}$ values than 800 m event specialists. Therefore, even if there is a within-event relationship between

$\dot{V}O_{2max}$ and the % $\dot{V}O_{2max}$ attained by 400 m event specialists during 400 m running, the $\dot{V}O_{2max}$ of these runners is unlikely to be large enough for the % $\dot{V}O_{2max}$ attained during 400 m running to be as low for 400 as for 800 m specialists.

*8.4.2B Implications for models of middle-distance running performance*

The findings of the present study extend those of part A and refute the assumption in Wood's (1999a) model that a between-event (within group) difference in the % $\dot{V}O_{2max}$ attained is appropriate for 400 and 800 m running. This between-event difference may be appropriate for 800 to 1500 m running, where the characteristics of these specialists are likely to be similar. However, the between-group difference in $\dot{V}O_{2max}$ and the between-group difference in the % $\dot{V}O_{2max}$ attained during 400 m running, among 400 and 800 m specialists, suggests that specific assumptions should be made in Wood's (1999a) model for at least the 400 m event.

To ensure that the % $\dot{V}O_{2max}$ attained during middle-distance running is accurately modelled it is also important to determine any factors other than $\dot{V}O_{2max}$, event duration, and event specialism which may influence the peak $\dot{V}O_2$ attained during middle-distance running. One such factor is pacing strategy since most of the values ascribed to the parameters in models of middle-distance running performance are based on data determined from constant speed running. This was the focus of study IV.

# CHAPTER 9

# STUDY IV: PACING STRATEGY AS A DETERMINANT OF PEAK $\dot{V}O_2$ DURING 800 M RUNNING

## 9.1 Background

### *9.1.1 Identifying the issues*

The values ascribed to the parameters in the models of middle-distance running performance (Di Prampero et al., 1993; Henry, 1954; Hill and Lupton, 1923; Lloyd, 1966, 1967; Sargent, 1926; Ward-Smith, 1985, 1999; Wood, 1999a) are typically based on data determined from constant speed running. This is mainly because limited data are available on the pacing strategies used in middle-distance running and the physiological responses to such strategies. Furthermore, certain parameters such as the time constant for $\dot{V}O_2$ kinetics can only be derived from constant speed running where the kinetics at any time are progressing towards a stable asymptotic value.

Nonetheless, the split times from international competitive events demonstrate that a constant speed is not employed during the 800 m and that a relatively fast start over the initial 200 m is the preferred strategy. Regardless of any pacing strategy used in 800 m running, the initial acceleration phase at the start, and its potential impact on physiological responses, is ignored when data determined during constant speed running are used to ascribe values to the parameters in the models.

In the studies that have investigated pacing strategies (Ariyoshi et al., 1979a, b; Léger and Ferguson, 1974) during short duration (i.e. < 240 s) running, there has been no clear rationale for the strategies adopted. That is, the strategies have not been based on those used in competitive events and, therefore, lack ecological validity. Spencer and Gastin (2001) developed their previous investigations [i.e. Spencer et al. (1996)] to customise middle-distance running to reflect an individual runner's race pace strategy. However, the lack of standardisation of these pacing strategies makes it difficult to make inferences about the effect of pacing on $\dot{V}O_{2peak}$. Furthermore, both Léger and

Ferguson (1974) and Spencer and Gastin (2001) failed to include a constant speed control condition in their experimental design.

To date, no study has investigated the $\dot{V}O_{2peak}$ attained during simulated 800 m competitive running, taking into consideration the acceleration phase and the pacing strategies used in competition. To address the fifth aim of this thesis, this study investigated the influence of an acceleration phase with a pacing strategy on $\dot{V}O_{2peak}$ during 800 m running. If it could be shown that the $\dot{V}O_{2peak}$ and, consequently, the $\%\dot{V}O_{2max}$ attained significantly differs between simulated 800 m track event runs and constant speed 800 m running, the ecological validity of the values ascribed to the parameters in models of middle-distance running performance would be questioned. Indeed, the performance predictions based on the values ascribed to the parameters in the models would be constrained to 800 m track events performed at a constant pace. Alternatively, if the $\%\dot{V}O_{2max}$ attained during 800 m running is unaffected by an acceleration phase or a pacing strategy, the ecological validity of the values ascribed to the parameters in the models would be demonstrated. The important considerations for this final study were that:

1. the acceleration phase at the start of 800 m competitive running could be accurately simulated on the motorised treadmill;
2. optimal competitive pacing strategies, as opposed to typical racing tactics, during 800 m running could be identified and accurately simulated on the motorised treadmill.

### *9.1.2 Pacing strategy as a determinant of $\dot{V}O_{2peak}$*

Spencer and Gastin (2001) extended their previous investigation to include an extra running event (200 m) and event specialists for each of the events studied (i.e. 200 to 1500 m). Furthermore, each race pace run was customised to reflect the athlete's race pace strategies: they were free-range non-constant pace runs. Similar findings to their previous study [i.e. Spencer et al. (1996)] for the 800 and 1500 m events were reported, with the $\dot{V}O_2$ attained reaching a plateau at ~ 88 and ~ 94% $\dot{V}O_{2max}$ for the 800 and 1500 m runs, respectively. However, as the focus of this study was not on pacing strategy, their experimental design did not include a constant speed 800 and 1500 m control condition and the effect of these customised pacing strategies on the $\dot{V}O_2$ attained is unclear.

Léger and Ferguson (1974) studied two different pacing strategies (fast-medium-very slow and slow-medium-slow) during an exhaustive ~ 200 s run. The % $\dot{V}O_{2max}$ attained for the slow start strategy (90%) was significantly different from that attained using the fast start strategy (88%). Since a constant speed control condition was not included in the experimental design it is not possible to assess the implications of these findings for the assumptions underpinning the models of middle-distance running performance.

Ariyoshi et al. (1979b) showed that the rate of increase in $\dot{V}O_2$ was significantly faster for a fast start 240 s run than for a slow start or constant pace strategy. However, there was no difference in the $\dot{V}O_{2peak}$ attained between any of the pacing strategies. It is interesting to note, however, that in this study and in that of Léger and Ferguson (1974) the $\dot{V}O_2$ attained plateaued at ~ 90% of $\dot{V}O_{2max}$.

In the present study, a concentrated effort was made to accurately simulate the acceleration phase and pacing strategy used in competitive 800 m running. This was done by:

1. determining the acceleration phase at the start of 800 m track running;
2. assessing the current pacing strategies used by international 800 m event specialists during performances within 2% of the 800 m World Record;
3. simulating the acceleration phase, both alone and in combination with a competitive race pace strategy, on the motorised treadmill;
4. comparing the $\dot{V}O_{2peak}$ attained during three different 800 m running protocols: a) constant speed b) constant speed combined with an acceleration phase and c) fast start speed combined with an acceleration phase.

## 9.2 Methods

### *9.2.1 Participants*

Eight male middle-distance runners (age 25.8 ± 3.3 yr; height 1.78 ± 0.1 m; mass 67.8 ± 4.7 kg) volunteered to participate. These runners had a personal best time of 112.0 ±

3.3 s for the 800 m, which is within 11% of the World Record (101.11 s) held by Wilson Kipketer. All were well habituated with laboratory procedures in general and with motorised treadmill running in particular. Each participant was in regular running training at the time of the study.

*9.2.2 Preliminary tests*

All participants initially completed a ramp test (0.16 $km.h^{-1}$ per 5 s) (see section 4.2.2 for a more detailed description of this ramp test) and an 800 m run with an acceleration phase, on a level motorised treadmill. The ramp test allowed an appropriate starting speed to be selected for future ramp tests to ensure that exhaustion would be reached in ~ 10 min (Buchfuhrer et al., 1983) for each participant (see section 4.2.2 for more detail of this process). The $\dot{V}O_2$ at which the lactate threshold occurred was determined by means of the V-slope method (Beaver et al., 1986) for each participant (see section 4.3.3). The corresponding speed for this $\dot{V}O_2$ was then determined from the participant's $\dot{V}O_2$-running speed relationship. The 800 m run allowed the participants to become familiar with the acceleration phase and the starting procedure for this run (see section 9.2.3.2).

*9.2.3 800 m test protocols*

9.2.3.1 Constant run ($C_{run}$)

The constant speed 800 m run ($C_{run}$) was the same as those reported thus far in this thesis. All of the event specialists who participated in this final study had participated in study II or III. The constant speed 800 m run was therefore based on the participants' most recent test performance and adjusted accordingly if necessary. That is, it was based on the average speed over the entire 800 m. As in previous studies, the motorised treadmill was set at the constant speed and the experimenter initiated a 10 s countdown when the participant was ready to start the test. The participant stood astride the motorised treadmill belt and at the start of the countdown used the support rails to suspend their body above the belt while they developed cadence in their legs. The test officially started, and the first collection of expirate was initiated, when the participant released the support rails and started running on the treadmill belt.

### 9.2.3.2 Acceleration run ($A_{run}$)

Six of the participants performed the first 200 m of an 800 m track run as they would at the start of a competitive event. These runs were performed in the same lane of an outdoor 400 m track and each participant performed four runs by themselves (i.e. the participants ran individually). Electronic timing lights were placed at 5, 10, 15, 20, 25, 50, 100, and 150 m from the starting line of the track lane. The speed for each section (i.e. the displacements) was then derived. A mean speed for each of these sections was derived from the repeat runs to yield eight speeds for each participant during the first 150 m of the run. A mean group speed for each of the eight sections was then derived (Figure 9.1).

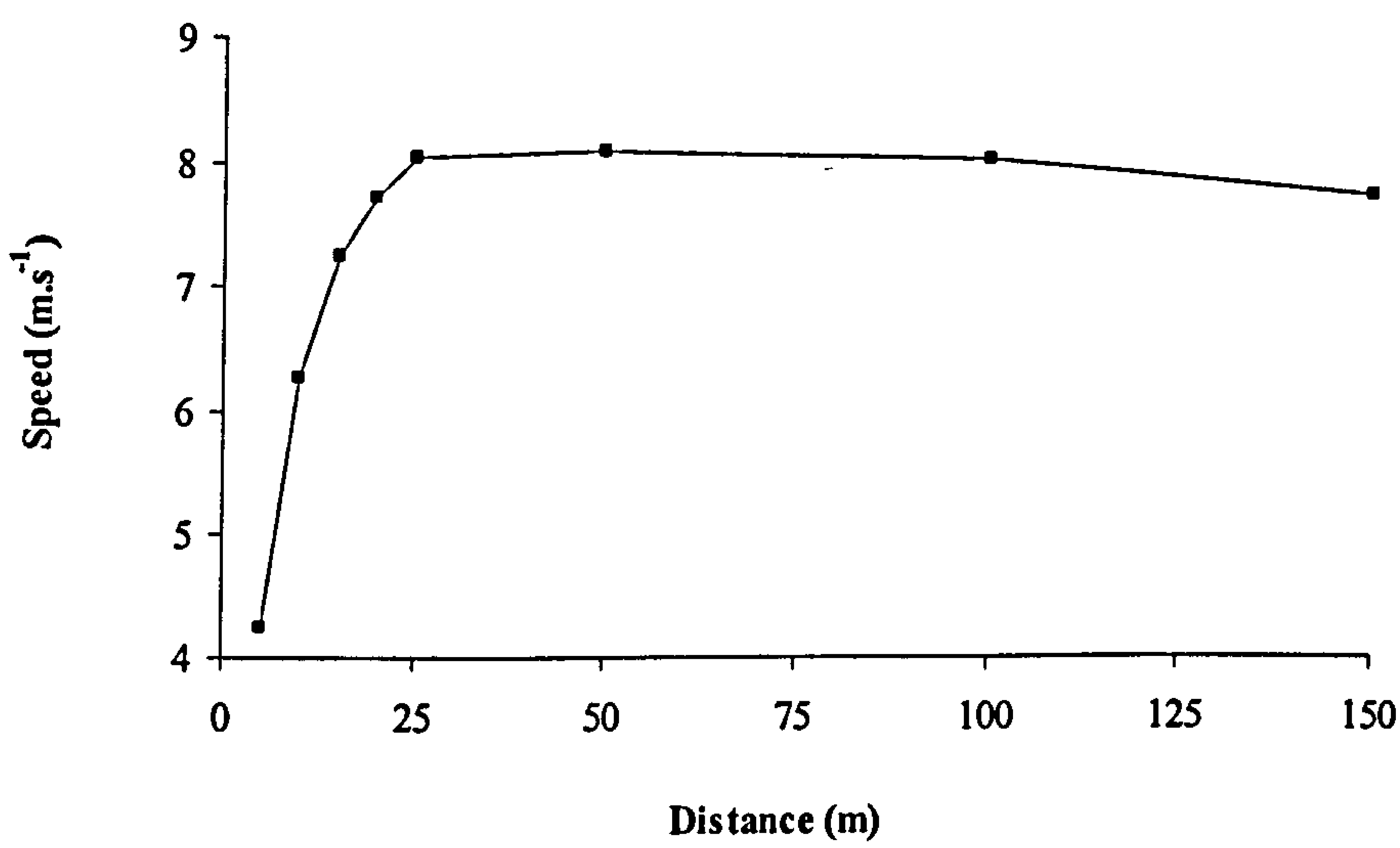



**Figure 9.1 Mean data for six participants showing the relationship between running speed and distance during a simulated start to an 800 m track run.**

Figure 9.1 shows that speed had peaked by 25 m but declined relatively little thereafter. The relationship between speed and distance during the starting acceleration phase appears to be approximately exponential and so was modelled as an exponential function, given by:

$$V(s) = A\,(1 - e^{-s/\tau}) \qquad (1)$$

where V is velocity (i.e. speed) in $m.s^{-1}$, s is the distance in m, A is the asymptote value, and $\tau$ is a rate constant. The value of the asymptote (i.e. A) was calculated as the mean group speed sustained between 25 and 150 m. The value of $\tau$ was derived from a semi-log plot of the midpoint distance (i.e. s) against the mean group asymptotic speed (7.94 $m.s^{-1}$) minus the mean group speed for each of the midpoint distances over which speed was increasing (i.e. 2.5, 7.5, 12.5, and 17.5 m). The reciprocal of the absolute value of the slope from this semi-log plot gave a rate constant equal to 5.3 m (i.e. 1/0.188). The semi-log plot is shown below in Figure 9.2.

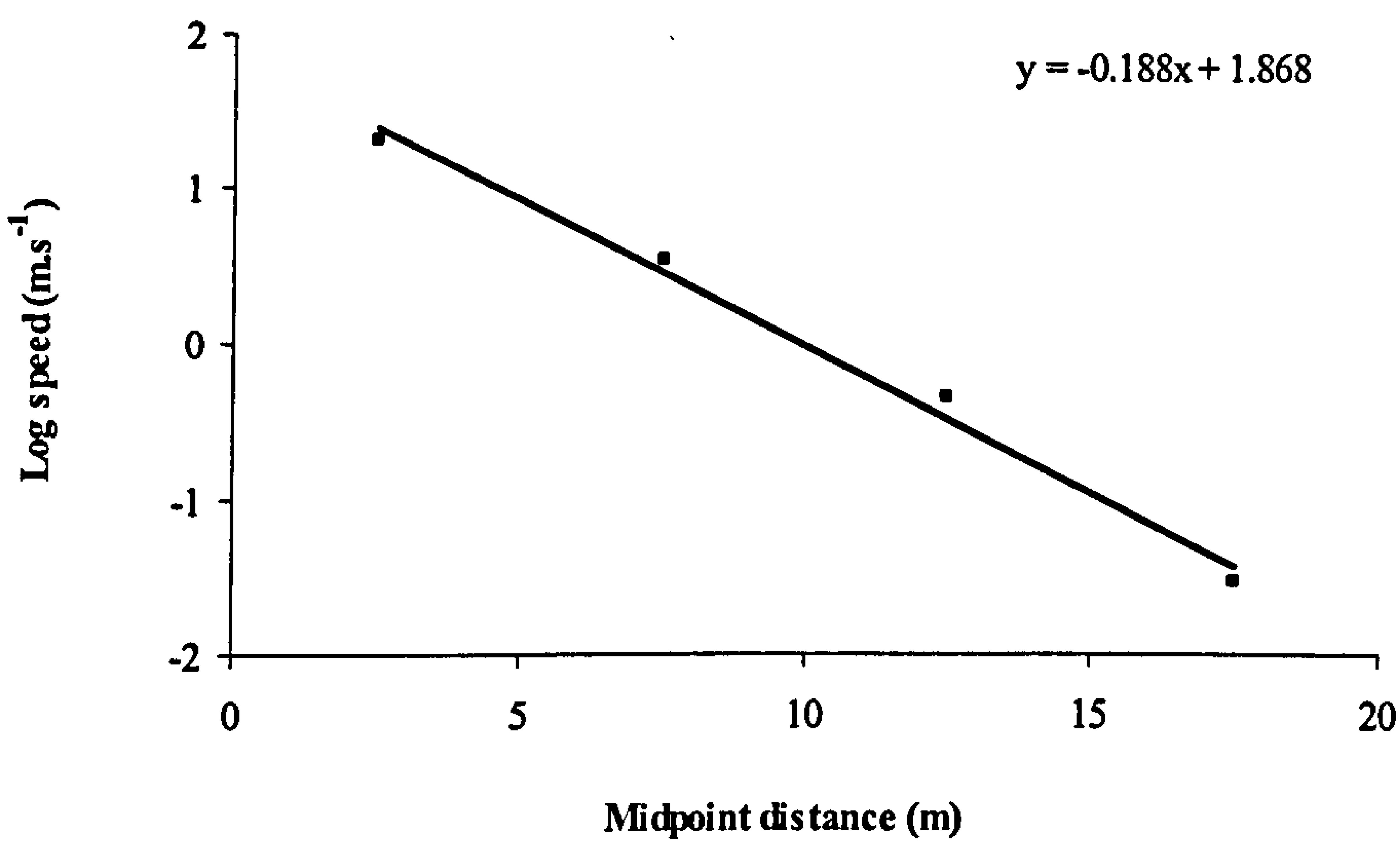



**Figure 9.2 Mean data showing the relationship between the natural log of the asymptotic speed minus the actual speed and distance over the initial 17.5 m of a simulated start to an 800 m track run.**

Equation (1) with a $\tau$ of 5.3 m was used to model the acceleration phase at the start of the 800 m $A_{run}$ for each participant. This was done using each participant's constant speed in $m.s^{-1}$ (see section 9.2.3.1) as the value of the asymptote in equation (1) and converting this acceleration profile to $km.h^{-1}$ (by multiplying by 3.6). The $A_{run}$, therefore, consisted of an acceleration phase over the first 25 m projecting to the constant speed from section 9.2.3.1, which was then sustained for the remainder of the test.

The test was conducted by setting the treadmill at an initial walking speed, with the participant stood astride the treadmill belt. A 10 s countdown was given prior to the start of the acceleration profile, during which the participant walked on the treadmill belt. Once the countdown reached zero the acceleration profile began and the participant started running. This point defined the start of the test and was when the first collection of expirate was initiated. The test protocol was equivalent to starting the 800 m event from a walking start as opposed to a standing one. This was necessary since the response of the treadmill belt from zero speed (i.e. a standing start on the treadmill belt) had a time delay and was initially too slow to accurately simulate the acceleration profile. Furthermore, pilot testing revealed that it was too difficult and, indeed, dangerous for participants to lower themselves onto the treadmill belt while it was accelerating as they could not cope with the rapid change in speed. The acceleration profile was programmed for each participant via the computer interface to the motorised treadmill (see section 4.1.2). An example $A_{run}$, showing both the starting protocol and the collection of expirate, is included on the compact disk attached.

9.2.3.3 Race run ($R_{run}$)

When the speeds over each of the four 200 m sections of 800 m performances within 2% of the 800 m World Record time are expressed relative to the speed sustained over the whole 800 m, it is evident that a fast start strategy is used. That is, the speed sustained over the first 200 m is 107.4%, the middle 400 m is ~ 98.3%, and the last 200 m is 97.5% of the average speed sustained over the entire 800 m. Using performance times within 2% of the World Record hopefully ensures that these racing strategies had optimal performance as the aim (i.e. achieving a fast time) and not tactics (i.e. winning the race).

For the $R_{run}$, equation (1) was used as in section 9.2.3.2 with the asymptote value as 107.4% of the constant speed in section 9.2.3.1, the second 400 m as 98.3% and the final 200 m as 97.5% of this constant speed for each participant. The speed was gradually decreased from 107.4% to 98.3% so that the change in speed was not abrupt. The starting procedure for this test was the same as for the $A_{run}$ (see section 9.2.3.2).

In summary, the three runs expressed relative to the constant 800 m speed [i.e. 800 (m)/seasonal best time(s)] for each participant, consisted of a run at 100% throughout

($C_{run}$), an acceleration phase to 100% ($A_{run}$), and an acceleration phase to 107.5% for the first 200 m followed by 98.3% for the middle 400 m and 97.5% for the remainder of the run ($R_{run}$). The runs were not terminated at 800 m; rather, each was continued for as long as possible. The speed profiles of these three runs are shown in Figure 9.3.

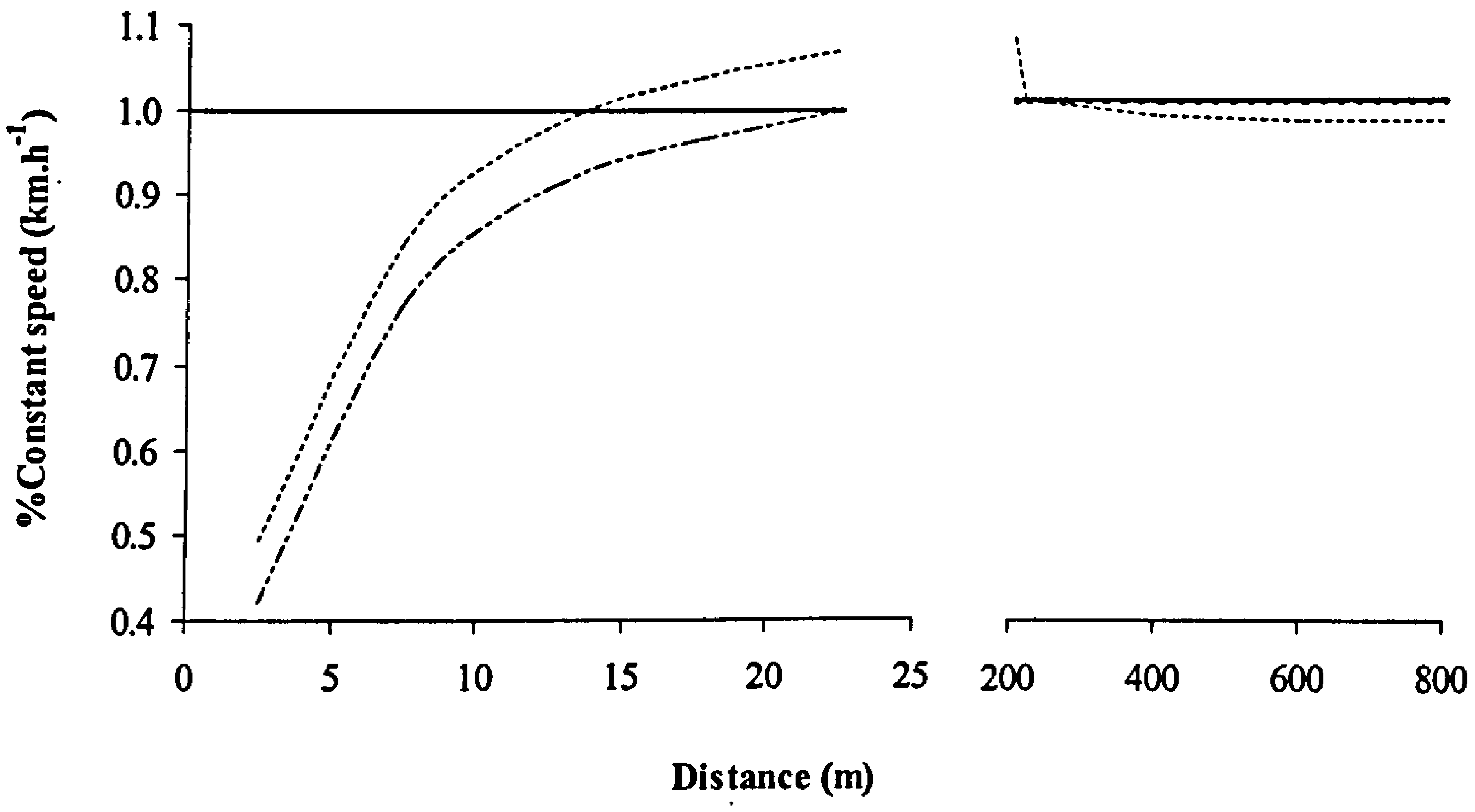



**Figure 9.3 Speed profiles of the $C_{run}$ (—), $A_{run}$ (-- -) and $R_{run}$ (----) 800 m test protocols.**

*9.2.4 Experimental design*

Each participant completed one ramp test (0.16 $km.h^{-1}$ per 5 s) and the three 800 m runs (i.e. $C_{run}$, $A_{run}$, $R_{run}$), all on a level motorised treadmill. Participants were encouraged to continue running for as long as possible in all tests. The preliminary tests described above were always completed first, but thereafter the eight participants completed the four tests (i.e. the ramp test, $C_{run}$, $A_{run}$, and $R_{run}$) in a random order. Two participants were allocated to each sequence within a 4 × 4 Latin Square to control for order and carryover effects. Participants completed their own sequence of tests at the same time of day. All five tests (i.e. the preliminary tests, ramp test, $C_{run}$, $A_{run}$, and $R_{run}$) were completed within 14 days, with at least 48 hours between each test session. Each of the tests (excluding the preliminary test) was preceded by a 5 min warm-up at 10% below the speed corresponding to the participant's lactate threshold (see section 7.2.2) to control for the effects of prior exercise on the determination of $\dot{V}O_2$ (Gerbino et al., 1996).

*9.2.5 Data collection*

The off-line Douglas bag system described in chapter 5 was used to determine all gas exchange variables. The sampling period was nominally 15 s over approximately the final 4 min of the ramp test and throughout each 800 m run. A whole number of breaths was always collected, so typically the actual period was not identical the nominal period. Every effort was made to ensure that the actual was as close to the nominal sampling period as possible. For the 15 s sampling periods, the actual period was usually between 15 and 20 s, and on no occasion was it less than 15 s.

*9.2.6 Treatment of data*

9.2.6.1 Defining $\dot{V}O_{2max}$

For the ramp test, a plateau in $\dot{V}O_2$ was modelled using the approach described in section 6.2.5.1. A 30 s moving average ($30s_{MOVE}$) was used to determine the value of this plateau (i.e. $\dot{V}O_{2max}$) (see section 6.4.3). The averaging always started with the final 15 s sampling period and moved back towards the start of the test. This $\dot{V}O_{2max}$ value was used as the reference point for the $\dot{V}O_{2peak}$ attained during the 800 m runs.

9.2.6.2 Defining $\dot{V}O_{2peak}$

For each 800 m run, a 30 s moving average ($30s_{MOVE}$) averaging approach was used to identify the highest $\dot{V}O_2$ attained (i.e. $\dot{V}O_{2peak}$). The averaging always started with the final 15 s sampling period and moved back towards the start of the test.

*9.2.7 Statistical analysis*

9.2.7.1 General

All tests were analysed at an alpha level of 0.05 and all data are presented as mean ± SD unless otherwise stated. Individual data can be found in Appendix IV, together with full results for each of the tests described below.

9.2.7.2 Pacing strategy as a determinant of $\dot{V}O_{2peak}$

Differences among the three 800 m runs (i.e. $C_{run}$, $A_{run}$, and $R_{run}$) in the % $\dot{V}O_{2max}$ attained were evaluated using repeated measures ANOVA. The degrees of freedom were corrected for any violation of the sphericity assumption. This correction was done in line with the recommendations of Huynh and Feldt (1976). That is, the Huynh-Feldt correction was used when an estimate of the true value for $\epsilon$ [the average of the Huynh-Feldt and the Greenhouse-Geisser $\epsilon$ (Howell, 1997)] was ≥0.75 and the Greenhouse-Geisser correction was used when this estimate was ≤0.75. Post hoc trend analysis was used to describe the influence of acceleration and pacing on the % $\dot{V}O_{2max}$ attained.

## 9.3 Results

### *9.3.1 Defining $\dot{V}O_{2max}$*

It was assumed that a plateau in $\dot{V}O_2$ had occurred if the SEE was lower for the plateau than for the linear model (see section 6.2.5.1). The SEE was lower for the plateau than for the linear model in all participants (1.77 ± 1.32 vs. 2.10 ± 1.21 ml.kg$^{-1}$.min$^{-1}$). Therefore, a $\dot{V}O_2$-plateau was evident in all participants. The value for this $\dot{V}O_{2max}$, derived using the $30s_{MOVE}$ averaging approach, was 67.2 ± 4.3 ml.kg$^{-1}$.min$^{-1}$.

### *9.3.2 Pacing strategy as a determinant of $\dot{V}O_{2peak}$*

Figure 9.4 shows data from a representative participant. Here, $\dot{V}O_{2peak}$ is 56.2 ml.kg$^{-1}$.min$^{-1}$, 58.1 ml.kg$^{-1}$.min$^{-1}$, and 61.6 ml.kg$^{-1}$.min$^{-1}$ for the $C_{run}$, $A_{run}$ and $R_{run}$, respectively; $\dot{V}O_{2max}$ determined from the ramp test is 65.0 ml.kg$^{-1}$.min$^{-1}$. These data yield 86.4, 89.4, and 94.7% for the % $\dot{V}O_{2max}$ attained during the $C_{run}$, $A_{run}$ and $R_{run}$, respectively.

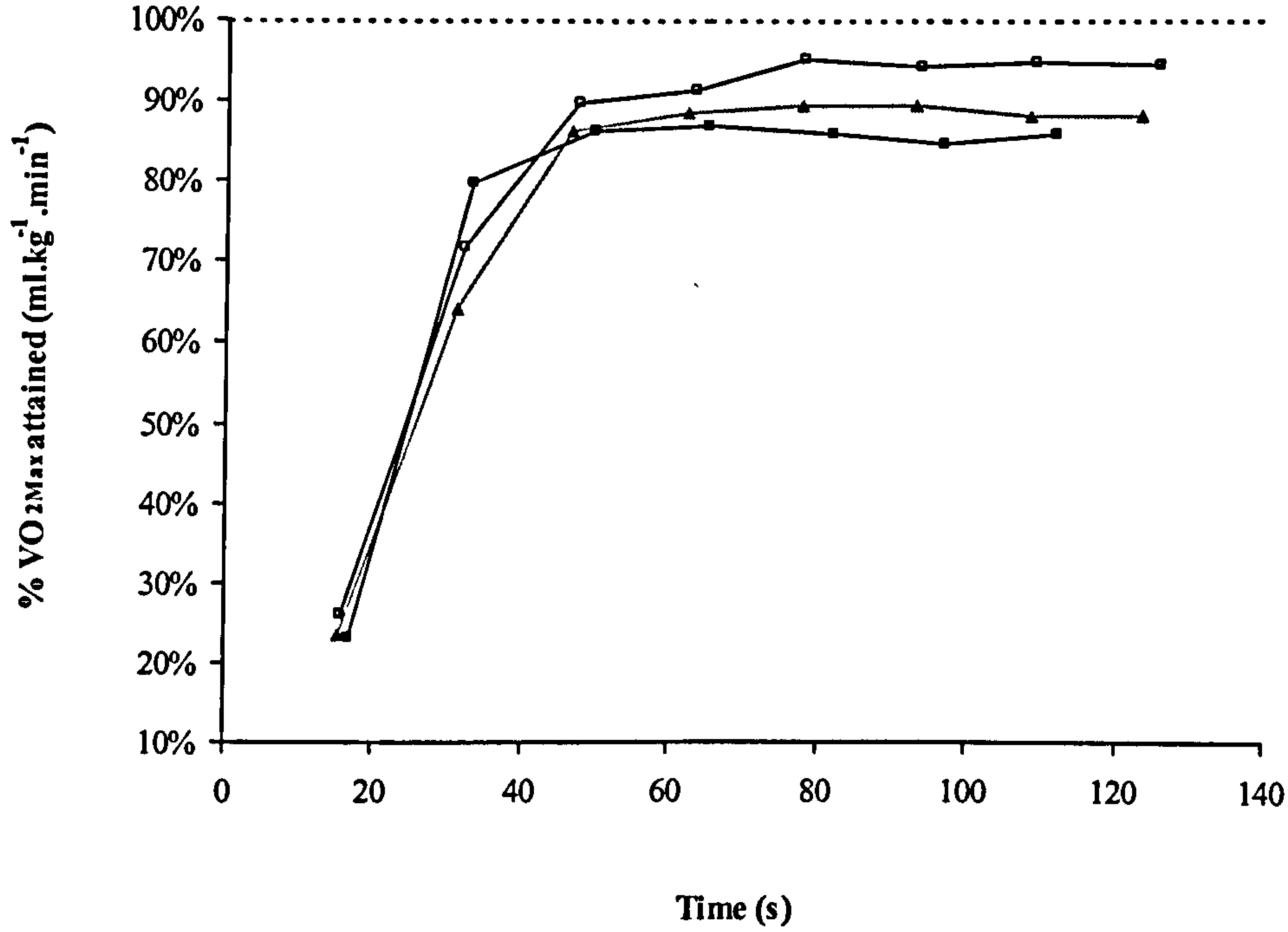



**Figure 9.4 Data from a representative participant showing the % $\dot{V}O_{2max}$ attained during the $C_{run}$ (■), $A_{run}$ (▲) and $R_{run}$ (□) 800 m runs.**

The time to exhaustion was similar for the $A_{run}$ (110.7 ± 15.3 s) and the $R_{run}$ (111.2 ± 20.0 s) but both these times were greater than that for the $C_{run}$ (107.9 ± 20.7 s). The mean $\dot{V}O_{2peak}$ was 60.1 ± 5.1 $ml.kg^{-1}.min^{-1}$, 61.1 ± 5.2 $ml.kg^{-1}.min^{-1}$, and 62.2 ± 4.9 $ml.kg^{-1}.min^{-1}$ for the $C_{run}$, $A_{run}$ and $R_{run}$, respectively. These yielded % $\dot{V}O_{2max}$ attained values of 89.3 ± 2.4%, 90.8 ± 2.8%, and 92.5 ± 3.1% for the $C_{run}$, $A_{run}$ and $R_{run}$, respectively. These mean group data are shown in Figure 9.5. The repeated measures ANOVA revealed that there was a significant main effect ($p = 0.048$). Post hoc trend analysis identified a significant linear trend ($p = 0.025$) with the % $\dot{V}O_{2max}$ attained being higher for the $A_{run}$ than the $C_{run}$, and higher still for the $R_{run}$.

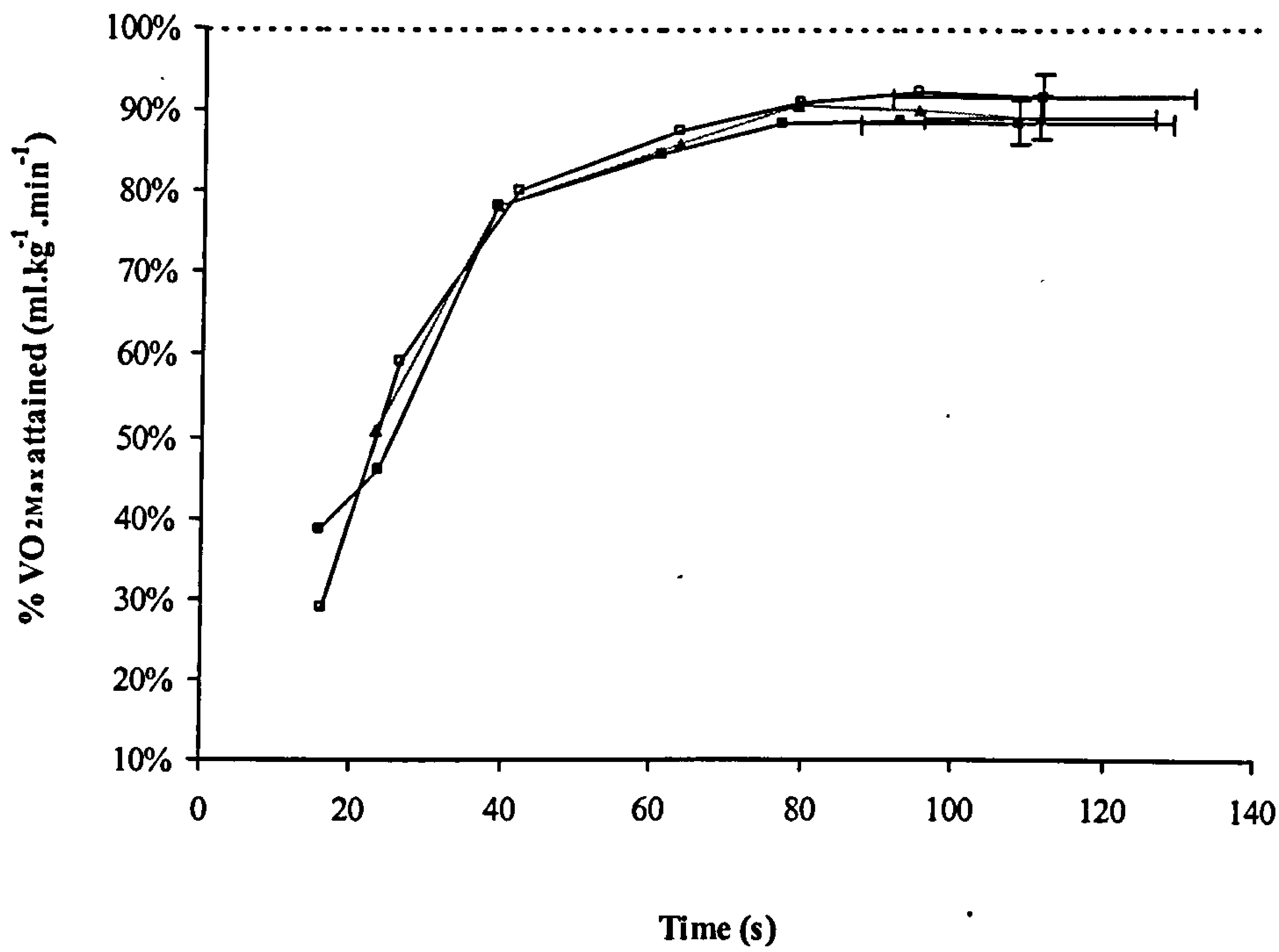



**Figure 9.5 Mean data for the group showing the % $\dot{V}O_{2max}$ attained during the $C_{run}$ (■), $A_{run}$ (▲) and $R_{run}$ (□) 800 m runs. For clarity error bars (representing one SD) have been omitted from all but the final data point.**

## 9.4 Discussion

### *9.4.1 Pacing strategy as a determinant of $\dot{V}O_{2peak}$*

The results of the present study lend further support to the findings from studies II and III that $\dot{V}O_{2max}$ cannot be attained during 800 m running. The highest % $\dot{V}O_{2max}$ attained here was 92.5%. Moreover, $\dot{V}O_2$ plateaued below $\dot{V}O_{2max}$ and was not tending towards an asymptote equivalent to $\dot{V}O_{2max}$. The acceleration phase at the start of 800 m running, alone or in combination with a fast start pacing strategy, had a significant effect on the % $\dot{V}O_{2max}$ attained: the % $\dot{V}O_{2max}$ attained was 1.5 and 3.2% higher for the $A_{run}$ and $R_{run}$, respectively, than for the $C_{run}$. The fact that $\dot{V}O_{2max}$ cannot be attained during simulated 800 m track running is important because the accuracy of the parameters in the models and the values ascribed to these parameters have typically been assessed by predicting track running performance (e.g. World Records).

The fact that $\dot{V}O_2$ plateaus below $\dot{V}O_{2max}$ and does not tend towards $\dot{V}O_{2max}$ during either constant speed running, from which the values ascribed to the parameters in the models are derived, and simulated track running, for which the accuracy of the assumed parameters in the models and their ascribed values is assessed, provides convincing evidence that $\dot{V}O_{2max}$ cannot be attained during 800 m running. More importantly, when the findings of the present study are coupled with those from studies II and III, the use of $\dot{V}O_{2max}$ to represent the asymptote for the highest $\dot{V}O_2$ attained during 800 m running is shown to be inappropriate when modelling middle-distance running performance with the exception of Wood (1999a), is refuted. Additionally, the findings here also refute the inherent assumption that $\dot{V}O_{2max}$ will be attained in the models that have used $\dot{V}O_{2max}$ as the assumed parameter for the asymptote of the $\dot{V}O_2$ kinetics with a low value ascribed to the assumed parameter for the time constant of the $\dot{V}O_2$ kinetics

*9.4.2 Implications for models of middle-distance running*

Since the use of $\dot{V}O_{2max}$ as the assumed parameter for the asymptote of the $\dot{V}O_2$ response for 800 m running has been shown to be inappropriate, the findings of the present study have no impact on the majority of models. Given that the difference in the % $\dot{V}O_{2max}$ attained is small between constant speed and simulated track running, the effect of pacing is also likely to have a limited impact on the model of Wood (1999a). Therefore, the effect of pacing on the % $\dot{V}O_{2max}$ attained during 800 m running is likely to be of more interest conceptually than practically.

These implications of pacing strategy for models of middle-distance running performance, along with other implications identified in previous studies, are discussed and evaluated in greater detail in the following chapter.

# *PART IV*

# *GENERAL DISCUSSION AND CONCLUDING REMARKS*

# CHAPTER 10

# GENERAL DISCUSSION

## 10.1 Methodological considerations

### *10.1.1 Ergometry*

All studies in this thesis were performed on a research standard motorised treadmill (Woodway Ergo ELG 70). Considerable attention was given to the use of this treadmill during high-speed running to ensure that it was both safe and accurate. Chapter 4 summarised the issues associated with the use of motorised treadmill ergometry and evaluated the Woodway treadmill that was used throughout this thesis. It was demonstrated that, across the range of speeds likely to be encountered, speed fluctuations were negligible without a runner and small with a runner. It was suggested that these fluctuations are likely to be considerably smaller for the Woodway treadmill used in this thesis than for other types of motorised treadmill.

### *10.1.2 Determination of $\dot{V}O_2$*

A novel Douglas bag system was used to determine all gas exchange variables. This system was designed to allow continuous and short collections of expirate to be made. It was described and evaluated in Chapter 5. The error associated with the determination of $\dot{V}O_2$ was shown to be small (< 1%) throughout the range of exercise intensities likely to be encountered in this thesis. The corresponding uncertainty was also small. It did however increase as the sampling period decreased or the exercise intensity increased. This was mainly due to a reduction in the uncertainty associated with the measurement of the volume of expirate. The combination of these two opposing effects resulted in an estimated technical uncertainty in the determination of $\dot{V}O_2$ of ± 1.9 ml.kg$^{-1}$.min$^{-1}$ for a 15 s sampling period during severe intensity exercise. Chapter 5 demonstrated, therefore, that the novel Douglas bag system developed for, and used throughout, this thesis allowed $\dot{V}O_2$ to be determined during severe intensity exercise with a high level of accuracy and precision.

### *10.1.3 Defining $\dot{V}O_{2max}$*

Throughout this thesis it was repeatedly demonstrated that the $\dot{V}O_2$-running speed relationship of trained runners plateaus over the closing stages of a ramp test. A $\dot{V}O_2$-plateau was evident in all participants and all tests when a 15 s sampling period was used in conjunction with the modelling approach of Wood (1999b). This modelling approach assumes that $\dot{V}O_2$ either increases as a linear function of running speed throughout the ramp test or increases as a linear function initially and then plateaus in the closing stages of the test. The former is consistent with Noakes' (1988, 1997, 1998, 2000) argument that $\dot{V}O_2$ continues to increase linearly throughout the closing stages of a progressive exhaustive exercise test. The latter is consistent with the notion, originally proposed by Hill and Lupton (1923) and still supported by the majority of exercise physiologists, that $\dot{V}O_2$ will plateau (at $\dot{V}O_{2max}$) over the closing stages of such a test.

The findings of this thesis suggest that the $\dot{V}O_2$ response of trained runners is consistent with the traditional and widely accepted notion of $\dot{V}O_{2max}$. The theoretical considerations presented in chapter 3 and addressed in study I (chapter 6) suggest that $\dot{V}O_2$ does plateau in the majority of trained runners. However, since this plateau typically lasts ~80 s, whether a plateau is identified will be determined by the methods and test protocols used. The modelling approach used in this thesis, which to date has only been applied to trained runners, appears to have considerable potential for addressing the issue of whether $\dot{V}O_2$ plateaus in other participant populations or exercise protocols.

While this modelling approach is useful for identifying a $\dot{V}O_2$-plateau and deriving the value of this plateau, it is constrained to those participants that demonstrate a plateau for an exercise protocol where a linear increase in $\dot{V}O_2$ followed by a plateau is expected. The approach taken in this thesis was to define $\dot{V}O_{2max}$ as the highest $\dot{V}O_2$ attained during the ramp test. The influence of averaging period and method on the reliability and validity of this highest $\dot{V}O_2$ was evaluated in study I (chapter 6). This study indicated that the highest $\dot{V}O_2$ attained, derived from a moving average of raw data determined using 15 s sampling periods, provides a valid representation of the criterion $\dot{V}O_{2max}$ (i.e. that derived from the plateau model). Both the bias and the test-retest variation in the highest $\dot{V}O_2$ attained decreased as the averaging period increased. However, it was important that the method used for associating a $\dot{V}O_2$ value with the plateau identified during a ramp test could also be used to identify the highest $\dot{V}O_2$ attained by participants in whom no plateau was observed during simulated middle-distance running events. A 30 s moving average approach was selected as it best satisfied these requirements.

This findings of this thesis lend support to the use of speed ramped tests on a level motorised treadmill to determine $\dot{V}O_{2max}$ in runners. The high incidence of a $\dot{V}O_2$-plateau in the present study is in agreement with the high (92%) incidence of a $\dot{V}O_2$-plateau reported by Draper et al. (1998) for a similar ramp test. Furthermore, this incidence is higher than has been reported for incremental protocols (Duncan et al., 1997; Rivera-Brown et al., 1994; Sheehan et al., 1987). It seems then that, contrary to the suggestion of Taylor et al. (1955), the trained runners studied in this thesis were not limited by cadence in a speed-ramped test on a level treadmill.

## 10.2 Determinants of the % $\dot{V}O_{2max}$ attained during 400 and 800 m running

### *10.2.1 Test-retest reliability of $\dot{V}O_{2peak}$*

The findings from study II (chapter 7) showed that test-retest determinations of $\dot{V}O_{2peak}$ during 800 m running were generally reliable, but more so in middle-distance runners with a higher $\dot{V}O_{2max}$. Indeed, the 95% limits of agreement for $\dot{V}O_{2peak}$ were ± 2.3 $ml.kg^{-1}.min^{-1}$ for runners with a high $\dot{V}O_{2max}$ in comparison to ± 3.5 $ml.kg^{-1}.min^{-1}$ for those with a lower $\dot{V}O_{2max}$.

### *10.2.2 $\dot{V}O_{2max}$*

This thesis showed, for the first time, that the $\%\dot{V}O_{2max}$ attained during constant speed 800 m running is negatively related to $\dot{V}O_{2max}$. As $\dot{V}O_{2max}$ increases the $\%\dot{V}O_{2max}$ attained during constant speed 800 m running decreases (chapter 7). In middle-distance runners with a high $\dot{V}O_{2max}$ ($65.7 \pm 3.0$ ml.kg$^{-1}$.min$^{-1}$), the $\%\dot{V}O_{2max}$ attained averaged 89.7% (range = 85.8 to 92.7%), whereas in middle-distance runners with a low $\dot{V}O_{2max}$ ($52.4 \pm 1.8$ ml.kg$^{-1}$.min$^{-1}$), the $\%\dot{V}O_{2max}$ attained averaged 96.5% (range = 93.4 to 98.7%). The former finding is in agreement with that of Spencer et al. (1996) who showed that ~ 90% $\dot{V}O_{2max}$ is attained in middle-distance runners with a high $\dot{V}O_{2max}$ (~ 65 ml.kg$^{-1}$.min$^{-1}$) during 800 m running. During 800 m running, the $\dot{V}O_2$ response of middle-distance runners with a low $\dot{V}O_{2max}$ has not previously been studied.

### *10.2.3 Test duration*

Part A of study III (chapter 8) showed that the $\%\dot{V}O_{2max}$ attained by 800 m specialists decreased significantly (from 89 to 86%) with a decrease in test duration (from 108 to 56 s). This suggests that there is a between-event (but within group) difference in the $\%\dot{V}O_{2max}$ attained, lending further support to the findings of Spencer et al. (1996) who showed that the $\%\dot{V}O_{2max}$ attained by a mixed group of 800 and 1500 m specialists was ~ 94 and ~ 90% $\dot{V}O_{2max}$ during 1500 and 800 m running, respectively. The fact that a similar group of 800 m specialists, with a similar $\dot{V}O_{2max}$ (65 vs. 69 ml.kg$^{-1}$.min$^{-1}$), attained 86% $\dot{V}O_{2max}$ during 400 m running in study III (part A) therefore completes the partial relationship between event duration and the $\%\dot{V}O_{2max}$ attained during 400 to 1500 m running established by Spencer et al. (1996).

### *10.2.4 Event specialism*

The results of study III (part B) showed a between-group difference in $\dot{V}O_{2max}$ among 400 and 800 m event specialists (57 vs. 69 ml.kg$^{-1}$.min$^{-1}$ for the 400 and 800 m event specialists, respectively). Furthermore, since the $\%\dot{V}O_{2max}$ attained during 400 m constant speed running by the 400 m specialists (94%) was significantly higher than that attained by the 800 m specialists (86%), there is a between-group (but within event) difference in the $\%\dot{V}O_{2max}$ attained during 400 m running. The between-group difference in $\dot{V}O_{2max}$ is consistent with the findings of Svedenhag and Sjödin (1984) who found 400 m specialists to have a lower $\dot{V}O_{2max}$ (63.7 ml.kg$^{-1}$.min$^{-1}$) than 800 m specialists (68.8 ml.kg$^{-1}$.min$^{-1}$), and with those of Spencer et al. (1996) and Spencer and Gastin (2001). The $\dot{V}O_2$ response of different event specialists for a given duration of middle-distance running has not previously been compared.

### *10.2.5 Pacing strategy*

The results of study IV (chapter 9) showed that the acceleration phase at the start of 800 m running, alone or in combination with a fast start pacing strategy, had a significant effect on the %$\dot{V}O_{2max}$ attained. The %$\dot{V}O_{2max}$ attained was 3.2% higher for a simulated competitive 800 m run on a motorised treadmill than for an equivalent constant speed run. Previous studies of the influence of pacing strategy on the $\dot{V}O_2$ response during middle-distance running have neither used pacing strategies derived from actual competition time splits nor included a constant speed run within the experimental design.

## 10.3 Possible mechanisms underpinning the determinants of $\dot{V}O_{2peak}$

Because physiologists are generally unaware that $\dot{V}O_{2max}$ is not attained during 400 and 800 m running by runners with high aerobic fitness, no studies have investigated the possible physiological mechanisms underpinning this phenomenon. The following discussion therefore draws on relevant literature to speculate about the potential contributing mechanisms.

Two findings are central to this discussion. First, it has been shown (Draper et al., 2003) that the same subjects who fail to attain $\dot{V}O_{2max}$ in an exhaustive square wave run lasting ~ 2 minutes do attain $\dot{V}O_{2max}$ when the duration of the run is 5 or 8 minutes. Second, it appears (see Figure 7.4) that over the closing stages of an exhaustive run at 800 m pace $\dot{V}O_2$ plateaus in those subjects whose aerobic fitness is high but continues to rise in those whose aerobic fitness is low. The first point suggests that the duration of the exercise, or more likely the time spent exercising above the lactate threshold, is an important determinant of whether $\dot{V}O_{2max}$ is attained in exhaustive exercise. The second suggests that the overall kinetics of the $\dot{V}O_{2max}$ response depend on the aerobic fitness of the subject.

The $\dot{V}O_2$ response to square wave exercise differs depending on whether the exercise is above or below the LT. For all exercise intensities, the pulmonary $\dot{V}O_2$ response is characterised by an initial delay (reflecting the muscle to lung transit time) followed by a rapid exponential increase. For sub-threshold exercise, this exponential increase takes $\dot{V}O_2$ to a steady state. However, for supra-threshold intensities the primary exponential component is supplemented by an additional, slower component. This additional component (commonly termed the $\dot{V}O_2$-slow component) is of delayed onset: for supra-threshold exercise lasting 6 minutes or more, it typically emerges after 80 to 110 seconds (Gaesser and Poole, 1996).

Research on the $\dot{V}O_2$-slow component arguably provides a useful framework for interpreting the findings of this thesis, as well as those of Spencer et al. (1996), Spencer and Gastin (2001), Draper et al. (2003) and Draper and Wood (2004). For example, it is possible that increasing the duration of exhaustive exercise from ~2 to ~5 minutes enables subjects to achieve $\dot{V}O_{2max}$ (Draper et al., 2003) because the $\dot{V}O_2$-slow component that emerges in the longer test is central to the attainment of $\dot{V}O_{2max}$. Similarly, it is possible that the $\dot{V}O_2$ response to an exhaustive run at 800 m pace includes a slow component in subjects whose aerobic fitness is low but not in those whose aerobic fitness is high. Whether an exhaustive run at 800 m pace is long enough for a slow component to emerge in the $\dot{V}O_2$ response is uncertain. Though Gaesser and Poole (1996) report that the $\dot{V}O_2$ slow component typically emerges after 80 to 110 seconds, the studies on which this statement was based all involved exercise lasting at least 6 minutes. There are just two studies in which the $\dot{V}O_2$ response has been modelled for exhaustive exercise lasting 2 minutes or less: Draper and Wood (2004) modelled the $\dot{V}O_2$ response of aerobically trained subjects to exhaustive running at 800 m pace (mean time to exhaustion of 118 seconds); Hughson et al. (2000) modelled the $\dot{V}O_2$ response of untrained subjects to exhaustive cycling at an intensity of ~125% $\dot{V}O_{2max}$ (Hughson et al. did not report the mean duration of this exhaustive exercise, but data from a representative subject suggest that it may have been in the region of 1.5 to 2 minutes). Both groups accounted for the initial delay. However, whereas Draper and Wood (2004) used a mono-exponential model to describe the $\dot{V}O_2$ response for the remainder of the test, Hughson et al. (2000) used a two-component model that included an additional, slower component. Each group justified their approach on the basis that the residuals for the selected model showed no obvious pattern (though only Draper and Wood presented the residuals). In the Hughson et al. study, the mean delay for the second component was 40.5 seconds, suggesting that the slow component emerged much earlier than has previously been reported for lower intensities. However, the standard error of this mean was 6.2 seconds (in contrast, the standard error for the delay of the primary component was 0.6 seconds). For 8 subjects, a standard error of 6.2 represents a SD of 17.5 seconds. The data of Hughson et al. do not therefore constitute conclusive evidence that the $\dot{V}O_2$-slow component does emerge relatively early in exhaustive exercise lasting ~ 2 minutes or less. Rather, they raise the possibility that this might occur. Further research is required to establish the influence of both exercise intensity and aerobic fitness on when (if at all) the $\dot{V}O_2$-slow component emerges. For heavy intensity cycling, high aerobic fitness has been shown to be associated with a relatively high gain for the primary component and a relatively low gain for the slow component (Barstow et al., 1996). It therefore seems plausible that the $\dot{V}O_2$ response to exhaustive running lasting ~2 minutes is dominated by the primary component in subjects whose aerobic fitness is high but includes a discernable slow component in those whose aerobic fitness is low.

In addition to suggesting that the $\dot{V}O_2$ response of aerobically trained runners (mean $\dot{V}O_{2max}$ of 69 ml.kg$^{-1}$.min$^{-1}$) does not include a slow component, the data of Draper and Wood (2004) show why in these runners $\dot{V}O_2$ reaches a plateau in the course of an exhaustive run at 800 m pace. For the mono-exponential response described, the time constant averaged 10.7 seconds. This is considerably faster than has been reported in previous studies of treadmill running (Carter et al., 2000, 2002; Hill et al., 2003), consistent with the observation of Scheuermann & Barstow (2003) that the time constant for the primary component of the $\dot{V}O_2$ response is negatively correlated with $\dot{V}O_{2max}$. This short time constant, when coupled with the average delay of 11.2

seconds, explains why the $\dot{V}O_2$ response of these runners appeared to plateau over the final minute of the run: the mean values indicate that, on average, 99% of the asymptotic amplitude would have been attained after 60.4 seconds.

As was the case for the aerobically trained subjects in this thesis (see Figures 7.4 and 8.2A), the runners studied by Draper and Wood (2004) demonstrated a submaximal plateau in the 800 m pace run. Scheuermann and Barstow (2003) report that the difference between the predicted $\dot{V}O_2$ (based on the sub-LT $\dot{V}O_2$-work rate relationship) and the attained $\dot{V}O_2$ (at the end of the primary phase of the $\dot{V}O_2$ response) for exhaustive cycling lasting between 3 and 5 minutes is positively correlated with aerobic fitness. Though it has yet to be established that a similar relationship exists for treadmill running, the relationship observed by Scheuermann and Barstow (2003) is consistent with the findings of this thesis. Scheuermann and Barstow isolated and focused on the primary component of the $\dot{V}O_2$ response. The Douglas bag method was used throughout the present thesis so it was not possible to isolate different components of the $\dot{V}O_2$ response. However, if it is accepted that the $\dot{V}O_2$ response of aerobically fit subjects to exhaustive running lasting ~2 minutes or less is dominated by the primary component (see above), Scheuermann & Barstow's findings about the $\dot{V}O_2$ attained at the end of the primary component can be applied to the highest $\dot{V}O_2$ attained in both 400 and 800 m pace running. The negative correlation observed in study II (Chapter 7) between $\dot{V}O_{2max}$ and the %$\dot{V}O_{2max}$ attained in the 800 m pace run is clearly consistent with Scheuermann & Barstow's findings. So too is the finding of study III (Chapter 8) that the peak $\dot{V}O_2$ for a 400 m pace run represented a significantly lower %$\dot{V}O_{2max}$ in the 800 m specialists (mean $\dot{V}O_{2max}$ of 69 $ml.kg^{-1}.min^{-1}$) than it did in the 400 m specialists (mean $\dot{V}O_{2max}$ of 56 $ml.kg^{-1}.min^{-1}$). The Scheuermann and Barstow study is the first to examine the gain of a specific component of the $\dot{V}O_2$ response for exercise where the predicted $\dot{V}O_2$ required is above $\dot{V}O_{2\,max}$.

It is possible that during severe intensity exercise oxygen delivery limits both the speed of the $\dot{V}O_2$ response and the $\dot{V}O_2$ attained (Hughson et al., 2000). However, it is more likely that the $\dot{V}O_2$ attained is limited either by oxygen demand or by oxygen demand in combination with oxygen delivery. Oxygen demand has received considerable attention in relation to the slow component of the $\dot{V}O_2$ response. Indeed, as has been stressed by Gaesser & Poole (1996), it is important to recognise that the $\dot{V}O_2$-slow component takes $\dot{V}O_2$ above that predicted from the $\dot{V}O_2$-work rate relationship for sub-LT work rates.

The majority of the $\dot{V}O_2$-slow component originates from exercising muscle (Poole, 1994). It is therefore not surprising that considerable attention has been focused on muscle fibre recruitment in connection with this component of the $\dot{V}O_2$ response to supra-LT exercise (e.g., Shinohara and Moritani 1992; Barstow et al., 1996; Pringle et al., 2003). The ramp tests used for the assessment of $\dot{V}O_{2\,max}$ throughout this thesis lasted ~10 minutes, whereas the 400 and 800 m runs typically lasted less than 60 and 120 seconds respectively. The number and type of fibres recruited is known to progress with both the force/speed of the action and the duration of the exercise, particularly for exercise that can only be sustained for a short duration (Vollestad et al., 1990; Shinohara and Moritani, 1992; Sejersted and Vollestad, 1992). The recruitment of a greater number of fibres in total, or a greater proportion of type II fibres, towards the end of the ramp test could influence the $\dot{V}O_2$ attained. In comparison with type I fibres, type II fibres are known to rely to a greater extent on the less efficient α–glycerophosphate shuttle, perhaps due to a saturation of the malate-aspartate shuttle (Whipp, 1994), resulting in a lower P:O ratio. This lower P:O ratio would in turn result in an increased oxygen demand (for a given rate of ATP turnover). Partial support for this argument comes from studies that have shown the oxygen cost of cycling at a given power output to be positively related to the percentage of type II fibres (Barstow et al., 1996; Coyle et al., 1992; Pringle et al., 2003). However, using the work rate: $\dot{V}O_2$ relationship to make inferences about the P:O ratio rests on the assumption that the ATP turnover rate is constant for a given external work rate (or speed in the case of running). This assumption is unlikely to be correct, especially for running where the involvement of the stretch-shortening cycle is considerable.

Both the type of fibres recruited and the duration for which they are recruited might also influence the extent to which perfusion (and thus presumably $O_2$ supply) matches the metabolic demand. Both the percentage of type I muscle fibres and the capillary:fibre ratio have been shown to be positively correlated with the gain of the primary component of the $\dot{V}O_2$ response for severe intensity cycling (Pringle et al., 2003). It is conceivable that metabolism-perfusion matching is better in a relatively prolonged exercise test (be it a square wave or a progressive test) than a square wave test that lasts ~2 minutes or less. Of particular interest for the findings of this thesis is the possibility that the relatively long time spent above the LT in the ramp test enhanced both the demand for and the supply of oxygen (relative to the 400 and 800 m pace runs). Similar reasoning could also be used to explain the finding that the 800 m specialists attained lower $\dot{V}O_2$ in a 400 than they did in an 800 m run (see Chapter 8). However, this explanation should be treated with caution, since $\dot{V}O_2$ was probably still rising at the point of exhaustion in the 400 m run.

A time-dependent influence on oxygen supply is a feature of the hypothesis presented by Wasserman et al. (1995). These authors postulate that time-dependent changes in blood pH and temperature result in greater unloading of $O_2$ via the Bohr effect. In fact, Wassermann et al. (1995) argue that time-dependent changes in pH (be it of the blood or the muscle) may be responsible both for creating the elevated demand associated with the $\dot{V}O_2$ slow component and for providing the means of meeting this elevated demand (via the Bohr effect). In relation to the $O_2$ demand, Wassermann et al. hypothesise that a decrease in muscle pH invokes a shift from the malate-aspartate shuttle to the less efficient α–glycerophosphate shuttle, thus increasing the $O_2$ demand. This hypothesis has potentially important implications for the findings of the present thesis, especially when considered in combination with the observation (Whipp, 1994) that the capacity of the malate-aspartate shuttle is lower in type II than type I muscle fibres. For example, both the rate and the extent of $H^+$ production may be lower during short duration exhaustive running in subjects whose aerobic fitness is high than in those whose fitness is low. Highly aerobically fit subjects would also be expected to have a relatively high capillary to fibre ratio and hence to demonstrate relatively high rates of lactate and $H^+$ efflux. The combination of these factors would be a more rapid and pronounced drop in muscle pH in the less fit subjects, which, according to Wasserman's hypothesis, would result in the $\dot{V}O_2$ response of these subjects demonstrating the relatively early onset of a relatively large slow component. If the low fit subjects also have a relatively low percentage of type I muscle fibres (c.f. 400 m specialists), the tendency for their $\dot{V}O_2$ response to demonstrate the early onset of a large slow component may be even more pronounced. Whether, the rate and extent of the drop in muscle pH for short duration exhaustive running does indeed vary with aerobic fitness remains to be established. It is important to appreciate, however, that the central focus of Wassermann et al.'s hypothesis is a time-dependent increase in the $O_2$ demand ($\dot{V}O_2$ required). This is also the case for hypotheses that focus on a time-dependent increase in muscle-fibre recruitment. The notion of a time-dependent increase in the $\dot{V}O_2$ required (for constant speed running) has profound implications for "traditional" approaches to calculating the $O_2$ deficit (e.g. Medbo et al., 1988).

Conley et al. (2001) argue that two primary determinants of the rate of oxidative phosphorylation are intramuscular pH and [phosphocreatine]. According to Conely et al. (2001), the rate of oxidative phosphorylation will be highest when pH is high and [phosphocreatine] is low but can reach high enough levels for $\dot{V}O_{2\,max}$ to be attained if either of these conditions is met. They use data from Richardson et al. (1995) to argue that [phosphocreatine] drops to very low levels in the closing stages of a progressive $\dot{V}O_{2\,max}$ test, thus compensating for a low pH. In addition, they present the rattlesnake tailshaker muscle as an example of muscle where, because of its high blood flow and small fibre diameter that facilitates lactate and $H^+$ efflux, pH is maintained at close to resting levels even during exercise that elicits $\dot{V}O_{2\,max}$. The arguments of Conley et al. (2001) have potential implications for the findings of this thesis. For example, the finding that the peak $\dot{V}O_2$ is lower for a run at 400 or 800 m pace than for a ramp test is consistent with these arguments if it is assumed that the intramuscular pH is lower, or the [phosphocreatine] higher, for the final stages of the constant speed run. It should however be noted that, in relation to muscle pH, the arguments of Conley et al. (2001) are contradictory to those of Wassermann et al. (1995): whereas Conley et al. argue that the rate of oxidative phosphorylation is likely to be highest when pH is high, Wassermann et al.'s hypothesis suggests that the $O_2$ demand is likely to be highest when pH is low. Whether Conley et al.'s arguments are consistent with the results of the present thesis in relation to intramuscular [phosphocreatine] is uncertain. It is certainly possible, for example, that during exhaustive running lasting 2 minutes or less [phosphocreatine] reaches a lower level in subjects whose aerobic fitness is low than in those whose aerobic fitness is high. Further research is required to establish, for a range of subject characteristics and exercise durations, how muscle [phosphocreatine] and pH change during severe intensity exhaustive exercise.

Greenhaff and Timmons (1998) suggest that interaction between aerobic and anaerobic metabolism is likely to be important in determining the time course of the $\dot{V}O_2$ response in the early stages of intense exercise. Studies in which the activation status of the pyruvate dehydrogenase complex (PDC) has been manipulated (Timmons et al., 1996, 1997, 1998) have revealed that this complex may be an important site for such interaction. Indeed, activation of the PDC before exercise in humans, via dichloroacetate administration, has been shown to reduce both the lactic acidemia and the depletion of intramuscular phosphocreatine for a given work rate (Timmons et al., 1996, 1998). This reduced dependence on anaerobic metabolism to meet the energy demand of exercise implies that the $\dot{V}O_2$ response could be faster with prior PDC activation. That is, the activation status of the PDC at exercise onset may constrain the $\dot{V}O_2$ response and increasing this status may result in greater oxidative ATP production and less ADP being rephosphorylated at the expense of intramuscular phosphocreatine.

Timmons's group did not determine $\dot{V}O_2$ in any of the aforementioned studies; rather, they speculated about the possible implications of their findings for the $\dot{V}O_2$ response. Rossiter et al. (2003) studied the influence of dichloroacetate administration on the $\dot{V}O_2$ response to heavy intensity cycling. They found that activation of the PDC reduced the amplitude but had no effect on the time constant for both the primary and the slow component. These findings indicate that, for heavy intensity knee extensor exercise, the initial (pre-exercise) activation status of the PDC influences the final $\dot{V}O_2$ attained [presumably by influencing the build up of fatigue metabolites, and thus the extent to which additional muscle fibres are recruited over the course of the exercise (Rossiter et al., 2003)]. Such an influence could, in part, explain the finding (see Chapter 7) that the $\% \dot{V}O_{2\,max}$ attained in an exhaustive run at 800 m pace was highest in the subjects with the lowest $\dot{V}O_{2\,max}$. However, this explanation rests on two important assumptions: 1) that the influence of the initial activation status of the PDC on the $\dot{V}O_2$ attained is the same for exhaustive running lasting ~2 minutes as for heavy intensity knee extensor exercise and 2) that, following a standardised (sub-threshold) warm-up (section 7.2.3), the activation status of the PDC is highest in those whose aerobic fitness is highest. The validity of these assumptions is presently unknown.

Connett and colleagues (Connett et al., 1985; Connett and Honig, 1989; Honig et al., 1992) have stressed the importance of the redox drive in allowing oxidative phosphorylation to proceed at a high rate when $PO_2$ is low. It is possible that NADH derived from glycolysis is an important stimulus for the increase in the rate of mitochondrial respiration that occurs at the onset of exercise (Connett et al., 1985). Equally, it is possible that the strength of the redox drive becomes an increasingly important determinant of the $\dot{V}O_2$ attained as exercise intensity increases. The implication would be that an individual who is capable of generating a high flux through glycolysis at the onset of exercise would also be capable of accelerating mitochondrial respiration at a high rate, and may additionally reach a relatively high peak $\dot{V}O_2$ in short duration exhaustive exercise. This may go some way towards explaining why the peak $\dot{V}O_2$ for an 800 m pace run was significantly higher for a "fast start" than for a constant speed strategy (see Chapter 9): the high ATP turnover rate associated with the fast start may have resulted in an increased flux through glycolysis, thus increasing the strength of the redox drive and allowing oxidative phosphorylation to proceed at a higher rate in the later stages of the run.

## 10.4 Assumptions in models of middle-distance running performance

The models of middle-distance running performance each contain a set of parameters. These typically relate to a store of anaerobic energy and a rate of aerobic energy supply. This thesis was concerned solely with the parameters representing the latter. All models embrace the concept of a maximum rate of aerobic energy supply (i.e. $\dot{V}O_{2max}$) and all include a parameter representing the highest $\dot{V}O_2$ attained. In relation to 400 and 800 m running, each model makes one of three assumptions about this parameter. First, that $\dot{V}O_{2max}$ will simply be attained, either immediately at the onset of exercise (Hill and

Lupton, 1923) or after a short delay (Lloyd, 1966, 1967). Second, that $\dot{V}O_2$ will increase exponentially towards $\dot{V}O_{2max}$ (Di Prampero et al., 1993; Henry, 1954; Péronnet and Thibault, 1989; Sargent, 1926; Ward-Smith, 1985, 1999). Third, that $\dot{V}O_2$ will rise towards an asymptote that is below $\dot{V}O_{2max}$ (Wood, 1999a). For the second of these assumptions, whether $\dot{V}O_{2max}$ is in fact attained within the duration of a 400 or 800 m event depends on the value that is ascribed to the parameter representing the time constant for the exponential rise in $\dot{V}O_2$.

The findings of this thesis show that the use of $\dot{V}O_{2max}$ to represent the asymptote for the highest $\dot{V}O_2$ attained during 800 m running is inappropriate. The fact that $\dot{V}O_2$ plateaued at ~ 90% $\dot{V}O_{2max}$ in aerobically fit 800 m runners during an 800 m pace treadmill run demonstrates that $\dot{V}O_2$ was not rising towards an asymptote equal to $\dot{V}O_{2max}$, supporting the assumption in Wood's (1999a) model that the asymptote for the highest $\dot{V}O_2$ attained during 800 m running is below $\dot{V}O_{2max}$. The implication is that the majority of models would have overestimated the aerobic energy contribution to 800 m running. Since these models can accurately predict performance by overestimating the aerobic energy contribution to 800 m running, other components of the models must be in error. Wood's (1999a) model therefore has the greatest potential to accurately predict middle-distance running performance. This model provides the focus for the remainder of this discussion.

Wood (1999a) assumes the $\% \dot{V}O_{2max}$ attained to be constant within a given event. The findings of this thesis suggest, however, that the $\% \dot{V}O_{2max}$ attained during 800 m running is negatively related to $\dot{V}O_{2max}$. This means that the $\% \dot{V}O_{2max}$ attained during 800 m running (and possibly also during 400 m running) will be lower for an individual in whom $\dot{V}O_{2max}$ is high than for an individual whose $\dot{V}O_{2max}$ is lower. For Wood's (1999a) model to be applicable to middle-distance runners of varying aerobic fitness, this within-event relationship between $\dot{V}O_{2max}$ and the $\% \dot{V}O_{2max}$ needs to be incorporated.

Wood (1999a) assumes that the $\% \dot{V}O_{2max}$ attained will decrease with event duration for a given runner. Specifically, he suggests that the $\% \dot{V}O_{2max}$ attained will be 85 and 94% for the 400 and 800 m events, respectively. The findings of this thesis support Wood's (1999a) assumption that the parameter representing the asymptote for the highest $\dot{V}O_2$ attained will be below $\dot{V}O_{2max}$ and will decrease with event duration. These findings suggest that the $\% \dot{V}O_{2max}$ attained by specialist 800 m runners will be 86 and 90% for the 400 and 800 m events, respectively. Spencer et al. (1996) report a $\% \dot{V}O_{2max}$ attained of ~90% for a similar group of event specialists with a similar $\dot{V}O_{2max}$. It appears, therefore, that while Wood's estimate of the $\% \dot{V}O_{2max}$ attained during 400 m running is appropriate, his corresponding estimate for the 800 m event is high. The implication is that Wood (1999a) may have overestimated the aerobic contribution to energy supply for the 800 m event. Wood's model, therefore, needs to be updated with values for the $\% \dot{V}O_{2max}$ attained during 800 m running based on the findings from the present thesis. His assumptions for the longer event durations also need to be tested (see section 10.7).

Wood (1999a) applied his model to the same hypothetical middle-distance runner ($\dot{V}O_{2max}$ of 75 $ml.kg^{-1}.min^{-1}$) for both the 400 and the 800 m events. In effect, therefore, he assumed that middle-distance runners who specialise in different events share the same physiological characteristics (at least in relation to aerobic energy production). It follows from this that different event specialists should both share the same $\dot{V}O_{2max}$ and attain the same percentage of this $\dot{V}O_{2max}$ during a given middle-distance event. However, the findings of this thesis show that, in comparison to 400 m specialists, $\dot{V}O_{2max}$ is higher, and the $\% \dot{V}O_{2max}$ attained during 400 m running is lower, for 800 m specialists. These between-group differences in $\dot{V}O_{2max}$ and the $\% \dot{V}O_{2max}$ attained during 400 m running suggest that event-specific values should be ascribed to the parameters representing $VO_{2max}$ and the $\%VO_{2max}$ attained in Wood's (1999a) model, at least for the 400 m event. Wood's model, therefore, needs to incorporate an event-specific value for $\dot{V}O_{2max}$ and further research is needed to establish how $\dot{V}O_{2max}$ may vary among specialists in the longer events not covered in the present thesis.

Wood (1999a) based several of his assumptions on the work of Spencer et al. (1996) who studied the $\dot{V}O_2$ response to constant speed treadmill running. The results of this thesis suggest, however, that the $\%\dot{V}O_{2max}$ attained during 800 m running is ~3% higher for a treadmill run that includes both an acceleration phase and a fast start pacing strategy than for a constant speed run. Although small, this difference does suggest that the pacing strategy adopted can influence the $\%\dot{V}O_{2max}$ attained during 800 m running. Because the influence is small, ignoring the role of pacing will have relatively little impact on the ability of a given model to predict performance. Nevertheless, the finding that pacing strategy influences the $\dot{V}O_2$ response for middle distance running has potentially important implications for the training and competitive strategies of middle-distance runners.

The findings of the present thesis have shown that modelling the aerobic energy contribution to 400 and 800 m running is more complex than previously thought. Nonetheless, Wood's (1999a) model offers a platform to build on in light of the findings from the present thesis and subject to further research (see section 10.7). The model should be developed and, in turn simplified, through the addition of three parameters that would remove the need for ascribing a range of event-specific values to the model. First, given that $\dot{V}O_{2max}$ varies between 400 and 800 m event specialists a single term describing the relationship between $\dot{V}O_{2max}$ and event duration could be incorporated to account for this (subject to accurately establishing this relationship with 1500 and 3000 m event specialists). This could be based on the highest recorded values for $\dot{V}O_{2max}$ among different event specialists and a separate parameter (see point 3 below) could be used to account for the within-event variation in $\dot{V}O_{2max}$. Second, given that the $\%\dot{V}O_{2max}$ attained has been shown in the present thesis to depend on event duration, a single term that describes the relationship between the $\%\dot{V}O_{2max}$ attained (based on the event-specific $\dot{V}O_{2max}$ term above) and event duration should be included to remove the need for ascribing specific values to each event. This approach assumes that an accurate relationship could be established and would be subject to further research into the $\%\dot{V}O_{2max}$ attained during the whole range of middle-distance events. Third, a similar approach could be used to account for the finding that the $\%\dot{V}O_{2max}$

attained varies within an event and a single term, similar to the relationship between % $\dot{V}O_{2max}$ attained and $\dot{V}O_{2max}$ shown in Study II, could be included (based on the two terms above) to account for this (assuming that such a relationship exists within each event duration and is not restricted to the 800 m).

## 10.5 Implications for the physiological assessment of middle-distance runners

If physiologists are to be confident that a true $\dot{V}O_{2max}$ has been defined during progressive exercise it is important that a two stage approach, similar to the one proposed in this thesis, is adopted. First, a $\dot{V}O_2$-plateau must be identified in the majority of participants for the experimenter to be confident that $\dot{V}O_{2max}$ has been attained for the test protocol and procedures used. A short sampling period (e.g. 15 s) should be used over the closing stages of the test to increase the density of data points to the point where a plateau is likely to be identified whenever it occurs. This plateau must then be identified. The modelling approach of Wood (1999b) is an objective method for doing so that has a clear theoretical basis. Second, the value of this $\dot{V}O_{2max}$ must be defined. Using a moving average, based on the raw 15 s data, and working back from the end of the test to derive the highest $\dot{V}O_2$ attained, provides a valid estimate that is, on average, within 1 ml.kg$^{-1}$.min$^{-1}$ of the criterion $\dot{V}O_{2max}$. This method can also be used to derive the highest $\dot{V}O_2$ attained during other exercise tests, such as constant speed running, ensuring that the variability in $\dot{V}O_2$ associated with the raw 15 s data is controlled. Furthermore, this method is not constrained to data determined using the Douglas bag method: it could also be applied to breath-by-breath $\dot{V}O_2$ data.

The findings of this thesis raise several important considerations for the assessment of aerobic fitness in middle-distance runners. First, since a high incidence of a $\dot{V}O_2$-plateau was evident in these runners, it is clear that running at high speeds during the ramp test on the level motorised treadmill did not prevent $\dot{V}O_{2max}$ from being attained. This suggests that a ramp test on a level treadmill should be used to determine $\dot{V}O_{2max}$ in middle-distance runners. Doing so would ensure that the $\dot{V}O_{2max}$ determined from the ramp test could potentially be attained during middle-distance running, thus providing an appropriate reference point for the highest $\dot{V}O_2$ attained during middle distance running.

Since this thesis showed that 800 m specialists with high aerobic fitness cannot attain $\dot{V}O_{2max}$ during 400 and 800 m running, it is important that a constant speed test of a duration specific to the runner's specialism *is included in the physiological assessment* of middle-distance runners. The primary aim of this test would be to determine the highest $\dot{V}O_2$ attained during constant speed running; this could then be used to derive the % $\dot{V}O_{2max}$ attained, using the highest $\dot{V}O_2$ from a ramp test on a level treadmill as the reference $\dot{V}O_{2max}$. As a secondary aim, the $\dot{V}O_2$ kinetics of the response could also be determined. Deriving the % $\dot{V}O_{2max}$ attained would be useful in identifying individuals for whom aerobic training may be relatively unimportant (i.e. those in whom the % $\dot{V}O_{2max}$ attained is particularly low; see section 10.6 below).

## 10.6 Implications for middle-distance running training and racing

For models of middle-distance running to be useful to middle-distance runners it is important not only that they are accurate in predicting performance but also that their parameters are meaningful. This thesis has supported the assumption in Wood's (1999a) model that middle-distance runners with a high $\dot{V}O_{2max}$ are unable to attain $\dot{V}O_{2max}$ during 400 or 800 m running. This raises important questions about the type of training that such runners typically do.

First, why is $\dot{V}O_{2max}$ high in these runners if it cannot be attained during middle-distance running? This could be due to runners and coaches alike, being unaware that $\dot{V}O_{2max}$ may not be attained by aerobically fit runners during 800 m running, focusing their training on increasing $\dot{V}O_{2max}$ in the belief that $\dot{V}O_{2max}$ (and not the % $\dot{V}O_{2max}$ attained) is an important determinant of performance in middle-distance running. Given that physiologists are generally unaware that $\dot{V}O_{2max}$ cannot be attained during 800 m running, it seems unlikely that coaches or athletes would be. Alternatively, it may be that middle-distance runners need a high $\dot{V}O_{2max}$ to tolerate the types of training they typically do, even though this high $\dot{V}O_{2max}$ cannot be attained during competitive running.

Second, could middle-distance runners train to increase their % $\dot{V}O_{2max}$ attained without compromising $\dot{V}O_{2max}$? If the interaction between the anaerobic and aerobic contributions to energy supply is an important determinant of the % $\dot{V}O_{2max}$ attained during middle-distance running, training could be focused on maintaining $\dot{V}O_{2max}$ while attempting to improve anaerobic capabilities (e.g. race pace interval type training) as opposed to being focused solely on increasing $\dot{V}O_{2max}$ (e.g. long distance running below race pace).

Third, could a middle-distance runner benefit from focusing on improving their anaerobic capabilities to such an extent that their $\dot{V}O_{2max}$ actually decreases? After all, it may be beneficial to performance if the highest $\dot{V}O_2$ attained during running increased at the expense of $\dot{V}O_{2max}$, which cannot be attained.

Fourth, how should event specialism influence the training of middle-distance runners? This thesis suggests that the 400 m specialists are a clearly defined group, whereas 800 and 1500 m specialists are less so as they may train for a combination of the 800 to 3000 m track events in the summer and cross-country events in the winter. This lack of focused training for a single event may prevent runners from focusing their training on the key determinants of performance in that event.

### 10.7 Recommendations for further research

At present, relatively little is known about the $\dot{V}O_2$ response for severe intensity exercise in general or specific middle-distance event durations. In particular, little is known about the $\dot{V}O_2$ response to different exercise durations within the severe domain or for specific middle-distance events. On the one hand, there is a need to characterise, for specific event specialists of varying standards, the $\dot{V}O_2$ response to the different middle-distance events. On the other, there is a need to establish whether the $\dot{V}O_2$

response is the same for track and treadmill running for middle-distance event durations.

This thesis raises several questions about the nature of the $\dot{V}O_2$ response to short duration exhaustive running (see section 10.3). For example, it is possible, but remains to be established, that whether the $\dot{V}O_2$ response to exhaustive running lasting ~2 minutes includes a slow component depends on the aerobic fitness of the subject. To investigate this issue, it would be necessary to model breath-by-breath data from a group of subjects who are heterogeneous for $\dot{V}O_{2\,max}$. Also of interest is the possibility that aerobically fit subjects who are unable to reach $\dot{V}O_{2\,max}$ during ~2 minutes of exhaustive running do reach $\dot{V}O_{2\,max}$ when the duration of the run is increased to ~5 minutes because the $\dot{V}O_2$-slow component that emerges in the 5 minute run takes $\dot{V}O_2$ to $\dot{V}O_{2\,max}$. Investigating this issue would again involve modelling breath-by-breath data. To investigate fully the role of exercise duration, and the associated development of the $\dot{V}O_2$-slow component, it would be of interest to study not only the previously studied durations of 2 and 5 minutes but also an intermediate duration.

The focus of this thesis was exclusively on treadmill running. There were two reasons for this: first, there is an extensive literature base on, and several well-developed models of, the determinants of running performance; second, the findings of Spencer at al. (1996) and Spencer and Gastin (2001), which were of interest because they appeared to challenge current thinking on $\dot{V}O_2$ kinetics and question the assumptions underlying the majority of these models, were focused on treadmill running. However, the majority of research on $\dot{V}O_2$ kinetics has used cycle ergometry. For exhaustive exercise lasting between 4 and 5 minutes, the overall kinetics are faster, and the contribution of the $\dot{V}O_2$-slow component is smaller, for running than for cycling (Hill et al., 2003). It would be of interest, therefore, to investigate the influence of exercise mode (running vs. cycling) on the $\dot{V}O_2$ response to severe intensity exercise across a range of exercise intensities. Draper et al. (2003) used the Douglas bag method to investigate this influence for exhaustive test durations of 2, 5 and 8 minutes. Future studies in this area should a) make use of breath-by-breath data collection and mathematical modelling to characterise the $\dot{V}O_2$ response and b) focus on exhaustive exercise lasting 5 minutes or less (for which studies comparing running with cycling are particularly scarce). The possibility that exercise mode and aerobic fitness interact to influence the $\dot{V}O_2$ response to such short duration exhaustive exercise should also be considered.

Possible physiological explanations for the findings of this thesis were discussed in section 10.3. Characterising the $\dot{V}O_2$ response to short duration exhaustive exercise, and the influence of both aerobic fitness and exercise intensity and mode on this response, should provide much-needed insight into which (if any) of these explanations is appropriate. A complimentary approach would be to investigate the influence on the $\dot{V}O_2$ response to short duration exhaustive exercise of those interventions or subject characteristics that have previously been shown to influence the $\dot{V}O_2$ response for lower intensities of exercise (focusing primarily, but not exclusively, on running). Interventions that appear to be worth investigating include prior heavy intensity exercise (Jones et al., 2003), administration of dichloroacetate (Rossiter et al., 2003) and manipulation of the treadmill gradient (level vs.uphill) (Pringle et al., 2002). In addition to aerobic fitness (which has already been discussed), the primary characteristics that would be of interest are muscle fibre type and capillary density (Pringle et al., 2003). Also of interest, however, would be the sex of the subjects. The studies presented in this thesis focused exclusively on males, as did those of Spencer et al. (1996), Spencer and Gastin (2001), Draper et al. (2003) and Draper and Wood (2004). It is therefore unclear whether the finding that the $\dot{V}O_2$ of aerobically fit individuals plateaus below $\dot{V}O_{2\,max}$ in exhaustive running lasting ~2 minutes applies to females. It may be that, because $\dot{V}O_{2\,max}$ is generally lower in females, the incidence of a sub-maximal plateau during such exhaustive running is also lower for females than for males. Alternatively, it may be that the incidence of this plateau is the same in males and females, provided their aerobic fitness levels are the same (relative to the sex-specific norm). A similar issue is whether, for a given intensity, the incidence of this sub-maximal plateau, or indeed the nature of the $\dot{V}O_2$ response, depends on the muscle mass involved in the exercise. By manipulating the active muscle mass, it may be possible to alter the balance between $O_2$ supply and $O_2$ demand of oxygen. Establishing how (or indeed whether) this manipulation affects the $\dot{V}O_2$ response to short duration exhaustive exercise could provide important information about the mechanisms that determine this $\dot{V}O_2$ response.

Finally, the hypotheses of Wassermann et al. (1995) (muscle and blood pH) and Conley et al. (2001) (muscle pH and [phosphocreatine]) provide a rationale for assessing the influence of severe intensity exhaustive exercise on muscle pH, muscle [phosphocreatine] and blood pH. Notwithstanding the limitations of the muscle biopsy technique (see, for example, Rossiter et al., 2003), it may be of interest to use this technique to measure muscle [phosphocreatine] and pH before and after exhaustive running. Though the temporal resolution would be much greater, such that the kinetics of the [phosphocreatine] response could be modelled, for NMR spectroscopy (Whipp et al., 1999), this technique is most commonly applied to knee extensor exercise and has never been applied to treadmill running. A fundamental difficulty with the finding that the $\dot{V}O_2$ of aerobically fit individuals plateaus below $\dot{V}O_{2\,max}$ in exhaustive running lasting ~2 minutes is that the exercise modes for which the mechanisms underpinning this phenomenon could best be investigated are those for which it is by no means certain that the phenomenon will be observed.

# CHAPTER 11

# SUMMARY AND CONCLUSIONS

## 11.1 Summary

The findings presented in the preceding chapters have important implications for modelling middle-distance running, assessing the physiological characteristics of middle-distance runners, and applying the findings of this assessment, in association with the models, to improve performance in middle-distance running. The important findings have already been discussed, and the purpose of this section is not to repeat this discussion. Rather it is to provide a brief summary of these findings and to place them within the context of the aims of the thesis, which were outlined in Chapter 1. There were five aims, each of which was achieved, as the findings summarised in the next five paragraphs show.

First, factors that determine whether $\dot{V}O_{2max}$ can be validly and reliably defined in middle-distance runners have been identified (section 6.4). The use of a short sampling period over the closing stages of a progressive test is one factor that is likely to influence the identification of a $\dot{V}O_2$-plateau, as is the method used to objectively quantify whether a plateau has transpired (section 6.4.1). The use of a valid method to ascribe a value to this plateau (i.e. $\dot{V}O_{2max}$), and to define the highest $\dot{V}O_2$ attained during other test protocols, is another important factor (see section 6.4.2). Other factors include the test type, since the incidence of a $\dot{V}O_2$-plateau reported in this thesis for a ramp test is higher than has been reported elsewhere for incremental tests (section 6.4.1) and the importance of using a level motorised treadmill for this ramp test when the aim is to ensure that the $\dot{V}O_{2max}$ derived represents that which could potentially be attained during middle-distance running. The approach taken to defining $\dot{V}O_{2max}$ in this thesis supports the notion of a maximal oxygen uptake and refutes some of the methodological arguments of Noakes (section 3.2).

Second, the $\dot{V}O_2$ response during 800 m running plateaus at ~90% in aerobically fit 800 m specialists (section 7.4.1). This is in agreement with that of Spencer et al. (1996) who showed that ~ 90% $\dot{V}O_{2max}$ is attained in middle-distance runners with a high $\dot{V}O_{2max}$ (~ 65 $ml.kg^{-1}.min^{-1}$) during 800 m running. Furthermore, this phenomenon is repeatable, as shown by the good test-retest reliability of the $\dot{V}O_{2peak}$ (section 7.4.1). A runner's $\dot{V}O_{2max}$ is an important determinant of the % $\dot{V}O_{2max}$ attained during constant speed 800 m running: the % $\dot{V}O_{2max}$ attained is negatively related to $\dot{V}O_{2max}$.

Third, the % $\dot{V}O_{2max}$ attained by 800 m specialists decreases with a decrease in test duration, suggesting that there is a between-event (but within group) difference in the % $\dot{V}O_{2max}$ attained during middle-distance running (section 8.4.1A). This supports the findings of Spencer et al. (1996) who showed that the % $\dot{V}O_{2max}$ attained by a mixed group of 800 and 1500 m specialists was ~ 90 and ~ 94% $\dot{V}O_{2max}$ during 800 and 1500 m running, respectively.

Fourth, there is a between-group difference in $\dot{V}O_{2max}$ and a between-group (but within event) difference in the % $\dot{V}O_{2max}$ attained during 400 m running between 400 and 800 m specialists (section 8.4.1B). The between-group difference in $\dot{V}O_{2max}$ is consistent with the findings of Svedenhag and Sjödin (1984) who found 400 m specialists to have a lower $\dot{V}O_{2max}$ than 800 m specialists and with those of Spencer et al. (1996) and Spencer and Gastin (2001).

Fifth, the % $\dot{V}O_{2max}$ attained is higher for a simulated competitive 800 m run on a motorised treadmill than for a constant speed run.

## 11.2 Conclusions

Several conclusions can be drawn from the data presented in this thesis. For many years, physiologists have believed that $\dot{V}O_{2max}$ will be attained in healthy individuals during progressive exercise to exhaustion, but recently this belief has been questioned. For trained middle-distance runners, $\dot{V}O_{2max}$ was attained in every progressive test conducted in this thesis, thereby supporting the belief of physiologists over many years.

Furthermore, the objective approach adopted in this thesis has great potential in future studies that require verification of the attainment of $\dot{V}O_{2max}$, and in the physiological assessment of middle-distance runners.

Models of middle-distance running performance have, with one exception (Wood 1999a), assumed that $\dot{V}O_{2max}$ will be attained during such events. Data presented in this thesis provide support for the one model that assumes $\dot{V}O_{2max}$ will not be attained, *but rather the $\dot{V}O_2$ response* will plateau below $\dot{V}O_{2max}$. In aerobically fit 800 m specialists, the $\dot{V}O_2$ response during 800 m running plateaus at ~90% $\dot{V}O_{2max}$. Furthermore, a negative relationship is observed between $\dot{V}O_{2max}$ and the $\%\dot{V}O_{2max}$ attained. When the $\dot{V}O_2$ response of middle-distance runners is compared during 400 m and 800 m race durations, it is evident that the $\%\dot{V}O_{2max}$ attained is lower in 400 m (~86%) compared with 800 m (~89%) race durations. Also, the event specialism of the runners is important, with 800 m specialists achieving lower $\%\dot{V}O_{2max}$ compared with 400 m specialists (86 vs 94%) during a trial of 400 m race duration. Interestingly, the one model (Wood 1999a) that assumed $\dot{V}O_{2max}$ will not be attained, also assumed that the $\dot{V}O_2$ attained will be positively related to the duration of the event, which is in agreement with the findings presented in this thesis. Wood (1999a) did not, however, assume that the specialist event of the runners would influence the $\%\dot{V}O_{2max}$ attained for a particular event duration. These between group differences in the $\%\dot{V}O_{2max}$ attained during 400 m running should be ascribed to the relevant parameter in Wood's model.

Providing parameters in models are meaningful, and they predict performance accurately, models of middle-distance running performance are useful to runners, and their coaches, for training and racing. The findings from the present thesis raise several important questions in this regard:

- Why is $\dot{V}O_{2max}$ higher than the $\dot{V}O_2$ attained during the runner's specialist event?

- Could a runner train to increase the $\% \dot{V}O_{2max}$ attained without compromising $\dot{V}O_{2max}$.

- Could a runner benefit from focusing on improving their anaerobic capabilities at the expense of their aerobic capabilities?

- How should event specialism influence the training of middle-distance runners?

The findings in the present thesis have allowed these questions to be raised in the knowledge that they are valid. Since these questions are fundamental to the training and racing strategies of middle-distance runners, they illustrate the practical contribution this thesis has made to the development of knowledge of middle-distance running.

# *PART V*

# *REFERENCES*

# REFERENCES


Abdul-Rasool, I. H., Chamberlain, J. H., Swan, P. C., and Mitchell, F. T. (1981) Measurement of respiratory gas exchange during artificial respiration. *Journal of Applied Physiology*, 51, 1451-1456.

Andersen, P. and Saltin, B. (1985) Maximal perfusion of skeletal muscle in man. *Journal of Physiology*, 366, 233-249.

Arieli, R., Ertracht, O., and Daskalovic, Y. (1999) Infrared $CO_2$ analyser error: an effect of background gas ($N_2$ or $O_2$). *Journal of Applied Physiology*, 86, 647-650.

Ariyoshi, M., Tanaka, H., Kanamori, K., Obara, S., Yoshitake, H., Yamaji, K., and Shephard, R. J. (1979b) Influence of running pace upon performance: effects upon oxygen intake, blood lactate, and rating of perceived exertion. *Canadian Journal of Applied Sports Sciences*, 4, 210-213.

Ariyoshi, M., Yamaji, K., and Shephard, R. J. (1979a) Influence of running pace upon performance: effects upon treadmill endurance time and oxygen cost. *European Journal of Applied Physiology*, 41, 83-91.

Armstrong, N. and Welsman, J. R. (1994) Assessment and interpretation of aerobic fitness in children and adolescents. *Exercise and Sport Science Reviews*, 22, 435-476.

Armstrong, N., Welsman, J. R., and Winsley, R. (1996) Is peak $\dot{V}O_2$ a maximal index of children's aerobic fitness? *International Journal of Sports Medicine*, 17, 356-359.

Åstrand, P-O., Cuddy, T. E., Saltin, B., and Stenberg, J. (1964) Cardiac output during submaximal and maximal work. *Journal of Applied Physiology*, 19, 268-274.

Åstrand, P-O. and Saltin, B. (1961) Oxygen uptake during the first minutes of heavy muscular exercise. *Journal of Applied Physiology*, 16, 971-976.

Bangsbo, J. (1996) Oxygen deficit: a measure of the anaerobic energy production during intense exercise? *Canadian Journal of Applied Physiology*, 21, 350-363.

Bangsbo, J. (1998) Quantification of anaerobic energy production during intense exercise. *Medicine and Science in Sports and Exercise*, 30, 47-52.

Bangsbo, J., Gollnick, P. D., Graham, T. E., Juel, C., Kiens, B., Mizuno, M., and Saltin, B. (1990) Anaerobic energy production and $O_2$ deficit-debt relationship during exhaustive exercise in humans. *Journal of Physiology*, 422, 539-559.

Bangsbo, J., Michalsik, L., and Petersen, A. (1993) Accumulated oxygen deficit during intense exercise and muscle characteristics of elite athletes. *International Journal of Sports Medicine*, 14, 207-213.

Barnett, C., Jenkins, D., Mackinnon, L., and Green, S. (1996) A new method for the calculation of constant supra-$\dot{V}O_{2\,peak}$ power outputs. *Medicine and Science in Sports and Exercise*, 28, 1505-1509.

Barstow, T. J., Jones, A. M., Nguyen, P. H., and Cassaburi, R. (1996) Influence of muscle fibre type and pedal frequency on oxygen uptake kinetics of heavy exercise. *Journal of Applied Physiology*, 81, 1642-1650.

Bassett, D. R. and Howley, E. T. (1997) Maximal oxygen uptake: "classical" versus "contemporary" viewpoints. *Medicine and Science in Sports and Exercise*, 29, 591-603.

Bassett, D. R. and Howley, E. T. (2000) Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Medicine and Science in Sports and Exercise*, 32, 70-84.

Bearden, S. E. and Moffatt, R. J. (2001) Leg electromyography and the $\dot{V}O_2$-power relationship during bicycle ergometry. *Medicine and Science in Sports and Exercise*, 33, 1241-1245.

Beaver, W. L. (1973) Water vapour corrections in oxygen consumption calculations. *Journal of Applied Physiology*, 35, 928-931.

Beaver, W. L. and Wasserman, K. (1992) Muscle RQ and lactate accumulation from analysis of the $\dot{V}CO_2$-$\dot{V}O_2$ relationship during exercise. *Clinical Journal of Sports Medicine*, 1, 27-34.

Beaver, W. L., Wasserman, K., and Whipp, B. J. (1986) A new method for detecting anaerobic threshold by gas exchange. *Journal of Applied Physiology*, 60, 2020-2027.

Berg, W. E. (1947) Individual differences in respiratory gas exchange during recovery from moderate exercise. *American Journal of Physiology*, 149, 597-610.

Bergh, U., Ekblom, B., and Åstrand, P-O (2000) Maximal oxygen uptake "classical" versus "contemporary" viewpoints. *Medicine and Science in Sports and Exercise*, 32, 85-88.

Billat, V. L., Morton, R. H., Blondel, N., Berthoin, S., Bocquet, V., Koralsztein, J. P., and Barstow, T. J. (2000) Oxygen kinetics and modelling of time to exhaustion whilst running at various velocities at maximal oxygen uptake. *European Journal of Applied Physiology*, 82, 178-287.

Bird, S. and Davison, R. (eds.) (1997) *BASES Physiological Testing Guidelines*. Leeds, The British Association of Sport and Exercise Sciences.

Bland, M. J. and Altman, D. G. (1986) Statistical methods for assessing agreement between two methods of clinical measurement. *The Lancet*, I, 307-310.

Bland, M. J. and Altman, D. G. (1999) Measuring agreement in method comparison studies. *Statistical methods in medical research*, 8, 135-160.

Blest, D. C. (1996) Lower bounds for athletic performance. *The Statistician*, 45, 243-253.

Boileau, R. A., Bonen, A., Heyward, V. H., and Massey, B. H. (1977) Maximal aerobic capacity on the treadmill and bicycle ergometer of boys 11-14 years of age. *Journal of Sports Medicine*, 17, 153-162.

Boileau, R. A., Mayhew, J. L., Riner, W. F., and Lussier, L. (1982) Physiological characteristics of elite middle and long distance runners. *Canadian Journal of Applied Sports Science*, 7, 167-172.

Boucher, C. A., Anderson, M. D., Schneider, M. S., Murphy, J. H., Okada, R. D., and Kanarek, D. J. (1985) Left ventricular function before and after reaching the anaerobic threshold. *Chest*, 87, 145-150.

Buchfuhrer, M. J., Hansen, J. E., Robinson, T. E., Sue, D. Y., Wasserman, K., and Whipp, B. J. (1983) Optimising the exercise protocol for cardiopulmonary assessment. *Journal of Applied Physiology*, 55, 1558-1564.

Carter, H., Jones, A.W., Barstow, T.J., Burnley, M., Williams, C.A., and Doust, J.H. (2000) Oxygen uptake kinetics in treadmill running and cycle ergometry: a comparison. *Journal of Applied Physiology*, 89, 899-907.

Carter, H., Pringle, J.S.M., Jones, A.M., and Doust, J.H. (2002) Oxygen uptake kinetics during treadmill running across exercise intensity domains. *European Journal of Applied Physiology*, 86, 347-354.

Casaburi, R., Daly, J., Hansen, J. E., and Effros, R. M. (1989) Abrupt changes in mixed blood gas composition after the onset of exercise. *Journal of Applied Physiology*, 67, 1106-1112.

Cerretelli, P., Sikand, R., and Farhi, L. E. (1966) Readjustments in cardiac output and gas exchange during onset of exercise and recovery. *Journal of Applied Physiology*, 21, 1345-1350.

Challis, J. (1997) Estimation and propagation of experimental errors. In : Bartlett, R. (ed.) *Biomechanical Analysis of Movement in Sport and Exercise*, 105-124. Leeds, The British Association of Sport and Exercise Sciences.

Chatterjee, S. and Chatterjee, S. (1982) New lamps for old: an exploratory analysis of running times in Olympic Games. *Applied Statistics*, 31, 14-22.

Christensen, E. H. and Högberg (1950) Steady-state, $O_2$-deficit and $O_2$-debt at severe work. *Arbeitsphysiologie*, 14, S251-254.

Cissik, J. H. and Johnson, R. E. (1972a) Myth of nitrogen equality in respiration: its history and implications. *Aerospace and Medicine*, 43, 755-758.

Cissik, J. H. and Johnson, R. E. (1972b) Regression analysis for steady state $N_2$ inequality in $O_2$ consumption calculations. *Aerospace and Medicine*, 43, 589-591.

Cissik, J. H., Johnson, R. E., and Hertig, B. A. (1972b) Production of gaseous nitrogen during human steady state exercise. *Aerospace and Medicine*, 43, 1245-1250.

Cissik, J. H., Johnson, R. E., and Rokosch, D. K. (1972a) Production of gaseous nitrogen in human steady-state conditions. *Journal of Applied Physiology*, 32, 155-159.

Clark, B. A. and McConnell, T. R. (1986) Comparison of treadmill testing protocols to assess $\dot{V}O_{2max}$ in well trained runners. *Medicine and Science in Sports and Exercise*, 18 (Suppl.), S36.

Clausell, N., Ludwig, E., Narro, F., and Ribeiro, J. P. (1993) Response of left ventricular diastolic filling to graded exercise relative to the lactate threshold. *European Journal of Applied Physiology*, 67, 222-225.

Collins, R. G., Musasche, V. W., and Howley, E. T. (1977) Preparation of matched reagents for use with the Scholander gas analyzer. *Journal of Applied Physiology*, 43, 164-166.

Conley, K.E., Kemper, W.F., and Crowther, G.J. (2001) Limits to sustainable muscle performance: interaction between glycolysis and oxidative phosphorylation. *Journal of Experimental Biology,* 204, 3189-3194.

Conley, D. L. and Krahenbuhl, G. S. (1980) Running economy and distance running performance of highly trained athletes. *Medicine and Science in Sports and Exercise*, 12, 357-360.

Connett, R. J., Gayeski, T. E., and Honig, C. R. (1985) Energy sources in fully aerobic rest-work transitions: a new role for glycolysis. *American Journal of Physiology*, 248, H922-H929.

Connett, R.J and Honig, C. R. (1989) Regulation of $\dot{V}O_2$ in red muscle: do current biochemical hypotheses fit in vivo data? *American Journal of Physiology*, 256, R898-R906.

Consolazio, C. F., Johnson, R. E., and Pecora, L. J. (1963) *Physiological Measurements of Metabolic Functions in Man*. New York, McGraw-Hill.

Cooper, C. B., Beaver, W. L., Cooper, D. M., and Wasserman, K. (1992) Factors effecting the component of the alveolar $CO_2$ output-$O_2$ uptake relationship during incremental exercise in man. *Experimental Physiology*, 77, 51-64.

Costill, D. L. (1970) Metabolic responses during distance running. *Journal of Applied Physiology*, 28, 251-255.

Costill, D. L. and Fox, E. L. (1969) Energetics of marathon running. *Medicine and Science in Sports*, 1, 81-88.

Coyle, E.F., Sidossis, L.S., Horowitz, J.F., and Beltz, J.D. (1992) Cycling efficiency is related to the percentage of type I muscle fibres. *Medicine and Science in Sports and Exercise,* 24 (7), 782-788.

Cumming, G. R. and Friesen, W. (1967) Bicycle ergometer measurement of maximal oxygen uptake in children. *Canadian Journal of Physiology and Pharmacology*, 45, 937-946.

Cunningham, D. A., Van Waterschoot, B. M., Paterson, D. H., Lefcoe, M., and Sangal, S. P. (1977) Reliability and reproducibility of maximal oxygen uptake measurement in children. *Medicine and Science in Sports and Exercise*, 9, 104-108.

Dal Monte, A., Fucci, S., and Manoni, A. (1973) The treadmill used as a training and simulator instrument in middle- and long-distance running. In: Cerquiglini, S., Venerando, A., and Wartenweiler, J. (Eds.). *Medicine and Sport: Biomechanics III*, 8, 359-363. Basel, S. Karger.

Daniels, J. and Daniels, N. (1992) Running economy of elite male and elite female runners. *Medicine and Science in Sports and Exercise*, 24, 483-489.

Davies, B., Daggett, A., Jakeman, P., and Mulhall, J. (1984) Maximum oxygen uptake utilising different treadmill protocols. *British Journal of Sports Medicine*, 18, 74-79.

Davies, C. T. M. and Sargeant, A. J. (1974) Physiological responses to one- and two-leg exercise breathing air and 45% oxygen. *Journal of Applied Physiology*, 36, 142-148.

Davis, J. A. (1995) Direct determination of aerobic power. In: Maud, P. J. and Foster, C. (eds). *Physiological Assessment of Human Fitness*, 9-17. Champaign, Illinois, Human Kinetics.

Davis, J. A., Frank, M., Whipp, B. J., and Wasserman, K. (1979) Anaerobic threshold alterations consequent to endurance training in middle-aged men. *Journal of Applied Physiology*, 46, 1039-1046.

Deakin, B. (1967) Estimating bounds on athletic performance. *The Mathematical Gazette*, 51, 100-103.

Di Bello, V., Santoro, G., Talarico, L., Di Muro, C., Caputo, M. T., Giorgi, D., Bertini, A., Bianchi, M., and Giusti, C. (1996) Left ventricular function during exercise in athletes and in sedentary men. *Medicine and Science in Sports and Exercise*, 28, 190-196.

Di Prampero, P. E., Capelli, C., Pagliaro, P., Antonutto, G., Girardis, M., Zampero, P., and Soule, R. G. (1993) Energetics of best performances of middle distances running. *Journal of Applied Physiology*, 74, 2318-2324.

Di Prampero, P. E. and Ferretti, G. (1999) The energetics of anaerobic muscle metabolism: a reappraisal of older and recent concepts. *Respiration Physiology*, 118, 103-115.

Draper, S. and Wood, D.M. (2004) The $\dot{V}O_2$ response for an exhaustive treadmill run at 800 m pace: a breath-by-breath analysis *European Journal of Applied Physiology* (in press).

Draper, S., Wood, D. M., and Fallowfield, J. L (2003) The $\dot{V}O_2$ response to exhaustive square wave exercise: influence of exercise intensity and the mode. *European Journal of Applied Physiology*, 90, 92-99.

Draper, S., Wood, D., and Fallowfield, J. L. (1998) Comparison of three protocols for the assessment of maximal oxygen uptake in runners. *Proceedings of the Third Annual Congress of the European College of Sports Science*, 271.

Dudka, L. T., Inglis, H. J., Johnson, R. E., Pechinski, J. M., and Plowman, S. (1971) Inequality of inspired and expired gaseous nitrogen in man. *Nature*, 232, 265-268.

Duncan, G. E., Howley, T. E., and Johnson, B. N. (1997) Applicability of $\dot{V}O_{2max}$ criteria: discontinuous versus continuous protocols. *Medicine and Science in Sports and Exercise*, 29, 272-278.

Ekblom, B. (1969) Effect of physical training on the oxygen transport system in man. *Acta Physiologica Scandinavica*, 328 (Suppl.), 5-45.

Ekblom, B. and Hermansen, L. (1968) Cardiac output in athletes. *Journal of Applied Physiology*, 25, 619-625.

Elliot, B. C. and Blanksby, B. A. (1976) An cinematographical analysis of overground and treadmill running by males and females. *Medicine and Science in Sports and Exercise*, 8, 84-87.

Farhi, L. E. (1972) Letters to the editor. *Journal of Applied Physiology*, 33, 282.

Foster, C., Costill, D. L., Daniels, J., and Fink, W. J. (1978) Skeletal muscle enzyme activity, fibre composition and $\dot{V}O_{2max}$ in relation to distance running performance. *European Journal of Applied Physiology*, 39, 73-80.

Foster, C., Coyle, R. B., Crowe, A., Dumit, M., Lettau, S., Young, H. M., and Volkert, P. (1997) Comparison of free range and graded exercise testing. *Medicine and Science in Sports and Exercise*, 29, 1521-1526.

Foster, C., Gal, R. A., Port, S. C., and Schmidt, D. H. (1995) Left ventricular ejection fraction during incremental and steady state exercise. *Medicine and Science in Sports and Exercise*, 27, 1602-1606.

Foster, C., Green, M. A., Snyder, A. C., and Thompson, N. N. (1993b) Physiological responses during simulated competition. *Medicine and Science in Sports and Exercise*, 25, 877-882.

Foster, C., Snyder, A. C., Thompson, N. N., Green, M. A., Foley, M., and Schrager, M. (1993a) Effect of pacing strategy on cycle time trial performance. *Medicine and Science in Sports and Exercise*, 25, 383-388.

Fox, E. L. and Bowers, R. W. (1973) Steady-state equality of respiratory gaseous $N_2$ in resting man. *Journal of Applied Physiology*, 35, 143-144.

Fox, E. L., Kirkendall, D. T., and Bartels, R. L. (1980) Linear determination of the $\dot{V}O_2$ half time response during exercise. *European Journal of Applied Physiology and Occupational Therapy*, 44, 77-81.

Freedson, P., Kline, G., Porcari, J., Hintermeister, R., McCarron, R., Ross, J., Ward, A., Gurry, M., and Rippe, J. (1986) Criteria for defining $\dot{V}O_{2max}$: a new approach to an old problem. *Medicine and Science in Sports and Exercise*, 18 (suppl.), S36.

Froelicher, V. F., Brammell, H., Davis, G., Noguera, I., Stewart, A., and Lancaster, M. C. (1974) A comparison of three maximal treadmill exercise protocols. *Journal of Applied Physiology*, 36, 720-725.

Furusawa, K., Hill, A. V., Long, C. N. H., and Lupton, H. (1924) Muscular exercise, lactic acid, and the supply and utilisation of oxygen – Part VIII. *Proceedings of the Royal Society of London: Series B*, 97, 167-176.

Gaesser, G. A. and Brooks, G. A. (1980) Glycogen repletion following continuous and intermittent exercise to exhaustion. *Journal of Applied Physiology*, 49, 722-728.

Gaesser, G. A. and Poole, D. C. (1996) The slow component of oxygen uptake kinetics in humans. In: Holloszy, J. O. (ed.) *Exercise and Sport Sciences Reviews*, 24, 35-70. Baltimore, Williams and Wilkins.

Gastin, P. B. and Lawson, D. L. (1994a) Variable resistance all-out test to generate accumulated oxygen deficit and predict anaerobic capacity. *European Journal of Applied Physiology*, 69, 331-336.

Gastin, P. B. and Lawson, D. L. (1994b) Influence of training status on maximal accumulated oxygen deficit during all-out cycle exercise. *European Journal of Applied Physiology*, 69, 321-330.

Geppert, J. and Zuntz, N. (1888) Ueber die Regulation der Athmung. *Pfleugers Archives*, 42, 189-245.

Gerbino, A., Ward, S. A., and Whipp, B. J. (1996) Effects of prior exercise on pulmonary gas-exchange kinetics during high-intensity exercise in humans. *Journal of Applied Physiology*, 80, 99-107.

Gilbert, R., Auchincloss, J. H. Jr., and Baule, G. H. (1967) Metabolic and circulatory adjustments to unsteady-state exercise. *Journal of Applied Physiology*, 22, 905-912.

Gleser, M. A. (1973) Effects of hypoxia and physical training on haemodynamic adjustments to one-legged exercise. *Journal of Applied Physiology*, 34, 655-659.

Gollnick, P. D. and Hermansen, L. (1973) Biochemical adaptations to exercise: anaerobic metabolism. In: Wilmore, J. H. (ed). *Exercise and Sports Sciences Reviews*, 1, 1-43. New York, Academic.

Gomes, P. S. C., Maciel, T. T., and Oliveira, A. A. (1997) Sampling variability does not seem to influence the determination of $\dot{V}O_2$ at peak and at the ventilatory threshold. *Medicine and Science in Sports and Exercise*, 29 (Suppl.), S259.

Goodman, J. M., Plyley, M. J., Leftowitz, C. A., Liu, P. P., and McLaughlin, P. R. (1991) Left ventricular functional response to moderate and intense exercise. *Canadian Journal of Sports Sciences*, 16, 204-209.

Green, H. J., Sutton, J., Young, P., Cymerman, A., and Houston, C. S. (1989) Operation Everest II: muscle energetics during maximal exhaustive exercise. *Journal of Applied Physiology*, 66, 142-150.

Green, S. (1994) A definition and systems view of anaerobic capacity. *European Journal of Applied Physiology*, 69, 168-173.

Green, S. (1995) Letters to the editor: Maximal oxygen deficit of sprint and middle distance runners. *European Journal of Applied Physiology*, 70, 192-193.

Green, S. and Dawson, B. T. (1993) Measurement of anaerobic capacities in humans: definitions, limitations and unsolved problems. *Sports Medicine*, 15, 312-327.

Green, S. and Dawson, B. T. (1995) The oxygen uptake-power regression in cyclists and untrained men: implications for the accumulated oxygen deficit. *European Journal of Applied Physiology*, 70, 351-359.

Green, S. and Dawson, B. T. (1996) Methodological effects on the $\dot{V}O_2$-power regression and the accumulated $O_2$ deficit. *Medicine and Science in Sports and Exercise*, 28, 392-397.

Green, S., Dawson, B. T., Goodman, C., and Carey, M. F. (1996) Anaerobic ATP production and accumulated oxygen deficit in cyclists. *Medicine and Science in Sports and Exercise*, 28, 315-321.

Greenhaff, P. L. and Timmons, J. A. (1998) Interaction between aerobic and anaerobic metabolism during intense muscle contraction. *Exercise and Sport Science Reviews*, 26, 1-30.

Hagberg, J. M., Nagle, F. J., and Carlson, J. L. (1978) Transient $O_2$ uptake response at the onset of exercise. *Journal of Applied Physiology*, 44, 90-92.

Haldane, J. S. (1912) *Methods of Air Analysis*. London, Griffin and Co.

Hall, J. R. and Brouillard, R. G. (1985) Water vapour pressure calculation. *Journal of Applied Physiology*, 58, 2090.

Hansen, J. E., Casaburi, R., Cooper, D. M., and Wasserman, K. (1988) Oxygen uptake as related to work rate increment during cycle ergometer exercise. *European Journal of Applied Physiology*, 57, 140-145.

Hansen, J. E., Sue, D. Y., and Wasserman, K. (1984) Predicted values for clinical exercise testing. *American Review of Respiratory Diseases*, 129 (Suppl.), S49-S55.

Harms, C. A., Babcock, M. A., McClaran, S. R., Pegelow, D. F., Nickele, G. A., Nelson, W. B., and Dempsey, J. A. (1997) Respiratory muscle work compromises leg blood flow during maximal exercise. *Journal of Applied Physiology*, 82, 1573-1583.

Hart, J. D. and Withers, R.T. (1996) The calibration of gas volume measuring devices at continuos and pulsatile flows. *Australian Journal of Science and Medicine in Sport*, 28, 61-65.

Hart, J. D., Withers, R. T., and Ilsley, A. H. (1992) The accuracy and precision of dry gas meters at continuos and sinusoidal flows. *European Respiratory Journal*, 5,1146-1149.

Henry, F. M. (1951) Aerobic oxygen consumption and alactic debt in muscular work. *Journal of Applied Physiology*, 3, 427-438.

Henry, F. M. (1953) The oxygen requirement of walking and running. *Research Quarterly*, 24, 169-175.

Henry, F. M. (1954) Time-velocity equations and oxygen requirements of "all-out" and "steady-pace" running. *Research Quarterly*, 25, 164-177.

Hermansen, L. (1969) Anaerobic energy release. *Medicine and Science in Sports*, 1, 32-38.

Hermansen, L. (1973) Oxygen transport during exercise in human subjects. *Acta Physiologica Scandinavica*, 399 (Suppl.), 1-104.

Hill, A. V. (1925a) *Muscular Activity*. London, Balliere, Tindall and Cox.

Hill, A. V. (1925b) The physiological basis of athletic records. *Lancet*, 2, 481-486.

Hill, A. V. (1927) *Muscular Movement in Man: the Factors Governing Speed and Recovery from Fatigue.* New York, McGraw-Hill.

Hill, A. V. (1933) *Living Machinery.* London, Bell and Sons.

Hill, A. V., Long, C. N. H., and Lupton, H. (1924a) Muscular exercise, lactic acid, and the supply and utilisation of oxygen – Parts IV-VI. *Proceedings of the Royal Society of London: Series B*, 97, 84-138.

Hill, A. V., Long, C. N. H., and Lupton, H. (1924b) Muscular exercise, lactic acid, and the supply and utilisation of oxygen – Part VII. *Proceedings of the Royal Society of London: Series B*, 97, 155-167.

Hill, A. V. and Lupton, H. (1922) The oxygen consumption during running. *Journal of Physiology*, 56, xxxii-xxxiii.

Hill, A. V. and Lupton. H. (1923) Muscular exercise, lactic acid, and the supply and utilisation of oxygen. *Quarterly Journal of Medicine*, 16, 135-171.

Hill, D. W. and Ferguson, C. S. (1999) A physiological description of critical velocity. *European Journal of Applied Physiology*, 79, 290-293.

Hill, D.W., Halcomb, J.N., and Stevens, E.C. (2003) Oxygen uptake kinetics during severe intensity running and cycling. *European Journal of Applied Physiology*, 89, 612-618.

Hill, D. W. and Stevens, E. C. (2001) The $\dot{V}O_2$ response at the onset of severe intensity exercise. *Canadian Journal of Applied Physiology*, 26, 350-355.

Hogan, M. C., Roca, J., West, J. B., and Wagner, P. D. (1989) Dissociation of maximal $O_2$ uptake from $O_2$ delivery in canine gastrocnemius in situ. *Journal of Applied Physiology*, 66, 1219-1226.

Holthoer, A. (1996) Validity of the $\dot{V}O_{2max}$ plateau-criterion in a short, progressive cycle ergometer test. *Proceedings of the First Annual Congress of the European College of Sports Science*, 504-505.

Honig, C. R., Connett, R. J., and Gayeski, T. E. (1992) $O_2$ transport and its interaction with metabolism; a systems view of aerobic capacity. *Medicine and Science in Sports and Exercise*, 24, 47-53.

Howell, D. C. (1997) *Statistical Methods for Psychology.* Wadsworth, Belmont.

Howley, E. T., Bassett, D. R., and Welch, H. G. (1995) Criteria for maximal oxygen uptake: review and commentary. *Medicine and Science in Sports and Exercise*, 27, 1292-1301.

Hughson, R. L. (1978) Oxygen uptake kinetics at the onset of supramaximal exercise. *Medicine and Science in Sports and Exercise*, 10, 43.

Hughson, R.L. and Morrissey, M.A. (1983) Delayed kinetics of $\dot{V}O_2$ in the transition from prior exercise. Evidence of $O_2$ transport limitation of $\dot{V}O_2$ kinetics: a review *International Journal of Sports Medicine,* 4, 31-39.

Hughson, R. L., O'Leary, D. D., Betik, A. C., and Hebestreit, H. (2000) Kinetics of oxygen uptake at the onset of exercise near or above peak oxygen uptake. *Journal of Applied Physiology*, 88, 1812-1819.

Huynh, H. and Feldt, L. S. (1976) Estimation of the box correction for degrees of freedom from sample data in the randomised block and split plot designs. *Journal of Educational Statistics*, 1, 69-82.

Jakeman, P. and Davies, B. (1979) The characteristics of a low resistance breathing valve designed for the measurement of high aerobic capacity. *British Journal of Sports Medicine*, 13, 81-83.

Jones, A.M., Koppo, K., and Burnley, M. (2003) Effects of prior exercise on metabolic and gas exchange responses to exercise. *Sports Medicine,* 33, 949-71.

Jones, N. L., Makrides, L., Hitchcock, C., and McCartney, N. (1985) Normal standards for an incremental progressive cycle ergometer test. *American Review of Respiratory Diseases*, 131, 700-708.

Karlsson, J. (1971) Lactate and phosphagen concentrations in working muscle of man. *Acta Physiologica Scandinavica* (Supp.), 358, 7-72.

Kayser, B., Narici, M., Binzoni, T., Grassi, B., and Cerretelli, P. (1994) Fatigue and exhaustion in chronic hypobaric hypoxia: influence of exercising muscle mass. *Journal of Applied Physiology*, 76, 634-640.

Keeling, C. D., Whorf, T. P., Wahlen, M., and van der Plicht, J. (1995) Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980. *Nature*, 375, 666-670.

Keeling, R. F. and Shertz, S. R. (1992) Seasonal and interannual variations in atmospheric oxygen and implications for the global carbon cycle. *Nature*, 358, 723-727.

Kennelly, A. (1926) Changes during the last twenty years in the world's speeds records of racing animals. *Proceedings of the American Academy of Arts and Sciences.* 61, 487-523.

Klausen, K., Secher, N. S., Clausen, J. P., Hartling, O., and Trap-Jensen, J. (1982) Central and regional circulatory adaptations to one-leg training. *Journal of Applied Physiology*, 52, 976-983.

Knight, D. R., Poole, D. C., Schaffartzik, W., Guy, H. J., Prediletto, R., Hogan, M. C., and Wagner, P. D. (1992) Relationship between body and leg $\dot{V}O_2$ during maximal cycle ergometry. *Journal of Applied Physiology*, 73, 1114-1121.

Koike, A., Weiler-Ravell, D., McKenzie, D. K., Zanconato, S., and Wasserman, K. (1990) Evidence that the metabolic acidosis threshold is the anaerobic threshold. *Journal of Applied Physiology*, 68, 2521-2526.

Krogh, A. and Lindhard, J. (1920) The changes in respiration at the transition from work to rest. *Journal of Physiology*, 53, 431-437.

Lacour, J. R., Padilla-Magunacelaya, S., Barthélémy, J. C., and Dormois, D. (1990) The energetics of middle-distance running. *European Journal of Applied Physiology and Occupational Therapy*, 60, 38-43.

Lamarra, N. and Whipp, B. J. (1995) Measurement of pulmonary gas exchange. In: Maud, P. J., and Foster, C. (Eds.) *The Physiological Assessment of Human Fitness*, 19-35. Champaign, Illinois, Human Kinetics.

Lamarra, N., Whipp, B. J., Ward, S. A., and Wasserman, K. (1987) Effect of interbreath fluctuations on characterizing exercise gas exchange kinetics. *Journal of Applied Physiology*, 62, 2003-2012.

Léger, L. A. and Ferguson, R. J. (1974) Effect of pacing on oxygen uptake and peak lactate for a mile run. *European Journal of Applied Physiology*, 32, 251-257.

Lewis, S. F. and Haller, R. G. (1986) The pathophysiology of McArdle's disease: clues to regulation in exercise and fatigue. *Journal of Applied Physiology*, 61, 391-401.

Linnarsson, D. (1974) Dynamics of pulmonary gas exchange and heart rate changes at start and end of exercise. *Acta Physiologica Scandinavica*, 415 (suppl.), 1-69.

Lloyd, B. B. (1958) A development of Haldane's gas-analysis apparatus. *Journal of Physiology*, 143, 5-6P.

Lloyd, B. B. (1966) The energetics of running: an analysis of world records. *Advancement of Science*, 22, 515-530.

Lloyd, B. B. (1967) World running records as maximal performances. *Circulation Research*, XX-XXI (Suppl.), 218-226.

Londeree, B. R. (1986) The use of laboratory test results with long distance runners. *Sports Medicine*, 3, 201-213.

Londeree, B. R., Moffit-Gerstenberger, J., Padfield, J. A., and Lottman, D. (1997) Oxygen consumption of cycle ergometry is nonlinearly related to work rate and pedal rate. *Medicine and Science in Sports and Exercise*, 29, 775-780.

Machta, L. and Hughes, E. (1970) Atmospheric oxygen in 1967 and 1970. *Science*, 168, 1582-1584.

Margaria, R. (1976) *Biomechanics and Energetics of Muscular Exercise.* Clarendon Press, Oxford.

Margaria, R., Aghemo, P., and Rovelli, E. (1966) Measurement of muscular power (anaerobic) in man. *Journal of Applied Physiology*, 21, 1662-1664.

Margaria, R., Cerretelli, P., Aghemo, P., and Sassi, G. (1963) Energy cost of running. *Journal of Applied Physiology*, 18, 367-370.

Margaria, R., Mangili, F., Cuttica, F., and Cerretelli, P. (1965) The kinetics of the oxygen consumption at the onset of muscular exercise in man. *Ergonomics*, 8, 49-54.

Mayhew, J. L. and Gross, P. M. (1975) Comparison of grade-incremented versus speed-incremented maximal exercise tests in trained men. *British Journal of Sports Medicine*, 9, 191-195.

McArdle, W. D., Katch, F. I., and Katch, V. L. (1996) *Exercise Physiology: Energy, Nutrition, and Human Performance.* Baltimore, Williams and Wilkins.

McConnell, T. R. (1988) Practical considerations in the testing of $\dot{V}O_{2max}$ in runners. *Sports Medicine*, 5, 57-68.

Meade, G. P. (1916) An analytic study of athletic records. *Scientific Monthly*, 2, 596-600.

Medbø, J. I., Mohn, A. C., Tabata, I., Bahr, R., Vaage, O., and Sejersted, O. H. (1988) Anaerobic capacity determined by maximal accumulated $O_2$ deficit. *Journal of Applied Physiology*, 64, 50-60.

Medbø, J. I. and Tabata, I. (1989) Relative importance of aerobic and anaerobic energy release during short-lasting exhaustive bicycle exercise. *Journal of Applied Physiology*, 67, 1881-1886.

Mitchell, J. H., Sproule, B. J., and Chapman, C. B. (1958) The physiological meaning of the maximal oxygen intake test. *Journal of Clinical Investigations*, 37, 538-547.

Morgan, D. W., Baldini, F. D., Martin, P. E., and Kkohrt, W. M. (1989) Ten kilometre performance and predicted velocity at $\dot{V}O_{2max}$ among well-trained male runners. *Medicine and Science in Sports and Exercise*, 21, 78-83.

Morton, R. H. (1984) New lamps for old? (Letter to the Editor). *Applied Statistics*, 33, 317-318.

Musch, T. I. and Brooks, G. A. (1976) Effect of diet and metabolic rate on open circuit calculations of $\dot{V}O_2$ and $\dot{V}CO_2$. *The Research Quarterly*, 47, 731-740.

Myers, J. and Bellin, D. (2000) Ramp exercise protocols for clinical and cardiopulmonary exercise testing. *Sports Medicine*, 30, 23-29.

Myers, J., Walsh, D., Sullivan, M., and Froelicher, V. F. (1990) Effect of sampling on variability and plateau in oxygen uptake. *Journal of Applied Physiology*, 68, 404-410.

Nelson, R. C., Dillman, C. J., Lagasse, P., and Bickett, P. (1972) Biomechanics of overground versus treadmill running. *Medicine and Science in Sports and Exercise*, 4, 233-240.

Niemelä, K., Palatsi, I., Linnaluoto, M., and Takkunen, J. (1980) Criteria for maximum oxygen uptake in progressive bicycle tests. *European Journal of Applied Physiology*, 44, 51-59.

Nigg, B. M., Boer, R. W., and Fisher, V. (1995) A kinematic comparison of overground and treadmill running. *Medicine and Science in Sports and Exercise*, 27, 98-105.

Noakes, T. D. (1988) Implications of exercise testing for prediction of athletic performance: a contemporary perspective. *Medicine and Science in Sports and Exercise*, 20, 319-330.

Noakes, T. D. (1997) Challenging beliefs: ex Africa semper aliquid novi. *Medicine and Science in Sports and Exercise*, 29, 571-590.

Noakes, T. D. (1998) Maximal oxygen uptake: "classical" versus "contemporary" viewpoints: a rebuttal. *Medicine and Science in Sports and Exercise*, 30, 1381-1398.

Noakes, T. D. (2000) Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance. *Scandinavian Journal of Medicine and Science in Sports*, 10, 123-145.

Norton, A. C. and Wilmore, J. H. (1975) Effects of water vapour on respiratory gas measurements and calculations. *The NSCPT Analyser*, 9, 6-9.

Olesen, H. L., Raabo, E., Bangsbo, J., and Secher, N. H. (1994) Maximal oxygen deficit of sprint and middle distance runners. *European Journal of Applied Physiology*, 69, 140-146.

Orr, G. W., Green, H. J., Hughson, R. L., and Bennett, G. W. (1982) A computer linear regression model to determine ventilatory anaerobic threshold. *Journal of Applied Physiology*, 52, 1349-1352.

Otis, A. B. (1964) Quantitative relationships in steady-state gas exchange. In: Fenn, W. O. and Rahn, H. (Eds) *Handbook of Physiology, Respiration: Section 3*, 681-698. Washington, D.C., American Physiological Society.

Ozcelik, O., Ward, S. A., and Whipp, B. J. (1999) Effect of altered body $CO_2$ stores on pulmonary gas exchange dynamics during incremental exercise in humans. *Experimental Physiology*, 84, 999-1011.

Paterson, D. H. and Whipp, B. J. (1991) Asymmetries of oxygen uptake transients at the on- and offset of heavy exercise in humans. *Journal of Physiology*, 443, 575-586.

Péronnet, F. and Thibault, G. (1989) Mathematical analysis of running performance and world running records. *Journal of Applied Physiology*, 67, 453-465.

Péronnet, F., Thibault, G., Rhodes, E. C., and McKenzie, D. C. (1987) Correlation between ventilatory threshold and endurance capability in marathon runners. *Medicine and Science in Sports and Exercise*, 19, 610-615.

Phillips, W. H. and Ross, W. D. (1967) Timing error in determining maximal oxygen uptake. *The Research Quarterly*, 38, 315-316.

Pianosi, P., Seargeant, L., and Haworth, J. C. (1995) Blood lactate and pyruvate concentrations, and their ratio during exercise in healthy children: developmental perspective. *European Journal of Applied Physiology*, 71, 518-522.

Poole, D.C. (1994) Role of exercising muscle in slow component of $\dot{V}O_2$. *Medicine and Science in Sports and Exercise*, 26, 1335-40.

Poole, D. C., Barstow, T. J., Gaesser, G. A., Willis, W. T., and Whipp, B. J. (1994) $\dot{V}O_2$ slow component: physiological and functional significance. *Medicine and Science in Sports and Exercise*, 26, 1354-1358.

Poole, D. C., Ward, S. A., Gardener, G. W., and Whipp, B. J. (1988) Metabolic and respiratory profile of the upper limit for prolonged exercise in man. *Ergonomics*, 31, 1265-1279.

Poole, D. C. and Whipp, B. J. (1988) Letters to the editor. *Medicine and Science in Sports and Exercise*, 20, 420-421.

Powers, S. K. and Howley, E. T. (1997) *Exercise Physiology: Theory and Application to Fitness and Performance*. Boston, McGraw-Hill.

Prieur, F., Busso, T., Castells, J., Bonnefoy, R., Bennoit, H., Geyssant, A., and Denis, C. (1998) Validity of oxygen uptake measurements during exercise under moderate hyperoxia. *Medicine and Science in Sports and Exercise*, 30, 958-962.

Pringle, J.S., Carter, H., Doust, J.H., and Jones, A.M. (2002) Oxygen uptake kinetics during horizontal and uphill treadmill running in humans. *European Journal of Applied Physiology*, 88, 163-169.

Pringle, J.S., Doust, J.H., Carter, H., Tolfrey, K, Campbell, I.T., and Jones, A.M. (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, 289-300.

Pugh, L. G. C. E. (1971) The influence of wind resistance in running and walking and the mechanical efficiency of work against horizontal or vertical forces. *Journal of Physiology*, 213, 255-276.

Ricci, B. (1979) Motor-driven treadmill calibration. *Journal of Sports Medicine*, 19, 267-270.

Richardson, R. S., Knight, D. R., Poole, D. C., Kurdak, S. S., Hogan, M. C., Grassi, B., and Wagner, P. D. (1995) Determination of maximal exercise $\dot{V}O_2$ during single leg knee-extensor exercise in humans. *American Journal of Physiology*, 268, H1453-1461.

Richardson, R. S., Poole, D. C., Knight, D. R., Kurdak, S. S., Hogan, M. C., Grassi, B., Johnson, E. C., Kendrick, K. F., Erickson, B. K., and Wagner, P. D. (1993) High muscle blood flow in man: is maximal $O_2$ extraction compromised? *Journal of Applied Physiology*, 75, 1911-1916.

Rivera-Brown, A. M., Rivera, M. A., and Frontera, W. R. (1992) Applicability of criteria for $\dot{V}O_{2max}$ in active adolescents. *Paediatric Exercise Sci*ence, 4, 331-339.

Rivera-Brown, A. M., Rivera, M. A., and Frontera, W. R. (1994) Achievement of $\dot{V}O_{2max}$ criteria in adolescent runners: effects of testing protocol. *Paediatric Exercise Sci*ence, 6, 236-245.

Roca, J., Hogan, M. C., Story, D., Bebout, D. E., Haab, P., Gonzalez, R., Ueno, O., and Wagner, P. D. (1989) Evidence for tissue diffusion limitation of $\dot{V}O_{2max}$ in normal humans. *Journal of Applied Physiology*, 67, 291-299.

Rossiter, H.B., Ward, S.A., Howe, F.A., Wood, D.M., Kowalchuk, J.M., Griffiths, J.R., and Whipp, B.J. (2003) Effects of dichloroacetate on $\dot{V}O_2$ and intramuscular $^{31}P$ metabolite kinetics during high intensity exercise in humans. *Journal of Applied Physiology*, 95, 1105-1115.

Rowell, L. B. (1986) *Human Circulation Regulation during Physical Stress*. Oxford, Oxford University Press.

Rowell, L. B., Saltin, B., Kiens, B., and Christensen, N. J. (1986) Is peak quadriceps blood flow even higher during exercise with hypoxaemia? *American Journal of Physiology*, 251, H1038-H1044.

Rowell, L. B., Taylor, H. L., Wang, Y., and Carlson, W. S. (1964) Saturation of arterial blood with oxygen during maximal exercise. *Journal of Applied Physiology*, 19, 284-286.

Rowland, T. W. (1993) Does peak $\dot{V}O_2$ reflect $\dot{V}O_{2max}$ in children?: evidence from supramaximal testing. *Medicine and Science in Sports and Exercise*, 25, 689-693.

Rowland, T. W. and Cunningham, L. N. (1992) Oxygen uptake plateau during maximal treadmill exercise in children. *Chest*, 101, 485-489.

Rumball, W. and Coleman, C. (1970) Analysis of running and the prediction of ultimate performance. *Nature*, 228, 184-185.

Ryder, R. W., Carr, H. J., and Herget, P. (1976) Analysis of running and the prediction of ultimate performances. *Nature*, 228, 184-195.

Saltin, B. (1986) The physiological and biochemical basis of aerobic and anaerobic capacities in man; effect of training and range of adaptation. In: Mæhlum, S., Nilsson, S., and Renström, P. (eds.) *Proceedings of the Second Scandinavian Conference in Sports Medicine*, 16-59. Norway.

Saltin, B. (1988) Capacity of blood flow delivery to exercising skeletal muscle in humans. *American Journal of Cardiology*, 62, 30E-35E.

Saltin, B. (1990a) Anaerobic capacity: past, present, and prospective. In: Taylor, A. W. et al. (eds.) *Biochemistry of Exercise VII*, 26-40. Champaign, Illinois, Human Kinetics.

Saltin, B. (1990b) Maximal oxygen uptake: limitation and malleability. In: Nazar, K., Terjung, R. L., Kaciuba-Uscilko, H., and Budohoski, L. (eds.) *International Perspectives in Exercise Physiology*, 26-40. Champaign, Illinois, Human Kinetics.

Saltin, B. and Åstrand, P-O. (1967) Maximal oxygen uptake in athletes. *Journal of Applied Physiology*, 23, 353-358.

Saltin, B., Blomqvist, G., Mitchell, J. H., Johnson, R. L., Wildenthal, K., and Chapman, C. B. (1968) Response to exercise after bed rest and after training. *Circulation*, 38 (Suppl. 7), 1-78.

Saltin, B., Nazar, K., Costill, D. L., Stein, E., Jansson, E., Essen, B., and Gollnick, P. D. (1976) The nature of the training response; peripheral and central adaptations to one-legged exercise. *Acta Physiologica Scandinavica*, 96, 289-305.

Saltin, B. and Strange, S. (1992) Maximal oxygen uptake: "old" and "new" arguments for a cardiovascular limitation. *Medicine and Science in Sports and Exercise*, 24, 30-37.

Sargent, R. M. (1926) The relation between oxygen requirement and speed in running. *Proceedings of the Royal Society of London: Series B*, 100, 10-22.

Savard, G. K., Richter, E. A., Strange, S., Kiens, B., Christensen, N. J., and Saltin, B. (1989) Noradrenaline spillover from skeletal muscle during exercise in humans: role of muscle mass. *American Journal of Physiology*, 257, H1812-H1818.

Scherrer, J. and Monod, H. (1960) Le travail musculaire local et la fatigue chez l'homme. *Journal of Physiology (Paris)*, 52, 419-501.

Scheuermann, B. W. and Barstow, T. J. (2003) $O_2$ uptake kinetics during exercise at peak $O_2$ uptake. *Journal of Applied Physiology*, 95, 2014-2022.

Scholander, P. F. (1947) Analyser for accurate estimation of respiratory gases in one-half cubic centimetre samples. *Journal of Biological Chemistry*, 167, 235-250.

Schutz, R. W. and Lui, Y. (1993) Track and field world record projections. *American Statistical Association: Proceedings of the section on Statistics in Sports*, 52-57.

Schutz, R. W. and Lui, Y. (1998) Statistical modelling in track and field. In: Bennett, J. (Ed) *Statistics in Sport*, 173-196. London, Arnold.

Secher, N. H., Clausen, J. P., Klausen, K., Noer, I., and Trap-Jensen, J. (1977) Central and regional circulatory effects of adding arm exercise to leg exercise. *Acta Physiologica Scandinavica*, 100, 288-297.

Sejersted, O.M. and Vøllestad, N.K. (1992) Increased metabolic rate associated with muscle fatigue. *Medicine and Sport Science,* 34, 115-130.

Sheehan, J. M., Rowland, T. W., and Burke, E. J. (1987) A comparison of four treadmill protocols for determination of maximum oxygen uptake in 10- to 12-year-old boys. *International Journal of Sports Medicine*, 8, 31-34.

Shinohara, M. and Moritani, T. (1992) Increase in neuromuscular activity and oxygen uptake during heavy exercise. *Ann Physiol Anthropol,* 11, 257-262.

Sidney, K. H. and Shephard, R. J. (1977) Maximum and submaximum exercise tests in men and women in the seventh, eighth, and ninth decades of life. *Journal of Applied Physiology*, 43, 280-287.

Simonson, E. (1927) Weitere beiträge zur physiologie der atmung und uebong. Pflüg. Arch. Physiolo., 215, 752.

Sloniger, M. A., Cureton, K. J., Prior, B. M., and Evans, E. M. (1997) Anaerobic capacity and muscle activation during horizontal and uphill running. *Journal of Applied Physiology*, 83, 2073-2079.

Smith, R. L. (1988) Forecasting records by maximum likelihood. *Journal of the American Statistical Association*, 83, 331-338.

Spencer, M. R. and Gastin, P. B. (2001) Energy system contribution during 200- to 1500-m running in highly trained athletes. *Medicine and Science in Sports and Exercise*, 33, 157-162.

Spencer, M. R., Gastin, P. B., and Payne, W. R. (1996) Energy system contribution during 400 to 1500 metres running. *New Studies in Athletics*, 11, 59-65.

Spriet, L. L., Soderlund, K., Bergstrom, M., and Hultman, E. (1987) Anaerobic energy release on skeletal muscle during electrical stimulation in men. *Journal of Applied Physiology*, 62, 611-615.

Stamford, B. A., Weltman, A., and Fulco, C. (1978) Anaerobic threshold and cardiovascular responses during one- versus two legged cycling. *Research Quarterly*, 49, 351-362.

Stenberg, J., Ekblom, B., and Messin, R. (1966) Hemodynamic response to work at simulated altitude. *Journal of Applied Physiology*, 21, 1589-1594.

Stringer, W. W., Hansen, J. E., and Wasserman, K. (1997) Cardiac output estimated noninvasively from oxygen uptake during exercise. *Journal of Applied Physiology*, 82, 908-912.

Svedenhag, J., Saltin, B., Johansson, C., and Kaijser, L. (1991) Aerobic and anerobic exercise capacities of elite middle-distance runners after two weeks of training at moderate altitude. *Scandinavian Journal of Medicine and Science in Sports*, 1, 205-214.

Svedenhag, J. and Sjödin, B. (1984) Maximal and submaximal oxygen uptakes and blood lactate levels in elite male middle- and long-distance runners. *International Journal of Sports Medicine*, 5, 255-261.

Svedenhag, J. and Sjödin, B. (1994) Body-mass-modified running economy and step length in elite male middle- and long-distance runners. *International Journal of Sports Medicine*, 15, 305-310.

Sykes, K. (1975) Technique and observation of angular gait patterns in running. *British Journal of Sports Medicine*, 9, 181-186.

Taylor, H. L., Buskirk, E., and Henschel, A. (1955) Maximum oxygen intake as an objective measure of cardio-respiratory performance. *Journal of Applied Physiology*, 8, 73-80.

Thoden, J. S. (1991) Testing aerobic power. In: MacDougall, J. D., Wenger, H. A., and Green, H. J. (eds.) *Physiological Testing of the High Performance Athlete*, 107-173. Champaign, Illinois, Human Kinetics.

Timmons, J. A., Gustafsson, T., Sundberg, C. J., Jansson, E., and Greenhaff, P. L. (1998) Muscle acetyl group availability is a major determinant of oxygen deficit in humans during submaximal exercise. *American Journal of Physiology*, 274, E377-E380.

Timmons, J. A., Poucher, S. M., Constantin-Teodosiu, D., Macdonald, I. A., and Greenhaff, P. L. (1997) Metabolic responses from rest to steady state determine contractile function in ischemic skeletal muscle. *American Journal of Physiology*, 273, E233-E238.

Timmons, J. A., Poucher, S. M., Constantin-Teodosiu, D., Worrall, V., Macdonald, I. A., and Greenhaff, P. L. (1997) Metabolic responses to canine gracilis muscle during contraction with partial ischemia. *American Journal of Physiology*, 270, E400-E406.

Topping, J. (1972) *Errors of Observation and Their Treatment.* London, Chapman and Hall.

Van Ingen Schenau (1980) Some fundamental aspects of the biomechanics of overground versus treadmill locomotion. *Medicine and Science in Sports and Exercise*, 12, 257-261.

Vieth, E. (1989) Fitting piecewise linear regression functions to biological responses. *Journal of Applied Physiology*, 67, 390-396.

Vøllestad, N.K. Wesche, J., and Sejersted, O.M. (1990) Gradual increase in leg oxygen uptake during repeated submaximal contractions in humans. *Journal of Applied Physiology,* 68, 1150-1156.

Wagner, P. D. (1992) Gas exchange and peripheral diffusion limitation. *Medicine and Science in Sports and Exercise*, 24, 54-58.

Wagner, P. D. (1995) Muscle $O_2$ transport and $O_2$ dependant control of metabolism. *Medicine and Science in Sports and Exercise*, 27, 47-53.

Wagner, P. D. (1996) Determinants of maximal oxygen transport and utilisation. *Annual Reviews in Physiology*, 58, 21-50.

Wagner, J. A., Horvath, S. M., Dahms, T. E., and Reed, S. (1973) Validation of open-circuit method for the determination of oxygen consumption. *Journal of Applied Physiology*, 34, 859-863.

Ward, S. A. (1999) Determinants and limitations of pulmonary gas exchange during exercise. In: Whipp and Sargeant (eds.) *Physiological Determinants of Exercise Tolerance in Humans*, 115-134. London, Portland Press.

Ward, S. A. and Whipp, B. J. (1992) Influence of body $CO_2$ store on the ventilatory-metabolic coupling during exercise. In: Hoda, Y., Miyamato, Y., Konno, K., and Widdicombe, J. G. (eds.) *Control of Breathing and its Modelling Perspective*, 425-443. New York, Plenum Press.

Ward-Smith, A. J. (1985) A mathematical theory of running based on the first law of thermodynamics, and its application to the performance of world-class athletes. *Journal of Biomechanics*, 18, 337-349.

Ward-Smith, A. J. (1999) The bioenergetics of optimal performances in middle-distance and long distance track running. *Journal of Biomechanics*, 32, 461-465.

Wasserman, K., Beaver, W. L., and Whipp, B. J. (1990) Gas exchange theory and the lactic acidosis (anaerobic) threshold. *Circulation*, 81 (Suppl.), II 14-30.

Wasserman, K., Hansen, J. L., Sue, D. Y., Whipp, B. J., and Cassaburi, R. (1994a) *Principles of Exercise Testing and Interpretation* (2nd edn.). Philadelphia, Lea and Febiger.

Wasserman, K., Stringer, W. W., and Casaburi, R. (1995) Is the slow component of exercise $\dot{V}O_2$ a respiratory adaptation to anaerobiosis? In: Semple, S. J. G., Aqdams, L., and Whipp, B. J. (eds.) *Modeling and Control of Ventilation*, 187-294. Plenum Press, New York.

Wasserman, K., Stringer, W. W., Casaburi, R., Koike, A., and Cooper, C. B. (1994b) Determination of the anaerobic threshold by gas exchange: biochemical considerations, methodology and physiological effects. *Zeitschrift Fur Kardiologie*, 83 (Suppl.), 1-12.

Wasserman, K., Van Kessel, A. L., and Burton, G. G. (1967) Interaction of physiological mechanisms during exercise. *Journal of Applied Physiology*, 22, 71-85.

Wasserman, K., Whipp, B. J., and Castagna, J. (1974) Cardiodynamic hyperpnea: hyperpnea secondary to cardiac output increase. *Journal of Applied Physiology*, 36, 457-464.

Wasserman, K., Whipp, B. J., Koyal, S. N., and Beaver, W. L. (1973) Anaerobic threshold and respiratory gas exchange during exercise. *Journal of Applied Physiology*, 35, 236-243.

Welch, H. G. and Pedersen, K. P. (1981) Measurement of metabolic rate in hyperoxia. *Journal of Applied Physiology*, 51, 725-731.

Weltman, A. (1995) *The Blood Lactate Response to Exercise.* Champaign, Illinois, Human Kinetics.

Whipp, B. J. (1994) The slow component of $O_2$ uptake kinetics during heavy exercise. *Medicine and Science in Sports and Exercise*, 26, 1319-1326.

Whipp, B. J., Davis, J. A., Torres, F., and Wasserman, K. (1981) A test to determine parameters of aerobic function during exercise. *Journal of Applied Physiology*, 50, 217-221.

Whipp, B. J., Lamarra, N., and Ward, S. A. (1987) Required characteristics of pulmonary gas exchange dynamics for non-invasive determination of the anaerobic threshold. In: Benchetrit, G., Baconnier, P., and Demongeot, J. (eds.) *Concepts and Formulations in the Control of Breathing*, 185-200. Manchester, Manchester University Press.

Whipp, B.J., Rossiter, H.B., Ward, S.A., Avery, D., Doyle, V.L., Howe, F.A., and Griffiths, J.R. (1999) Simultaneous determination of muscle 31P and $O_2$ uptake kinetics during whole body NMR spectroscopy. *Journal of Applied Physiology*, 86, 742-747.

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

Whipp, B. J., Wasserman, K., Davis, J. A., Lamarra, N., and Ward, S. A. (1980) Determinants of $O_2$ and $CO_2$ kinetics during exercise in man. In: Cerretelli, P. and Whipp, B. J. (eds.) *Exercise Bioenergetics and Gas Exchange*, 175-185. Elvesier, Amsterdam.

Williams, C. S. (1997) *The effect of running speed on* $\dot{V}O_2$ *kinetics in the severe exercise domain.* (Masters Thesis) University of North Texas, USA.

Williams, C. S., Ehler, K. L., Ramirez, C. P., Poole, D. C., Smith, J. C., and Hill, D. W. (1998) Effect of running velocity on $\dot{V}O_2$ kinetics during treadmill running in the severe intensity domain. *Medicine and Science in Sports and Exercise*, 30 (Suppl.), S55.

Williams, K. R. (1985) Biomechanics of running. *Exercise and Sport Science Reviews*, 13, 389-441.

Wilmore, J. H. and Costill, D. L. (1973) Adequacy of the Haldane transformation in the computation of exercise $\dot{V}O_2$ in man. *Journal of Applied Physiology*, 35, 85-89.

Wood, D. M. (1999a) Physiological demands of middle-distance running. In: Fallowfield, J. L. and Wilkinson, D. M. (eds.) *Improving Sports Performance in Middle and Long-Distance Running.* Chichester, Wiley.

Wood, D. M. (1999b) Assessment of maximal oxygen consumption in runners: new concepts on an old theme. (Doctoral Thesis) University of Southampton, UK.

Wood, D. M., Myers, S. D., and Fallowfield, J. L. (1998) Variability in $\dot{V}O_2$ decreases as exercise intensity increases: implications for the identification of a $\dot{V}O_2$-plateau. Proceedings of the Third Annual Congress of the European College of Sports Science, 502.

WMO: World Meteorological Organisation (1996) Guide to meteorological instruments and methods of observation. *WMO Publication*, 8, 1-21.

# *PART VI*

# *APPENDICES*

# APPENDIX I: STUDY I

**Table AI.1 Participant characteristics for Study I (individual data).**

| Participant | Mass (kg) | Height (m) | Age (years) |
|---|---|---|---|
| 1 | 71.2 | 1.80 | 27 |
| 2 | 65.0 | 1.70 | 28 |
| 3 | 66.9 | 1.72 | 35 |
| 4 | 77.3 | 1.82 | 24 |
| 5 | 65.0 | 1.69 | 28 |
| 6 | 79.8 | 1.89 | 28 |
| 7 | 66.1 | 1.84 | 20 |
| 8 | 84.5 | 1.85 | 20 |
| **n** | **8** | **8** | **8** |
| **MEAN (M)** | **72.0** | **1.8** | **26.3** |
| **SD** | **7.6** | **0.01** | **4.9** |

**Table AI.2 Peak $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$) for six sampling/averaging periods and for repeat tests (individual data).**

| | Sampling/averaging period (s) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 15A | 15B | 45C | 45D | 30A | 30B | 30A | 30B | 45A | 45B | 45A | 45B |
| | RAW | RAW | RAW | RAW | STAN | STAN | MOVE | MOVE | STAN | STAN | MOVE | MOVE |
| 1 | 56.1 | 57.3 | 55.9 | 56.3 | 55.5 | 57.2 | 55.5 | 57.2 | 55.2 | 57.2 | 55.3 | 57.2 |
| 2 | 69.2 | 68.3 | 68.8 | 69.0 | 69.0 | 68.1 | 69.0 | 68.1 | 68.9 | 67.7 | 68.9 | 67.7 |
| 3 | 67.1 | 66.7 | 65.0 | 64.8 | 66.5 | 66.5 | 66.7 | 66.5 | 66.4 | 66.6 | 66.4 | 66.6 |
| 4 | 68.4 | 68.9 | 68.9 | 68.3 | 68.1 | 68.3 | 68.4 | 68.3 | 67.9 | 67.7 | 68.2 | 67.7 |
| 5 | 66.0 | 66.5 | 66.1 | 66.3 | 65.5 | 65.8 | 65.5 | 66.4 | 65.2 | 66.0 | 65.2 | 66.0 |
| 6 | 56.6 | 55.5 | 56.0 | 55.4 | 56.1 | 54.8 | 56.1 | 55.0 | 55.8 | 54.7 | 56.0 | 55.1 |
| 7 | 66.9 | 65.4 | 66.2 | 65.7 | 66.2 | 65.2 | 66.3 | 65.2 | 66.0 | 64.8 | 66.0 | 64.8 |
| 8 | 58.1 | 57.0 | 56.9 | 58.1 | 57.8 | 56.5 | 57.8 | 56.5 | 57.4 | 56.3 | 57.4 | 56.3 |
| **n** | **8** | **8** | **8** | **8** | **8** | **8** | **8** | **8** | **8** | **8** | **8** | **8** |
| **M** | **63.5** | **63.2** | **63.0** | **63.0** | **63.1** | **62.8** | **63.2** | **62.9** | **62.8** | **62.6** | **62.9** | **62.7** |
| **SD** | **5.6** | **5.6** | **5.7** | **5.5** | **5.6** | **5.6** | **5.7** | **5.7** | **5.7** | **5.5** | **5.7** | **5.5** |

**Table AI.3 SEE for the linear and plateau model for repeat tests (individual data).**

| | Linear SEE | | | | Plateau SEE | | | |
|---|---|---|---|---|---|---|---|---|
| | 15A | 15B | 45C | 45D | 15A | 15B | 45C | 45D |
| 1 | 2.57 | 1.13 | 1.33 | 1.08 | 1.11 | 0.84 | 0.34 | 0.78 |
| 2 | 1.24 | 1.43 | 1.82 | 1.58 | 0.99 | 1.12 | 1.23 | 1.29 |
| 3 | 0.97 | 1.89 | 2.27 | 1.10 | 0.83 | 1.22 | 0.92 | 0.66 |
| 4 | 1.70 | 1.58 | 1.84 | 1.74 | 0.94 | 1.24 | 1.23 | 1.29 |
| 5 | 1.08 | 2.08 | 1.63 | 1.01 | 0.59 | 0.80 | 0.66 | 0.54 |
| 6 | 1.15 | 1.40 | 0.69 | 0.73 | 0.92 | 1.03 | 0.76 | 0.58 |
| 7 | 2.34 | 2.12 | 1.35 | 2.32 | 1.41 | 1.32 | 0.68 | 1.36 |
| 8 | 1.30 | 1.24 | 0.89 | 0.68 | 1.22 | 0.94 | 0.95 | 0.76 |
| **n** | **8** | **8** | **8** | **8** | **8** | **8** | **8** | **8** |
| **M** | **1.54** | **1.61** | **1.48** | **1.28** | **1.00** | **1.06** | **0.85** | **0.91** |
| **SD** | **0.61** | **0.38** | **0.52** | **0.56** | **0.25** | **0.19** | **0.30** | **0.35** |

**Table AI.4 Plateau value ($ml.kg^{-1}.min^{-1}$) and duration (s) derived from the plateau model for repeat tests (individual data).**

| | Value ($ml.kg^{-1}.min^{-1}$) | | | | Duration (s) | | | |
|---|---|---|---|---|---|---|---|---|
| | 15A | 15B | 45C | 45D | 15A | 15B | 45C | 45D |
| 1 | 54.7 | 57.1 | 55.5 | 55.6 | 165.0 | 57.4 | 67.2 | 59.0 |
| 2 | 68.0 | 67.4 | 68.5 | 68.7 | 72.8 | 69.0 | 87.5 | 68.6 |
| 3 | 66.4 | 65.8 | 64.7 | 64.2 | 33.5 | 75.2 | 122.5 | 58.5 |
| 4 | 67.7 | 67.4 | 68.5 | 68.1 | 90.6 | 79.0 | 87.7 | 76.5 |
| 5 | 65.2 | 65.5 | 65.2 | 65.4 | 62.9 | 110.4 | 94.2 | 63.4 |
| 6 | 55.8 | 54.4 | 55.4 | 55.1 | 59.0 | 68.0 | 26.9 | 33.2 |
| 7 | 65.3 | 64.2 | 66.1 | 65.5 | 114.4 | 129.0 | 69.5 | 115.8 |
| 8 | 57.2 | 56.1 | 56.3 | 57.5 | 55.3 | 73.6 | 28.3 | 20.1 |
| **n** | **8** | **8** | **8** | **8** | **8** | **8** | **8** | **8** |
| **M** | **62.5** | **62.2** | **62.5** | **62.5** | **81.69** | **82.69** | **72.99** | **61.89** |
| **SD** | **5.6** | **5.4** | **5.8** | **5.6** | **41.48** | **24.25** | **32.72** | **28.68** |

# APPENDIX II: STUDY II

**Table AII.1 Participant characteristics for Study II (individual data).**

| Participant | Mass (kg) | Height (m) | Age (years) | 800 m PB (s) | Ramp peak $\dot{V}O_2$ (ml.kg$^{-1}$.min$^{-1}$) | Ramp peak speed (km.h$^{-1}$) |
|---|---|---|---|---|---|---|
| 1 | 93.3 | 1.8 | 21 | - | 50.7 | 17.7 |
| 2 | 94.0 | 1.8 | 21 | - | 50.7 | 17.4 |
| 3 | 73.0 | 1.6 | 21 | - | 51.0 | 18.2 |
| 4 | 89.2 | 1.9 | 24 | - | 52.1 | 21.2 |
| 5 | 75.3 | 1.9 | 19 | - | 53.2 | 17.6 |
| 6 | 79.0 | 1.7 | 21 | - | 54.6 | 18.0 |
| 7 | 92.7 | 1.9 | 20 | - | 54.8 | 19.4 |
| 8 | 76.8 | 1.8 | 22 | - | 56.4 | 20.0 |
| 9 | 73.6 | 1.8 | 20 | 115.2 | 61.9 | 21.4 |
| 10 | 69.7 | 1.8 | 30 | 105.7 | 64.8 | 22.7 |
| 11 | 69.7 | 1.8 | 30 | 110.6 | 64.8 | 22.7 |
| 12 | 66.1 | 1.8 | 20 | 114.9 | 64.9 | 22.1 |
| 13 | 65.0 | 1.7 | 27 | 114.3 | 65.4 | 22.2 |
| 14 | 73.7 | 1.8 | 26 | 114.1 | 66.5 | 22.7 |
| 15 | 62.2 | 1.7 | 27 | 110.1 | 71.8 | 24.1 |
| **n** | **15** | **15** | **15** | **15** | **15** | **15** |
| **MEAN (M)** | **76.9** | **1.8** | **23.3** | **112.1** | **58.9** | **20.5** |
| **SD** | **10.6** | **0.1** | **3.8** | **3.5** | **7.1** | **2.3** |

**Table AII.2 Peak $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$) and test duration (s) for repeat 800 m runs (individual data).**

| | Speed ($km.h^{-1}$) | Time A (S) | Time B (S) | $\dot{V}O_2$A ($ml.kg^{-1}.min^{-1}$) | $\dot{V}O_2$B ($ml.kg^{-1}.min^{-1}$) | Mean $\dot{V}O_2$ | Mean Time | % $\dot{V}O_2$ max |
|---|---|---|---|---|---|---|---|---|
| 1 | 19.0 | 109.1 | 113.7 | 48.4 | 49.4 | 48.9 | 111.4 | 96% |
| 2 | 18.0 | 132.0 | 132.2 | 49.5 | 48.2 | 48.9 | 132.1 | 96% |
| 3 | 19.0 | 131.1 | 128.9 | 47.4 | 49.8 | 48.6 | 130.0 | 95% |
| 4 | 19.5 | 112.6 | 110.3 | 50.3 | 51.1 | 50.7 | 111.4 | 97% |
| 5 | 19.0 | 99.3 | 96.4 | 52.8 | 52.2 | 52.5 | 97.8 | 99% |
| 6 | 19.5 | 111.6 | 115.6 | 52.7 | 49.4 | 51.1 | 113.6 | 93% |
| 7 | 20.5 | 100.0 | 100.2 | 53.3 | 54.3 | 53.8 | 100.1 | 98% |
| 8 | 20.0 | 93.4 | 99.5 | 54.9 | 54.8 | 54.8 | 96.4 | 97% |
| 9 | 23.4 | 138.0 | 131.5 | 55.7 | 54.7 | 55.2 | 69.0 | 89% |
| 10 | 25.0 | 108.4 | 111.5 | 57.0 | 56.2 | 56.6 | 109.9 | 87% |
| 11 | 25.0 | 64.9 | 64.8 | 55.0 | 56.2 | 55.6 | 64.9 | 86% |
| 12 | 23.4 | 125.4 | 122.6 | 61.4 | 59.0 | 60.2 | 124.0 | 93% |
| 13 | 24.0 | 110.7 | 112.7 | 60.3 | 60.3 | 60.3 | 111.7 | 92% |
| 14 | 24.0 | 79.4 | 80.0 | 61.3 | 59.8 | 60.6 | 79.7 | 91% |
| 15 | 25.0 | 92.8 | 86.5 | 64.5 | 64.1 | 64.3 | 46.4 | 90% |
| **n** | **15** | **15** | **15** | **15** | **15** | **15** | **15** | **15** |
| **M** | **21.6** | **107.2** | **92.6** | **55.0** | **54.6** | **54.8** | **99.9** | **93%** |
| **SD** | **2.7** | **20.0** | **41.4** | **5.1** | **4.7** | **4.9** | **24.9** | **4%** |

**Output AII.1 Paired samples t-test comparing the two data points averaged to define peak $\dot{V}O_2$ for the high and low $\dot{V}O_{2max}$ groups.**

**Paired Samples Test**

| | | Paired Differences | | | | | t | df | Sig. (2-tailed) |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Std Deviation | Std. Error Mean | 95% Confidence Interval of the Difference Lower | 95% Confidence Interval of the Difference Upper | | | |
| Pair 1 | LOWMAX1 - LOWMAX2 | .7025 | 1.44365 | .38583 | -.1310 | 1.5361 | 1.821 | 13 | .092 |
| Pair 2 | HIGHMAX1 - HIGHMAX2 | .0417 | 60448 | .16156 | -.3073 | 3907 | 258 | 13 | 800 |

## Output AII.2 Independent samples t-test comparing the % $\dot{V}O_{2\,max}$ attained between the high and low $\dot{V}O_{2\,max}$ groups.

**Independent Samples Test**

| | | Levene's Test for Equality of Variances | | t-test for Equality of Means | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | 95% Confidence Interval of the Difference | |
| | | F | Sig | t | df | Sig (2-tailed) | Mean Difference | Std. Error Difference | Lower | Upper |
| MAXATT2 | Equal variances assumed | .738 | .407 | 5.372 | 12 | .000 | .0657 | .01223 | .03906 | .09237 |
| | Equal variances not assumed | | | 5.372 | 11.270 | .000 | .0657 | .01223 | .03887 | .09256 |

## Output AII.3 Pearson's correlation between the % $\dot{V}O_{2\,max}$ attained and $\dot{V}O_{2\,max}$ for the group (n = 15).

**Correlations**

| | | MAX1 | MAXATT1 |
|---|---|---|---|
| MAX1 | Pearson Correlation | 1 | -.765** |
| | Sig. (2-tailed) | . | .001 |
| | N | 15 | 15 |
| MAXATT1 | Pearson Correlation | -.765** | 1 |
| | Sig. (2-tailed) | .001 | . |
| | N | 15 | 15 |

**. Correlation is significant at the 0.01 level (2-tailed).

# APPENDIX III: STUDY III

**Table AIII.1 Participant characteristics for Study III (individual data).**

| Participant | Mass (kg) | Height (m) | Age (years) | PB (s) | Ramp peak $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$) | Ramp peak speed ($km.h^{-1}$) |
|---|---|---|---|---|---|---|
| **800m** | | | | | | |
| 1 | 70 | 1.79 | 30 | 105.7 | 65.0 | 22.7 |
| 2 | 65 | 1.67 | 26 | 110.1 | 70.9 | 22.2 |
| 3 | 74 | 1.85 | 22 | 115.2 | 67.1 | 21.4 |
| 4 | 62 | 1.76 | 25 | 110.9 | 75.7 | 23.4 |
| 5 | 65 | 1.81 | 21 | 114.9 | 64.5 | 21.3 |
| 6 | 74 | 1.87 | 25 | 114.1 | 72.5 | 22.8 |
| **n** | **6** | **6** | **6** | **6** | **6** | **6** |
| **M** | **68.3** | **1.8** | **24.8** | **111.8** | **69.3** | **22.3** |
| **SD** | **4.9** | **0.1** | **3.2** | **3.7** | **4.5** | **0.8** |
| **400 m** | | | | | | |
| 1 | 70 | 1.66 | 20 | 51.4 | 55.7 | 18.7 |
| 2 | 83 | 1.89 | 22 | 51.2 | 54.7 | 18.3 |
| 3 | 79 | 1.78 | 22 | 49.7 | 57.2 | 19.8 |
| 4 | 67 | 1.78 | 19 | 50.1 | 55.3 | 19.6 |
| 5 | 67 | 1.76 | 22 | 50.8 | 64.4 | 20.9 |
| 6 | 81 | 1.80 | 23 | 50.2 | 50.1 | 16.8 |
| **n** | **6** | **6** | **6** | **6** | **6** | **6** |
| **M** | **74.5** | **1.8** | **21.3** | **50.6** | **56.23** | **19.00** |
| **SD** | **7.3** | **0.1** | **1.5** | **0.7** | **4.67** | **1.41** |

**Table AIII.2 Peak $\dot{V}O_2$ (ml.kg$^{-1}$.min$^{-1}$) and test duration (s) for 400 and 800 m runs (individual data).**

| | 400 m | | | | 800 m | | | |
|---|---|---|---|---|---|---|---|---|
| | Speed (km.h$^{-1}$) | Time (s) | $\dot{V}O_2$ (ml.kg$^{-1}$.min$^{-1}$) | % $\dot{V}O_2$ max | Speed (km.h$^{-1}$) | Time (s) | $\dot{V}O_2$ (ml.kg$^{-1}$.min$^{-1}$) | % $\dot{V}O_2$ max |
| **800m** | | | | | | | | |
| 1 | 27.7 | 54.6 | 55.4 | 85% | 25.1 | 108.4 | 57.0 | 88% |
| 2 | 26.2 | 55.4 | 62.3 | 88% | 25.0 | 92.8 | 64.5 | 91% |
| 3 | 26.7 | 55.4 | 54.0 | 81% | 23.4 | 138.0 | 55.7 | 83% |
| 4 | 24.8 | 57.9 | 65.4 | 86% | 25.0 | 106.5 | 70.5 | 93% |
| 5 | 24.8 | 58.9 | 58.0 | 90% | 23.4 | 125.4 | 61.4 | 95% |
| 6 | 24.8 | 52.5 | 61.4 | 85% | 24.0 | 79.4 | 61.3 | 85% |
| **n** | **6** | **6** | **6** | **6** | **6** | **6** | **6** | **6** |
| **M** | **25.8** | **55.79** | **59.4** | **86%** | **24.3** | **108.4** | **61.7** | **89%** |
| **SD** | **1.2** | **2.33** | **4.4** | **3%** | **0.8** | **21.2** | **5.4** | **0.05** |
| **400 m** | | | | | | | | |
| 1 | 26.7 | 54.3 | 51.8 | 93% | | | | |
| 2 | 25.7 | 52.9 | 53.3 | 97% | | | | |
| 3 | 27.7 | 58.4 | 51.9 | 91% | | | | |
| 4 | 26.7 | 48.4 | 51.7 | 93% | | | | |
| 5 | 24.8 | 60.2 | 61.1 | 95% | | | | |
| 6 | 24.8 | 56.4 | 47.0 | 94% | | | | |
| **n** | **6** | **6** | **6** | **6** | | | | |
| **M** | **26.07** | **55.10** | **52.78** | **94%** | | | | |
| **SD** | **1.1** | **4.23** | **4.62** | **2%** | | | | |

**Output AIII.1 Paired samples t-test comparing the % $\dot{V}O_{2\,max}$ attained by 800 m event specialists during the 400 and 800 m runs.**

**Paired Samples Test**

| | | Paired Differences | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Std Deviation | Std. Error Mean | 95% Confidence Interval of the Difference Lower | Upper | t | df | Sig (2-tailed) |
| Pair 1 M800 - M400 | 0333 | .02368 | .00967 | .0085 | 0582 | 3 448 | 5 | 018 |

# Output AIII.2 Independent samples t-test comparing the % $\dot{V}O_{2\,max}$ attained by 400 and 800 m event specialists during 400 m running.

**Independent Samples Test**

| | | Levene's Test for Equality of Variances | | t-test for Equality of Means | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | 95% Confidence Interval of the Difference | |
| | | F | Sig | t | df | Sig. (2-tailed) | Mean Difference | Std. Error Difference | Lower | Upper |
| ALL400 | Equal variances assumed | .576 | .465 | -5.121 | 10 | .000 | -.0812 | .01585 | -.11648 | -.04585 |
| | Equal variances not assumed | | | -5.121 | 8.917 | .001 | -.0812 | .01585 | -.11707 | -.04526 |

# APPENDIX IV: STUDY IV

**Table AIV.1 Participant characteristics for Study IV (individual data).**

| Participant | Mass (kg) | Height (m) | Age (years) | PB (s) | Ramp peak $\dot{V}O_2$ (ml.kg$^{-1}$.min$^{-1}$) | Ramp peak speed (km.h$^{-1}$) |
|---|---|---|---|---|---|---|
| 1 | 74 | 185 | 22 | 115.2 | 62.3 | 21.4 |
| 2 | 70 | 179 | 30 | 105.7 | 65.0 | 22.7 |
| 3 | 62 | 167 | 26 | 110.1 | 71.8 | 25.1 |
| 4 | 66 | 181 | 21 | 114.9 | 66.0 | 22.1 |
| 5 | 74 | 187 | 25 | 114.1 | 66.5 | 22.8 |
| 6 | 70 | 179 | 30 | 110.6 | 65.0 | 23.1 |
| 7 | 65 | 170 | 27 | 114.3 | 65.4 | 22.5 |
| 8 | 62 | 176 | 25 | 110.9 | 75.7 | 23.4 |
| **n** | **8** | **8** | **8** | **8** | **8** | **8** |
| **M** | **67.8** | **178.0** | **25.8** | **112.0** | **67.2** | **22.9** |
| **SD** | **4.7** | **6.7** | **3.3** | **3.3** | **4.3** | **1.1** |

**Table AIV.2 Peak $\dot{V}O_2$ (ml.kg$^{-1}$.min$^{-1}$) and test duration (s) for three 800 m pace runs (individual data).**

| | C Pace | | | R Pace | | | A Pace | | |
|---|---|---|---|---|---|---|---|---|---|
| | Time (s) | $\dot{V}O_2$ (ml.kg$^{-1}$.min$^{-1}$) | % $\dot{V}O_2$ max | Time (s) | $\dot{V}O_2$ (ml.kg$^{-1}$.min$^{-1}$) | % $\dot{V}O_2$ max | Time (s) | $\dot{V}O_2$ (ml.kg$^{-1}$.min$^{-1}$) | % $\dot{V}O_2$ max |
| 1 | 126.8 | 54.7 | 88% | 126.7 | 57.3 | 92% | 128.0 | 54.4 | 87% |
| 2 | 111.5 | 56.2 | 86% | 125.2 | 61.6 | 95% | 122.9 | 58.1 | 89% |
| 3 | 78.0 | 63.8 | 89% | 80.7 | 63.9 | 89% | 98.4 | 63.4 | 88% |
| 4 | 138.3 | 59.0 | 89% | 125.9 | 59.6 | 90% | 107.1 | 61.2 | 93% |
| 5 | 80.0 | 59.8 | 90% | 79.4 | 58.5 | 88% | 81.8 | 60.0 | 90% |
| 6 | 111.5 | 56.2 | 86% | 125.2 | 61.6 | 95% | 122.9 | 58.1 | 89% |
| 7 | 110.7 | 60.3 | 92% | 113.2 | 62.0 | 95% | 116.6 | 61.5 | 94% |
| 8 | 106.5 | 70.5 | 93% | 113.4 | 73.1 | 97% | 108.2 | 72.1 | 95% |
| **n** | **8** | **8** | **8** | **8** | **8** | **8** | **8** | **8** | **8** |
| **M** | **107.9** | **60.1** | **89%** | **111.2** | **62.2** | **92%** | **110.7** | **61.1** | **91%** |
| **SD** | **20.7** | **5.1** | **2%** | **20.0** | **4.9** | **3%** | **15.3** | **5.2** | **3%** |

## Output AIV.1 Repeated Measures ANOVA comparing differences among the three 800 m runs in the $\% \dot{V}O_{2\,max}$ attained.

**Mauchly's Test of Sphericity[b]**

Measure: MEASURE_1

| Within Subjects Effect | Mauchly's W | Approx. Chi-Square | df | Sig | Epsilon[a] Greenhouse-Geisser | Huynh-Feldt | Lower-bound |
|---|---|---|---|---|---|---|---|
| RUN | .432 | 5 040 | 2 | .080 | .638 | .716 | .500 |

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b.
Design: Intercept
Within Subjects Design: RUN

**Tests of Within-Subjects Effects**

Measure: MEASURE_1

| Source | | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| RUN | Sphericity Assumed | .004 | 2 | .002 | 4.888 | .025 |
| | Greenhouse-Geisser | .004 | 1.275 | .003 | 4.888 | .048 |
| | Huynh-Feldt | .004 | 1.433 | .003 | 4.888 | .042 |
| | Lower-bound | .004 | 1.000 | .004 | 4.888 | .063 |
| Error(RUN) | Sphericity Assumed | .006 | 14 | .000 | | |
| | Greenhouse-Geisser | .006 | 8.927 | .001 | | |
| | Huynh-Feldt | .006 | 10.029 | .001 | | |
| | Lower-bound | .006 | 7.000 | .001 | | |

**Tests of Within-Subjects Contrasts**

Measure: MEASURE_1

| Source | RUN | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| RUN | Linear | .001 | 1 | .001 | 8.079 | .025 |
| | Quadratic | .003 | 1 | .003 | 4.350 | .075 |
| Error(RUN) | Linear | .001 | 7 | .000 | | |
| | Quadratic | .005 | 7 | .001 | | |

THESIS CONTAINS

VIDEO CD DVD TAPE CASSETTE