AN ASSESSMENT OF PERFORMANCE TESTING IN MIDDLE DISTANCE RUNNING.

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A dissertation submitted to the Faculty of Health Sciences,
University of the Witwatersrand, Johannesburg
in fulfilment of the requirements for the degree of
Master of Science in Medicine.

DECLARATION

I declare that this dissertation is my own, unaided work except to the extent indicated in the acknowledgements and by the reference citations. It is being submitted for the Degree of Master of Science in Medicine at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at this or any other University.

7th of November, 2005

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ZAC van HEERDEN

I certify that the studies contained in this dissertation have the approval of the Committee for Research on Human Subjects (Medical). The clearance certificate number is M00/10/13.

Signature of student	Date
Signature of supervisor	Date

To my family, who have always encouraged me and inspired me to achieve more than I believed was possible.

To Kim, for her unerring support and encouragement.

LIST OF PRESENTATIONS AND PUBLICATIONS ARISING FROM THE STUDY

1. Lathan, Z., McKinon, W. & Rogers, G.G. (2003)
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ABSTRACT

Most performance assessments on athletes involve an excessive amount of testing procedures. The efficacy of these tests is not always apparent, and their application is not always practical. Elite male middle-distance runners (n=20) were used to assess the physiological determinants of 800 meter running performance. We used testing methods recommended by the *South African Sports Commission*, which included body composition, joint flexibility, muscular strength, -power and -endurance, as well as a Wingate test (anaerobic capacity) and an isokinetic evaluation. An assessment of maximal running speed and acceleration at distances up to 300 meters was conducted on a standard tartan track. In addition, maximal oxygen consumption (VO_{2max}), running economy, *onset of blood lactate accumulation* (OBLA) and the *maximal accumulated oxygen deficit* (MAOD) were determined.

Measured values were correlated with competitive performance times using the Pearson product-moment correlation technique, with the Bonferroni correction for multiple comparisons. Wingate mean- and minimum power, as well as running times at 40, 60, 70, 80, 90, 150 and 300 meters were found to be significantly correlated to performance ($r^2 > 0.4$; $p < 0.01$). A multiple correlation comparison was used to determine a significant difference between correlations with performance time for the different variables. A stepwise multiple regression determined that 300 meter time-trial time was the strongest predictor of performance, accounting for 79% of the variability in performance, which was a better predictor of performance than a prediction model. The following formula was derived to estimate 800 meter performance from 300 meter time-trial time:

800m time = 37.1062 + 2.17(300m time) [time in seconds]

The tests most able to predict 800 meter running performance were sport-specific track tests of high-speed running ability and tests of anaerobic capacity (especially the Wingate cycle ergometer test).

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1. INTRODUCTION

An effective testing programme must measure variables that are relevant to the sport concerned, and be as sport-specific as possible (MacDougall and Wenger, 1991). Therefore, the efficacy of a sport-specific battery of testing procedures can be evaluated by assessing the relationship between test results and measurements of performance.

The objective of performance testing in athletes is to provide results and information that facilitate the development an efficient training programme and enhanced performance. The ability to monitor physical and physiological development due to training, as well as recovery processes and readiness to compete, can provide an athlete with a significant advantage (MacDougall and Wenger, 1991; Pyke, 2000). Due to the large number of physical and physiological assessments that exist, the choice of the correct methods is often difficult (Ziltener & Leal, 2005). The lack of objective information to guide this choice is a significant problem.

Current testing protocols employ an approach where all elements of performance are assessed, with little regard for the relevance or suitability of assessment procedures in relation to the sport concerned, despite the lack of definitive evidence pertaining to the relationship between these assessments and actual performance.

1.1. Relevance and suitability of testing procedures

The most relevant and suitable testing procedures will fall into one (or more) of the following three categories:

i. prediction of performance;
ii. monitoring of training;
iii. injury prevention and management.

Modern athletes are subjected to the stresses of regular competition as well as financial pressures, and have limited time available to spend on assessment procedures. Tests must therefore be both time- and cost-effective, as well as highly practical, where the results can be used to influence training methods and other types of interventions.

In addition to these factors, the sensitivity of a testing procedure to changes in physical condition also needs to be considered. This will affect the validity and reliability of a procedure, the efficacy of the testing battery of which it is a part, and the degree to which it can assist athletes and scientific support. (Pyke, 2000)

1.2. Hypothesis and objectives

The hypothesis tested in this study was that certain elements of the test batteries used to assess middle-distance running are not related to actual performance.

The objective of the study was to determine which elements should be retained in an effective and practical test battery, with respect to the prediction of performance and monitoring of training.

1.3. Research design and considerations

We specifically concentrated on the prediction of performance, as this could be objectively measured using statistical procedures. In order to evaluate the ability of tests to accurately predict performance, we examined the following considerations:

1. Certain tests may be effective predictors of performance;
2. Some predictive variables may be more effective than others;
3. Significant variables might be combined into a prediction model.

The findings of the study are intended to assist in the development and refinement of current testing procedures used to assess middle-distance running, and by so doing, improve the effectiveness of testing and associated training methods.

2. LITERATURE REVIEW

2.1. INTRODUCTION

The purpose of this literature review is to highlight the problematic selection of testing procedures used to assess the abilities of middle-distance runners. The financial pressures faced by modern athletes often limit time available for assessment procedures. Athletes tend to concentrate on training methods, nutritional supplementation and ergogenic aids to maintain and enhance their competitive performances. Sub-elite athletes have even less time and financial resources to utilise scientific procedures and expertise to improve their training and performances.

Middle-distance running is a relatively complex event, drawing on both aerobic resources and anaerobic reserves. As it is extremely difficult to train both of these metabolic pathways simultaneously, the importance of scientific assessments as part of training prescription cannot be understated. In addition to assessments and development of these two capacities, tests that evaluate body composition and muscular function may reveal a competitive advantage, which could be used to contribute to ultimate success.

I will attempt to detail those which have been shown to be of value, and test their validity in assessing the ability of the modern middle-distance runner. For purposes of brevity, I have collated the specific details of certain testing procedures in the attached annexures.

2.1.1 Development of middle-distance events

Competitive running dates back to ancient times. The most well-documented history is of Greek and Roman origin, particularly that of the ancient Olympic games (776 BC to 493 AD). In these games, the closest distance corresponding to modern middle-distance events was the “24 stades” (4615 metres), which consisted of 24 laps of the stadium (Gardiner, 1965; Harris, 1972).

The modern Olympic games were revived in 1896, where the 800m and 1500m were two of the six track events included as standard middle-distance events, Edwin Flack of Australia winning both (IAAF, 2004; Mechikoff & Estes, 1998; van Dalen *et al*, 1971).

The predecessor of the 800 metres was the half-mile (880 yards or 804.67m), and was first run in Britain around 1830. The 1500 metres was derived from the mile (1609.32) which is still run today, although as a non-standard distance. It was originally run on the 500-metre tracks of continental Europe in the 1800s. The 5000- and 10 000 metres are metric adaptations of the 3-mile (4828m) and 6-mile (9656m) events. (IAAF, 2004)

Middle-distance events are traditionally defined as the track events which fall between the short-distance (or sprinting) events, such as the 100m, 200m, 400m and hurdle events (110m and 400m), and the longer distance events, such as the 10 000m, half-marathon (21.1km) and marathon (42.2km) distances. There is much debate over which events are defined as middle-distance, with some authors including distances up to 10 000m in this category (Brandon, 1995; Snell, 1990). Traditionally, the 800m, 1500m and the mile are described as true middle-distance events, but most authors would include the 3000m and 5000m, as well as the steeple-chase events (2000m and 3000m), in this category. (IAAF, 2004; Snell, 1990)

From a physiological perspective, it is clear that the shorter middle-distance events have large anaerobic and aerobic contributions (especially the 800m and 1500m), but as the distance and duration of the events increase, the aerobic component becomes dominant. For this reason, it may be erroneous to regard the 10 000m as a middle-distance event, due to the large aerobic component required for success, despite the high running velocity which must involve significant anaerobic energy. This notion is supported by Peter Snell, a former top middle-distance runner and, more recently, a recognized academic in the field of exercise physiology (Brandon, 1995; Snell, 1990).

For the purposes of this dissertation and the research project, I have chosen to concentrate on shorter middle-distance events, particularly 800m and 1500m, as these events are without doubt middle-distance events, both in terms of athletic terminology, and from a physiological perspective.

Table 2.1 (overleaf) demonstrates the progression of world records in middle-distance events from the early 1900s through to present times.

Table 2.1 Progression of world records in the 800m and 1500m events.

800m		1500m	
First official world record			
Ted Meredith (USA)	1:51.9 (1912)	Abel Kiviat (USA)	3:55.8 (1912)
Record progression			
Rudolf Harbig (GER)	1:46.6 (1939)	Jules Ladoumegue (FRA)	3:49.2 (1930)
Peter Snell (NZL)	1:44.3 (1967)	Stanislav Jungwirth (TCH)	3:38.1 (1957)
Sebastian Coe (GBR)	1:42.37 (1979)	Herb Elliot (AUS)	3:35.6 (1960)
Sebastian Coe (GBR)	1:41.73 (1981)	Steve Cram (GBR)	3:29.67 (1985)
Current world records			
Wilson Kipketer (DEN)	1:41.11 (1997)	Hicham El Guerrouj (MAR)	3:26.00 (1998)
Top performers			
Peter Snell (NZL) (1960s)		Herb Elliot (AUS) (1960s)	
Alberto Juantoreno (CUB) (1970s)		Sebastian Coe (GBR) (1980s)	
Sebastian Coe (GBR) (1980s)		Said Aouita (MAR) (1980s)	
Wilson Kipketer (DEN) (1990s)		Noureddine Morceli (ALG) (1990s)	
		Hicham El Guerrouj (MAR) (1990s, 2000s)	

(IAAF, 2004)

At these times and speeds, it is clear that middle-distance running is not dependant on aerobic metabolism alone, but also requires significant contribution from anaerobic energy sources (Brandon, 1995; Snell, 1990).

2.1.2 History of physiological measurements and middle-distance athletes

Measurement of exercise related capacities, such as cardiovascular and respiratory function, date back to the pioneering work of Hill and Lupton in the 1920s, who investigated the relationship between muscular effort, lactic acid production and oxygen consumption. During the same period, Sargent investigated the relationship between running speed and oxygen kinetics, and was one of the first to use middle-distance runners in experimental research. (Hill & Lupton, 1923; Sargent, 1926)

Table 2.2 and 2.3 (on pages 11 and 12) summarize the history of the research dealing with the physical and physiological characteristics of middle-distance runners.

In 1966, Carter conducted a comprehensive study on Peter Snell, one of the most successful middle-distance runners at that time (Carter *et al*, 1966). Dill and his colleagues conducted a similar longitudinal study on sixteen elite middle-distance athletes, using similar methods (Dill *et al*, 1967). In 1974, Jack Daniels published the results of a five-year study on Jim Ryun, a 3-time Olympian, silver medalist in the 1968 Olympic Games and former world record-holder in the mile, 1500m and 880 yards (Daniels, 1974). All these studies were conclusive in their findings that elite middle-distance runners required a large aerobic capacity.

The examination of aerobic capacity and related variables, including neuromuscular function, in elite middle-distance running continues to this day.

Researchers such as Medbo (1988) and Hermansen (1973) expanded the study of aerobic function in the 1980s and early 1990s to include examinations of anaerobic capacity. Other investigators, such as Maffulli (1991ab), Weyand (1994) and Bangsbo (1993), have utilised middle-distance runners for these types of studies. All these studies have indicated that middle-distance runners also require an above average level of anaerobic capacity, in addition to aerobic function. (Brandon, 1995; Medbo *et al*, 1988; Scott *et al*, 1991)

Prominent investigators to utilise athletes in their studies of biochemical function include Svedenhag & Sjodin (1984) and Lacour (2003). Studies have focused on lactate production and removal, as well as the effect of ammonia, and the influence of buffering mechanisms. The results of these studies are somewhat contradictory in their findings, but it appears that middle-distance runners may benefit from improved buffering and removal of the chemical by-products of exercise. (Brandon, 1995; Svedenhag & Sjodin, 1984)

Tanner was amongst the first to examine the role of physique and other physical characteristics with respect to competitive performance in the early 1960s. This groundbreaking work was continued into the 1980s by researchers such as Carter, Ross and Marfell-Jones. (Snell, 1990; Tanner, 1964)

The studies of Carter (1966) and Dill *et al* (1967) mentioned previously, also included examinations of physical or structural characteristics. Studies of the physical characteristics of athletes were conducted at the Olympic Games starting in 1960

(Correnti & Zauli, 1964; Tanner, 1960), as well as in 1968 (deGaray *et al*, 1974) and 1972 (Novak *et al, 1976*). This work all culminated in the *Montreal Olympic Games Anthropological Project* (MOGAP), which studied the physical characteristics of a wide range of athletes at the 1976 Olympic Games, including prominent track-and-field athletes. The research was published throughout the early to mid-1980s, and assisted in the development of many sport-specific assessment techniques and formulae. (Carter *et al*, 1966, 1982abc, 1984ab; Carter & Yuhasz, 1984; Dill *et al*, 1967; Tanner, 1964)

The recent trend in physiological assessment has been primarily in the areas of anaerobic performance, muscular function (particularly isokinetic strength and dynamic function) and biomechanical aspects (such as stride length and the effect of body mass), where a number of investigators have all utilized middle-distance runners in experimental samples. (Maldonado *et al*, 2002; Snell, 1990; Ward-Smith, 1999)

This work all lends to the continued development and refinement of testing procedures that assist in the attainment of maximal performance in middle-distance running. The gap in the literature is primarily in the region of training methods and how the advanced assessment procedures can be used to improve training and competitive performance.

Table 2.2 Landmark studies involving the physical characteristics of male middle-distance runners.

YEAR	AUTHORS	TOPIC
1964	Tanner	Physical characteristics of elite athletes
1966	Carter et al	Assessment of Peter Snell (elite athlete)
1967	Dill et al	Longitudinal study of 16 elite runners
1982a	Carter et al	Body composition of elite athletes
1982b	Carter et al	Somatotypes of elite athletes
1982c	Carter et al	Anthropometry of elite athletes
1982	Ross et al	Proportionality of elite athletes
1983	Fleck	Body composition of elite American athletes
1984a	Carter	Somatotypes of elite athletes
1984b	Carter	Age and body size of elite athletes
1984	Carter & Yuhasz	Body composition of elite athletes
1984	Ross & Ward	Proportionality of elite athletes
1985	Kenney & Hodgson	Predictive variables of performance
1986	Housh et al	Body composition and physical characteristics
1987	Withers et al	Body fat and density in male athletes
1992	Brandon & Boileau	Metabolic, mechanical & physique variables
1998	Manning & Pickup	Symmetry and performance
2002	Maldonado et al	Effects of body mass and height

Table 2.3 Selected studies involving the physiological characteristics of male middle-distance runners, representing the direction of investigation (1920 – 2002).

YEAR	AUTHORS	TOPIC
1926	Sargent	Oxygen cost of running at different speeds
1955	Astrand	Power production and oxygen consumption
1966	Carter et al	Assessment of Peter Snell (elite athlete)
1967	Dill et al	Longitudinal study of 16 elite runners
1967	Saltin & Astrand	Maximal oxygen consumption in athletes
1974	Daniels	Longitudinal study of Jim Ryun (elite athlete)
1980	Conley & Krahenbuhl	Running economy
1981	Taunton et al	Anaerobic performance
1982	Boileau et al	Physiological characteristics of elite runners
1984	Svedenhag & Sjodin	Oxygen consumption and blood lactate
1985	Kenney & Hodgson	Predictive variables of performance
1988	Housh et al	Contribution of variables to performance
1990	Lacour et al	Energetics
1991a,b	Maffulli et al	Aerobic power (a); Anaerobic threshold (b)
1992	Brandon & Boileau	Metabolic, mechanical & physique variables
1992	Daniels & Daniels	Running economy
1992	Padilla et al	Physiological correlates of performance
1993	Bangsbo et al	Oxygen deficit and muscle characteristics
1993	di Prampero et al	Energetics of middle-distance running
1994	Olesen et al	Maximal oxygen deficit
1994	Weyand et al	Predictive value of peak oxygen deficit
1998	Craig & Morgan	Accumulated oxygen deficit
1999	Hill	Energy system contributions
1999	Renoux et al	Oxygen deficit and maximal aerobic power
1999	Ward-Smith	Bio-mechanical relationship with bioenergetics
2002	Maldonado et al	Influence of mass and height on energy cost

2.1.3 Development of pertinent physiological assessments

The current literature suggests that many of the components of traditional test batteries used to assess elite middle-distance athletes are not as important as they might seem. In fact, many of the test components are no longer routinely used, and others have been simplified to increase their application and reduce the cost and time of testing. An example of this is the measurement of body composition, where body fat percentage calculations have been dropped in favour of the sum of skinfolds technique, which is simpler, and can effectively be used to track an athlete's development. (SASC, 2003; Smith *et al*, 2000)

Some researchers debate the legitimacy of the claim that maximal oxygen consumption and running economy have any effect on competitive performance and success (Bassett & Howley, 1997, 2000; Noakes, 1998, 2000), although the majority of researchers still support its importance in middle-distance performance, and recognize that VO_{2max} and running economy are important determinants of the required aerobic capacity for these events (Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992).

Conversely, the importance of anaerobic function and muscular contractility in middle-distance effort has received more emphasis, and is a growing area for both research and performance enhancement, and has been coupled with advances in nutritional supplementation strategies, so common in the modern sporting arena. (SASC, 2003; Smith *et al*, 2000)

These aspects will be dealt with in more detail in Section 2.7, *Standardised Testing Protocols*, where the testing batteries of various national associations and scientific institutions will be examined in more detail.

In the following sections of this literature review, the primary areas of assessment currently conducted on high-performance middle-distance runners will be highlighted. Procedures used by researchers and practitioners in different countries, utilize a wide variety of methods and equipment, and it should be noted that many procedures lack sufficient records of repeatability and validity data. This is due to the fact that this has not been a dedicated area of research, primarily because the study of physical and physiological characteristics has dominated the literature, rather than practical methodological studies of reliability and efficacy.

2.2 BIOENERGETICS OF MIDDLE-DISTANCE RUNNING

2.2.1 Aerobic energy contribution

The three important components of aerobic energy contribution in middle-distance running are *maximal oxygen consumption* (VO_{2max}), *running economy* and *lactate (or anaerobic) threshold*.

Approximately 40% of the total energy used during an 800 metre run, and up to 65% during a 1500 metre run, is provided by aerobic metabolism (Astrand *et al*, 2003). It is clear that although anaerobic energy is required, aerobic capacity is also a determinant of success in middle-distance events (Brandon, 1995).

Both long- and middle-distance runners are known to possess higher levels of aerobic function, although there is some variation in middle-distance runners. Long-distance runners need to provide energy for prolonged periods of time, and are typically able to operate at an intensity corresponding to a level of approximately 75 – 90% of VO_{2max} for over two hours (Daniels, 1985; Brandon, 1995). Middle-distance runners, however, are able to sustain intensities corresponding to above 110% of the velocity of VO_{2max}, but only for periods of approximately 10 minutes (Daniels, 1985; Brandon, 1995).

Aerobic energy contribution takes place in the form of providing energy through glycolysis and the tricarboxylic acid cycle, utilizing primarily glucose, glycogen and other carbohydrates, as well as a small amount of lipid (Astrand *et al*, 2003; Snell, 1990). The effect of lactic acid build up in muscle and buffering capacity are important elements in understanding the contribution of aerobic energy. There are a number of factors that play a role during the phosphocreatine cycle and glycolysis that affect lactate levels, such as enzyme concentrations, endocrine hormone responses and muscle fibre type (Astrand *et al*, 2003; Billat, 1996; Bret *et al*, 2003). Unless there is balance between the production and removal of lactate, accumulation will result. This process is affected by a number of factors other than oxygen delivery and availability, such as concentrations of plasma epinephrine, calcium, lactate dehydrogenase and phosphofructokinase. Importantly, lactate is produced in skeletal muscle tissue at all levels of exercise, but under submaximal conditions is easily exchanged (either by oxidation or recycling) and accumulation does not take place. (Astrand *et al*, 2003; Billat, 1996; Bret *et al*, 2003)

In addition, aerobic metabolism which provides approximately 40 to 66% of the energy requirement during a 800m run only provides energy during the latter stages of the run. The initial energy requirement, in addition to the remainder, must be met by other forms of energy production, which consequently induce excess lactate production (Astrand *et al*, 2003; Brandon, 1995; Billat, 1996; Spencer & Gastin, 2001).

2.2.2 Anaerobic energy contribution

As stated previously, a large amount of the energy required for middle-distance running is derived from aerobic sources, but the balance (35 – 60%) needs to be made up from anaerobic energy (Astrand *et al*, 2003; Brandon, 1995).

Furthermore, it has been determined that an athlete with a 200-metre run time of 22.5 seconds would require a VO_{2max} of 75 $ml.kg^{-1}.min^{-1}$ to achieve an 800-metre time of 1 min 45 seconds. Runners with a lower maximal aerobic capacity are still able to surpass this time, but require a faster running speed and greater anaerobic capacity in order to compensate for the reduction in aerobic energy contribution (Snell, 1990; Brandon, 1995).

Contributions from the two energy systems occur simultaneously, although the dominant energy source early in the run will be primarily anaerobic (Lacour *et al*, 1990). After a period of approximately 45 seconds, aerobic energy begins to be utilized to a greater extent, as oxygen consumption starts to reach maximal values (Brandon, 1995; Snell, 1990).

The initial anaerobic energy sources for events of this intensity are stored phosphocreatine, ATP and oxygen attached to myoglobin. Anaerobic glycolysis (with the concomitant production of lactate) is an essential subsequent metabolic pathway for energy production in middle-distance running, as metabolic stores only account for about 20kJ of available energy. The ability to tolerate elevated blood lactate concentration is therefore an important contributor to performance, as is the efficient removal and resynthesis of the by-products of anaerobic metabolism. (Astrand *et al*, 2003; Maffulli, 1991a)

2.2.3 Acid-base responses

The **lactate (or anaerobic) threshold** is indicated by a number of markers, the most simple of which is the work intensity where an accumulation of more than 4 $mmol.L^{-1}$ in the blood occurs, and is also known as the *onset of blood lactate accumulation* (OBLA). There are also a number of more complicated procedures, utilizing statistical and regression techniques to determine the point at which blood lactate begins to accumulate. Examples of these are the semi-log and log-log techniques (Heck *et al*, 1985; Beaver *et al*, 1985; Yeh *et al*, 1983).

The lactate threshold is an important indicator of the ability to recruit aerobic power, and subsequently the degree to which an athlete can sustain a high intensity of work output (Astrand *et al*, 2003; di Prampero *et al*, 1993). Unless aerobic metabolism is the dominant supplier of energy, anaerobic glycolysis will be the primary source of energy, which will lead to the accumulation of lactate and protons, ultimately resulting in a decline of muscular function (Snell, 1990; Ward-Smith, 1999). Measurements of the lactate threshold can effectively be used as markers of aerobic training state (Coen *et al*, 1991; Craig, 1987).

Other investigators have debated the inconsistency and unreliable nature of lactate measurements as a valid measurement, and have studied the volatility of its reaction to influences, such as circadian rhythms, nutrition and endocrine hormone responses (Bourdon, 2000; Swart & Jennings, 2004). However, a large number of researchers and practitioners regularly use lactate measurements to measure intensity of effort, recovery processes, and to assist in the accurate prescription of training (Bourdon, 2000; Craig, 1987).

Buffering capacity is therefore an important limiting factor in middle-distance running performance. The ability to absorb excess protons produced by anaerobic processes will allow an athlete to compete at a higher intensity for a longer period of time. A number of researchers have investigated the mechanisms of improving buffering capacity (Potteiger, 2000; Sharp *et al*, 1986). The findings of these studies are conclusive in terms of providing evidence that training needs to be race-specific in terms of speed and intensity. This will cause adaptation of metabolic processes (by increasing anaerobic enzymes and circulatory improvements) and improve buffering capacity of both muscle cells and the extracellular environment (Parkhouse & McKenzie, 1984; Sharp *et al*, 1986). Use of repetition running and interval training have been shown to be the best training types to cause these adaptations and adjustments (Snell, 1990; Potteiger, 2000).

2.2.4 Muscle fibre type and distribution

Studies of muscle fibre type and distribution in middle-distance athletes have been relatively inconclusive, as there is a large amount of variability in this group of athletes. As expected, athletes that depend on aerobic energy will possess a larger degree of type 1 fibres (slow oxidative), whilst those that utilize higher running speeds and anaerobic reserve may be predominantly type 2a and 2b fibres (fast oxidative-glycolytic and fast glycolytic) (Astrand *et al*, 2003). Costill *et al* (1976) found that middle-distance runners tend to have an even distribution of both type 1 and type 2a fibres. The metabolic properties of these fibres needs to be enhanced by specific training, an important implication for competitive success.

2.2.5 Biomechanical factors

The primary biomechanical factor studied in middle-distance running has been the influence of running speed and stride length on running economy, as well as the measurement of power output during simulated performances (Daniels & Daniels, 1992; Ward-Smith, 1999). Research studies evaluating the relationship between running speed and economy have found that middle-distance runners (800 and 1500m) were the most economical at running speeds above marathon pace, when compared to athletes competing in other running events (Daniels & Daniels, 1992). In addition, middle-distance athletes are also more prone to fluctuations in running economy and in variations to stride length dependant on the progression of speed and racing tactics (Daniels & Daniels, 1992; Svedenhag & Sjodin, 1994).

Some investigators have found that stride length and the effect of running speed on economy are highly stable (Brisswalter & Legros, 1994; Brisswalter *et al*, 1996), whereas other researchers have found large degrees of variability (Morgan *et al*, 1991). Clearly this work is inconclusive and incomplete, and requires further investigation.

Studies investigating submaximal and maximal power outputs have been conducted on a wide range of ergometers and treadmills, as well as utilizing simulated performances on specially designed running tracks. Results indicate that middle-distance runners have above average capacity, particular in assessments of peak power output, such as the Wingate test. (Granier *et al*, 1995; Nummela *et al*, 1996ab; Taunton *et al*, 1981)

2.3 ANTHROPOMETRY

Anthropometrical measurements provide an assessment of an athlete's musculo-skeletal status at any given time (Ross & Marfell-Jones, 1991). They are therefore, invaluable in relation to four important aspects of athletic performance and development:

i) efficacy of nutritional and exercise interventions that alter body composition;
ii) estimation of ideal body mass (for certain events or sports);
iii) formulation of appropriate dietary recommendations and exercise prescription;
iv) monitoring of growth, development, maturation and age-related changes in body composition.

(Heyward & Stolarczyk, 1996)

Anthropometric measurements can therefore be useful monitors of changes that occur due to training methods and nutritional interventions, particularly through measurements of muscle and fat mass. Four different types of anthropometrical measurements are used:

i) body dimensions (mass and stature);
ii) limb and segmental girths (circumferences of musculo-skeletal structures);
iii) limb, joint and segmental breadths (diameters);
iv) skinfold thickness measurements.

(Heyward & Stolarczyk, 1996; Norton *et al*, 2000; Ross & Marfell-Jones, 1991)

Raw values, such as the *sum of skinfolds*, *segmental circumferences* and *bone diameters*, are often used for comparative purposes to assess changes due to growth, maturation and training adaptations. These values are also used to derive other measurements such as somatotypes, anthropometrical indices (such as body mass index and ponderal index) and body composition values.

2.3.1 Body composition

Body composition can be determined by a number of methods, including indirect estimation from other variables, such as anthropometric or conductivity measurements, and from techniques based on prediction models. These methods include:

- Hydrostatic (underwater) weighing
- Dual-energy X-ray absorptiometry
- Skinfold methods (using skinfold thickness measurements)
- Bio-electrical impedance analysis
- Near-infrared interactance
- Anthropometric methods
- Ultrasonic methods

(Gnaedinger *et al*, 1963; Heyward & Stolarczyk, 1996)

Methods involving measurements of skinfold thickness are routinely used in the assessment of athletes, as they require the simplest equipment in comparison to other techniques. Anthropometric methods (using other anthropometric values) are not used as commonly, due to the difficulty of the measurement techniques involved. Bio-electrical impedance analysis, although uncomplicated and practical, suffers from a lack of reliability, due to differences in testing equipment, and non-compliance to pre-test procedures by test subjects (especially dietary intake). (Heyward & Stolarczyk, 1996; Ross and Marfell-Jones, 1991; Norton *et al*, 2000)

There are a number of different body composition models, involving chemical, metabolic and anatomical divisions of the human body. The most simple of these is the *two-component model*, which separates the body into fat and fat-free (or lean) masses (Brozek *et al*, 1963; Heyward & Stolarczyk, 1996; Siri, 1961).

The most complete and applicable model for athletic subjects, is the *four-component anatomical model*, which separates the body into four components:

i) adipose tissue (fat);
ii) muscular tissue;
iii) skeletal tissue (bone and primary articular attachments);
iv) residual tissue (skin, hair and other viscera).

(Drinkwater, 1984; Friedl *et al*, 1992; Heyward & Stolarczyk, 1996)

The measurement of adipose tissue is of particular importance with regard to the assessment of nutritional status and associated interventions. Measurement of muscle mass is commonly used to assess the effect of appropriate training programmes, whilst measurement of skeletal tissue is commonplace in the study of growth and maturation. Table A.1 (on page 194 in the annexure) lists equations commonly used to determine the proportion of fat mass in elite male middle-distance runners.

Calculations of body composition variables can be time-consuming and inaccurate, and the new trend is towards the sum of skinfolds measurement, where a number of important skinfold site measurements are merely summed. This score can then be easily used for comparative purposes during re-assessments of an athlete. (Smith *et al*, 2000)

The measurement of muscle mass (also known as lean- or fat-free mass) is another routine measurement. Martin *et al* (1990) developed a formula for the calculation of muscle mass in man, employing simple anthropometric variables, using the measurements listed below:

- height in cm (S)
- mid-thigh girth in cm, and anterior thigh skinfold in mm
- calf girth in cm and medial calf skinfold in mm
- forearm girth in cm (FG)

Mid-thigh (CTG) and calf girths (CCG) are corrected for fat content. Formulae used for this procedure are shown in the annexure. Tables A.2 and A.3 (on page 195 in the annexure) list important equations pertinent to the determination of fat-free (or lean) mass in adult, male athletes.

Norms associated with the measurement of body composition values are dependant on a number of factors:

i) event intensity and duration;
ii) predominant training methods;
iii) ethnic group and socio-cultural influences;
iv) environmental influences.

(Carter *et al*, 1982; Norton *et al*, 2000)

Norms for a number of body composition variables, including height and mass are shown in Table 2.4 (overleaf).

Table 2.4 Body composition norms for elite male middle-distance athletes.

MEASUREMENT	Smith *et al*, 2000	Carter *et al*, 1984ab 1960	1968	1972	1976	Pollock *et al*, 1963	Thorland *et al*, 1981
Height (cm)	181.6 ± 6.0	177.7	178.0	177.2	178.3	176.0 ± 5.0	177.3 ± 5.8
Mass (kg)	75.8 ± 6.2	67.8 ± 7.8	65.1 ± 7.1	63.2 ± 6.8	65.5 ± 6.7	63.1 ± 5.3	65.9 ± 5.9
Sum of skinfolds (mm)	36.1[1] ± 7.4	17.7[2] ± 4.4	___	29.9	32.4 ± 5.9	36.7* ± 7.4	___
Body fat percentage (%)	___	___	___	___	___	5.0 ± 3.5	7.3 ± 2.3
Fat-free (lean mass) (kg)	___	___	___	___	___	59.9 ± 4.9	58.3 ± 5.3

[1] Sum of 7 skinfolds : tricep, bicep, subscapular, supra-iliac, abdominal, anterior thigh and medial calf.

[2] Sum of 6 skinfolds : tricep, subscapular, supra-iliac, abdominal, anterior thigh and medial calf.

2.3.2 Somatotyping and proportionality

Somatotyping (or somatotopy) is a technique used to describe and quantify physique and external body shape. It was first described by Sheldon (1940), and progressed and developed by a number of researchers, including Lindsay Carter, Barbara Heath and William Ross. The dominant technique used in the assessment of athletes is the Heath-Carter method. The initial data collection consists of the following:

- 4 skinfolds (triceps, subscapular, supraspinale and medial calf)
- 2 joint breadths (bi-epicondylar – distal humerus; bi-condylar – distal femur)
- 2 girths (flexed upper arm and calf[3])

The somatotype consists of three ratings between 0 and 7 for three components. The three components are defined as follows:

- Endomorphy (relative adiposity)
- Mesomorphy (relative musculoskeletal robustness)
- Ectomorphy (relative linearity)

Details of the calculations used in the procedure are shown in Table A.4 (in the annexure) on page 196. Somatotype norms for elite male middle-distance athletes are shown in Table 2.5 (page 30).

[3] girths are subsequently corrected for subcutaneous fat content

In addition to the anthropometric formulae, the somatotype classification can also be performed by means of a photoscopic method, involving the assessment of scaled photographs. Views of the subject posing in the anatomical position, but with the forearm in the neutral position, are taken from the front, rear and left-side.

(Carter, 1980; Ross & Marfell-Jones, 1991; Ross *et al*, 1988)

Proportionality is a mathematical procedure that establishes a relationship between measured anthropometrical variables and a standard unisex reference body (the Ross phantom). Statistical methods are used to determine z-scores for each measured variable in comparison to the reference body. Anthropometric measurements are converted to z-scores, which indicate the degree to which a particular anthropometric variable differs from the phantom reference. A positive z-score indicates that the measured value is proportionately greater than the reference, whereas a negative value indicates that it is proportionately smaller. The magnitude of the z-score indicates the number of standard deviations by which the measured value differs from the reference.

(Carter, 1982c; Drinkwater, 1984; Ross & Marfell-Jones, 1991)

The objective of the technique is to provide a conceptual frame for analysing patterns and distributions of anthropometric variables. Proportionality data can be used to establish anthropometric patterns in particular populations, or to assist in the identification of particular physical characteristics.

(Carter, 1982c; Ross *et al*, 1988; Ross & Marfell-Jones, 1991)

In my opinion, proportionality data is of limited value unless testing is done on a regular basis. Details of the procedures used for proportionality measurements are shown in Tables A.5 and A.6 on pages 197 and 198 respectively in the annexure.

Table 2.5 Somatotype and proportionality norms for elite male middle-distance athletes.

SOMATOTYPE	Carter et al, 1982	Carter, 1984
Endomorphy		1.5
Mesomorphy	5.0 (± 1.33)	4.3
Ectomorphy	2.9 (± 1.04)	3.6

PROPORTIONALITY	Ross et al, 1982	Ross et al, 1984
Proportional body mass (mean)	61.7 kg	
Body mass mean z-score	- 0.33	
Standard error	0.52	
Extremity lengths[4]		↑
Trunk height		↓
All breadths		↓
Calf girth		↓
Tricep skinfold		↓

[4] All other recorded variables (not listed in this table) are similar between male middle-distance runners and the population norm. A positive value (↑) indicates that the mean z-score for this attribute is lower than the population norm, and a negative value (↓) indicates the opposite.

In conclusion, anthropometrical measurements of elite male middle-distance athletes have yielded that the ideal body type or physique should be a combination of moderate height, light weight and low body fat. This should provide an athlete with a mechanical advantage in these high-intensity running events. Their somatotypes characteristics should yield either dominant ectomorphic or mesomorphic characteristics. Proportionality data indicates the importance of long limbs and shorter trunk for these events. (Carter, 1982c, 1984; Ross *et al*, 1984; Tanner, 1964)

Successful competitors who fit this profile are:

- *Wilson Kipketer*, the current world-record holder (64 kg; 1.72m)
- *Hezekiel Sepeng*, Olympic silver-medalist (58kg; 1.78m).

However, a number of successful competitors do not fit this profile, such as:

- *Sebastian Coe*, the former world record-holder (75kg; 1.75m)
- *Joaquim Cruz*, 1984 Olympic gold-medalist (77kg; 1.88m)
- *Nils Schumann*, 2000 Olympic gold-medalist (70kg; 1.92m).

(Carretta, 2004; IAAF, 2004)

Due to these discrepancies, measurements of physical characteristics may only be of limited value in predicting performance and competitive success, and are probably best suited to be used as indicators of nutritional and training state.

2.4 MUSCULAR ASSESSMENT

2.4.1 Flexibility measurements

Flexibility is defined as the “range of motion at a single joint, or a series of joints” (Hubley-Kozey, 1991), and is a measure of the ability of muscle and tendon structures to elongate in opposition to the physical restrictions and resistance provided by joint structures. The resistance and restrictions to joint range of motion (ROM) include neurogenic, myogenic, articular and connective tissue (frictional) constraints (Alter, 1998; Hutton, 1992).

Flexibility measurements are primarily used as injury prevention measures, and research has shown that improvements in flexibility can reduce the incidence of injuries (particularly musculotendinous strains) (Alter, 1998; Hubley-Kozey, 1991). Conversely, other investigators have found that excessive laxity of joints may in fact contribute to the incidence of injuries (Cross & Worrell, 1999; Jackson et al, 1978).

The need for good flexibility, and therefore the importance of flexibility measurements in distance running is considered to have low relevance (Hubley-Kozey, 1991). There may, however, be some relationship between the flexibility of lower limb structures with stride length, power production and economy (Gleim et al, 1990; Hortobagyi et al, 1985; Shorten, 1987). In addition, flexibility may be an important tool for injury prevention, particularly due to the chronic overuse conditions induced by training and competition.

Most testing batteries for middle-distance runners employ flexibility measurements, but most are not justified, or of limited practical use. The Australian Sports Commission, a leading authority on test procedures and their practical use, does not recommend any flexibility measurements as part of its testing procedures for high-performance runners (Smith et al, 2000).

The primary joints recommended by other investigators in middle-distance events are listed below, with recommended tests in parentheses:

i) HIP (modified Thomas test – iliopsoas and quadriceps femoris),

ii) KNEE (straight leg hamstring test and modified Thomas test),

iii) ANKLE (ankle dorsi- and plantarflexion), and

iv) LUMBAR REGION (modified sit-and-reach – hip extensor group).

(Hubley-Kozey, 1991; SASC, 2003; SISA , 2000)

These testing procedures are widely used, and may actually serve a practical purpose in high-performance running, particularly in terms of identifying injury risk in specific muscle groups (especially the hip extensor and ankle plantarflexor groups). However, a lack of definitive practical guidelines and misuse of flexibility training methods reduces the effectiveness of the measurements (Harvey & Mansfield, 2000).

2.4.2 Muscular strength, power and endurance

2.4.2.1 Rationale for measurement

Muscular strength and power are important components of performance in many sports and athletic events (Abernethy & Wilson, 2000). There is a distinct difference between these two, and the influence of muscular endurance must also be recognized.

Muscular strength is defined as peak force development during maximum voluntary contraction (MVC). Muscular power is defined as the rate at which mechanical work is performed (Sale, 1991). Muscular endurance is described as the ability to produce force over an extended time period, prior to the onset of fatigue (Enoka, 1988; Sale, 1991, 1992). Muscular endurance should not be confused with aerobic endurance and capacity.

Higher levels of muscular strength and power would be of advantage to a middle-distance athlete in terms of improving maximal speed and acceleration. Strength training generally increases muscle size and therefore mass, and thus, running economy may be affected due to the increased mass, canceling out the speed advantage (Enoka, 1998; Sale, 1991, 1992). It is possible to increase muscular strength, power and contractility without increasing muscle size and mass, by using training methods that facilitate neural adaptation with minimal structural increase, where the focus is on proprioception and muscular co-ordination (Enoka, 1988).

The purposes of muscular strength, power and endurance testing are:

i) determining the relevance and importance of muscular strength and power to performance;

ii) developing an athlete profile (individual and collective);

iii) monitoring of training progress;

iv) monitoring the rehabilitation of injuries.

(Sale, 1991; Wrigley & Strauss, 2000)

2.4.2.2 Criteria for the selection of testing methods

i) Specificity : testing of strength and power should be made as specific as possible to the sport concerned, by incorporating the following aspects of muscular action:

- Muscle group involvement
- Movement pattern
- Contraction type
- Velocity of movement

ii) Data acquisition and analysis : easy and effective set-up as well as uncomplicated collection and analysis of test data are necessary when testing athletes, and the use of computerized systems is therefore an important factor in test selection.

iii) Feasibility : a primary constraint in the testing of athletes is the availability and cost of specialized equipment. Consequently, specificity is often reduced when commonly available equipment is preferred to more expensive or unavailable dynamometry devices (Sale, 1991).

For this reason, tests of muscular function in athletes are usually restricted to the first level of specificity (i.e. assessing single-joint movements involving the appropriate muscle groups). Isokinetic dynamometry is widely considered to be the most acceptable method for satisfying all these criteria (Sale, 1991; SASC, 2003; Wrigley & Strauss, 2000).

The Australian Sports Commission, a leading authority on test procedures and their practical use, does not recommend any muscular strength or power measurements as part of its testing procedures for high-performance runners (Smith et al, 2000).

2.4.2.3 Static measurement

Static muscular strength refers to the assessment of muscular function under static conditions, where an athlete is connected to a closed chain device, such as a dynamometer or weightlifting apparatus. The measurements are also relatively crude, with only simple variables such as total mass or force recorded (Abernethy & Wilson, 2000; Sale, 1991).

There are three types of static muscular strength measurements:

1. **Weightlifting manoevres** involve measurement of the heaviest weight that can be lifted through a specified range of movement. The *one-repetition maximum* (1RM) is a common technique used for these assessments (details of the procedure are detailed in the annexure). It is recommended that this testing be specific to the movement pattern of the sport involved (Abernethy & Wilson, 2000; Baechle *et al*, 2000; Sale, 1991).

   Tests which may be of use in middle-distance athletes include 1RM measurements using the *incline leg press* and *back*- or *front squat* (SASC, 2003; SISA, 2000).

2. **Isometric tests** requires subjects to exert maximal force against a static resistance. They have been one of the most popular methods of strength assessment over the last 50 years, primarily due to their simplicity, reliability and

ease of standardization. Unfortunately, they are of limited practical value in athletic assessment as they do not have a sufficient relationship with dynamic muscular strength or function (particularly in sport skills that involve complex high-speed recruitment patterns), and therefore are not recommended for use (Sale, 1991; Wilson, 2000).

3. **Isotonic tests** involve the measurement of force under conditions of constant tension. Unlike isokinetic tension, where velocity of movement is constant, isotonic dynamometers measure the velocity of movement. Arguably, it is impossible for muscles to generate a constant force during any sports skill, with the exception of a static contraction, due to the acceleration and retardation effects that occur during almost all co-ordinated movements (Sale, 1991)

2.4.2.4 Dynamic measurement

Dynamic muscular strength refers to the assessment of muscular function under dynamic conditions, where an athlete is connected to a dynamometer or other device that is able to more accurately and objectively record measurements of muscular function, particularly at numerous joint angles and velocities.

There are three types of dynamic muscular strength measurements:

1. Isokinetic dynamometry

Isokinetic contraction is defined as muscular contraction under conditions of constant angular velocity (Baltzopoulos & Brodie, 1989). The device employed to measure this form of muscular action was first produced in the late 1960s, and is electromechanical in nature, where the resistance of the dynamometer is equal to the muscular forces produced throughout the range of motion (Kannus, 1994).

The integration of isokinetic dynamometers with computerized data acquisition and analysis allows for rapid measurement of numerous parameters, as well as quick and easy interpretation of results (Baltzopoulos & Brodie, 1989; Kannus, 1994).

The ease of use and real-time data, as well as the adaptability of the equipment, are an advantage in the testing of athletes. The primary disadvantage of this type of testing is that isokinetic (constant velocity) movements seldom occur during human performance tasks, and that testing takes place by means of isolating joint structures, which reduces specificity. There is also the possibility of injury during assessment procedures, due to the high-intensity of effort and load exerted (Baltzopoulos & Brodie, 1989; Kannus, 1994). Isokinetic movements and assessments have nevertheless been widely employed in rehabilitation, muscular assessment, training and for injury prevention for over two decades (Baltzopoulos & Brodie, 1989; Wrigley & Strauss, 2000).

There are a number of measurement parameters that can be obtained from isokinetic testing, but a large number of these lack validity, reproducibility and relevance (Kannus, 1994). Peak or maximum torque is one parameter that does not suffer from these shortcomings, and is recommended for both assessment and research procedures. Measurements of muscular endurance, using work performed during multiple repetitions at high velocity (greater than $240^{\circ}.s^{-1}$) have been shown to be of value (Baltzopoulos & Brodie, 1989; Kannus, 1994).

Other parameters, such as angular positions (especially for peak torque), torque-velocity relationships and reciprocal muscle group ratios, although widely used, have not been shown to be significantly reliable and of limited practical value (Baltzopoulos & Brodie, 1989; Kannus, 1994).

The most emphatic advantage of the isokinetic dynamometer is that it is widely available, due to its orthopaedic and rehabilitative uses, and is also highly adaptable. Protocols for assessments are easily modified according to the specialized requirements of an athletic event, in terms of the type and velocity of contraction. Most dynamometers can also be used to assess other elements of muscular function, such as limb acceleration and dynamic flexibility (Sale, 1991; Wrigley & Strauss, 2000).

In addition, newer and more practical protocols, such as force-velocity curves can be obtained, as improvements in technology and electronics take place (Sale, 1991; Vandewalle *et al*, 1987). For a description of measurements using force-velocity curves, see page 61. The isokinetic dynamometer cannot be ignored as an extremely useful and versatile assessment tool, despite some limitations.

Table 2.6 Selected values for isokinetic variables pertinent to male middle-distance runners for knee flexion and extension.

Peak extensor torque ($N.m.kg^{-1}$)	$60^{o}.s^{-1}$	approx[5] 2.7
	$180^{o}.s^{-1}$	approx 1.6
	$300^{o}.s^{-1}$	approx 0.8
Flexor : extensor peak torque ratio (%)	$60^{o}.s^{-1}$	64 ± 8.0
Concentric peak torque (N.m)	$60^{o}.s^{-1}$	225 – 250
Eccentric peak torque (N.m)	$60^{o}.s^{-1}$	275 – 400[6]

(Rankin & Thompson, 1983; Johansson, 1992)

[5] These values are approximated, as they were derived from figures with imprecise scale.
[6] NOTE the much higher variability in eccentric torque, when compared to the concentric range.

2. Controlled variable velocity and resistance tests

Measurements of muscular action that more closely mimic the recruitment and contraction patterns found in complex motor skills have been developed, but are heavily reliant on advanced and expensive equipment. The focus of such procedures involves controlling the velocity and resistance at different points within the range of motion.

Most movement patterns employed in sport skills are neither isotonic nor isokinetic in nature. The force-velocity relationship of muscular contraction changes throughout the range of motion (Sale, 1991). It is now possible to determine the pattern of movement velocity during skilled movements, particularly through the use of video footage and computerized three-dimensional motion analysis. Using this data, it is possible to programme a dynamometer to simulate the resistance and velocity pattern of skilled movements to more accurately measure muscular function (Wrigley & Strauss, 2000).

Traditional strength curves are derived from isometric or isokinetic devices (Hay, 1992), but as advances in the available technology take place, the accuracy of assessment procedures will improve, allowing more practical and realistic methods to be used in the assessment of athletic performance.

3. Isoinertial (stretch-shortening cycle) tests

Isoinertial strength refers to a constant resistance to motion, rather than a constant load. Tests that evaluate isoinertial properties commonly employ measurement of the stretch-shortening cycle (Logan *et al*, 2000; Sale, 1991).

The groundbreaking work in the capacity of the stretch-shortening cycle was orchestrated by Paavo Komi, particularly *in vivo* experiments where force transducers were implanted into human subjects, which were used to measure (in combination with electromyography) elastic forces during various movement tasks, such as running, jumping and landing (Komi, 1990; Komi *et al*, 1987ab).

The tests employ large muscle-mass movements, particularly jumping (where gravity acts as the constant resistance). The simplest equipment used are measurement boards to calculate jump heights. With technological advancement, force plates and platforms are used during the movements to determine force, work, power and impulse. Specialized dynamometers can also be used to measure concentric and eccentric phases of the test movements (Logan *et al*, 2000; Sale, 1991).

Force-velocity curves are also easily constructed by manipulating the resistance during successive jumps. This is done by altering the mass of the subject (in standard jumps), or by changing jump height (in eccentric drop or depth jumps) (Logan *et al*, 2000; Sale, 1991).

There are two types of isoinertial strength assessments:

i) <u>Maximal isoinertial strength tests</u>

Maximal isoinertial strength is defined as the maximum resistance that can be overcome. It can be subdivided into two further categories, dependant on the muscle action associated with the phase of force production:

a) *Maximal concentric strength* – determined by the greatest resistance that can be overcome concentrically. Typical tasks involve positive work through the range of motion (against gravity), such as lifting or jumping.

b) *Maximal eccentric strength* – determined by the greatest resistance that can be resisted eccentrically. Typical tasks involve negative work through the range of motion (with gravity), such as landing from jumps or controlling a mass.

Typical assessments are low-repetition maximum tests such as the one-repetition maximum (1RM) test, utilizing weight machines or traditional weightlifting apparatus.

(Logan *et al*, 2000; Sale, 1991)

ii) <u>Isoinertial speed-strength tests</u>

Isoinertial speed-strength is defined as the capacity to overcome resistance with the greatest possible contraction speed. There are three different categories of isoinertial speed-strength, based on different means of producing power:

a) *Short-term (starting) strength* – defined as the ability to produce the greatest possible strength in the shortest time possible, requiring rapid force production at the beginning of the contraction. (Logan *et al*, 2000; Sale, 1991)

b) *Explosive strength* – defined as the ability to continue to develop force at a rapid rate after the initiation of a movement. (Logan *et al*, 2000; Sale, 1991)

c) *Isoinertial stretch-shortening cycle (SSC) strength* – also known as reactive strength, and is a combination of muscular force production, reflex activity of neuromechanical devices, and elastic properties of the non-contractile elements of the musculo-skeletal system. This combination allows for rapid recruitment and contraction of muscle fibre in order to produce higher amounts of force. (Logan *et al*, 2000; Sale, 1991)

4. Tests and equipment used in the evaluation of isoinertial strength:

i) <u>One-repetition maximum (1RM) tests</u> : Lower body evaluation typically involves the squat or leg press, whilst the bench press is normally used for the upper body. These tests are not particularly effective measures of isoinertial strength as the movements are performed under control (at low velocity), as opposed to skilled movements, which take place at high velocities with a relative lack of control.

ii) Jump tests : The different forms of the vertical jump test (see section 3.3.5.1 on page 111) have been reliable measures of explosive strength and maximal muscular power for over 40 years, and continue to set the benchmark in isoinertial evaluation of the lower body, particularly with the use of force plates and platforms, reaction boards and transducers.

iii) Machine throws : This is a more recent derivation of the jump tests modified to allow assessment of the upper body. The use of equipment specifically designed to measure force production and impulse during throwing movements has made these assessments feasible.

(Logan *et al*, 2000; Sale, 1991)

It is obvious that tests of isoinertial strength appear to be the most effective means of combining assessments of muscular strength and simulation of actual performance. They are, however, highly dependant on the availability and operation of technologically advanced instrumentation which allows for accurate and simplified (through data filtering) acquisition and analysis of data.

(Logan *et al*, 2000; Sale, 1991)

2.5 ANAEROBIC ASSESSMENT

Anaerobic capacity is defined as the maximal amount of energy (specifically *adenosine triphosphate*) that can be used and resynthesized by means of anaerobic processes during short-duration maximal exercise. It is extremely difficult to measure anaerobic capacity because, unlike oxygen consumption, there is no practical parameter that can be easily measured to directly determine energy production or consumption. (Astrand *et al*, 2003; Green & Dawson, 1993)

As stated previously, 40 – 66% of the energy used during middle-distance events is derived from aerobic sources (Astrand *et al*, 2003). The balance of the energy requirement (35 – 60%) must therefore be met by anaerobic metabolism. A study of cross-country runners determined that anaerobic work capacity, together with VO_{2max}, accounted for 58% of the variability in performance (Bulbulian *et al*, 1986). This demonstrates the significant contribution of anaerobic metabolism during high-intensity running.

Komi *et al* (1977) evaluated the anaerobic performance capacities of athletes from a wide range of events, and separated them into three distinct categories:

i) the "phosphagen" group, which contains power-based athletes and ski-jumpers;
ii) the "anaerobic glycolysis" group, containing ice-hockey players and alpine skiers;

iii) the remainder of the athletic events were categorized into the "aerobic demand" group, consisting of events with varying degrees of aerobic function.

Middle-distance athletes (a group of 800 m runners) fell into the third category, where aerobic demand was dominant. Anaerobic capacity (particularly anaerobic or speed-endurance) was determined to be an important performance element for middle-distance runners. This finding is supported by Bulbulian *et al* (1986), who highlights the "multifactorial" approach in evaluating middle-distance running performance, stressing the combination of both anaerobic and aerobic capacity.

Table 2.7 (overleaf) shows a variety of anaerobic performance test data for 800m athletes

Table 2.7 Selected anaerobic performance test data for 800m athletes (n=6).

Measurement	Mean	Standard deviation
Vertical velocity ($m.s^{-1}$)[A]	1.4	± 0.2
Muscular power ($kg.m.s^{-1}$)[B]	101.8	± 19.3
Total leg force (kg)[B]	296.0	± 84.0
Relative leg force (kg / kg body mass)[B]	4.06	± 1.06
Peak blood lactate ($mmol.L^{-1}$)[C]	13.9	± 2.1
% fast twitch fibres[D]	55	± 16

[A] Obtained from the Margaria step test (see section 2.5.4.3)

[B] Obtained from strength dynamometry

[C] Obtained after maximal treadmill runs and arm ergometry

[D] Obtained from *vastus lateralis* biopsy

(adapted from Komi 1977)

Tests are separated into two types, which will be examined in further detail in the subsequent sections.

Tests of anaerobic and peak power typically involve evaluations of force-velocity relationships, vertical jump tests, step or staircase runs, and cycle ergometer tests. They involve measurement of the alactic anaerobic systems that utilize phosphocreatine pathways and other forms of stored energy.

(Astrand *et al*, 2003; Vandewalle *et al*, 1987)

Tests of anaerobic capacity (also known as anaerobic endurance) include measurements of maximal oxygen debt, ergometer power, oxygen deficit and peak blood lactate concentration.

(Green & Dawson, 1993; Vandewalle *et al*, 1987)

Bouchard *et al* (1991) discriminate between three types of anaerobic capacity:

i) short-term anaerobic performance capacity (approximately 10 seconds duration);
ii) intermediate-term anaerobic performance capacity (approximately 30 seconds);
iii) long-term anaerobic performance capacity (approximately 90 seconds).

For the purposes of this review, I will use this classification system to describe the types of tests used to evaluate anaerobic capacity in athletes.

2.5.1 Short-term anaerobic performance capacity

Tests of short-term anaerobic capacity (which evaluate peak- or anaerobic power) are designed to measure the alactic anaerobic processes that utilize the phosphocreatine cycle (Astrand *et al*, 2003; Vandewalle *et al*, 1987). They therefore should be substantially less than ten seconds in duration, and should elicit maximal exertion (Bouchard *et al*, 1991).

2.5.2 Intermediate-term anaerobic performance capacity

This category consists of both alactic (phosphocreatine) and lactic (anaerobic glycolysis) components, with proportions contributing approximately 30% to 70% respectively. Bouchard *et al* (1991) recommend a duration of approximately 30 seconds for tests of this nature. The Wingate test is the benchmark assessment for this category, although research has shown that the lactic anaerobic capacity is not fully exhausted by this procedure (Bouchard *et al*, 1991; Vandewalle *et al*, 1987).

2.5.3 Long-term anaerobic performance capacity

This category consists of tests that fully exhaust the lactic anaerobic processes and are about 90 seconds in duration. 90 to 95% of the required energy is provided by anaerobic glycolysis, with small contributions from phosphocreatine (initially) and aerobic sources (Astrand *et al*, 2003; Bouchard *et al*, 1991; Vandewalle *et al*, 1987).

2.5.4 Tests of anaerobic performance capacity

2.5.4.1 Track tests

Track tests are the most simple to set up and conduct, and require only rudimentary equipment to measure accurate time and distance accurately. The use of sophisticated timing equipment, such as photo-electric cells and timing mats, greatly increases measurement accuracy. This also assists in eliminating tester and equipment errors, as well as removing factors such as reaction time from test results.

(Bouchard *et al*, 1991; Smith *et al*, 2000)

The advantages of track tests are their simplicity and specificity (particularly for sports and athletic events that involve running). They are also easily modified to assess different performance capacities. The primary disadvantages are the sources of timing error (where rudimentary equipment is used), and although the results can be applied practically to prescribe training, re-testing does not always reveal changes in performance. This is due to the large number of biomechanical factors, such as stride length and frequency, that affect running speed and ability. (Bouchard *et al*, 1991; Snell, 1990)

Running distances can be altered as follows to assess the three different types of anaerobic capacity:

i) short-term capacity : less than 60m distance (up to 100m, dependant on the ability of the athlete;

ii) intermediate-term capacity : 200 – 300m (dependant on the ability of the athlete);

iii) long-term capacity : 90 second run (approximately 600 -700m).

(Bouchard *et al*, 1991)

2.5.4.2 Jump tests

There are a number of jump tests that have been used to assess physical and athletic ability over the last 80 years, including the standing long jump, standing triple jump, and vertical jump tests. For the purposes of this review, I will concentrate on the vertical jump, as it is the only test in this category that has sufficient empirical and biomechanical relevance and validity with regards to the assessment of athletes.

The fundamental objective of the vertical jump is to maximize take-off velocity whilst overcoming the resistance of gravity, which is dependant on muscular strength, speed and co-ordination (Dowling & Vamos, 1993) and has been shown to be a reliable indicator of hip and thigh power production under high-speed anaerobic conditions (Adams *et al*, 1992).

There are a number of variations of the test:

i) standard *vertical jump* test (no step before jump; arm swing allowed);

ii) *counter-movement jump* test (no step; no arm swing allowed);

iii) modified versions of the above, allowing a number of steps prior to jumping, which incorporated action of the stretch-shortening cycle.

(Bouchard *et al*, 1991; Ellis *et al*, 2000)

The most important elements of assessment measured during vertical jump tests are:

i) the ability to produce maximum muscular force;

ii) the ability to utilize the stretch-shortening cycle to maximize power production.

(Blazevich & Jenkins, 1998; Vandewalle *et al*, 1987)

The tests are typically performed following measurement of body mass, using equipment designed to measure the difference between standing stretch height and jump height. The use of sophisticated equipment, such as timing mats and force platforms, provide more information during assessments, and can help to eliminate sources of tester and measurement error. (Ellis *et al*, 2000)

Short-term anaerobic performance capacity is measured by means of single jumps. Conversely, intermediate-term capacity is measured by means of the 60-second vertical jump test, where the subject performs as many counter-movement jumps as possible during the test duration. For the latter, the total flight time attained in each jump is summed to produce a result. A timing mat and computerized system are required to conduct this test. (Bouchard *et al*, 1991)

There are a number of different formulae used to calculate power output during the vertical jump tests, such as those of Gray and Lewis (see Vandewalle *et al*, 1987), which have been shown to be relatively inaccurate. The formula devised by Dowling and Vamos (1993) is the most biomechanically correct and complete:

$$\text{Peak power (watts)} = [78.5 \times \text{jump height(cm)}] + [60.6 \times \text{mass(kg)}] - [15.3 \times \text{height(cm)}] - 1308$$

(Dowling & Vamos, 1993)

2.5.4.3 Step or staircase run tests

The Margaria stairclimb test, devised in the 1960s, is the dominant test of this nature, and is a test of short-term anaerobic performance capacity (Bouchard *et al*, 1991). The procedure involves a two meter run-up, followed by climbing 17.5 cm high stairs two at a time, as quickly as possible. Timing devices are set up on the 8^{th} and 12^{th} stairs. (Margaria, 1963; Vandewalle *et al*, 1987)

A number of modifications have been attempted, most notably that of Kalamen, which was identical in every respect, except that stairs were climbed three at a time. Other modifications include changes to the run-up distance (up to 6m) and the step height.

(Vandewalle *et al*, 1987)

The following formula is used to calculate power output from the step test:

Power (W) = [body mass (kg) x 9.81] x [step rate (/min)]

(Bouchard *et al*, 1991; Margaria, 1963; Vandewalle *et al*, 1987)

A norm of 16.7 $W.kg^{-1}$ was reported for elite-level runners (di Prampero *et al*, 1970).

2.5.4.4 Cycle ergometer tests

Cycle ergometer tests are often the most practical assessments to perform, as the ergometer is easy to set up and operate. The equipment provides an accurate measure of work and power output, as the braking forces (resistance) and consequent effort applied to the flywheel are easy to calibrate, apply and monitor. In fact, the popularity of the Margaria test waned significantly with the appearance of the Wingate anaerobic cycle test and technologically advanced ergometers during the mid-1970s. (Tharp *et al*, 1985; Vandewalle *et al*, 1987)

Table 2.8 (overleaf) shows a selection of anaerobic cycle ergometer tests used in the assessment of athletes, with appropriate references.

Table 2.8 Cycle ergometer test protocols used for the assessment of anaerobic capacity in athletes.

TEST	Resistance	Duration	Ergometer	Reference
Short-term anaerobic performance capacity				
Quebec 10-second test	0.09 $kp.kg^{-1}$	10 sec	Monark	Bouchard *et al*, 1991, p. 196
10-second max ergometer sprint	electrical	10 sec	Repco	Ellis *et al*, 2000, p. 136
Intermediate-term anaerobic performance capacity				
Wingate anaerobic cycle test	0.075 – 0.1 $kp.kg^{-1}$	30 sec	Monark	Bar-Or, 1987
De Bruyn-Provost constant-load	400 W	To fatigue	N/A	Bouchard *et al*, 1991, p. 202
Long-term anaerobic performance capacity				
Quebec 90-second test	0.05 $kp.kg^{-1}$	90 sec	Monark	Bouchard *et al*, 1991, p. 206
120 second maximal test	3.4 kp.rev-1 (± 5.6 kp)	120 sec	Monark	Bouchard *et al*, 1991, p. 207
Intermittent & anaerobic recovery tests				
Critical Power test	3 incremental loads	45 sec min	Monark	Bulbulian *et al*, 1996
5 x 6 second repeat effort test	electrical	5 x 6 sec	Repco	Ellis *et al*, 2000, p. 137

Of all these tests, only the Wingate has been regularly used for research and the assessment of middle-distance athletes, with the exception of the tests described by the Canadian Association for Sport Sciences (Bouchard et al, 1991), which are routinely used in Canada. Relative measures ($W.kg^{-1}$) derived from the Wingate test have been significantly correlated with sprint and run times in a number of studies (Tharp et al, 1985; Inbar et al, 1979). The test has also been extensively used to determine the aerobic and anaerobic contributions to high-intensity effort (Granier et al, 1995), and has been shown to be a valid measure of high-intensity short-duration exercise, together with isokinetic testing (Patton & Duggan, 1987).

Table 2.9 (overleaf) shows typical values derived from male middle-distance runners for the Wingate test.

In addition to these standard parameters, force-velocity curves can be constructed using a cycle ergometer. This is done by repeating exercise bouts at different loads or resistance in order to determine the optimal load for peak power production. Isokinetic dynamometry, however, remains the best means for conducting this procedure, as the data can be analysed and presented in real-time format, and yields a larger amount of information. The procedure is mono-articular in nature, and therefore, unlike the cycle ergometer, cannot determine whole-body anaerobic performance. (Bouchard *et al*, 1991; Bar-Or, 1987; Patton & Duggan, 1987; Vandewalle *et al*, 1987)

Table 2.9 Wingate test norms for male middle-distance runners.

Variable	Unit	Value	Standard deviation	Reference
Anaerobic power	W	842	± 123	Granier *et al*, 1995, p. 62
	$W.kg^{-1}$	13	± 2	
Mean power	W	578	± 64	
	$W.kg^{-1}$	9	± 1	
Power decrease	%	52	± 4	
Total work	J	17962	± 2190	
Peak power	$W.kg^{-1}$	10.0	---	Taunton *et al*, 1981
Total work	$J.kg^{-1}$	249	---	
Peak power	$W.kg^{-1}$	13.8	± 0.5	Scott *et al*, 1991

2.5.4.5 Isokinetic evaluation

The use of isokinetic dynamometry is widespread in athletic assessment, as detailed in section 2.4.2.4, and can also easily and effectively be employed in the assessment of anaerobic assessment. Measurements of peak power, total work performed and indices of fatigue (or power decline) are easily obtained. The disadvantage of isokinetic measurements with regard to anaerobic assessment is that they are primarily mono-articular, and therefore cannot measure whole-body anaerobic performance. (Bouchard *et al*, 1991; Wrigley & Strauss, 2000)

The speed of contraction is set at a speed specific to the demands on the joint and surrounding musculature being assessed, and the test duration can then be altered according to the pattern set out on page 50, as follows:

- short-term anaerobic performance capacity : 10 seconds
- intermediate-term anaerobic performance capacity : 30 seconds
- long-term anaerobic performance capacity : 60 – 120 seconds

All contractions are assessed at maximal exertion, in order to be valid measures of anaerobic capacity. (Bouchard *et al*, 1991)

Another important assessment that can be conducted using the isokinetic dynamometer is the force-velocity curve, where the optimal level of force production and resistance for maximal power output (a function of force and velocity) can be determined (Vandewalle *et al*, 1987). This type of assessment can be of practical value to the athlete in terms of prescribing appropriate training methods.

A hyperbolic (exponential) relationship between muscular force and the velocity of contraction has been determined from the analysis of ballistic contractions in a number of mono-articular joints, especially those of the appendicular skeleton (Vandewalle *et al*, 1987). Mathematical derivations from these curves have shown that maximal power production is only possible in a relatively small range of force application (see Figure 2.1 overleaf).

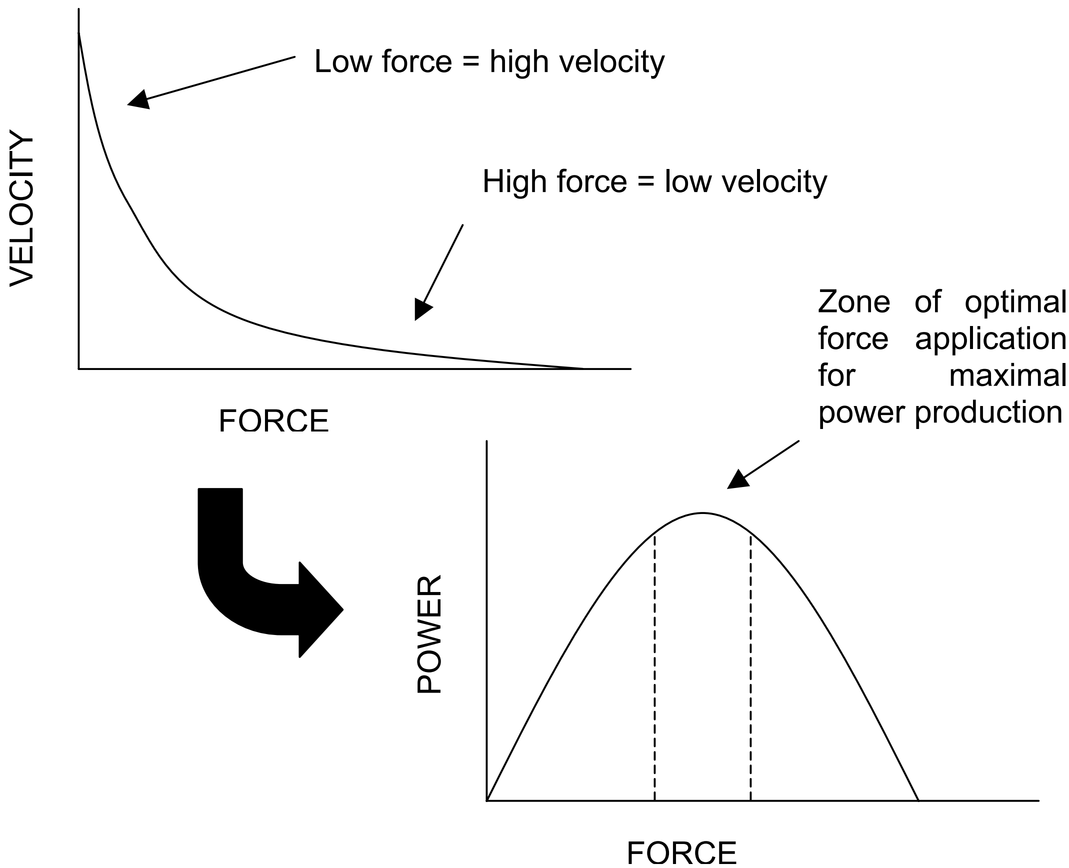


Figure 2.1 Relationship between a force-velocity curve and peak power determination.

(Adapted from Vandewalle *et al*, 1987)

Determinations of peak power using the force-velocity curve can be used to monitor training progress over long periods of time, and to accurately prescribe training methods, especially resistance settings and training loads (repetitions, sets and frequency) to improve athletic performance. (Wrigley & Strauss, 2000)

2.5.4.6 Treadmill tests

There are a number of tests utilizing the motorized treadmill as an ergometer specific to the exercise mode of running, and therefore highly applicable to middle-distance running performance.

It is extremely difficult to determine work and power output during treadmill running, as the effort comprises an "open chain" component, where the body is not in contact with the ergometer. This is in opposition to the "closed chain" work performed on cycle ergometers, which can be accurately measured, as the body is in constant contact with the device. As a result, test results are expressed as $mLO_2.kg^{-1}.min^{-1}$ or time and velocity variables, rather than Joules or Watts.

A number of different tests and protocols have been developed for the assessment of peak power and anaerobic capacity in elite athletes. Some tests measure physiological variables (such as heart rate and biochemical markers) to assess test performance, whilst others evaluate components of mechanical performance (velocity and time to exhaustion).

(Bouchard *et al*, 1991; Rusko *et al*, 1993; Vandewalle *et al*, 1987)

The **submaximal 60-second run test** is conducted on a motorized treadmill at a velocity of 22 km.h^{-1}, with an inclination of 4%. The original version was conducted at 18 km.h^{-1} at 10%, but this was revised to be more sensitive to the neuromuscular demands of running quickly on a relatively level surface. The athlete is required to run at the required speed for a full minute. The warm-up consists of a 5 to 10 minute run, including four 10 – 15 second maximal efforts, followed by a five-minute recovery period prior to the commencement of the test. Blood samples are collected 2 minutes prior to the test, and at 2, 4 and 6 minutes after completion of the run. Split times are provided for the subject every 15 seconds, and a countdown over the last 15 seconds.

(Smith *et al*, 2000; Telford, 1991)

Table 2.10 Normative data for high-performance runners tested using the submaximal 60-second run test.

	Heart rate (bpm)				Lactate (mmol.L^{-1})		pH		Bicarbonate (mmol.L^{-1})	
	15 s	30 s	45 s	60 s	Pre-	Peak-post	Pre-	Min-post	Pre-	Min-post
Mean	150	165	172	183	3.2	8.7	7.376	7.275	21.2	14.7
±	9	5	5	10	1.7	1.9	0.020	0.039	1.6	2.2
Min	134	158	164	170	1.2	5.4	7.334	7.214	18.8	11.5
Max	159	170	178	194	6.2	12.8	7.403	7.348	24.1	18.4

(Smith *et al*, 2000)

i) The **maximal short-duration test** is a progression of the previous test, and is also conducted on a motorized treadmill at a velocity of 22 $km.h^{-1}$, inclined at 4%. It is normally conducted after this test, with at least a 15-minute recovery period. The athlete is required to run at maximal exhaustion until failure. Blood samples are collected 2 minutes prior to the test, and 4, 6, 8 and 10 minutes after the completion of the test. No indication of time is provided to the subject.

Table 2.11 Normative data for high-performance runners tested using the maximal short-duration test.

Parameter		Range	Mean
Time to exhaustion		56 – 122	91 ± 24
Lactate ($mmol.L^{-1}$)	Pre-test	3.6 – 10.5	5.9 ± 2.1
	Peak post-test	9.6 – 19.7	13.9 ± 3.0
pH	Pre-test	7.311 – 7.377	7.346 ± 0.022
	Min post-test	7.080 – 7.232	7.152 ± 0.054
Bicarbonate ($mmol.L^{-1}$)	Pre-test	13.0 – 20.6	17.4 ± 2.6
	Min post-test	5.4 – 12.2	8.7 ± 2.2

(Smith *et al*, 2000)

ii) The **Cunningham and Faulkner treadmill test** is conducted on a treadmill at a velocity of 8 $mi.h^{-1}$ (12.8 $km.h^{-1}$). The time to failure (in seconds) is recorded. Lactate is measured 5 and 15 min after the completion of the test. No data obtained from elite male middle-distance runners are available for this test.

(Bouchard *et al*, 1991)

iii) The **maximal anaerobic running power (MARP) test** was developed to evaluate anaerobic running power in athletes. It is an intermittent-incremental test, with stages 20 seconds in length (not including a 5 second acceleration phase) followed by a 100 second recovery period. The treadmill inclination is set at 5º throughout the test. Treadmill stage starts at 3.97 $m.s^{-1}$ (14.3 $km.h^{-1}$), and increases by 0.35 $m.s^{-1}$ (1.26 $km.h^{-1}$) each stage. The number of stages is determined by the anaerobic capacity of each subject, as the test ends when the subject can no longer keep up with the running speed.

(Rusko *et al*, 1993; Vuorimaa *et al*, 1996)

It is difficult to measure mechanical work performed during treadmill running, and the measurement of oxygen consumption hampers the ability of subjects to run at high velocity. For these reasons, a standard formula (ACSM, 2000) is employed to estimate oxygen consumption during each run:

$$VO_2 = (12 \times \text{velocity}) + [54 \times (\text{grade} \times \text{velocity})] + 3.5$$

VO_2 in $mlO_2.kg^{-1}.min^{-1}$; treadmill velocity in $m.s^{-1}$, and grade expressed as a fraction.

(ACSM, 2000; Rusko *et al*, 1993)

Prior to the running test, three counter-movement jumps are conducted on a force platform, and change in the height of the centre of gravity determined from a force-time curve. During the running test, three identical jumps are performed during each recovery period, 15, 25 and 35 seconds after each run. Finally, three counter-movement jumps are performed 2½, 5 and 15 minutes after failure, following the running test. Blood samples are collected at rest, 40 seconds after each run, and 2.5, 5 and 10 minutes after failure, and analysed for lactate concentration.

(Rusko *et al*, 1993)

Exhaustion is determined as the point where the subject can no longer keep up with the treadmill speed. The maximal running power (calculated as $mLO_2.kg^{-1}.min^{-1}$) is determined from the last completed 20-second run. If the subject is able to complete 10 seconds of the stage prior to failure, 1 $mlO_2.kg^{-1}.min^{-1}$ is added to the maximal running power, and 0.06 $m.s^{-1}$ to the running speed recorded. Each additional 2 seconds adds another 1 $mlO_2.kg^{-1}.min^{-1}$ to the maximal running power, and 0.06 $m.s^{-1}$ to the running speed. Investigations evaluating modifications to the test protocol suggest that greater inclinations may yield better results (Nummela *et al*, 1996c), although this reduces the specificity related to high-speed track running (Rusko *et al*, 1993)

The test has been shown to be a valid test of anaerobic energy production and both reliable and reproducible. It is sensitive to differences in event speciality, with different results obtained by sprinters, middle-distance runners and endurance athletes. It also compares favourably with the Wingate cycle ergometer test, although they are not highly correlated (r = 0.42 – 0.59) and seem to measure slightly different qualities, due to the differences in mode and test duration.

(Nummela et al, 1996a, 1996b; Paavolainen *et al*, 1994; Vuorimaa *et al*, 1996)

Normative data for the MARP test for male middle-distance runners is shown in Table 2.12 (below).

Table 2.12 Normative data derived from the MARP test for male middle-distance runners.

Reference :	Nummela *et al*, 1996a	(n=8)
Variable	**Unit**	**Mean (± sd)**
Maximal power	$mlO_2.kg^{-1}.min^{-1}$	120.7 (± 6.2)
Peak [LA]	$mmol.L^{-1}$	15.8 (± 2.7)
Power @ 5 $mmol.l^{-1}$ [LA]	$mlO_2.kg$	102.5 (± 7.4)
Power @ 10 $mmol.L^{-1}$ [LA]	$mlO_2.kg$	116.1 (± 6.0)
CMJ_{rest}	cm	39.1 (± 4.1)
$CMJ_{decrease}$	%	11.5 (± 4.4)
Power decline	$mlO_2.kg^{-1}.min^{-1}$	52.9 (± 7.3)

[LA] = blood lactate concentration; CMJ = countermovement jump

Reference :	Vuorimaa *et al*, 1996	(n=5)
Variable	**Unit**	**Mean (± sd)**
V_{20m}	$m.s^{-1}$	9.2 (± 0.2)
CMJ	cm	43.8 (± 4.0)
$MART_1$	$mlO_2.kg^{-1}.min^{-1}$	121.0 (± 4.4)
$MART_3$	$mlO_2.kg^{-1}.min^{-1}$	99.2 (± 1.6)
$MART_5$	$mlO_2.kg^{-1}.min^{-1}$	97.0 (± 0.9)

V_{20m} = maximal 20m sprinting speed; CMJ = countermovement jump

In this study the MARP was repeated with a different number of 20-second runs were completed, as indicated by the suffices in $MART_1$, $MART_3$ and $MART_5$.

2.5.4.7 Maximal accumulated oxygen deficit (MAOD)

Tests of maximal accumulated deficit (MAOD) are purported to be the most reliable and reproducible measure of anaerobic function in athletes. The procedure was first devised by Krogh and Lindhard in the 1920s, describing the oxygen deficit as the accumulated deficiency in oxygen from the beginning of exercise to the steady state level. The technique was revisited in the late 1960s, particularly by Hermansen, who described the deficit as the difference between the curves of O_2 demand and O_2 supply (O_2 uptake). (Medbo *et al*, 1988; Graham, 1996; Hill, 1996)

Figure 2.2 shows the deficit area between these two curves.

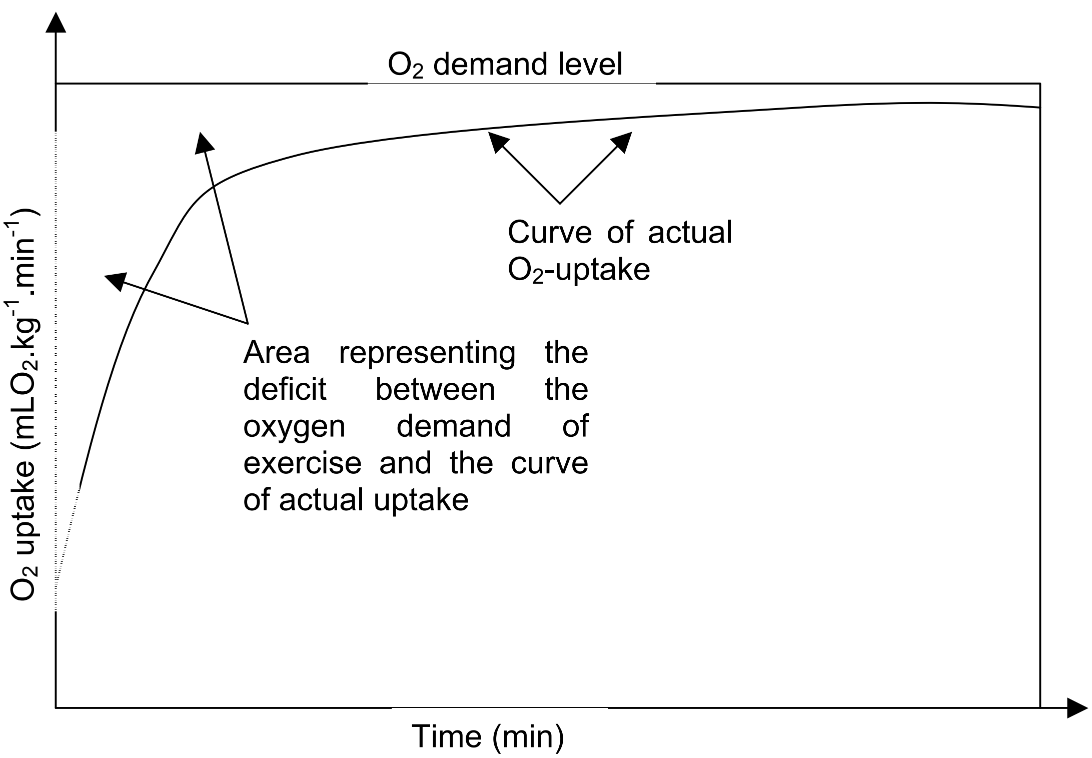


Figure 2.2 The accumulated oxygen deficit represented as the difference between O_2 demand and actual uptake.
(Medbo *et al*, 1988; Bangsbo, 1996)

The test procedure consists of determining oxygen uptake values at a range of submaximal values. It is recommended that the exercise intensity approaches that of VO_{2max}. A linear regression curve is then fitted to the relationship between VO_2 and exercise intensity. Energy demand is then set arbitrarily at a level between 10 and 30% above VO_{2max} (making the required effort supramaximal). An extrapolation technique is then used to determine the exercise intensity at which this energy demand will be elicited (Bangsbo, 1996; Medbo *et al*, 1988; Hill, 1996).

The subject is then required to exercise at the supramaximal intensity for between two and four minutes (until exhaustion) whilst oxygen consumption and other variables (such as heart rate and blood lactate level) are recorded. MAOD is then mathematically determined as the difference between the energy demand and the actual oxygen uptake (Bangsbo, 1996; Hill, 1996; Medbo *et al*, 1988;).

A large amount of research has been conducted with regards to the validity, reliability and recommended technique for the MAOD testing procedure (Hill, 1996; Medbo *et al*, 1988).

One important finding was that the oxygen demand for the supramaximal run could be determined without extrapolating from submaximal exercise intensities. Instead, the energy demand can be determined from other anaerobic tasks involving measurement of oxygen consumption (Hill, 1996).

Important refinements of the testing technique have been derived from research with regard to the duration and number of both the submaximal and supramaximal exercise bouts, as well as the effect of treadmill inclination (or resistance in ergometers) on the test result.

Buck and McNaughton (1999) recommend a minimum of ten submaximal bouts during the submaximal part of the procedure to accurately determine a regression equation for the relationship between oxygen consumption and exercise intensity. This recommendation is in contrast to other studies which only use 5-8 runs (Gastin *et al*, 1995; Green & Dawson, 1996; Hill 1996). This is supported by the original work by Krogh, Lindhard, Hermansen and Medbo (Medbo *et al*, 1988).

The length of the supramaximal bout has been determined to be most accurate when at least two minutes in length (Medbo *et al*, 1988; Medbo, 1996). Low treadmill inclination have been shown to yield poorer results than higher elevations. An elevation in excess of 10%, appears to elicit the greatest test values for the MAOD (Olesen *et al*, 1994).

An interesting discovery is the high correlation ($r = 0.83$; $p<0.001$) that exists between the MAOD procedure and the MART (another anaerobic treadmill test – section 2.5.4.6) (Maxwell & Nimmo, 1996). This has practical implications, as the MART is less time-consuming and easier to set-up and conduct, and therefore may be a better alternative for the purposes of training monitoring.

Figures 3.14 and 3.15 on pages 121 and 122 in the *METHODS* section illustrates the technique used to determine supramaximal energy demand and concomitant exercise intensity, as well as the method for determining the MAOD used in this study. The technique used was derived from work by Medbo *et al* (1988), Scott *et al* (1991), Weyand *et al* (1994) and Bangsbo *et al* (1996).

Normative data derived from assessments of MAOD in male middle-distance runners are shown in Table 2.13 (below).

Table 2.13 Normative data for male middle-distance runners for the MAOD.

Reference	**MAOD mean (± sd) ($mlO_2.kg^{-1}$)**	**Test duration (seconds)**	**n**
Medbo *et al* (1988)	approx. 75.0	approx. 170	3
Scott *et al* (1991)	74.2 (± 7.2)	120 - 180	5
Bangsbo *et al* (1993)	51.9 (± 3.8)	181 (± 0.16)	14
Weyand *et al* (1994)	46.8 (± 11.0)	120 - 240	13

The advantage of the MAOD is that it factors out the contribution of aerobic energy during short-term maximal effort, providing an accurate assessment of the anaerobic yield. It has also been validated by means of comparisons made with biochemical measurements (Finn *et al*, 2000; Green & Dawson, 1996).

A basic assumption made when determining the MAOD is that the mechanical efficiency of supramaximal effort is the same as that of submaximal work. Another limitation of the technique is that extrapolation of the linear relationship between VO_2 and submaximal exercise intensities may not provide an accurate measure of the oxygen requirement (Finn *et al*, 2000; Green & Dawson, 1996)

Although the MAOD is reported to be a valid and reliable indicator of anaerobic capacity, numerous researchers have found a poor correlation between MAOD results and competitive performance in homogenous groups of middle-distance runners (Craig & Morgan, 1998; Olesen *et al*, 1994).

2.5.4.8 Sport-specific track tests for middle-distance runners

Sport-specific track tests are highly practical tests used to measure the running performance of athletes in a familiar environment, and can be used effectively for accurate training prescription and monitoring of progress. The limitations of these types of tests are primarily that they measure a limited number of variables, due to the lack of equipment that can be utilized in field conditions, and are restricted to kinematic variables, such as running velocity, acceleration, work and power output. (SASC, 2003; SISA, 2000; Smith *et al*, 2000)

i) 40 meter sprint test

The 40m sprint test is commonly used for the assessment of short-distance speed acceleration in a wide variety of athletes. Photo-electric cells are placed at the start, and at 5, 10, 20 and 40m intervals (SASC, 2003; SISA, 2000).

ii) 60 meter sprint test

The 60m sprint test is used primarily in Australia as a measure of maximal running velocity (particularly in athletes). Photo-electric cells are placed at 10 meter intervals from the start to the 60 meter mark (0, 10, 30 and 60m intervals are the most necessary) (Smith *et al*, 2000).

iii) 90 meter sprint test

The 90m sprint test is used to assess linear speed over a longer distances, and is indirectly a measure of speed-endurance, as it will be able to detect any decrease of speed at the end of the distance. A single photo-electric cell and timing mat is placed at the start, with additional photo-electric cells at 40, 50, 60, 70, 80 and 90 meter intervals (SASC, 2003).

iv) Time-trial runs (150m & 300m)

Time-trial runs over longer distances (particularly 200 – 600m) are often used to measure speed-endurance capacity. Timing devices can be used to measure velocity at different points in the run, which assist in determining the effects of fatigue on running performance (SASC, 2003; SISA, 2000; Smith *et al*, 2000).

v) Short-duration track test (3 x 300-meter field test)

This test is used primarily in Australia as a measure of anaerobic running efficiency at different sprinting velocities. Three 300 meter runs are conducted, with a ten minute recovery period after the first run, and a twenty minute rest after the second run. The first run is conducted at a pace of approximately 80% of the personal best, whilst the subsequent runs are conducted at paces of 90 and 95-100% respectively.

Blood samples are collected at the following times, and analyzed for blood lactate:

- 2 and 5 minutes after the first 300m run;
- 2, 5 and 8 minutes after the second run;
- 5, 8 and 12 minutes after the third run.

Graphs of heart rate and blood lactate (in relation to running time and velocity) are produced, and can be used to assess training response. Shifts in these curves over successive tests can be used to determine the adaptation caused by training.

(Smith *et al*, 2000)

vi) Field test for determining performance during anaerobic glycolysis

The test is conducted on a standard 400m athletics track. The first part of the test requires the subject to run 6 – 8 laps without interruption, increasing their speed every 200m. A linear relationship between the heart rate (which is monitored continuously) and running speed is expected, up to a deflection point, where the relationship is disrupted. This deflection point represents the anaerobic threshold. The linear relationship (prior to the deflection), is extrapolated to the level of maximum heart rate to determine maximal aerobic running speed. (Borsetto *et al*, 1989)

The second part of the test takes place after a 30-minute recovery period, and consists of a 1200m run. Athletes are expected to run a distance of 1000m and reach the running speed at which the deflection point occurred in the first part of the test. The last 200m is run at maximal pace, and running speed for this interval is determined. (Borsetto *et al*, 1989).

The maximal aerobic running speed (test 1) is then subtracted from maximal running speed (test 2), to determine the speed generated by anaerobic glycolysis. Blood samples are also collected during and after the test, and analyzed for lactate concentration. The concentration of blood lactate is a reliable indicator of the utilization of anaerobic glycolysis, and is highly correlated with test performance. (Borsetto *et al*, 1989)

vii) High-intensity field tests to estimate maximal oxygen consumption.

Berthon *et al* (1997) have validated the use of a 5-minute track test to estimate maximal oxygen consumption (VO_{2max}). The test consists of a 10 minute warm-up at approximately 70% of maximal heart rate. Subjects are then instructed to run at maximal intensity for a duration of 5 minutes, and cover as much distance as possible. The running distance is then used to calculate VO_{2max} using the following formula:

VO_{2max} (ml.kg^{-1}.min^{-1}) = 39 d	[d = 5-min running distance in km]

This test has been highly correlated with direct measurement of maximal oxygen consumption on a treadmill ($r=0.9$; $p<0.001$) and with track performance over various distances. The correlation with 3000m time was most significant ($r=0.94$; $p<0.01$), whilst that with 800m performance was the lowest ($r= 0.64$; $p<0.01$).

(Berthon *et al*, 1997)

Table 2.14 Normative data for sport-specific track tests involving male middle-distance runners.

Test	**Normative data**	**Reference**
40 meter sprint test	Senior males : 5.29 ± 0.27 (s)	SASC, 2003
	Under 19 males : 5.39 ± 0.28 (s)	
90 meter sprint test	12.0 $m.s^{-1}$	SASC, 2003
150 meter time-trial run	14.7 – 15.7 s	SASC, 2003
300 meter time-trial run	32.0 – 36.2 s	SASC, 2003

Target times for the 3 x 300 meter field test (Smith *et al*, 2000)

300m PB (s)	Approx 80% PB	Approx 90% PB	Approx 95% PB
40	48 – 50	44 – 45	< 42
37	45 – 47	41 – 42	< 39
33	41 – 43	36.5 – 38	< 35.5

Field test for determining speed obtained through anaerobic glycolysis

(Borsetto *et al*, 1989)

	400 – 800m runners	5000 – 10 000m runners
Maximal anaerobic running speed	9.7 (± 1.8)	6.22 (± 0.7)
($km.h^{-1}$)	9.3 – 13.2	6.3 – 8.9

2.6 AEROBIC ASSESSMENT

The purpose of the aerobic assessment is twofold:

i) to determine the maximum amount of oxygen that can be transported and utilized during metabolic processes that produce aerobic energy, and
ii) to determine the ability of the body to maintain a high intensity of effort over a prolonged period of time.

(Astrand *et al*, 2003; Thoden, 1991; Withers *et al*, 2000)

As mentioned previously, 40 – 65 % of the energy requirement for middle-distance events is provided by aerobic energy (Section 2.2.1 – Astrand *et al*, 2003). Theoretically, any event that lasts longer than 45 – 60 seconds must have an aerobic component, and for this reason, assessments of aerobic function are necessary in middle-distance runners (Astrand *et al*, 2003; Thoden, 1991; Withers *et al*, 2000).

The rate at which aerobic metabolism can supply sufficient energy is dependant on:

i) the chemical capacity of tissue to utilize oxygen, and
ii) the transport capacity of the body to supply this oxygen requirement

(Astrand *et al*, 2003; Snell, 1990; Thoden, 1991)

The combined function of these two capacities can be measured during simulated performance, using equipment designed to estimate the metabolic activity of the body, by directly measuring oxygen consumption. The technique most widely used is the metabolic cart, which calculates the body's total oxygen consumption from measurement of the O_2 uptake by the respiratory system, as a direct determination of energy expenditure (Astrand *et al*, 2003; Thoden, 1991; Withers *et al*, 2000).

Maximal oxygen consumption (VO_{2max}) has received a large amount of attention with regards to the identification of endurance capacity, and has been highly correlated to distance running performance in heterogenous groups (of mixed ability). In homogenous groups, particular amongst elite performers with high VO_{2max} values, there is a poor correlation. Other aerobic parameters such as running economy and velocity at VO_{2max} (vVO_{2max}) have been shown to be highly correlated to performance (Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992).

2.6.1 Running economy

Running economy is defined as the relationship between oxygen consumption (VO_2) and running velocity (Astrand *et al*, 2003; Daniels & Daniels, 1992).

Research indicates that the combined influence of VO_{2max} and running economy can be combined into a mathematical model to predict performance, particularly in homogenous groups. The efficacy of one particular method has been evaluated, using the quotient maximal oxygen uptake divided by the net energy cost of running, to calculate Va_{max}. This technique accounted for 58% of the variability in distance running performance over 1500 to 3000m (Abe *et al*, 1998).

Assessments of running economy typically involve measurement of submaximal oxygen consumption at predetermined speeds and inclinations. Treadmill inclination should not exceed 1º, as this alters the normal biomechanics and stride pattern of running (SISA, 2000). Oxygen consumption and treadmill velocity data are combined mathematically to determine the energy cost of running. The following formula yields energy cost in mLO_2 per kilometer covered:

RE ($ml.km^{-1}$) = [(submaximal VO_2) – (resting VO_2)] / running velocity

VO_2 in $ml.kg^{-1}.min^{-1}$; running velocity in $km.min^{-1}$

(Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; di Prampero *et al*, 1993)

Running economy is influenced by a number of factors, such as age, training state, cadence (stride rate and frequency), body mass, shoe mass, biomechanics, wind or air resistance and altitude (Daniels et al, 1985; Daniels & Daniels, 1992; Pugh, 1970).

Norms associated with male middle-distance runners are difficult to assess and compare due to the different assessment procedures employed by different researchers, where there is little consistency or standardization in terms of protocol type, test velocities, inclination and running ability. Examples of testing protocols with associated references pertinent to the assessment of elite male middle-distance runners are shown in the annexure in Table A.7 on page 199.

2.6.2 Maximal oxygen uptake ($VO2_{max}$)

Maximal oxygen consumption (VO_{2max}) is defined as the maximum volume of oxygen that can be extracted from the atmosphere by respiratory processes, transported by the cardiovascular system to active tissues, where it is utilized to produce energy to fuel the processes that allow for exercise of maximal intensity (Astrand *et al*, 2003; Brandon 1995).

The purpose of assessment of maximal oxygen consumption is to determine the rate at which aerobic metabolism can supply the energy demand associated with exercise of high intensity. VO_{2max} in athletes is primarily dependant on oxygen utilization (particularly by active skeletal muscle), and oxygen transport by means of the pulmonary and circulatory systems (Astrand *et al*, 2003; Thoden, 1991).

Assessment of VO_{2max} in elite-class middle-distance athletes is normally conducted using a motorized treadmill and calibrated metabolic cart. There is much debate surrounding the most effective test protocol for determining VO_{2max} accurately, with both continuous and intermittent protocols often used (Astrand *et al*, 2003). Most researchers are in favour of the use of continuous-incremental protocols, with small increases in intensity (controlled by changes to treadmill velocity and/or grade) every 30 – 60 seconds. This technique has been shown to be reliable and reproducible when used with elite-class distance runners (Conley & Krahenbuhl, 1980; Hill & Rowell, 1996; McMiken & Daniels, 1976).

However, the running speed and duration of middle-distance events are more suited to the use of intermittent-incremental protocols, as the recovery periods allow for higher levels of effort (allowing for more specific simulations of actual performance), and limit the influence of fatigue on test results. Stage durations of 3 – 5 minutes are similar to competitive conditions, and therefore improve the specificity and validity of testing protocols (Thoden, 1991; Withers *et al*, 2000).

The following criteria are recommendations for determination of VO_{2max}:

i) observation of a plateau in oxygen consumption values, regardless of increases in intensity or workload;
ii) Respiratory quotient (RQ) greater than 1.1;
iii) 5-minute post-exercise blood lactate concentration greater than 8.0 $mmol.L^{-1}$.

(Withers et al, 2000, p. 122)

Examples of continuous and intermittent-incremental protocols used by leading researchers are shown in the annexure in Table A.8 and A.9 on pages 200 to 203.

Table 2.15 (overleaf) shows values derived for maximal oxygen consumption involving male middle-distance runners.

Table 2.15 Maximal oxygen consumption data for elite male middle-distance runners.

Reference		VO_{2max} value
Saltin & Astrand (1967)		75.0 (± 2.0) (n=5)
Snell (1990)		72.3 -82.0 (n=6)
Scott *et al* (1991)		66.5 (± 5.5) (n=5)
Brandon (1995)	800m	61.6 – 62.7 (n=96)
	1600m	60.9 – 62.5 (n=26)
	3000m+	60.9 – 62.5 (n=82)
Smith *et al* (2000)		65 – 80 (norm for 800 – 1500m athletes)

From this data, it is clear that although a high VO_{2max} is a necessary component for middle-distance running performance, there is much variability (a range of approximately 20 $ml.kg^{-1}.min^{-1}$ equating to 25%) in reported findings. Therefore, it can be surmised that VO_{2max} testing can be used to identify ability, but not necessarily to predict performance. This finding is supported by numerous authors. (Daniels & Daniels, 1992; Hill and Rowell, 1996; Noakes *et al*, 1990)

Running velocity at VO_{2max} (vVO_{2max}) is an associated variable, which has been shown to be of value in predicting distance running performance by a number of researchers, and may be of value as an assessment tool for middle-distance athletes (Billat *et al*, 1994; Hill & Rowell, 1996; Morgan *et al*, 1989).

2.6.3 Lactate threshold

The primary purpose of the measurement of blood lactate concentration is to investigate the balance between production and removal of lactate. Where production exceeds removal, accumulation is the result. It is widely accepted that there is a highly-individual, critical intensity of exercise where there is a significant increase in blood lactate. Controversy exists regarding the reason for the lactate accumulation. Some experts are of the opinion that accumulation is related to the inability of aerobic metabolism to completely meet the energy demand of exercise, which must then be supplemented by anaerobic sources. Others believe that lactate accumulation is not related to anaerobic metabolism. (Astrand *et al*, 2003; Donovan & Brooks, 1983; Heck *et al*, 1985)

There are two conflicting viewpoints concerning the nature of lactate accumulation. Many investigators support the notion of an exponential rise, where the point at which accumulation starts to increase in a non-linear fashion is described as the "lactate threshold" (also known as the aerobic- or anaerobic threshold). (Astrand *et al*, 2003; Billat, 1996; Donovan & Brooks, 1983). Other investigators do not support this exponential relationship, and have shown the existence of a continuous linear rise in proportion to combinations of intensity and duration (Hughson *et al*, 1987).

There are a number of methods for determining the point at which lactate accumulation occurs, in addition to a number of blood collection techniques. Assessment of blood lactate is normally conducted using relatively non-invasive collection techniques, with catheterization of arterial or venous blood vessels yielding the most accurate measurements. Lancing of fingers and earlobe sites to collect capillary blood is a simpler and less painful alternative. Restriction of an athletes normal running style and mechanics should not be affected by blood collection (Thoden, 1991; Smith *et al*, 2000).

A commonly used method of determining a threshold is to find the 4 $mmol.L^{-1}$ level (onset of blood lactate accumulation or OBLA), and to relate it to exercise intensity. The OBLA defines the position of the lactate curve and assumes the rise in plasma lactate concentration, as exercise intensity increases, is an exponential function. This level of blood lactate has been shown to be indicative of an intensity of effort above which trained athletes will incur continual increases in lactate concentration (Billat, 1996; Heck *et al*, 1985). Other methods involve regression techniques, where lactate values are plotted against measures of work intensity, such as oxygen consumption (VO_2) and power production (watts). The dominant techniques are the log-log and semi-log techniques (Beaver *et al*, 1985; Yeh *et al*, 1983). Figure 2.3 shows the data plotting technique and subsequent determination of the lactate threshold.

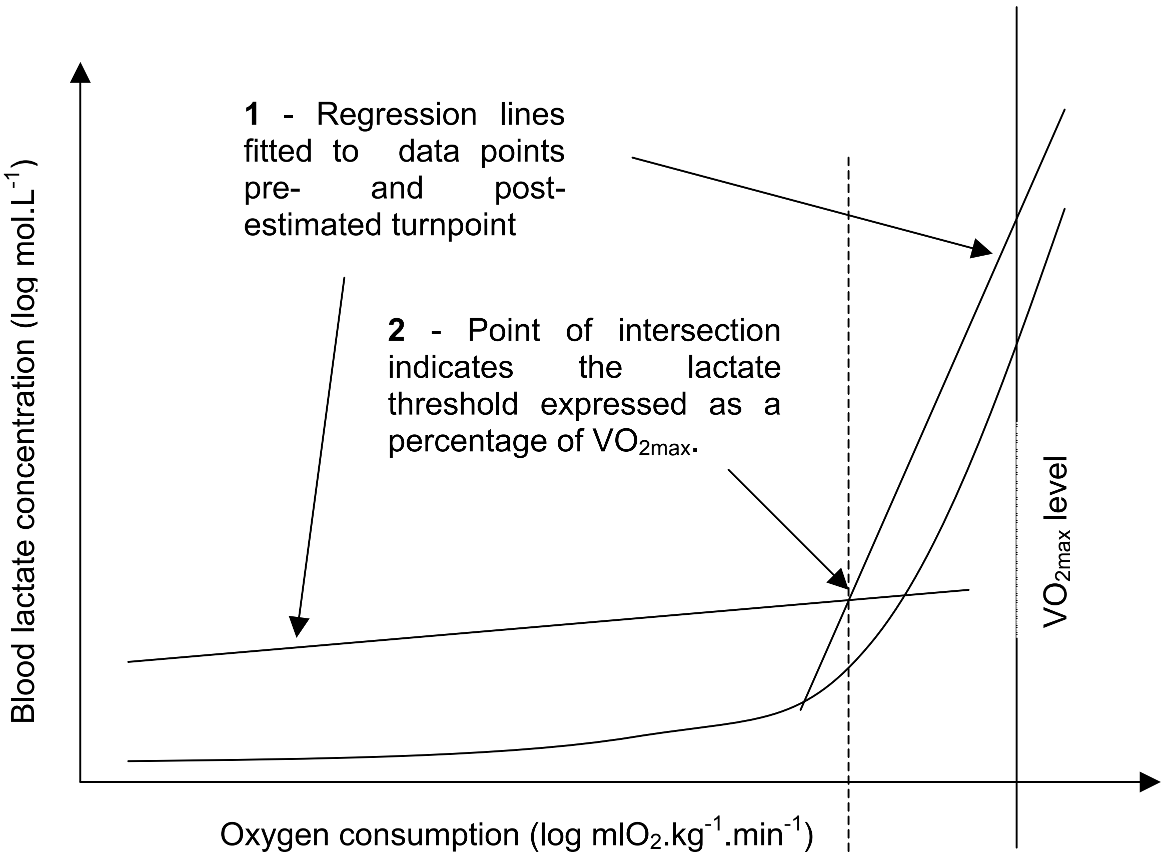


Figure 2.3 Data plotting technique for determination of the lactate threshold using the log-log technique. (Beaver *et al*, 1985; Yeh *et al*, 1983)

One important aspect of lactate threshold is that there is a high degree of individual variability, and measurements can fluctuate in response to training state, diet and recovery level (Astrand *et al*, 2003; Billat, 1996; Coen *et al*, 2001; Donovan & Brooks, 1983). The relationship between lactate measurements and competition-related performances have been the subject of critical evaluation, and in some cases have been contradicted (Pyne et al, 2001; Swart & Jennings, 2004). However, their practical use is well-established and documented, and has been widely practiced to assist athletes with appropriate prescription of training intensity and duration (Coen *et al*, 1991; Craig, 1987).

In middle-distance athletes, a delay in the onset of blood lactate accumulation during exercise of maximal and supramaximal intensity will yield a competitive advantage, as the deleterious effects of elevated blood lactate levels (such as decreased pH) will be reduced (Billat, 1996; Snell,1990). Lactate exchange ability (the ability to remove lactate from muscle to preserve its function by means of oxidation or recycling) has been shown to improve the ability to sustain exercise close to 2 minutes in duration, such as the 800m. In a research study, long-middle-distance runners were shown to have a better capacity to sustain high-intensity exercise than sprinters (Bret *et al*, 2003).

Testing protocols normally involve periodic measurement of blood lactate levels during successive stages of submaximal intensity, up to (and sometimes beyond) a level corresponding to VO_{2max}. These assessments are often combined with evaluations of running economy and VO_{2max}, and can be either continuous or intermittent-incremental in nature. Continuous-incremental protocols are the most commonly employed method used to assess middle-distance runners (Smith *et al*, 2000; Thoden, 1991).

The techniques for the assessment of the individual lactate threshold have also been shown to be highly reliable, as they are not unduly affected by factors such as previous warm-up, and changes to elements of testing protocols, such as increases in the length of test stages. They are also not prone to high degrees of inter-observer variability (Coen *et al*, 2001).

Important applications of lactate threshold testing are for the prediction of performance, and for accurate prescription and control of training intensity (Billat, 1996; Donovan & Brooks, 1983; Smith *et al*, 2000). There is a significant relationship between post-exercise blood lactate concentration and performance in events lasting one to two minutes (such as the 800m), and is probably an indicator of the total energy produced by anaerobic metabolism (Astrand *et al*, 2003; Billat, 1996).

Blood lactate levels can also be used to monitor training, as these measurements are reliable indicators to determine the dominance of either aerobic or anaerobic processes. Control of training intensity can be implemented in order to accurately stress either the aerobic, anaerobic or a combination of metabolic pathways (Billat, 1996).

Measurement of blood lactate concentration and determination of the lactate threshold are of interest to athletes and trainers, and provide a practical application for assessment procedures. They are therefore often included in testing batteries for middle-distance runners (Coen *et al*, 1991; Craig, 1987).

2.7 STANDARDISED TESTING PROTOCOLS

There is no internationally accepted test battery for the assessment of elite, middle-distance runners. Furthermore, there is also a lack of substantial research dealing with the selection of appropriate testing procedures, despite the involvement of middle-distance runners in physiological research. A number of national federations have attempted to develop and institute a standardised test battery for the middle-distance events, which I have outlined and analyzed in the following sections.

2.7.1 South African Sports Confederation and Olympic Committee (SASCOC)

SASCOC recommends the use of a large number of tests for all track athletes, some of which may not be specifically related to competitive performance. Certain procedures are designed to assess injury risk, and assist with appropriate design and prescription of intervention strategies. Many of the methods, however, lack justification in terms of their selection and rationale. Furthermore, there is a large amount of variation allowed, in terms of the test equipment and protocols that can be used, which reduces reliability and reproducibility. The protocol is too generic, catering for all track events other than the 10 000m and marathon, and is in need of revision with regards to the specific needs of each type of track event. The current focus is biased towards the shorter-distance track events (up to 400m), and does not provide sufficient assessment of endurance capacity.

The protocol is relatively comprehensive in assessing all areas relating to competitive performance, monitoring of training and injury management, but lacks practical guidelines with regards to the interpretation and use of test results. Insufficient normative data is provided, and no standardized reporting format exists, which ultimately does not allow for efficient communication between testing staff, athletes and coaches, further reducing the practicality and efficiency of the programme.

(SASC, 2003; SISA, 2000)

Table 2.16 Current SASCOC protocol for track athletes (non-specific).

ANTHROPOMETRY	
Body fat	sum of seven skinfolds (tricep, bicep, subscapular, suprailiac, abdominal, thigh, calf)
Body fat percentage	Durnin & Wolmersley formula
Muscle mass	Martin formula
FLEXIBILITY	
Lumbar region and hip extensors	Modified sit-and-reach
Hip extensors / knee flexors	Straight leg hamstring test
Hip flexors / knee extensors	Modified Thomas test
Ankle ROM	Ankle plantarflexion / dorsiflexion
ISOKINETIC EVALUATION	
Knee flexion:extension	60º.s-1 (concentric + eccentric; functional ratios)
HIGH-INTENSITY AND AGILITY	
Anaerobic capacity and peak power output	Wingate test
Max running velocity / acceleration	40-meter sprint test
MUSCULAR STRENGTH, POWER AND ENDURANCE	
Maximal leg strength	1RM leg press
Local muscular endurance	Underhand pull-ups
	1-minute push-up test
	2-minute sit-up test
Maximal leg power	Vertical jump test
SPORT-SPECIFIC TESTS	
Maximum leg power	Standing long jump
Maximum running speed	90-meter sprint test
Speed-endurance	150 meter endurance run
	300 meter endurance run

(SASC, 2003; SISA, 2000)

2.7.2 Australian Sports Commission (ASC)

The ASC has developed a complete, standardized and rigid assessment structure for a nationwide programme. The testing of high-performance runners is relatively comprehensive, effective and efficient, and described in meticulous detail. This allows for reproducibility of procedures, in addition to a standardized reporting system, allowing for effective communication between testers, athletes and coaches, and assisting in monitoring of training progress.

A particular strongpoint of the ASC protocols is that tests are selected that can contribute to the prescription and monitoring of training methods, which are integrated with the test results and reports.

There are a few weaknesses evident in the protocol, such as:

- The rigid type of prescription, which does not allow the tester to modify procedures according to local conditions or individual variations;
- The running protocol is too generic and should be differentiated according to the type of track event (sprint or distance);
- The equipment used is highly prescriptive, and therefore cannot be conducted by facilities that do not have access to the specialized equipment – specifically those outside Australia.

(Smith *et al*, 2000; Telford, 1991)

Despite these weaknesses, the ASC protocols are the most advanced of their type internationally, and serve as the benchmark for correct practice. Table 2.17 summarizes the tests included in the ASC protocol for high-performance runners.

Table 2.17 Current ASC protocol for high-performance runners.

ROUTINE HEMATOLOGY

RBC count

Haematocrit

Haemoglobin concentration

Mean cell volume

WBC count

Serum ferritin concentration

ANTHROPOMETRY

Height

Mass

Sum of seven skinfolds (bicep; tricep; subscapular; abdominal; mid-thigh; medial calf)

TREADMILL TESTS

Progressive maximal test (intermittent-incremental protocol : maximal aerobic power)

Submaximal 60-second run (lactate accumulation on treadmill)

Maximal short-duration test

TRACK TESTS

3 x 300m field test : anaerobic running efficiency

60m sprint test

(Smith *et al*, 2000; Hahn *et al*, 2000)

2.7.3 Canadian Association of Sport Sciences (CASS)

The Canadian Association of Sport Sciences was the first national institution outside of the former Communist bloc to attempt to standardize their testing methods by means of widespread publication and education programmes.

The testing protocols are separated into major sections which deal with separate capacities, such as aerobic capacity, muscular strength, muscular power, and kinanthropometry. They are authored by internationally-renowned experts in each field.

The primary shortcoming of these publications is that firstly the tester needs to be able to select appropriate tests from a list of available procedures, which compromises standardization and reproducibility, and that secondly there are no direct specific guidelines for different sporting events. The tester needs to utilize a large body of ambiguous theory to select an appropriate test for a specific athlete. As a result, different testers or facilities may select different tests or protocols for the same athletic event, which compromises standardization.

The publications are nevertheless invaluable in assisting researchers and practitioners to attain high levels of competence.

(MacDougall *et al*, 1991; Quinney *et al*, 1987)

2.7.4 Other protocols

Other national associations, particularly in the United States, United Kingdom and Continental Europe, do not have any prescribed programme for athletic assessment. Instead, a more flexible system is employed, where specialists attend to the assessment and training needs of each athlete at regional or national medical and training centres.

This allows for a highly individualized approach and may have certain benefits for athletes, as well as allowing testers to experiment, research and improve their own knowledge and competence.

Conversely, standardization and reproducibility are both compromised, and the dependency of athletes and development processes on individual scientists is increased (Hale *et al*, 1988; IAAF, 2004).

In recent years, the IAAF has embarked on an international programme to improve the level of scientific support available to both athletes and their coaches, and make equipment and facilities more accessible by accrediting testing centres in different international regions. As yet, no standardized assessment programme or training prescription system has been adequately developed, but is an exciting area for future development (IAAF, 2004).

2.8 SUMMARY

In conclusion, the large volume and variety of available testing procedures and techniques has been demonstrated. From a practical viewpoint, the task remains to suggest the most pertinent and effective test battery for the purposes of predicting performance, monitoring training progression, and ensuring adequate maintenance of the athlete. In addition, the adequate identification and management of injury risk and nutritional state are also important factors.

This is a highly problematic task, as the selection of appropriate testing procedures is subject to the opinions, learning and practical experiences of individual practitioners, and can also be constrained by equipment and facility availability, as well as other constraints imposed on or by athletes to be evaluated, such as time and financial pressures. This is a contentious area that has been identified by a number of investigators as a new area of research (MacDougall & Wenger, 1991; Ziltener & Leal, 2005). Physical and physiological characteristics of middle-distance runners and the measurement procedures that have been utilised are relatively completely understood. However, the practical use and the subsequent intervention strategies to be employed need to be systematically and methodically unpacked, in order to provide a standard framework to both improve performance and limit injury.

3. METHODS

3.1 SUBJECTS

This study was approved by the *Committee for Research on Human Subjects* (Medical), *University of the Witwatersrand* (clearance certificate no.: M00/10/13). All subjects participated voluntarily, and provided informed consent.

Twenty elite male middle-distance athletes aged 18 – 26 years were selected for the study. Elite athletes were defined as having an 800-metre time faster than 2 minutes or a 1500-metre time faster than 4 minutes. The range of seasonal best performance times are shown in Table 3.1.

Table 3.1 Range of performance times (November 2002 – April 2003)[7].

DISTANCE	Range of times
800m	1min 46sec – 2min 1sec
1500m	3min 39sec – 4min 2sec
3000m	8min 26sec – 8min 54sec
5000m	13min 53sec – 14min 45sec

[7] Compiled using seasonal best times obtained during the 2002/3 competitive season.

3.2 TESTS

The testing of physical capacity was conducted over a period of at least eight separate days extending over a period of 2 – 3 weeks. Details of the individual tests are shown below.

3.2.1 Tests recommended by the South African Sports Commission

Parts of the tests were those recommended for middle-distance track athletes by the *South African Sports Commission* (SASC) High-Performance Programme, and its predecessor the *Sports Information and Science Agency* (SISA). These tests are indicated by means of an asterisk (*) (SASC, 2003; SISA, 2000).

3.2.2 Other assessment procedures

The remainder were tests that have been shown to have application to middle-distance running performance (Brandon, 1995; Brandon & Boileau, 1992; Snell, 1990).

Figure 3.1 Photograph of technique used to measure medial calf skinfold thickness.

Figure 3.2 Photograph of technique used to measure medial calf girth.

3.3 PROCEDURES

3.3.1 Anthropometry*

All anthropometrical assessments were conducted prior to any physical activity, and subjects were instructed not to train on the day prior to the testing. Measurements were recorded at the following skinfold sites: triceps, biceps, sub-scapular, supra-iliac, abdominal, anterior thigh and medial calf. The *sum of skinfolds* was calculated from the sum of these seven skinfold sites (Smith *et al*, 2000). *Body fat percentage* was determined from calculations of body density using the Durnin & Wolmersley 4-site technique (1974), from measurements at tricep, bicep, sub-scapular and supra-iliac skinfold sites. Body density was converted to body fat percentage as a proportion of total body mass using the Brozek formula (Brozek *et al*, 1963).

Muscle mass was determined by means of a formula based on measurements of forearm-, midthigh- and maximal calf girths. Thigh and calf girths were corrected for subcutaneous fat content using the appropriate skinfold measurements (Martin *et al*, 1990).

Figure 3.3 Photograph of the modified sit-and-reach test.

3.3.2 <u>Flexibility</u>*

All flexibility assessments were conducted prior to any physical activity, and subjects were instructed not to train on the day prior to the testing. Bilateral lumbar and hamstring flexibility was assessed by means of the *modified sit-and-reach test* using a standard sit-and-reach box (SASC, 2003; SISA, 2000). Unilateral hamstring flexibility was assessed by means of the *straight leg hamstring test* using a Leighton flexometer (Hubley-Kozey, 1991; SASC, 2003; SISA, 2000). Unilateral flexibility of the hip flexor group (iliopsoas) and knee extensor group (quadriceps femoris) was measured by means of the *modified Thomas test (MTT)* using a standard 30 cm plastic goniometer (Harvey, 1998; SASC, 2003; SISA, 2000). *Ankle plantarflexion and dorsiflexion* was assessed by means of goniometry (Hubley-Kozey, 1991; SASC, 2003; SISA, 2000).

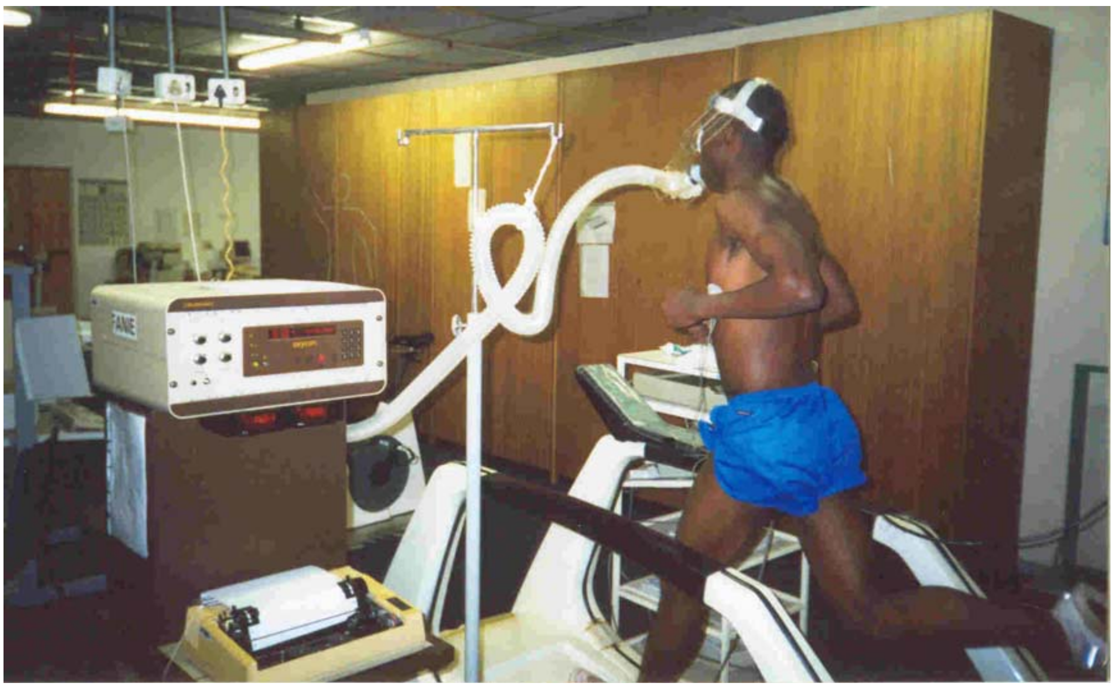


Figure 3.4 Photograph of aerobic assessments conducted using a motorized treadmill and metabolic cart.

3.3.3 Aerobic assessment

3.3.3.1 Running economy

In addition to tests recommended by the SASC, *running economy* was assessed using a calibrated metabolic cart (Mijnhardt Oxycon OX-4, Mijnhardt, Bunnik, Holland) and a motorized treadmill (Powerjog EG10, Sport Engineering Ltd., Birmingham, England). We measured heart rate with a 3-lead ECG (HP 78351A, Hewlett-Packard GMBH, Boblingen, Germany). The warm-up and familiarization procedure consisted of a 10-minute run on a level grade at 10 $km.h^{-1}$. This was followed by 4-5 minutes of static stretching.

After measuring the standing VO_2, running economy was determined by measuring the VO_2 on a level treadmill at a velocity of 12 $km.h^{-1}$ at 30-second intervals, during steady-state exercise (2-5 minutes).

Running economy was calculated using the following formula:

$$RE\ (ml.km^{-1}) = [(VO_2\ at\ 12km.h^{-1}) - (VO_2\ at\ rest)] \div running\ velocity\ (km.min^{-1})$$

$$(VO_2\ in\ ml.kg^{-1}.min^{-1})$$

(Daniels & Daniels, 1992; Conley & Krahenbuhl, 1980)

Additional measurement of running economy at different velocities was conducted as part of the assessment of *maximal accumulated oxygen deficit* (MAOD) (see section 3.3.7.2), subsequent to assessment of maximal oxygen consumption (see section 3.3.3.2).

Oxygen consumption was measured on a level treadmill at 30-second intervals, using an intermittent-incremental protocol. Each submaximal stage was three minutes in duration, starting at a velocity of 10 $km.h^{-1}$ and progressing by 1 $km.h^{-1}$ every stage, until 90% of the VO_{2max} had been achieved. Final stage velocities ranged from 18 to 22 $km.h^{-1}$, which was dependant on the individual abilities of the subjects. Blood lactate was measured using a portable system (see section 3.3.3.3) at the end of each stage.

A running economy value was calculated for each stage of the assessment using the formula shown on the previous page. Running economy was subsequently determined as the average of values from the stages prior to attainment of the lactate threshold (section 3.3.3.3).

3.3.3.2 Maximal oxygen consumption (VO_{2max})

Using the same equipment, VO_{2max} was determined by means of an intermittent-incremental method. The maximal test was conducted on a treadmill with a constant speed of 13 $km.h^{-1}$. The initial elevation was set between 9 and 12%, dependant on the running economy and perceived ability of the athlete. Each stage was 3 minutes in length, followed by a 5 – 10 minute rest. The inclination was increased by 1% at the start of each stage, until VO_{2max} was reached. Not more than three maximal runs were attempted on any day of testing, to avoid undue influence of fatigue. If a result was not obtained, the procedure was repeated on a subsequent day. The test was only considered successful if two consecutive measurements differed by less than 1.0 $ml.kg^{-1}.min^{-1}$. The average of the measurements was taken as the VO_{2max}.

3.3.3.3 Lactate threshold

Lactate threshold was measured on a separate day. The test was conducted on the treadmill during a progressive increase in work intensity at three minute intervals. Oxygen consumption was determined during steady state exercise using the metabolic cart.

Blood lactate was measured using a portable system (Accusport, Bohringer-Mannheim, Mannheim, Germany) at the end of each three minute submaximal stage, starting at 10 $km.h^{-1}$ and progressing by 1 $km.h^{-1}$ every stage, until 90% of the VO_{2max}

Figure 3.5 Photograph of the static muscular strength assessment conducted using a 45º incline leg press.

had been achieved. Heart rate was measured with a 3-lead ECG (HP 78351A, Hewlett-Packard GMBH, Boblingen, Germany).

The lactate turn-point was determined using a semi-log technique (Beaver *et al*, 1985; Yeh *et al*, 1983), and expressed as a percentage of VO_{2max}.

3.3.4 Static and dynamic muscular strength

3.3.4.1 Static muscular strength*

*Muscular strength** was assessed by means of the *one-repetition maximum (1RM) test*, using a standard incline leg press inclined at 45º. The warm-up routine consisted of five minutes of steady-state cycling at 50-60 watts on a cycle ergometer, followed by 3-5 minutes of static stretching. The specific warm-up and familiarization routine consisted of ten repetitions at 100kg followed by a 2-3 minute rest. The next stage consisted of 3-5 repetitions at 50% of estimated 1RM, followed by a 2-3 minute rest. The final stage of the warm-up consisted of 2-3 repetitions at 75% of estimated 1RM, followed by a 2-3 minute rest (Baechle *et al*, 2000; SASC, 2003; SISA, 2000).

Subsequently, the first attempt at 1RM was made, followed by the standard 2-3 minute rest. Increases in load of 5 – 20 kg were determined according to the subject's ability, until the 1RM load was attained. This was required to occur in no more than five attempted lifts per session (one day), otherwise the procedure was repeated on a subsequent day (Baechle *et al*, 2000; SASC, 2003; SISA, 2000).

Figure 3.6 Photograph of the dynamic muscular strength assessment conducted using an isokinetic dynamometer.

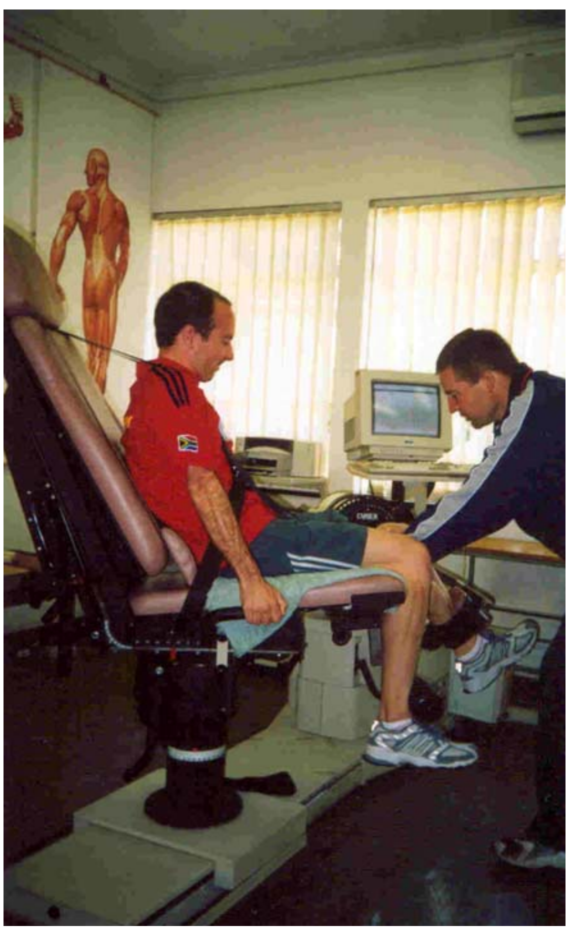


Figure 3.7 Photograph illustrating position of the isokinetic dynamometer, as well as seat back and –bottom angles.

3.3.4.2 Isokinetic evaluation* (dynamic muscular strength)

We conducted an isokinetic evaluation of the knee extensors and –flexors on a CYBEX T1000 isokinetic dynamometer (Cybex Norm™, Cybex Division of Lumex Inc., Ronkonkoma, NY). Seat back angle was set at 60º and seat bottom angle at 15º. Both limbs were tested at 60º per second (SASC, 2003; SISA, 2000). The warm-up routine consisted of five minutes of steady-state cycling at 50-60 watts on a cycle ergometer, followed by 3-5 minutes of static stretching, especially of the knee extensors and -flexors. A specific warm-up and familiarization procedure consisting of 12 submaximal to maximal repetitions was conducted, following calibration and preparation of the dynamometer.

We measured peak concentric torque for both knee extensors and –flexors at 60º per second. The best of three individual one-repetition trials, separated by 1-minute rest periods was recorded. Where concentric strength was sufficient (peak extensor torque > 3 $N.m.kg^{-1}$ and peak flexor torque > 2 $N.m.kg^{-1}$), an eccentric test was conducted (Perrin, 1993). We initially conducted a familiarization procedure on the athletes, involving nine eccentric repetitions, progressing from submaximal to maximal effort. Peak eccentric torque for knee extensors and –flexors was measured at 60º per sec. The best of three consecutive one-repetition trials, conducted without interval was recorded. The majority of subjects (17 of 20) did not qualify for the eccentric portion of the isokinetic evaluation due to insufficient concentric strength.

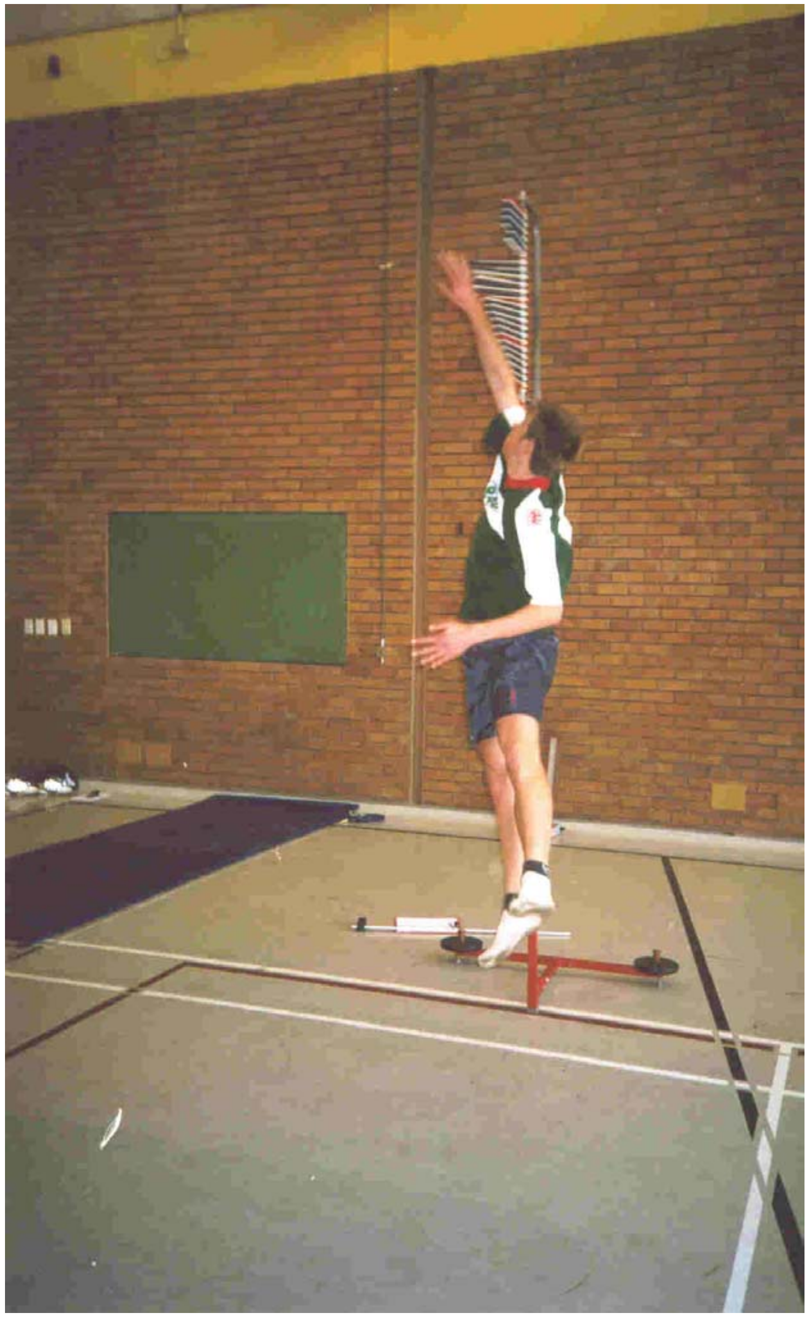


Figure 3.8 Photograph of the vertical jump test, using the Vertec® vertical jump meter.

3.3.5 <u>Muscular power</u>*

3.3.5.1 Vertical jump test

Peak leg power was assessed using the vertical jump test. We performed the test with a Vertec vertical jump meter (Vertec, Questek Corp., Northridge, CA) (Baechle *et al*, 2000). The warm-up routine involved low-velocity running for 3-5 minutes followed by static stretching. The subject was then provided with instructions specific to the test (SASC, 2003; SISA, 2000). The jump meter was calibrated according to the subject's standing stretch height, and the subjects were allowed one practice jump. The best of three trials was recorded.

Peak leg power (in watts) was calculated using the following formula:

Peak power (watts) = [78.5 x jump height(cm)] + [60.6 x mass(kg)] – [15.3 x height(cm)] – 1308

(Dowling & Vamos, 1993)

Figure 3.9 Photograph of the standing long jump test, conducted using a gymnastics mat to prevent impact-related injury during landing.

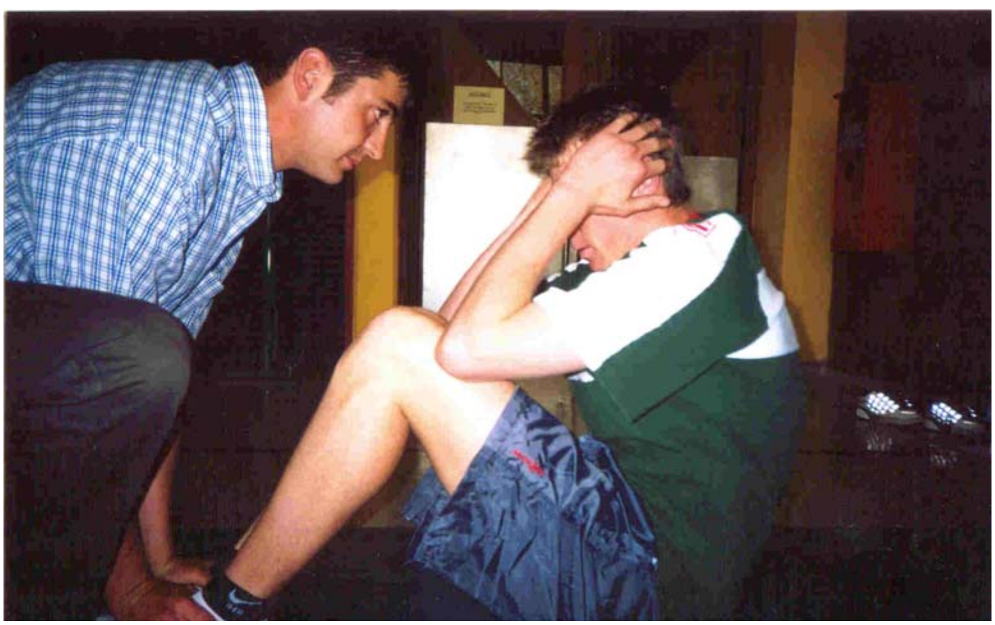


Figure 3.10 Photograph of the two-minute sit-up test, showing location of the tester, and position to be attained to complete one repetition.

3.3.5.2 Standing long jump test

The *standing long jump test** was conducted after the vertical jump test (see previous page) and was used as an assessment of muscular power. It was conducted on a standard gymnasium floor, with a landing surface constructed from thin gymnastics landing mats, in order to prevent injury associated with impact during the landing. The best of three trials (in cm) was recorded. (SASC, 2003; SISA, 2000)

3.3.6 <u>High-intensity muscular endurance</u>

3.3.6.1 Local muscular endurance (LME)*

The LME evaluation consisted of three tests:

i. The 2-minute sit-up test:

Subject's feet were fixed and they had to execute repetitions in such a way that their hands remained in contact with the head at all times. In order for a repetition to be recorded, the elbows had to touch the knees or lower thigh during the concentric phase. During the eccentric phase, the subject had to return to a position where the lower back touched the ground. (SASC, 2003; SISA, 2000) The 2-minute sit-up test involved the maximum number of repetitions performed in two minutes.

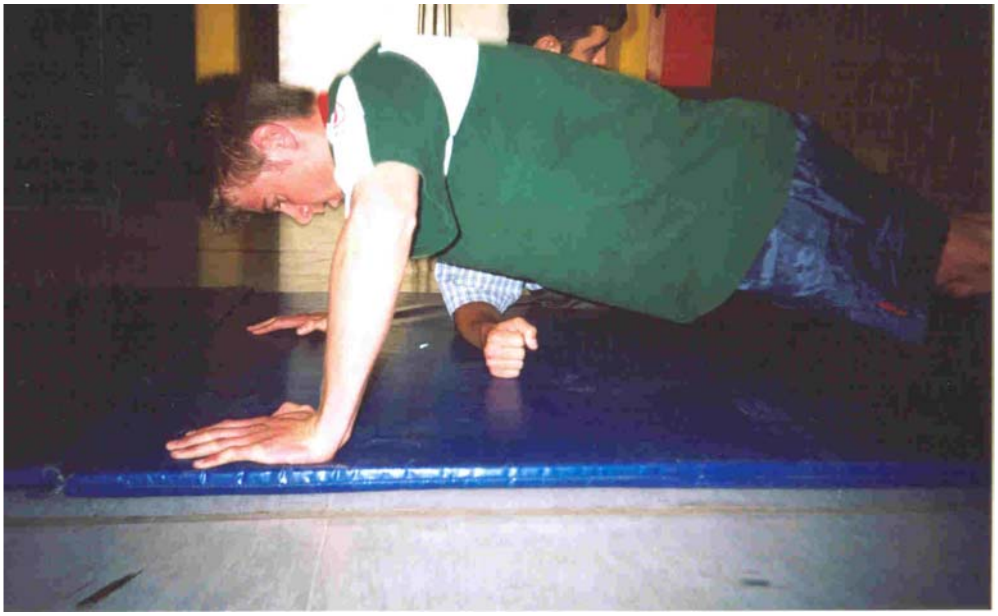


Figure 3.11 Photograph of the one-minute press-up test, showing location of the tester, and position to be attained to complete one repetition.

ii. The 1-minute press up test

Subject's were expected to execute repetitions in such a way that their chest would touch the tester's fist placed on the ground below them, and then return to a position where their elbows were in full extension. (SASC, 2003: SISA, 2000) The 1-minute press-up test involved the maximum number of repetitions performed in one minute.

The 2-minute sit-up and 1-minute press-up tests were conducted following the vertical- and standing long jump tests and therefore did not require any additional warm-up.

iii. The maximum pull-up test:

This test was conducted on a separate day to avoid the influence of fatigue. The test was conducted on a standard pull-up bar with a supinated (open) grip and a gripwidth of approximately 10cm. The subject was instructed to bend the legs at the knee and cross the feet to prevent excessive strain on the lumbar spine. The subject was instructed to lift the chin above the bar and return to a position where the elbows were in full extension during each repetition. The subject was required to perform the maximum number of repetitions without rest (SASC, 2003; SISA, 2000).

Figure 3.12 Photograph of the Wingate cycle ergometer test, conducted on a Monark 834E.

3.3.6.2 High-intensity (whole-body) muscular endurance*

We assessed high-intensity endurance using one of the standard Wingate tests (SASC, 2003; SISA, 2000). The test was conducted on a mechanically braked cycle ergometer (Monark 834E, Monark-Bodyguard AB, Varberg, Sweden). A standard warm-up was conducted on a separate cycle ergometer for a duration of 5 minutes, followed by 4-5 minutes of static stretching. The familiarization procedure involved a maximal effort at the test load for a duration of 5 seconds followed by a 2 minute rest period. The test load was set at 10% of the subject's body mass. We measured high-intensity endurance as the slope of the decline in power output over a 30-second period of maximal effort cycling. The muscle mass involved in this test is large enough to represent whole-body high-intensity muscular endurance (Bar-Or, 1987).

3.3.7 Anaerobic assessment

3.3.7.1 Peak- and mean power output (Wingate cycle ergometer test)

We assessed peak- and mean power output using one of the standard Wingate tests (SASC, 2003; SISA, 2000). The test was conducted on the Monark cycle ergometer at the same time as the measurement of high intensity muscular endurance (section 3.2.8.2). Calibration procedures using known masses and resistance settings were conducted prior to the start of assessment procedures on this sample.

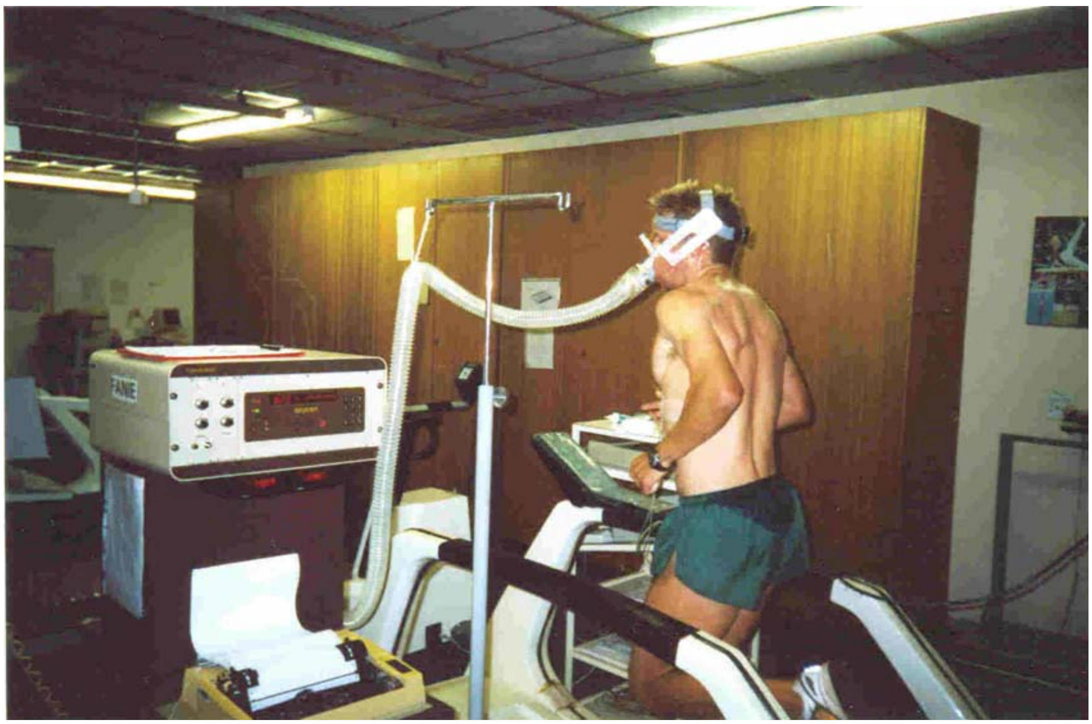


Figure 3.13 Photograph of the maximal accumulated oxygen deficit (MAOD) test, conducted on a level grade motorized treadmill and metabolic cart.

The test load was set at 10% of the subject's body mass. We measured peak power output as the highest power output over a 5-second period. Mean power output was calculated from six 5-second intervals collected during the 30-second test of maximal effort cycling.

3.3.7.2 Maximal accumulated oxygen deficit (MAOD)

We determined the *maximal accumulated oxygen deficit* (MAOD) as a second measure of anaerobic capacity. The test was conducted over two separate days. Four athletes were unavailable for the testing due to long-term injury, and thus only sixteen sets of data were collected for this test.

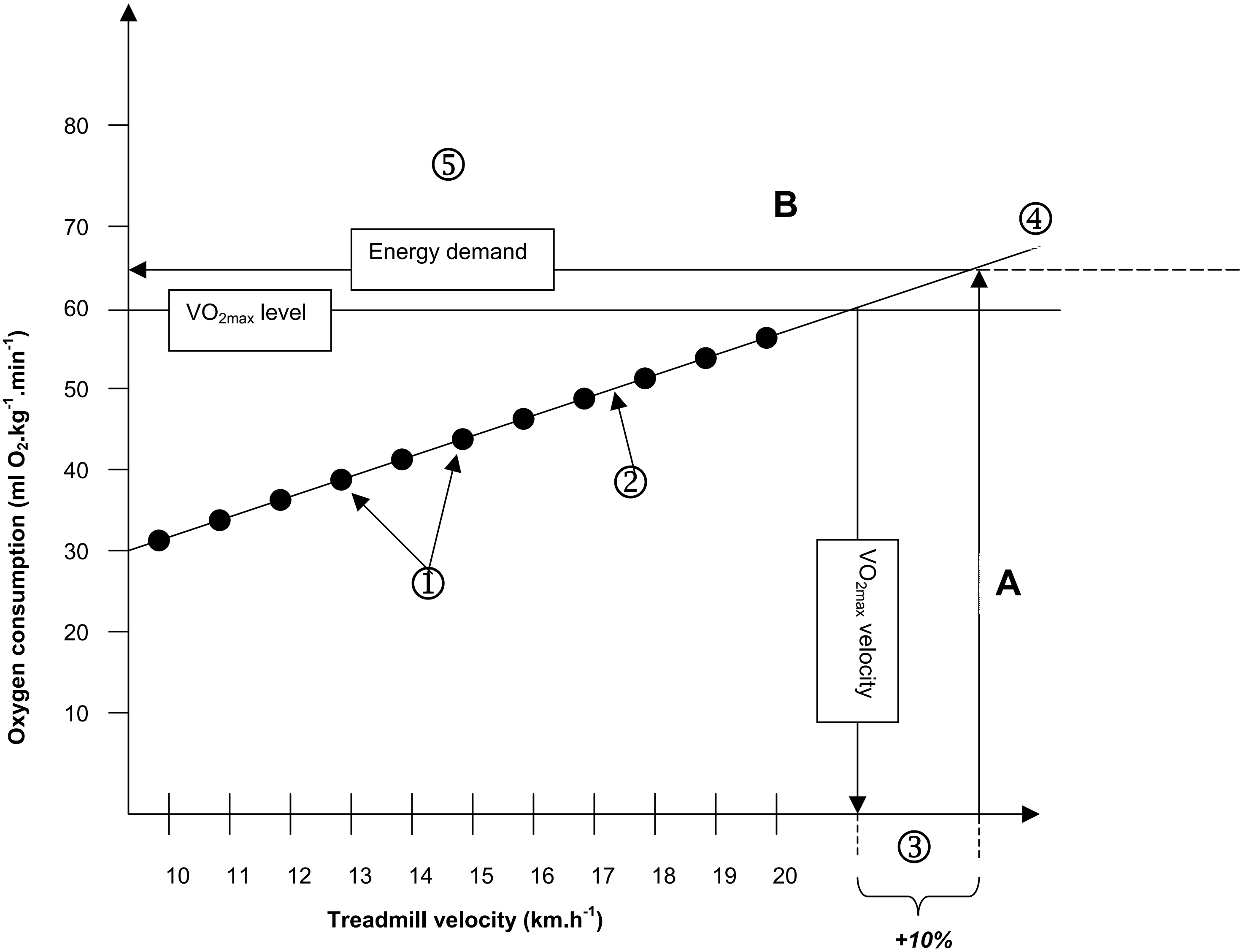
Day one of the determination was conducted on a level grade (0%) motorised treadmill (Powerjog EG10, Sport Engineering Ltd, Birmingham, England). The warm-up consisted of a 6 minute run at 8 $km.h^{-1}$, followed by 4 – 5 minutes of static stretching. We measured oxygen consumption using a calibrated metabolic cart (Mijnhardt Oxycon OX-4, Mijnhardt, Bunnik, Holland) during progressive submaximal runs, starting at 10 $km.h^{-1}$, and increasing by 1 $km.h^{-1}$ at the end of every stage, up to at least 90% of the VO_{2max} (determined on a previous day). Each stage was separated by a 1-minute rest period. Most athletes completed a minimum of 9 stages (18 $km.h^{-1}$), with some completing up to 13 stages (22 $km.h^{-1}$).

The data collected during day one was used to calculate the running speed for the supramaximal run to be conducted on a separate day (see figure 3.14 on page 121).

Supramaximal exercise was performed using a validated technique (Medbo *et al*, 1988; Scott *et al*, 1991) where intensity (treadmill speed) was related to oxygen consumption. The supramaximal run was conducted on a separate day, following a minimum 24-hour rest period, during which no training or physical exertion was allowed.

The warm-up procedure consisted of a 10 minute run at 10 $km.h^{-1}$ on the same treadmill on which the test was to be conducted (for familiarisation purposes), followed by 5 – 10 minutes of static stretching. The supramaximal run was conducted at a level grade (0%) on the same motorised treadmill at a speed calculated from the linear regression technique relating to oxygen consumption obtained on day one.

We determined the maximal accumulated oxygen deficit as the difference between the oxygen demand (calculated from data collected on day one) and the oxygen uptake measured using the metabolic cart on day two (Medbo *et al*, 1988; Scott *et al*, 1991) (see figure 3.15 on page 122). Where the speed achieved during the test differed slightly from the calculated test speed, the oxygen demand value was re-calculated using data collected on day one. The technique described by Medbo *et al* (1988) is designed to elicit fatigue in 2-4 minutes (Scott *et al*, 1991). Subjects were instructed to run at the supramaximal speed, until total exhaustion intervened.



① Plot oxygen consumption at submaximal speeds to within 10% of VO_{2max}.

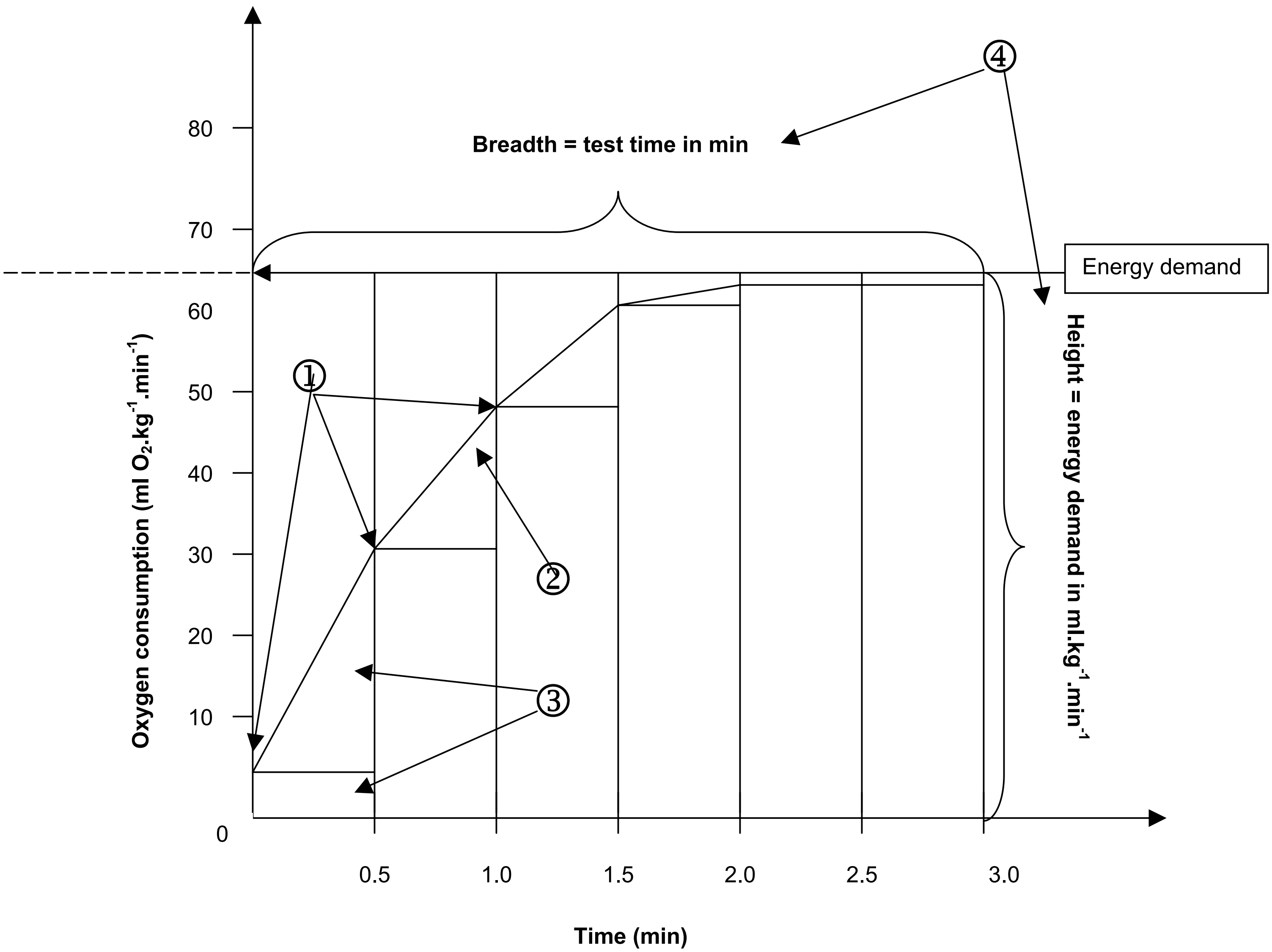
② Fit regression line to individual data points.

③ Determine vVO_{2max} (velocity), and add 10% to this value (line **A**).

④ Extrapolate regression line in ② to meet line of **vVO_{2max} + 10%** (line **A**).

⑤ Energy demand is set at the level of intersection of lines **A** and **B**.

Figure 3.14 Method for determining supramaximal running speed and consequent energy demand for the *maximal accumulated oxygen deficit* (MAOD) test.



① Plot VO_2 values for each 30 seconds of the supramaximal run including *resting* VO_2.

② Join data points as shown to form curve.

③ Determine total area under curve (sum of areas of rectangle + triangle) (in mL.kg^{-1}).

④ TOTAL area (mL.kg^{-1}) = HEIGHT (ml.kg^{-1}.min^{-1}) x BREADTH (min)

⑤ MAOD = TOTAL area – area under curve in mL.kg^{-1}.

Figure 3.15 Method for determining the *maximal accumulated oxygen deficit* (MAOD).

Figure 3.16 Photographs showing equipment used to conduct the sport-specific track tests on a standard surface.

3.3.8 Assessment of high-speed running ability*

We performed a battery of track tests measuring linear speed, acceleration and endurance on a standard tartan athletics track. A thorough warm-up was conducted prior to the track testing, and involved steady-state low-intensity running, static stretching and higher intensity sport-specific drills (SASC, 2003; Smith *et al*, 2000; SISA, 2000).

The first of the tests was the 40-metre sprint test, where photo-electric cells (Speed Light, Swift Performance Equipment, Norsearch Pty.(Ltd), Lismore, NSW, Australia) were placed at the start, and at 5-, 10-, 20- and 40 meters, and assessed acceleration and short-range speed.

The second test involved a sprint over 90 meters with photo-electric cells placed at 50-, 60-, 70-, 80- and 90 meters, and was used to assess maximum short-distance running speed and speed-endurance.

The last test was a 300-metre time-trial, which involved a maximal run with photo-electric cells placed at the start, at 150 meters and 300 meters, and was used to assess both maximum longer distance running speed and speed-endurance.

3.3.9 <u>Time trial</u>

An ***800-meter time-trial*** was conducted on a separate day on a standard tartan athletics track, under conditions of normal ambient temperature (22 – 28°C) and wind speed ($v < 1.0\ m.s^{-1}$). The 800-meter run was used as a standardized distance for all middle-distance athletes as the most likely to yield a reproducible result.

The reasons for this assumption were based on the following:

(1) distance and duration were closest to typical high-intensity training distances,
(2) most commonly run event in this sample of athletes,
(3) least likely to be influenced by racing tactics and fatigue-related performance decline.
(Snell, 1990; Ward-Smith, 1999)

The time-trial performance was not conducted under competitive conditions, in order to standardize the technique for all subjects, who were assessed at different times.

The time-trial performance time was compared to seasonal and personal best times, and where significantly different, the time-trial was repeated. The recorded time was used for statistical analysis.

3.4 STATISTICAL PROCEDURES

3.4.1 Data presentation

Data are shown in tables showing the range, mean, standard deviation and r^2 values. r^2 values for each variable were calculated in relation to performance times for the 800-meter time-trial (see section 3.3.2). Variables that are significantly related to performance are marked with an asterisk (*).

3.4.2 Correlation analysis

Correlations between the measured performance times and other measurements were determined using the Pearson product-moment correlation technique. Running times were converted to speed (in $m.min^{-1}$) for this purpose. The Bonferroni correction (for multiple comparisons) was used to control for type 1 error. As a consequence, variables were considered to be significantly related at $p \leq 0.014$ (n=20) and $p \leq 0.016$ (n=16)[8]. These p-values were calculated by applying the following formula:

$p_2 = \frac{p_1}{\sqrt{N}}$	(where p_1 = original level of significance; p_2 = corrected level of significance; N = number of observations)

[8] The difference in n is due to the fact that four subjects were unable to complete the MAOD test. p-values differ due to the difference in number of observations.

3.4.3 Multiple correlation comparison

A multiple correlation comparison was conducted using a technique described by Steiger (1980). Software produced by Steiger was used to analyze the data (Multicorr Version 2.4, James H. Steiger, University of British Columbia).

In order to use the technique, we constructed an 18 x 18 circumplex identity matrix. The selected variables represented all areas of the testing procedures, with the exception of flexibility scores, and from all three groups of significance (see section 4.2.9 – Table 4.9). Only 18 variables could be used due to software constraints. Flexibility scores were not used as it was difficult to identify one representative test, or to produce a rating of flexibility from all six tests.

3.4.4 Multiple regression

A multiple regression technique, involving backwards stepwise elimination was used to identify test variables that were the strongest predictors of performance. We also attempted to develop a prediction model for 800-meter performance from significant variables using this technique.

4. RESULTS

4.1 TIME TRIAL

The time trial time was used as the dependant variable for the statistical correlation procedure. There was a highly significant relationship when seasonal best performance over 800 meters was correlated with the time trial performance ($r = 0.89$; $p<0.01$). A summary of the difference between seasonal best and time trial performance is shown in Table 4.1 (overleaf).

Some of the time trial performances differ by more than 10% from the seasonal best time. This is primarily due to the fact that the assessment was conducted during the “off-season”, when the bulk of the training is endurance-related, and running speed is affected negatively. Despite this difference, we used the time trial measurement as it was measured during the same time period as the other testing procedures, and allowed us to control extraneous variables, such as environmental conditions and motivational factors related to competitive performance.

Table 4.1 Comparison between seasonal best times and the recorded time-trial over 800 metres.

Subject	Seasonal best (sec)	Time trial (sec)	% difference
1	114.0	123.3	-8.16%
2	130.0	139.6	-7.39%
3	109.5	115.9	-5.85%
4	118.0	125.5	-6.36%
5	108.3	113.5	-4.8%
6	114.0	116.2	-1.93%
7	111.0	121.3	-9.28%
8	118.0	131.4	-11.36%
9	122.0	126.5	-3.69%
10	118.0	125.3	-6.19%
11	109.0	120.3	-10.37%
12	114.0	120.0	-5.26%
13	109.2	113.8	-4.21%
14	112.0	121.3	-8.3%
15	106.3	116.9	-10.02%
16	110.2	117.7	-6.81%
17	107.1	114.6	-7.0%
18	104.98	117.7	-12.12%
19	120.2	124.4	-3.49%
20	118.4	126.0	-6.42%
MEAN	113.7	121.6	-6.95%
SD	±6.25	±6.48	±0.73

4.2 TESTS

4.2.1 Anthropometry*

All anthropometrical measurements (including body density, body fat percentage, sum of skinfolds and muscle mass) were not significantly correlated with performance. A summary of the results obtained from anthropometric assessments is shown in Table 4.2 below.

Table 4.2 Norms and ranges of anthropometrical assessments.

	Range	Mean (± sd)	r^2
Body density ($g.mL^{-1}$)	1.066 – 1.086	1.077 ± 0.005	0.05
Body fat (%)	6.7 – 14.5	10.3 ± 1.998	0.05
Sum of skinfolds (mm)	31.7 – 63.4	42.3 ± 8.66	0.10
Muscle mass (kg)	31.7 – 49.4	39.04 ± 4.376	0.30

4.2.2 Flexibility*

No measures of flexibility were significantly correlated with performance. A summary of the results obtained from the flexibility assessments is shown in Table 4.3 (overleaf).

Table 4.3 Norms and ranges of flexibility measurements.

		Range	Mean (± sd)	r^2
Modified sit and reach (cm)		19.0 – 43.5	29.2 ± 7.6	0.00
Straight leg hamstring test (°)	L	53 – 103	79.4 ± 18.0	0.02
	R	56 – 111	82.6 ± 17.7	0.02
MTT (iliopsoas angle) (°)	L	-11 to 15	2.6 ± 7.8	0.00
	R	-11 to 14	3.5 ± 7.3	0.01
MTT (quadriceps angle) (°)	L	22 – 78	51.1 ± 13.0	0.05
	R	21 – 71	50.5 ± 10.7	0.03
Ankle dorsiflexion (°)	L	13 – 30	22.6 ± 4.5	0.11
	R	14 – 36	22.7 ± 6.2	0.2
Ankle plantar flexion (°)	L	15 – 44	26.8 ± 7.2	0.09
	R	14 – 46	26.3 ± 8.2	0.07
Ankle ROM (°)	L	40 – 62	49.0 ± 7.3	0.01
	R	35 – 67	49.2 ± 8.2	0.03

4.2.3 Aerobic assessment

4.2.3.1 Running economy, maximal oxygen consumption & lactate threshold

No aspects of the aerobic assessment were significantly correlated to performance. A summary of the results obtained from the aerobic tests conducted are shown in Table 4.4 (below).

Table 4.4 Norms and ranges of measurements derived from the aerobic assessment.

	Range	Mean (± sd)	r^2
VO_{2max} ($ml.kg^{-1}.min^{-1}$)	53.7 – 70.8	63.5 ± 51.6	0.09
Running economy ($ml.kg^{-1}.km^{-1}$)^A	154.5 – 201.3	177.8 ± 12.0	0.00
Running economy ($ml.kg^{-1}.km^{-1}$)^B	161.8 – 207.0	183.9 ± 9.4	0.09
Blood lactate turnpoint ($ml.kg^{-1}.min^{-1}$)	36.6 – 55.3	47.7 ± 5.0	0.09
Blood lactate turnpoint (% VO_{2max})	62.4 – 88.8	74.6 ± 8.0	0.20

^{A} Determined from a single 5-min run at $12km.h^{-1}$, 0% gradient

^{B} Determined from 9 to 13 submaximal runs (10 – $22km.h^{-1}$); 0% gradient

4.2.4 <u>Static and dynamic muscular strength</u>

4.2.4.1 Static muscular strength*

Absolute and relative measures of static strength were not significantly related to performance after the Bonferroni correction. The absolute measure was obtained from the mass lifted during the incline leg press one-repetition maximum (1RM) test, and the relative amount was determined from the mass lifted expressed as a percentage of body mass. A summary of the results obtained from the 1RM test is shown in Table 4.5 (overleaf).

4.2.4.2 Isokinetic evaluation* (dynamic muscular strength)

There were no significant relationships between the variables measured during the isokinetic evaluation and performance. A summary of the results obtained during the isokinetic evaluation is shown in Table 4.5 (overleaf).

Table 4.5 Norms and ranges of muscular strength measurements.

		Range	Mean (± sd)	r^2
Peak concentric knee extensor torque (N.m) (60°.s^{-1})	L	130 - 267	199.0 ± 32.8	0.14
	R	148 – 281	204.3 ± 28.2	0.01
Peak concentric knee extensor torque (N.m.kg^{-1}) (60°.s^{-1})	L	2.28 – 3.57	3.2 ± 3.3	0.02
	R	2.59 – 3.74	3.2 ± 3.1	0.11
Peak concentric knee flexor torque (N.m) (60°.s^{-1})	L	96 – 165	119.2 ± 18.7	0.06
	R	92 – 171	124.2 ± 22.5	0.05
Peak concentric knee flexor torque (N.m.kg^{-1}) (60°.s^{-1})	L	1.62 – 2.43	1.9 ± 0.2	0.01
	R	1.6 – 2.46	2.0 ± 2.4	0.01
Concentric flex:ext ratio (%)	L	49.8 – 74.6	60.7 ± 9.1	0.04
	R	48 – 78.5	61.0 ± 8.2	0.02
Incline leg press (kg)		150 – 360	259.3 ± 57.8	0.32
Incline leg press (% mass)		253.4 – 534.2	407.4 ± 73.8	0.19

4.2.5 <u>High-intensity muscular endurance</u>

4.2.5.1 Local muscular endurance (LME)*

No measures of local muscular endurance were significantly related to performance. A summary of the results obtained from tests measuring local muscular endurance is shown in Table 4.6 (overleaf).

4.2.5.2 High-intensity (whole-body) muscular endurance*

Minimum power output measured by means of the Wingate cycle ergometer test was significantly correlated to performance after the Bonferroni correction. Power drop was not significantly related. A summary of the results pertaining to muscular endurance obtained from the Wingate test is shown in Table 4.6 (overleaf).

Table 4.6 Norms and ranges for measurements of local muscular endurance.

	Range	Mean (± sd)	r^2
2-minute sit-up test (reps)	43 – 107	75.0 ± 16.8	0.10
1-minute press-up test (reps)	28 – 60	44.0 ± 7.9	0.14
Maximal pull-up test (reps)	1 – 16	10.2 ± 3.9	0.00
Min power ($w.kg^{-1}$)	6.5 – 9.8	7.49 ± 0.75	0.22*
Mean power (w)	450.9 – 826.0	633.9 ± 97.8	0.34*
Power drop ($w.sec^{-1}$)$^+$	3.4 – 14.6	10.0 ± 3.2	0.10
Power drop ($w.sec^{-1}.kg^{-1}$)$^+$	0.06 – 0.21	0.16 ± 0.05	0.04

* denotes $p<0.05$; $^+$ Power drop obtained from the Wingate test.

4.2.6 Muscular power*

No measurements derived from the vertical jump test were correlated significantly with performance after the Bonferroni correction. A summary of the results obtained from tests measuring muscular power is shown in Table 4.7 (page 138).

4.2.7 Anaerobic assessment

4.2.7.1 Peak- and mean power output (Wingate cycle ergometer test)

Absolute measurements (in watts) for mean and minimum power output derived from The Wingate test were significantly correlated to performance after the Bonferroni correction. A summary of the results pertaining to anaerobic capacity obtained from the Wingate test is shown in Table 4.7 (overleaf).

4.2.7.2 Maximal accumulated oxygen deficit (MAOD)

Results obtained from the maximal accumulated oxygen deficit test were not significantly related to performance. A summary of the results obtained from the MAOD testing procedure is shown in Table 4.7 (overleaf).

Table 4.7 Norms and ranges for muscular power & anaerobic capacity.

	Range	Mean (± sd)	r^2
Vertical jump height (cm)	43.2 – 61.0	52.1 ± 6.06	0.14
Vertical jump (% standing height)	23.7 – 34.5	29.6 ± 3.31	0.09
Peak power (w) [C]	2789 – 5237.8	3930.5 ± 686.2	0.25
Standing long jump (cm)	194 – 236	217.0 ± 13.85	0.10
Standing long jump (% height)	111.5 – 136.4	123.7 ± 8.69	0.03
Peak power (w) [D]	524.8 – 1042.2	799.2 ± 136.35	0.32
Peak power ($w.kg^{-1}$) [D]	8.88 – 14.69	12.48 ± 1.472	0.19
Mean power (w)	450.9 – 826.0	633.9 ± 97.76	0.34*
Mean power/kg ($w.kg^{-1}$)	7.63 – 11.01	9.91 ± 0.954	0.22
Accumulated oxygen uptake ($ml.kg^{-1}$)	108.8 – 162.6	132.2 ± 15.63	0.00
Accumulated oxygen deficit ($ml.kg^{-1}$)	28.0 – 82.5	57.5 ± 15.58	0.00

[C] Determined from the vertical jump test

[D] Determined from the Wingate cycle ergometer test

* denotes $p<0.05$

4.2.8 <u>Assessment of high-speed running ability*</u>

Many significant relationships between time, velocity and acceleration derived from the 40m, 90m and 300m track tests were found. The most significant measures were maximal running times and velocities recorded at intervals over 40 to 90 meters, as well as time-trials over 150 and 300 meters. A summary of the results obtained from the track tests is shown in Table 4.8 (overleaf).

Table 4.8 Norms and ranges of measurements derived from the event-specific track tests.

	Time (seconds)			Velocity ($m.s^{-1}$)			Acceleration ($m.s^{-2}$)		
	Range	Mean (±sd)	r^2	Range	Mean (± sd)	r^2	Range	Mean (± sd)	r^2
0 – 5m	1.04 – 1.36	1.20 ± 0.08	0.13	3.68 – 4.81	4.21 ± 0.282	0.14	2.7 – 4.62	3.55 ± 0.48	0.14
5 – 10m	0.66 – 0.80	0.74 ± 0.04	0.31	6.25 – 7.58	6.77 ± 0.327	0.28	2.53 – 4.7	3.49 ± 0.60	0.09
10 – 20m	1.15 – 1.33	1.24 ± 0.06	0.30	7.52 – 8.70	8.04 ± 0.343	0.30	0.34 – 1.52	1.03 ± 0.31	0.02
20 – 40m	2.05 – 2.51	2.29 ± 0.13	0.57*	7.97 – 9.76	8.72 ± 0.446	0.54*	0.09 – 0.55	0.30 ± 0.13	0.31
50 – 60m	1.00 – 1.29	1.13 ± 0.08	0.47*	7.75 – 10.00	8.90 ± 0.572	0.45*	0.25 – 1.30	0.80 ± 0.29	0.31
60 – 70m	0.99 – 1.27	1.14 ± 0.08	0.46*	7.87 – 10.10	8.88 ± 0.606	0.44*	-0.49 – 0.45	-0.01 ± 0.26	0.01
70 – 80m	0.97 – 1.28	1.15 ± 0.09	0.40*	7.81 – 10.31	8.74 ± 0.63	0.37*	-0.46 – 0.21	-0.12 ± 0.21	0.01
80 – 90m	1.02 – 1.33	1.19 ± 0.09	0.45*	7.52 – 9.80	8.52 ± 0.623	0.42*	-1.03 – 0.21	-0.18 ± 0.30	0.00

	Time (seconds)		
	Range	Mean (± sd)	r^2
0 – 150m	16.16 – 21.50	19.30 ± 1.65	0.74*
0 – 300m	34.90 – 44.30	39.25 ± 2.76	0.80*
150 – 300m	18.10 – 22.80	19.75 ± 1.29	0.67*

* denotes $p<0.05$

4.3 STATISTICAL ANALYSIS

4.3.1 Correlation analysis

Variables were separated into two groups based on the results of the correlation analysis and subsequent correction:

GROUP 1

Variables that were not significantly related to performance in the 800-meter time-trial after the Bonferroni correction, and which therefore do not have a significant influence on performance.

GROUP 2

Variables that were significantly related to performance in the 800-meter time-trial after the Bonferroni correction, and which therefore have a significant influence on performance.

Details of these groups are shown in Table 4.9 (overleaf).

Table 4.9 Groupings of variables in relation to correlation analysis.

GROUP 1 Not significant after Bonferroni correction

- Body density
- Body fat (relative)
- Sum of skinfolds
- Muscle mass (relative)
- Vertical jump (absolute)
- Standing long jump (all)
- All flexibility measurements
- All LME measurements
- Wingate power drop (absolute & relative)
- Isokinetic measurements (absolute and relative)
- V02max
- vV02max
- Running economy
- All measurements involving blood lactate
- Test durations, treadmill gradients and velocities
- MAOD – uptake and deficit
- Time, velocity @ 5m
- Acceleration 0→ 5m, 5 → 10m, 10 → 20m, 60 → 70m, 70 → 80m, 80 →90m
- Muscle mass (absolute)
- Anaerobic leg power (vertical jump)
- Incline leg press 1RM (absolute)
- Incline leg press 1RM (relative)
- Wingate peak power (absolute & relative)
- Wingate minimum power (relative)
- Wingate mean power (relative)
- Resting VO2
- Time, velocity @ 10m
- Time, velocity @ 20m
- Acceleration 20 → 40m
- Acceleration 50 → 60m

GROUP 2 Significant after Bonferroni correction

- Wingate minimum power (absolute)
- Wingate mean power (absolute)
- Time, velocity @ 40m
- Time, velocity @ 60m
- Time, velocity @ 70m
- Time, velocity @ 80m
- Time, velocity @ 90m
- Time, velocity @ 150m
- Time, velocity @ 300m
- Time, velocity 150 → 300m

4.3.2 Multiple correlation comparison

This procedure was limited by software constraints, where a maximum of 18 variables could be accommodated. For this reason, we first conducted the correlation analysis (section 4.3.1) to determine which variables fro suited for inclusion in the multiple correlation procedure. We also suspected that the sample size (n=20) would not be sufficient in terms of providing a definite result, and that we would need to consider further analysis, such as a multiple regression technique (section 4.3.3).

The multiple correlation comparison technique determined that the correlations between all variables were highly significant ($p<0.01$). The 18 variables used to construct the circumplex identity matrix and their cross-correlation values are shown in Table 4.10 (overleaf).

Due to sample size, it was not possible to accurately assess which of the variables were most significant. In order to evaluate these relationships we used a multiple regression technique. (section 4.3.3)

Table 4.10 18 x 18 circumplex identity matrix showing cross-correlations (r).

	Body fat	Muscle mass	Peak power (VJ)	Incline leg press	Peak power (Wingate)	Min power (Wingate)	Mean power (Wingate)	Power drop (Wingate)	EXTENSORS (MAX)	FLEXORS (MAX)	[blood LA] turnpoint	MEAN RE	VO_{2max}	VO_{2max} velocity	MAOD	velocity @ 40m	velocity @ 90m	300m time
Body fat	1.00																	
Muscle mass	-0.11	1.00																
Peak power (VJ)	-0.11	0.79	1.00															
Incline leg press	-0.21	0.78	0.51	1.00														
Peak power*	0.05	0.65	0.60	0.64	1.00													
Min power*	0.18	0.77	0.72	0.71	0.76	1.00												
Mean power*	0.13	0.74	0.72	0.68	0.94	0.90	1.00											
Power drop*	-0.04	0.34	0.30	0.38	0.86	0.33	0.67	1.00										
EXTENSORS+	-0.03	0.68	0.82	0.40	0.53	0.58	0.62	0.32	1.00									
FLEXORS+	0.10	0.53	0.62	0.36	0.66	0.57	0.63	0.52	0.72	1.00								
LA turnpoint	0.18	-0.67	-0.63	-0.22	-0.58	-0.51	-0.56	-0.37	-0.55	-0.50	1.00							
MEAN RE	0.06	-0.23	-0.46	-0.13	0.11	-0.32	-0.11	0.37	-0.41	-0.15	0.07	1.00						
VO_{2max}	-0.29	0.14	0.14	0.14	0.36	0.12	0.14	0.40	0.06	0.25	-0.40	0.40	1.00					
VO_{2max} velocity	-0.01	0.10	0.04	0.19	0.24	0.20	0.03	0.16	-0.02	0.37	-0.17	0.04	0.76	1.00				
MAOD	-0.46	0.03	0.35	-0.28	-0.03	-0.10	-0.12	0.00	0.45	0.24	-0.52	-0.27	0.51	0.19	1.00			
velocity @ 40m	-0.29	0.59	0.65	0.52	0.42	0.62	0.53	0.12	0.33	0.26	-0.51	-0.54	0.06	-0.12	0.23	1.00		
velocity @ 90m	-0.01	0.25	0.37	0.29	0.32	0.41	0.36	0.13	0.00	0.16	-0.29	-0.43	0.01	0.11	-0.01	0.69	1.00	
300m time	0.27	-0.57	-0.62	-0.55	-0.58	-0.72	-0.64	-0.26	-0.34	-0.33	0.65	0.31	-0.30	-0.23	-0.17	-0.83	-0.70	1.00

* derived from the Wingate anaerobic cycle ergometer test

+ derived from the isokinetic evaluation (60°.s^{-1}) (maximum value from left and right limb)

4.3.3 <u>Multiple regression</u>

The multiple regression method, using backwards stepwise elimination isolated the 300-meter time-trial time as the most significantly related variable. The technique also identified that an accurate prediction model incorporating the most significant variables could not be developed, primarily due to problems with multiple co-linearity.

The variables which were selected for inclusion in a prediction model were:

- 0-40m time
- 0-60m time
- 0-70m time
- 0-80m time
- 0-90m time
- 0-150m time
- 0-300m time
- Minimum power (watts) from the Wingate test
- Minimum power (in watts per kg) from the Wingate test
- Mean power (watts) from the Wingate test

Of these, only the 300m time-trial did not have significant problems with multiple co-linearity, and was thus selected for the prediction equation.

The following equation was developed to predict 800-meter performance using only the 300-meter time-trial:

$$800m\ time = 37.1062 + 2.17(300m\ time) \qquad \text{[time in seconds]}$$

The variable included in the equation (300-m time) was significant at the 0.015 level. An r^2 value of 0.8 was calculated for the relationship between 300m time and the 800m time trial performance, an additional justification of its selection as the primary predictive variable. In addition, partial- and model-r^2 values derived from the stepwise multiple regression, determined that this equation accounts for 79% of the variability in performance.

Table 4.11 (overleaf) demonstrates the difference between the actual 800-meter time-trial performance and predicted time using the above equation.

Table 4.11 Difference between actual 800-meter time and formula-based prediction.

Subject	Actual time (sec)	Predicted time (sec)	% difference
1	123.3	123.6	-0.25%
2	139.6	133.3	4.54%
3	115.9	116.8	-0.76%
4	125.5	126.5	-0.81%
5	113.5	119.5	-5.28%
6	116.2	117.9	-1.47%
7	121.3	122.5	-1.00%
8	131.4	130.0	1.10%
9	126.5	127.5	-0.82%
10	125.3	127.0	-1.32%
11	120.3	118.2	1.77%
12	120.0	125.3	-4.40%
13	113.8	114.2	-0.33%
14	121.3	118.8	2.03%
15	116.9	112.7	3.56%
16	117.7	115.3	2.01%
17	114.6	117.3	-2.39%
18	117.7	115.6	1.79%
19	124.4	122.2	1.74%
20	126	127.9	-0.79%
MEAN	121.6	121.6	-0.05%
SD	±6.48	±5.76	±2.43

Standard error of estimate = 0.26

5. DISCUSSION

5.1 Categorization of tests of physical performance

Scientific assessments used to evaluate middle-distance athletes can be separated into three distinct categories:

1) tests that predict performance;
2) tests involved in the monitoring of training;
3) tests associated with injury prevention and management.

The purpose of this research project was to assess the predictive value of various physical tests with regard to competitive performance. It is difficult to statistically and objectively assess the efficacy of testing procedures with regards to injury prevention and management. It can probably be assumed that the best predictive tests will also constitute the most suitable tests for the monitoring of training progression, but they must not be produce high levels of discomfort or excessive fatigue, as this limits they frequency with which they can be conducted, which needs to be frequent.

5.2 Statistical evaluation of testing procedures

We grouped the tests into two categories, based on their statistical significance and ability to predict performance (see section 4.3.1). Only two types of tests were statistically significant, in terms of their predictive ability. All other tests showed no statistical significance, and therefore, were of no predictive value.

Testing procedures that show no significant predictive value, may nevertheless have merit in terms of other important elements of a complete assessment and intervention programme, such as injury prevention and rehabilitation. They may also deserve additional investigation, particularly as statistical procedures may not always reveal the full value of a procedure, in relation to the intended clinical and practical applications (MacDougall & Wenger, 1991: Puke, 2000; Ziltener & Leal, 2005).

5.3 Value of non-significant tests with regard to middle-distance running

Other investigators have reported that certain tests are valuable indicators of 800m potential and performance (di Prampero *et al*, 1993; Weyand *et al*, 1994). Our study has indicated that these tests were not related to performance. However, our findings may be related to the homogeneity within our group of elite subjects, which narrows the range of the data in some tests. In addition, the tests performed at altitude for a high intensity event, such as the 800m, may have influenced the outcome of some of the assessments.

Other test measurements have been shown to be of value by other investigators, part of the reason they were included in this study. Maximal oxygen consumption has often been anecdotally connected with champion performers in middle-distance events (Daniels, 1974; Snell, 1990), and has also been statistically correlated with running performance (Conley & Krahenbuhl, 1980; di Prampero et al, 1993). Similar connections have been made in terms of running economy, particularly at high running velocities (Brandon, 1995; Daniels & Daniels, 1992), although little attention has been paid to these measurements with respect to competitive conditions.

Lactate threshold, although a contentious area of study (Pyne *et al*, 2001; Swart & Jennings, 2004), has often been suggested as an effective measure of performance in high-velocity running, particularly due to the involvement of anaerobic processes in the intense efforts involved in competition (Svedenhag & Sjodin, 1984; Hill, 1999).

The theory and application of maximal accumulated oxygen deficit has also been extensively researched and debated, with high-performance runners often used as research subjects, due to their increased capacity for anaerobic work. A number of researchers have supported the notion of the maximal accumulated oxygen deficit as a predictor of performance and a valid training monitor in these events (Bangsbo, *et al*, 1993; Medbo *et al*, 1988; Scott *et al*, 1991; Weyand *et al*,1994).

5.4 Prediction of performance

Two types of tests were identified as viable predictors of performance in our study:

i) the Wingate cycle ergometer test, and

ii) tests of high-speed running ability (sport-specific track tests).

These two tests reflect the importance of peak power production and anaerobic capacity (Bar-Or, 1987; Granier *et al*, 1995; McKenzie *et al*, 1982), as well as sport-specific high-speed running ability (Kenney, 1985) with regard to competitive performance in middle-distance running under the conditions of our study .

5.5 Training monitoring

Certain assessments can effectively be used to monitor the progress of training programmes and assist in the development of appropriate interventions. Assessments that are the best predictors of performance may also be effective monitors of training progression. In this study, these were aspects of the Wingate cycle ergometer test (confirmed by Granier *et al*, 1995; McKenzie *et al*, 1982) and the 300m sprint test.

Other assessments that have been used by others to reflect training response include:

- Muscle mass (anthropometric measurement) (Martin *et al*, 1990);
- Static muscular strength assessment (1RM) (Baechle *et al*, 2000);
- Lactate threshold (Svedenhag & Sjodin, 1984).

5.6 Injury prevention and management

Certain tests have been shown to be invaluable in identifying injury risk. Appropriate exercise prescription and intervention subsequent to the testing may assist in preventing injury. Where injuries have occurred, these tests can also be used to effectively monitor rehabilitation and assess when an athlete is ready to return to training and competition. Assessments of joint and muscular flexibility, especially of the hip extensors and knee flexors have been shown to be of importance in identifying injury risk in middle-distance athletes (Hubley-Kozey, 1991).

Isokinetic evaluations, particularly to assess the condition of the knee flexors and extensors, as well as investigation of bilateral differences and functional ratios between agonist and antagonist muscle groups, have been shown to be of value in both injury prevention and rehabilitation (Johansson, 1992; Kannus, 1994).

5.7 Assessment procedures requiring additional development

5.7.1 Isokinetic testing

The isokinetic assessment was only conducted at low speed ($60^{o}.s^{-1}$), which is a standard evaluation of muscular strength (Wrigley & Strauss, 2000). Assessment at higher speeds to assess *muscular strength* at functional velocities ($180^{o}.s^{-1}$) (mistakenly referred to as *muscular power*) and *muscular endurance* (high number of repetitions at $240^{o}.s^{-1}$ or greater) (Baltzopoulos & Brodie, 1989) may have yielded a different result with regard to prediction of performance than that found in this study. In addition, a force-velocity curve can be constructed if the assessment is conducted at multiple speeds (preferably more than six) (Ishiko, 1974; James *et al*, 1994). This will allow the determination of the maximum isometric force , the maximum velocity of contraction (v_{max}), and peak power ($N.m.s^{-1}$). These measurements have been greatly under-utilised as potential predictors of performance, training monitors and in the management of injury.

5.7.2 Maximal accumulated oxygen deficit (MAOD)

The MAOD procedure was conducted on a level grade treadmill, which may have compromised the ability of the procedure to accurately determine anaerobic capacity. At the high speeds at which the supramaximal assessment was conducted, it became difficult for some of the subjects to maintain a balanced and composed running style. If the final supramaximal run had been completed on an inclined treadmill, the resulting lower speed (Nummela *et al*, 1996a; Olesen *et al*, 1994) would eliminate this problem and may have yielded a different result.

5.8 Applications of testing

It is clear that elements of an effective testing battery for high-performance middle-distance runners can be used to predict performance, monitor training or assist with injury prevention and management. Therefore the probable link between the tests used to predict performance and the monitoring of training progression, should allow their effective incorporation into the design of periodized training programmes. In the case of four-week microcycle periodization (Fry *et al*, 1991), the one week designated for regeneration (recovery), is an opportunity to use appropriate testing as part of training monitoring and injury prevention.

Figure 5.1 (overleaf) demonstrates a periodised training load strategy to prevent or delay conditions associated with overtraining and other overuse. A mesocycle (represented in figure 5.1) consists of four separate microcycles. Training intensity commences at a moderate intensity; it progresses to two “shock microcycles” consisting of increased intensity, intended as a stimulus for adaptation. This is followed by a large taper, where intensity and training load is dropped significantly (30-50% of peak load) to allow for regeneration and adaptation. (Fry *et al*, 1991)

It is during this regeneration microcycle that testing procedures designed to monitor training progression and prediction of performance or competition readiness should be conducted. The type of testing conducted will depend on the individual needs of the athlete, the type of training being conducted in accordance with the principles of periodisation, and the level of exertion required. It is an opportunity to conduct tests with a significant physiological load that would normally interfere with training during other periods, such as high-intensity aerobic, anaerobic and muscular function tests.

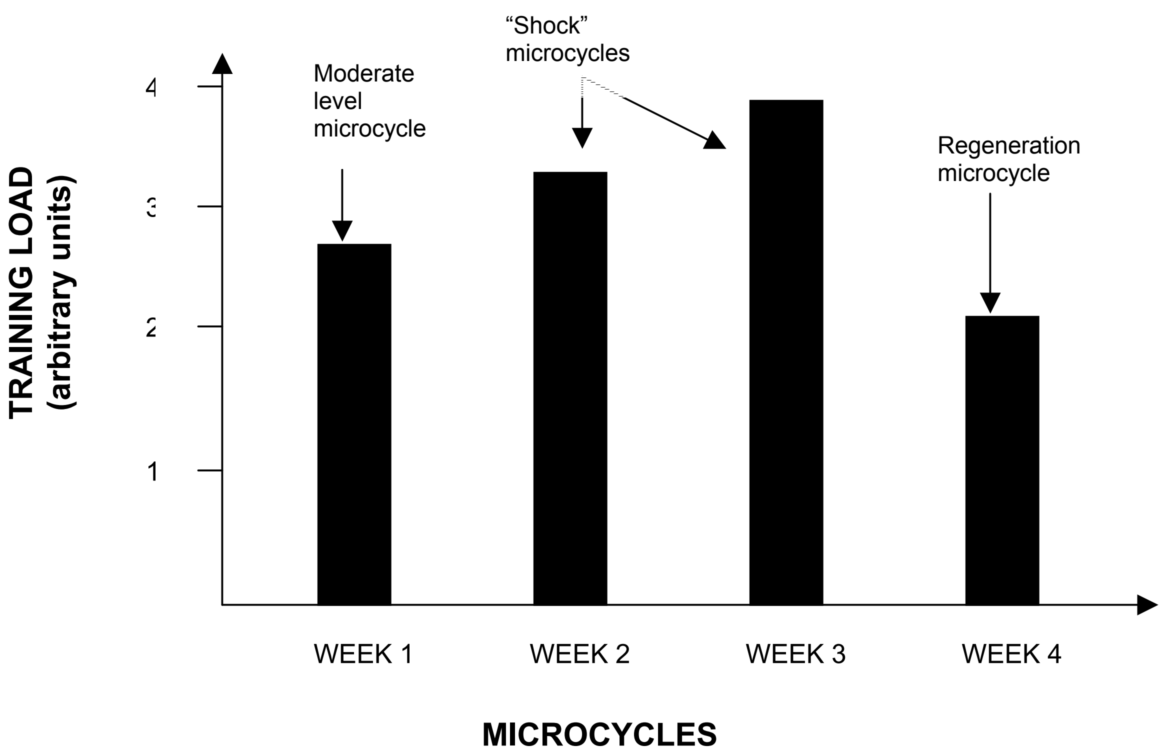


Figure 5.1 *Use of the regeneration week during training microcycles.*

(Fry et al, 1991, p.54)

5.9 Conclusion

5.9.1 Revision of current testing procedures and protocols

We suggest revision of current testing procedures and protocols used in the assessment of middle-distance runners. It is clear that this country's high performance programme is cluttered by inappropriate testing procedures. This study has shown that prediction of 800m performance and monitoring of its training can be achieved most effectively with two groups of tests (Wingate cycle ergometer and track tests).

Some of the tests were not correlated to performance because they are better suited to assess the risk of injury and its management (Hubley-Kozey, 1991). These include (in particular) flexibility tests and isokinetic evaluations. The latter are especially effective because the tests are able to simulate contraction types, velocities and ranges of motion specific to the movements of a given event. They also provide a diagnosis of muscular weaknesses, imbalances and dysfunctions (Johansson, 1992; Kannus, 1994).

5.9.2 Routes for further investigation

The lack of efficacy of assessments found to be not significantly related to performance in this study should be confirmed in a repeat study. Because of positive results in previous studies these include:

- Maximal oxygen consumption (VO_{2max});
- Running economy;
- Lactate threshold;
- Maximal accumulated oxygen deficit (MAOD).

One possible reason for the limited relationship between performance and these variables is the homogenous subject group resulting in a narrow data range. A second possible reason is that all assessments were performed at an altitude of 1800m.

The methods of assessment used for the isokinetic evaluation and maximal accumulated oxygen deficit should be evaluated and, if necessary, developed to suit the unique demands of middle-distance running.

5.9.3 Recommended testing procedures

In my opinion, based on this evaluation of the available literature, and an in-depth understanding of the methods employed by numerous investigators and national associations, together with the statistical results obtained from this study, the following components of physical fitness need to be evaluated:

i. Anthropometrical measurements (particularly monitoring of muscle mass
ii. Maximal oxygen consumption (using an intermittent protocol)
iii. Running economy (at racing velocity)
iv. Blood lactate concentration profile (lactate threshold)
v. Anaerobic performance capacity (particularly speed-endurance)
vi. Muscular strength and power (using isokinetic or iso-inertial methods)
vii. Muscular endurance and contractility (particularly speed-endurance)
viii. Sport-specific tests (time-trials and environmental tests)

In addition, the following procedures can assist with correct monitoring of injury and nutritional profile:

i. Anthropometrical measurements (particularly monitoring of body fat and muscle mass)
ii. Flexibility measurements (particularly of pelvic, knee and ankle region)
iii. Blood profiles (assessment of nutritional markers and chemical products associated with metabolism and injury)

iv. Muscular strength and power (under conditions simulating actual performance conditions – contraction rate and duration)
v. Muscular endurance and contractility (under conditions simulating actual performance conditions – contraction rate and duration)

It is a difficult prospect to attempt to develop a complete, yet concise, testing battery that is able to cater for the individual needs of all athletes. Many practitioners attempt to provide assessment programmes that evaluate all areas of training and performance, instead of focusing on testing procedures that are pertinent to the type of training and injury risk profile, as well as conducive to the provision of a satisfactory level of intervention. Assessments should cater for both the immediate needs of an athlete, and projected long-term development. This can only be done if athletes, coaches and scientific support staff collaborate and co-operate to produce a highly-organised and properly periodised training plan, with regular intervals allowing for effective assessment and subsequent intervention.

It is my hope that this study will foster the idea that the large amount of testing currently being conducted only serve a limited practical purpose, and there is much room for improvement and development, with regard to the way that athletes and the support staff work together in the quest for peak performance.

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Table A.1 Equations commonly used in the determination of fat mass in male, adult athletes.

Reference	Formula	Method
Durnin & Womersley (1974)	17-19: $D_B = 1.1533 - (0.0643 \times \log\Sigma_{SF})$ 20-29: $D_B = 1.1620 - (0.0630 \times \log\Sigma_{SF})$ 30-39: $D_B = 1.1631 - (0.0632 \times \log\Sigma_{SF})$	SKINFOLD Triceps, biceps, subscapular, supra-iliac
Jackson & Pollock (1978)	$D_B = 1.109380 - 0.0008267(\Sigma_{3SF}) + 0.0000016(\Sigma_{3SF})^2 - 0.0002574(age)$	SKINFOLD Chest, abdominal, thigh
Jackson & Pollock (1978)	$D_B = 1.112 - 0.00043499(\Sigma_{7SF}) + 0.00000055(\Sigma_{7SF})^2 - 0.00028826(age)$	SKINFOLD Chest, mid-axillary, triceps, subscapular, abdominal, anterior supra-iliac and thigh
Carter (1982)	$\%BF = (\Sigma 6SF \times 0.1051) + 2.585$	SKINFOLD Triceps, anterior thigh, medial calf, subscapular, anterior supra-iliac, abdominal

The following formulae are used to convert body density to fat mass

(as a percentage of body mass):

Brozek *et al* (1963) : %BF[9] = $[(4.57 / D_B) - 4.142] \times 100$

Siri (1961) : %BF = $[(4.95 / D_B) - 4.5] \times 100$

[9] %BF = body fat percentage; D_B = body density (in $g.cc^{-1}$)

Table A.2 Equations for the determination of fat-free (lean) mass in male, adult athletes.

Reference	Formula	Method
Lohman (1992)	FFM[10] = 0.485(HT^2/R) = 0.338(BM) + 5.32	Bio-electrical impedance
Segal *et al* (1988)	FFM = 0.00066360(HT^2) – 0.02117(R) + 0.62854(BM) – 0.12380(age) + 9.33285	Bio-electrical impedance
Wilmore & Behnke (1969)	FFM = 39.652 + 1.0932(BM) + 0.8370(bi-iliac D) + 0.3297(AB_1 C) – 1.008(AB_2 C) – 0.6478(knee C)	Anthropometric See footnote[11]
Oppliger *et al* (1991)	FFM = 1.949 + 0.701(BM) + 0.186(HT^2 / R)	Bio-electrical impedance

Table A.3 Equations and technique for the determination of muscle mass in male, adult athletes using the Martin formulae. (Martin et al, 1990)

Muscle mass (g) = S(0.0553CTG² + 0.0987FG² + 0.0331CCG²) - 2445

- height in cm (S)
- mid-thigh girth in cm, and anterior thigh skinfold in mm
- calf girth in cm and medial calf skinfold in mm
- forearm girth in cm (FG)

Mid-thigh (CTG) and calf girths (CCG) are corrected using the following formula:

$$\text{Corrected girth (cm)} = \text{measured total girth (cm)} - \left(\pi \times \frac{\text{sk inf old(mm)}}{10}\right)$$

[10] FFM = fat-free mass; HT = height (cm); BM = body mass (kg); R = resistance / impedance (Ω)
[11] D = diameter; C = circumference; AB_1 = abdominal circumference midway between level of xiphoid and umbilicus; AB_2 = abdominal circumference midway between iliac crest and lower ribs

Table A.4 Summary of equations used in the Heath-Carter method.

Endomorphy	=	$(0.1451\chi) - (0.00068\chi^2) + (0.0000014\chi^3) - (0.7182)$[12]
		Endormorphic component can be corrected for height by multiplying by: [170.18 / height in cm].
Mesomorphy	=	$(0.858E) + (0.601K) + (0.188A) + (0.161C) - (0.131H) + 4.5$
	E =	bi-epicondylar breadth of distal humerus (cm)
	K =	bi-condylar breadth of distal femur (cm)
	A =	corrected arm girth (cm)
	C =	corrected calf girth (cm)
	H =	standing height (cm)
Ectomorphy	=	0.732 (RPI[13]) – 28.50 , if RPI > 40.75
	=	0.463 (RPI) – 17.63 , if 40.75 > RPI > 38.25
	=	0.1, if RPI < 38.25 (minimal rating)

(Carter, 1980)

[12] χ = sum of triceps, subscapular and supraspinale skinfolds
[13] RPI = reciprocal of the ponderal index [RPI = height (cm) / $mass^3$ (kg)]

Table A.5 Summary of equations used for proportionality calculations.

Anthropometric measurements are converted to z-scores using the following formula:

$$z = \frac{1}{PSD}\left[AV\left(\frac{170.18}{s}\right)^{d} - PV\right]$$

PSD	=	phantom standard deviation
AV	=	measured anthropometric variable
s	=	stature / height (cm)
PV	=	phantom variable
d	=	dimensional component[14]

(Drinkwater, 1984; Ross & Wilson, 1974)

Phantom values, standard deviations and required measurements are shown in Table A.6 overleaf.

[14] d=1 for lengths, breadths, girths and skinfold thicknesses; d=2 for areas; d=3 for masses and volumes

Table A.6 Phantom reference values and standard deviations used in the calculation of fractionated body mass

SKINFOLDS(mm)	PHANTOM VARIABLE	SD	HEIGHTS (cm)	PHANTOM VARIABLE	SD
Triceps	15.4	4.47	Acromiale	139.37	5.45
Subscapular	17.2	5.07	**Radiale**	107.25	5.36
Supra-iliac	15.2	4.47	**Stylion**	82.68	4.13
Abdominal	25.4	7.78	**Dactylion**	63.83	3.38
Thigh	27.0	8.33	**Tibiale**	44.82	2.56
Calf	16.0	4.67	**Iliospinale**	94.11	4.71
			Trochanterion	86.40	4.32
			Sitting	89.92	4.50
DIAMETERS (cm)	**PHANTOM VARIABLE**	**SD**	**LENGTHS (cm)**	**PHANTOM VARIABLE**	
Bi-acromial	38.04	1.92	Arm	32.53	1.77
Bi-iliac	28.84	1.75	**Forearm**	24.57	1.37
Bi-condylar (femur)	9.52	0.48	**Hand**	18.85	0.85
Transverse chest	27.92	1.74	**Upper limb**	57.10	2.74
A/P chest	17.50	1.38	**Thigh**	40.92	2.52
Bi-epicondylar (humerus)	6.48	0.35	**Leg**	39.88	2.27
			Acropodion	25.50	1.16
GIRTHS (cm)	**PHANTOM VARIABLE**	**SD**	**GENERAL**	**PHANTOM VARIABLE**	**SD**
Arm relaxed	26.89	2.33	**Stature (cm)**	170.18	6.29
Arm corrected	20.05	3.67	**Body mass (kg)**	64.58	8.60
Arm flexed	29.41	2.37	**Lean mass (kg)**	52.45	6.14
Forearm relaxed	25.13	1.41	**Absolute fat (kg)**	12.13	3.25
Wrist	16.35	0.72	**Relative fat (%)**	18.78	5.20
Chest (meso)	87.86	5.18			
Chest corrected	82.36	4.68			
Abdomen	79.06	6.95			
Thigh	55.82	4.23			
Thigh corrected	47.33	3.59			
Calf	35.25	2.30			
Calf corrected	30.22	1.97			
Ankle	21.71	1.33			

(Drinkwater, 1984; Ross & Wilson, 1974; Ross *et al*, 1982)

Table A.7 Running economy protocols used in the assessment of male middle-distance athletes.

Reference	Stage	Treadmill inclination	Treadmill speed	Stage duration	Recovery period	Oxygen consumption	Lactate measurement
Boileau *et al* (1982)	1	0%	201 $m.min^{-1}$				×
	2	0%	241 $m.min^{-1}$				×
	3	0%	282 $m.min^{-1}$				×
	4	0%	322 $m.min^{-1}$				×
Brisswalter & Legros (1994)	1	0%	75% of speed at VO_{2MAX}	6 min	N/A	Final 3 min of stage	✓
McMiken & Daniels (1976)	1	0%	241 $m.min^{-1}$	6 min	3 min	Final 3 min of each stage	×
	2	0%	268 $m.min^{-1}$	6 min	3 min		×
	3	0%	295 $m.min^{-1}$	6 min	3 min		×
Daniels & Daniels (1992)	1	0%	268 $m.min^{-1}$	6 min	5 min	Final 2 min of each stage	✓
	2	0%	290 $m.min^{-1}$	6 min	5 min		✓
	3	0%	310 $m.min^{-1}$	6 min	5 min		✓
	4	0%	330 $m.min^{-1}$	6 min	5 min		✓
	5	0%	350 $m.min^{-1}$	6 min	5 min		✓
	6	0%	370 $m.min^{-1}$	6 min	5 min		✓
	7	0%	390 $m.min^{-1}$	6 min	5 min		✓
Smith *et al* (2000) (ASC)	1	1%	10–12 $km.h^{-1}$	3 min	1 min	Final 2 min of each stage	✓
	2	1%	+ 2 $km.h^{-1}$	3 min	1 min		✓
	↓	1%	+ 2 $km.h^{-1}$	3 min	1 min		✓
			TO EXHAUSTION				✓
Svedenhag *et al* (1994)	1	0%	15/16 $km.h^{-1}$	4 min	0 min	Final 60 –90 sec of each stage	✓
	2	0%	17/18 $km.h^{-1}$	4 min			
	3	0%	18/19 $km.h^{-1}$	4 min			
	4	0%	19/20 $km.h^{-1}$	4 min			
SISA (2000)	1	1°	16.6 $km.h^{-1}$	6 – 10 min	4 – 5 min	Final 5 min of each stage	✓
	2	1°	@ 42.2 km pace	6 – 10 min	4 – 5 min		✓
	3	1°	@ 21.1 km pace	6 – 10 min	4 – 5 min		✓

Table A.8 Testing protocols used for the assessment of maximal oxygen consumption in male middle-distance runners.

Reference	TYPE[15]	WARM-UP	START SETTINGS	INCREMENTAL INCREASE	Recovery period	Measurement of oxygen consumption	Lactate measurement
Saltin & Astrand (1967)	C	6-7 min at submaximal intensity (cycle ergometer)	20 km.h^{-1} 1.5°	+ 1.5° every 3 minutes to failure	N/A	Continuous	2 – 3 samples taken within 10 min of final run
Hermansen (1973) & Medbo *et al* (1988)	I						
Noakes *et al* (1990)	C	10 – 15 min < 50% of VO_{2max}	12 km.h^{-1} 0%	+ 0.5% at 60 sec, then every 30 sec	N/A	Continuous	
Scott *et al* (1991)	C		**Constant speed** (individually selected)	+ 3% every 2 min	N/A	Continuous (30 second intervals)	Not measured
Maffulli *et al* (1991b)	C	10 –15 min	15 km.h^{-1} 0°	+ 1° every 60 seconds	N/A	Continuous 5 sec interval + 15 sec mean	5 min after end of test

[15] C = continuous-incremental; I = intermittent-incremental

Reference	TYPE[16]	WARM-UP	START SETTINGS	INCREMENTAL INCREASE	Recovery period	Measurement of oxygen consumption	Lactate measurement
Daniels & Daniels (1992)	C	5 – 7 x 6 min submaximal to maximal runs 0%	Max velocity < 350 m.min-1 0% (2 min)	+ 1% every 2 min from minute 3	N/A	30 sec bags from 3.5 min to failure	30 sec after the end of each run
di Prampero *et al* (1993)	C		10 $km.h^{-1}$ 1.7° (5 min)	+ 2 $km.h^{-1}$ every 4 min	N/A	Last 30 sec of each constant load period	At end of test
Brisswalter & Legros (1994)	I		40% of VO_{2max} velocity 3% for 15 minutes	+ 2 km.h-1 every 4 min thereafter	1 min betw-een each stage	Last 2 min of each stage	During 1 min break between each stage
Svedenhag & Sjodin (1994)	C	10 min + 4 x 4 min runs at submaximal intensity + 15 - 20 min rest	15.5-17 $km.h^{-1}$ (individual ly selected so total test duration = 6 – 8 min) 0°	+ 0.5° every 30 sec (first 4 min) + 0.5° every 60 sec thereafter	N/A	Last 30 sec of each stage	At end of test
Weyand *et al* (1994)	I	2.9 $m.s^{-1}$ 0% (5 min)	7 x 5 min runs (individual ly selected) 0°	Increase velocity at start of each stage	5 min	1 min mean every 15 sec	At end of each stage

[16] C = continuous-incremental; I = intermittent-incremental

Reference	TYPE[17]	WARM-UP	START SETTINGS	INCREMENTAL INCREASE	Recovery period	Measurement of oxygen consumption	Lactate measurement
Craig & Morgan (1998)	C		At velocity of 5 km race pace 0%	+ 2% every 2 min after first 4 min	N/A	1 min samples 30 sec samples near failure point	Not measured
Jones (2002)	C	14 km.h-1 1% + 1 km.h-1 every 4 min to 23 km.h-1	25 km.h-1 1%	+ 2 km.h-1 every 60 sec	N/A	Last 30 sec of each stage OR continuous	
Smith et al (2000)	I	Brief submax	10-12 km.h-1 1% (3 min)	+ 2 km.h-1 every 3 min	1 min	Continuous	At end of each stage

[17] C = continuous-incremental; I = intermittent-incremental

Table A.9 Other testing protocols used in the assessment of maximal oxygen consumption.

Reference	EVENT / POPULATION	TYPE[18]	START SETTINGS	INCREMENTAL INCREASE	Recovery period	Measurement of oxygen consumption	Lactate measurement
Buskirk & Taylor (1957)	ALL	I	7 miles.h-1 at grade suitable to individual capacity (3 min)	+ 2.5% at start of every 3 min stage	3-10 min	1min 45sec to 2min 45sec	Not measured
Conley & Krahenbuhl (1980)	10km (elite)	C	214 m.min-1 0% (4 min)	+ 2.5% every 4 min	N/A	Continuous	Not measured
Rusko et al (1993)	400m	C	6.3 km.h-1 1°	Increase speed every 3 min (individually selected)	N/A	Continuous (30 sec bags)	Every 3 min at end of each stage
Berthon et al (1997)	ALL	C	5 min at speed correspondin g to 70% max HR (220-age) 1°	+ 1.5 km.h-1 every 3 min	N/A	Last 30 sec of each stage	At end of test

[18] C = continuous-incremental; I = intermittent-incremental