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THE RELATIONSHIPS BETWEEN BLOOD-BORNE AND GAS-EXCHANGE DESCRIPTORS OF ANAEROBIC CAPACITY AND SHORT- DISTANCE RUNNING PERFORMANCES

by

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We accept this thesis as conforming
to the required standard

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Abstract

The purpose was to establish the utility of maximal accumulated O_2 deficit (MAOD) , O_2 debt (O_2D) and maximal blood lactate (BLa^-_{max}) as measures of anaerobic capacity for a well-trained athletic population. To do this , the relationships between the anaerobic variables: MAOD , O_2D , BLa^-_{max} following a treadmill sprint run (TSR[BLa^-_{max}]) and an all-out 400m sprint (AOS[BLa^-_{max}]) , and four short-distance running performances (AOS400m , 400m , 800m and 1500m) were determined in 17 male varsity athletes (track , soccer and rugby) and 4 recreational athletes. The aerobic variables of maximal aerobic power ($\dot{V}O_{2max}$) and ventilatory threshold (V_T) were assessed using a motor-driven treadmill , and stepwise multiple regression analysis was used to determine the relative contribution of the aerobic and anaerobic variables in predicting running performances. Regression analysis was also performed on data collected for the 13 non-track athletes (split-group analysis). $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) and V_T ($mL \cdot kg^{-1} \cdot min^{-1}$) were correlated ($p < 0.05$) with 800m ($r = -0.62$, $R^2 = 0.38$) and 1500m time ($r = -0.49$, $R^2 = 0.24$) , respectively , whilst $\dot{V}O_{2max}$ ($m \cdot s^{-1}$) and V_T ($m \cdot s^{-1}$) accounted for 44% ($r = -0.70$, $p < 0.001$) and 64% ($r = -0.80$, $p < 0.001$) of the variance in 1500m performance , respectively. O_2D was correlated with AOS400m ($r = 0.62$) , yet all other anaerobic variables were not correlated ($p > 0.05$) with the running performances. The split-group analysis demonstrated that the aerobic variables were still significant predictors of the running performances , whereas the anaerobic variables accounted for minimal variance (1-34%) in all performances.

minimal variance (1-34%) in all performances. These findings suggest that the four anaerobic variables are not useful estimates of anaerobic capacity in well-trained athletic populations , or that anaerobic capacity was not a major predictor of the running performances assessed for this population. Furthermore , that the four anaerobic variables were generally not related with each other suggests that the metabolic bases of these variables differed , and as a result , they do not describe the same metabolic construct.

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DEDICATION

This thesis is dedicated to James Charles Green and Edith Betty Green for their continual love , support and understanding.

Introduction

As the intensity of muscular work increases and the ATP (adenosine triphosphate) requirements exceed that which can be maintained entirely by aerobic metabolism , ATP production is augmented using anaerobic sources (di Prampero, 1981). At supra-$\dot{V}O_{2max}$ power outputs , the ability to sustain muscular power output is partly dependent upon the total volume of ATP regenerated via anaerobic metabolism , a volume defined as the anaerobic capacity (Bouchard et al., 1982). Since the capacity of anaerobic glycolysis to regenerate ATP is greater than that which occurs via the alactic mechanism (di Prampero, 1981) , the anaerobic capacity will mainly be limited by the maximal H^+ ion concentration that can be tolerated at the muscle level before glycolysis is inhibited at the rate-limiting step of phosphofructokinase (PFK) (Hermansen & Osnes, 1972; Sutton et al., 1981) and/or interference with the contractile proteins occurs (Sahlin, 1978). It has been suggested that the maximal production of H^+ and La^- ions is mainly dependent on the buffering capacity of skeletal muscle and blood (Sahlin, 1978). The relative importance of these buffering mechanisms depends on the rate of La^- and H^+ ion production by the muscle , the rate of La^- and H^+ ion efflux from contracting muscle (Benadé & Heisler, 1978) and the rate of $La^-$and H^+ ion removal from the muscle site during exercise (Hermansen & Vaage, 1977).

Since it is has been assumed that performance in athletic activities characterised by the ability to sustain supra-$\dot{V}O_{2max}$ power outputs is partly determined by the anaerobic capacity (Berg & Keul, 1984) , it is of benefit to such athletes to accurately measure anaerobic capacity. However , the problem of determining valid invasive and non-invasive criterion measures of anaerobic capacity is complex (Katch et al., 1977). Although invasive measures such as muscle and blood lactate , pH and buffering capacity are often used to describe anaerobic metabolism (Bell & Wenger, 1989; Jacobs, 1981; Costill et al., 1983) , the difficulty in quantifying the total anaerobic capacity still exists.

The measures of maximal blood lactate concentration ($[BLa^-_{max}]$) (Margaria et al., 1964; di Prampero, 1981; Mero, 1988) and O_2 debt (Paterson et al., 1986) have been used to assess anaerobic capacity in different populations , yet the validity (Brooks & Gaesser, 1980; Berg & Keul, 1985) and reliability (Fric et al., 1988; Graham & Andrew, 1973) of these measures are controversial. Recently , the maximal accumulated O_2 deficit (MAOD) was purported to accurately quantify anaerobic capacity (Medbø et al., 1988; Medbø & Tabata, 1989) , yet its reliability and validity have not been confirmed.

The utility of a variable may be reflected in its reliability , practicability and validity. In the diagnosis of athletic performance or prescription of training programs , the utility of a physiological or metabolic measure can be reflected in its ability to predict performance (Berg & Keul, 1984). Therefore , in comparison to other measures purported to estimate anaerobic capacity , the relative contribution that MAOD makes to the prediction of an athletic performance which is dependent upon the anaerobic capacity of the performer , will provide insight into its validity and assist in establishing its utility.

Statement of the Problem

The purpose of this study is to establish the degree to which MAOD , in comparison to other descriptors of anaerobic capacity , can predict a running performance that is dependent upon the anaerobic capacity of the individual. To solve this problem , the following analyses were performed:

1. a series of correlational analyses (Pearson r) between descriptive measures of anaerobic metabolism (including MAOD) and running performance over distances of 400 , 800 and 1500m.

2. multiple regression procedures to establish the relative power of the anaerobic descriptors to predict performance in relation to other physiological and anthropometric determinants of performance.

Methods

Subjects

Seventeen male varsity and four recreational athletes from the University of Victoria volunteered as subjects and signed informed consent (Appendix C). The sample was composed of athletes competing in track 400m (n = 2) , 1500m (n = 2), 3km steeplechase (n = 2) , 5-10km (n = 2) ; soccer (n = 3) , rugby (n = 6) and recreational sport (n = 4). The experimental procedures were approved by the Human Subjects Committee (University of Victoria). Subject characteristics are displayed in Table 1.

Testing Procedures

Prior to testing , the subjects were familiarised with the procedures and physical demands of each test , and asked to refrain from vigorous physical activity 24 hours prior to testing , as well as consumption of food 3 hours prior to testing. All laboratory tests were performed under standardised environmental conditions (temp. = 20-21.5 ^{o}C). All equipment was calibrated immediately prior to , and following each testing session. The testing schedule is outlined in Figure 1.

Anthropometry

Anthropometric measures included height (non-stretched) , weight and the sum of four skinfolds: tricep , bicep , subscapular and suprailiac. Percent body fat was estimated using the formula of Durnin & Womersley (1974).

$\dot{V}O_{2max}$ / V_T

$\dot{V}O_{2max}$ (maximal aerobic power) and V_T (ventilatory threshold) were determined on a Quinton (model 24-22) motor-driven treadmill. At 6% grade and an initial speed of 2.22-2.44 $m \cdot s^{-1}$ (5-5.5 mph) , the treadmill speed was increased 0.22 $m \cdot s^{-1}$ per 2 minutes until V_T was detected via inspection , thereafter , the speed was increased 0.22 $m \cdot s^{-1}$ per minute until $\dot{V}O_{2max}$ was achieved. The criteria used to determine achievement of $\dot{V}O_{2max}$ were: 1) an increase in $\dot{V}O_2 \leq 2.0$ $mL \cdot kg^{-1} \cdot min^{-1}$ per increase in speed; 2) RER (Respiratory Exchange Ratio) ≥ 1.1; 3) no change in heart rate (HR) over the last speed increment. $\dot{V}O_{2max}$ was considered to have been achieved when two of the three criteria were fulfilled.

In accordance with a method proposed by Wasserman (1986) , V_T was identified using the following criteria: 1) the $\dot{V}_E/\dot{V}O_2$ curve , having been flat or decreasing , begins to rise disproportionately while the $\dot{V}_E/\dot{V}CO_2$ curve remains constant or decreases; 2) the slope of the RER-treadmill speed curve , having been flat or rising slowly , becomes more positive and is > 1.0. The time at which these inflection points occurred were identified using a computer-based regression program (Jones & Molitoris, 1984) and verified by visual inspection. If the previous methods were not successful in delineating an inflection point , V_T was identified as the time at which the RER exceeded 1.0. $\dot{V}O_{2max}$ and V_T were expressed in $mL \cdot kg^{-1} \cdot min^{-1}$ and $m \cdot s^{-1}$ @ 6% incline.

Respiratory gases were collected and analysed each 30 seconds using a Beckman Metabolic Measurement Cart (MMC). Prior to , and following each test , the MMC was calibrated and reassessed for drift using commercially prepared gas mixtures. All gas volumes were expressed as STPD. HR was recorded each minute throughout the test and during a 3-5 minute recovery using a PE 3000 Sportstester.

Treadmill Sprint Run (TSR)

Subjects completed a 5 minute seated rest during which gas samples were collected at the 3rd , 4th and 5th minute and an average resting $\dot{V}O_2$ was calculated. Subjects then completed a 4 minute warm-up run at 2.4 $m{\cdot}s^{-1}$ on a zero incline , and immediately following , the speed and incline were reset and the TSR initiated. Each subject was required to run to exhaustion (i.e. unable to maintain the required running speed) on a 6% incline at a speed approximating 110-115% $\dot{V}O_{2max}$. Speeds were selected to cause exhaustion within 2.5-3.5 minutes (refer to Appendix B for method). The elapsed time of the TSR run was measured from the moment at which the subject began running unsupported on the treadmill , to the moment at which the hands of the subject were replaced on the support rail. Time was recorded to the nearest 0.1 second. Strong verbal encouragement was provided throughout the TSR.

Vertical work outputs generated during the TSR were calculated using the equation $[BW(kg) * 9.81(m{\cdot}s^{-1})] * \%incline * speed(m{\cdot}s^{-1}) * time$. Work outputs were expressed in joules and kg·m.

$\dot{V}O_{2SS}$-Speed Test (VST)

To estimate the individual O_2 demand of the TSR , each subject completed a VST on two separate occasions. During the VST the treadmill incline remained constant at 6% while the speed was varied so that each subject completed 5 consecutive , 5 minute workloads corresponding to relative power outputs of approximately 75% , 80% , 85% , 90% and 95% V_T. $\dot{V}O_2$ and HR were measured as described previously and steady-state levels of $\dot{V}O_2$ ($\dot{V}O_{2ss}$) were determined by averaging $\dot{V}O_2$ values over the 4th and 5th minutes. $\dot{V}O_{2ss}$-Speed data values collected from both tests were then pooled for each subject and analysed using SAS linear regression. The resultant linear function $\dot{V}O_2 = a + b.m{\cdot}s^{-1}$ was used to calculate the O_2 demand (Fig. 2a) of the TSR.

Although this procedure used a limited range within which to determine a $\dot{V}O_{2ss}$-Speed regression line , it was considered to more accurately reflect efficiency at submaximal power outputs than that procedure described by Medbø et al. (1988). Since these investigators measured $\dot{V}O_2$ at speeds within the range of 50-95% $\dot{V}O_{2max}$, it is assumed that at the higher power outputs (>AT) $\dot{V}O_2$ did not accurately reflect the total energy expenditure since: 1) the exponential increase in blood La^- concentrations above AT (Campbell , Hughson & Green, 1987) suggest an increasing energetic contribution from anaerobic sources at these power outputs; 2) since La^- is resynthesized to glucose or glycogen during exercise , there exists an obligatory increase in the $\dot{V}O_2$ requirement without the accomplishment of external work (Rowell et al., 1966) , and; 3) that $\dot{V}O_2$ does not achieve a steady-state at power outputs above AT (Casaburi et al., 1987; Whipp & Wasserman, 1986).

Although the use of AT and V_T as similar physiological constructs is controversial (M^{c}Lelland & Gass, 1989; Neary et al., 1985) , in this study V_T was assumed to approximate AT. Based on this assumption , the VST power output range was selected so as not to exceed AT , but to maximize the difference between absolute speeds at which subjects could run with a consistent gait.

Maximal Accumulated O_2 Deficit (MAOD)

Fifteen seconds prior to the TSR , expired gas was collected and thereafter at 15 second intervals until exhaustion , at which a final sample was collected. The $\dot{V}O_2$-time values were subjected to Quasi-Newton nonlinear regression analysis (Systat Manual, 1988) and were best described by the function: $VO_2(t) = \beta(1 - e^{-(t - t_d)/\tau})$, where β is the asymptotic $\dot{V}O_2$ value , t_d is a time-delay parameter and τ is the time constant , commonly expressed as the $t_{1/2}$ response ($0.693 * \tau$) which is the time for the $\dot{V}O_2$ to achieve 50% of the difference between the $\dot{V}O_2$ value at $t = 0.25$ min. and β.

This function is frequently reported to describe $\dot{V}O_2$ kinetics during rest-submaximal work transitions (Hughson & Morrisey, 1983; Whipp & Wasserman, 1986). The justification for the use of a single-component model with a time delay is based on the observation that it provides a better fit than models without a time delay (Whipp, 1971) which artificially force a regression through the origin (Hughson & Morrisey, 1983). In this study , the model with the t_d parameter was observed to provide a better fit to the data ($SS_{RES} = 59.4$) compared to the model without the t_d parameter ($SS_{RES} = 114.1$). Although Whipp & Wasserman (1986) question the validity of using β to describe an asymptotic $\dot{V}O_2$ at supra-AT (anaerobic threshold) power outputs , its use in this study seems justified since: a) the observed $\dot{V}O_2$ values did reach an asymptotic value within approximately 1-2 minutes , and subsequently oscillated with similar amplitudes about this asymptotic value (Figure 2b) , and; b) the function is used only to determine a nonlinear 'line of best fit' and not to construct a theoretical basis of $\dot{V}O_2$ kinetics at supra-$\dot{V}O_{2max}$ power outputs.

The accumulated O_2 uptake was calculated by integration of the mono-exponential function with respect to TSR time. MAOD was calculated as the difference between the accumulated O_2 uptake over the period $t = 0.25$ min. to the time corresponding to exhaustion (Fig. 2b). The O_2 deficit incurred over the initial 15 seconds of the TSR was omitted from the calculations of MAOD since the initial delay that has been observed in the $\dot{V}O_2$ response to submaximal exercise (Whipp & Wasserman, 1986) could not be accurately determined.

O_2 Debt

Resting $\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$) and a value equal to the resting $\dot{V}O_2$ plus 10% of this resting $\dot{V}O_2$ (resting $\dot{V}O_2$ +10%) were calculated prior to the TSR. In accordance with the method described by Roberts & Morton (1978) , this latter value (resting $\dot{V}O_2$ +10%) was required to be achieved for two consecutive samples during recovery before the recovery period was considered complete. Immediately at the end of the TSR the treadmill was stopped , the chair was replaced on the stationary belt and the subject reseated. Expired gas samples were collected at 15 second intervals for the first 2 minutes of recovery , and thereafter , at 1 minute intervals until $\dot{V}O_2$ had achieved the criterion previously described.

Individual parameters for the $\dot{V}O_2$-recovery curve were determined using Quasi-Newton nonlinear regression. As reported in previous studies (Katch, 1973; Roberts & Morton, 1978) , the $\dot{V}O_2$-recovery curve data was best described by the function $\dot{V}O_2(t) = a1\ (e^{-k1.t}) + a2\ (e^{-k2.t}) + C$. The first two terms in the equation describe the 'fast' and 'slow' components of the $\dot{V}O_2$-recovery curve , respectively (Cerretelli, 1984) , whereas C is an approximation of the mathematically-derived asymptote and not the criterion baseline as used in the study of Roberts & Morton (1978). The rate constants , k1 and k2 , were related to the $t_{1/2}$ response for the fast and slow components respectively , using the equation $t_{1/2} = 0.693 * k^{-1}$.

To facilitate a comparison with previous studies (Katch, 1973; Roberts & Morton, 1978) , the $\dot{V}O_2$-recovery curve was not considered to commence until 15 seconds after the cessation of the TSR. The area defined by this initial $\dot{V}O_2$ value , the time (t = 0.25min) and the ordinate was included in the total O_2 debt (Fig. 3). When curve parameters had been determined , subsequent integration of the solution yielded the accumulated $\dot{V}O_2$ during recovery. To determine O_2 debt , subsequent adjustments were made for the area below the criterion baseline (subtracted from total $\dot{V}O_2$) as well as the $\dot{V}O_2$ during the first 15 seconds of recovery (added to the total $\dot{V}O_2$). In accordance with the procedure of Roberts & Morton (1978) , calculation of the area between the $\dot{V}O_2$-recovery curve and the recovery baseline over the time period t= 0-2.25 min yielded an estimate of the 'alactic' portion of the O_2 debt (alactic debt). The O_2 debt and alactic debt were expressed in $mL \cdot kg^{-1}$ and L.

Field Performances

In accordance with the testing schedule (Fig. 1) subjects completed an all-out 400m sprint (AOS) , as well as a standard 400m , 800m and 1500m run on a synthetic 400m track. Time was recorded to the nearest 0.1 second. Warm-up procedure was consistent with the procedure followed prior to the TSR and $\dot{V}O_{2max}/V_T$ test, and the order of the performances was randomised to minimise testing effect. Descriptive statistics of wind velocity and ambient temperature are reported in Table 9 (Appendix A).

Blood Lactate

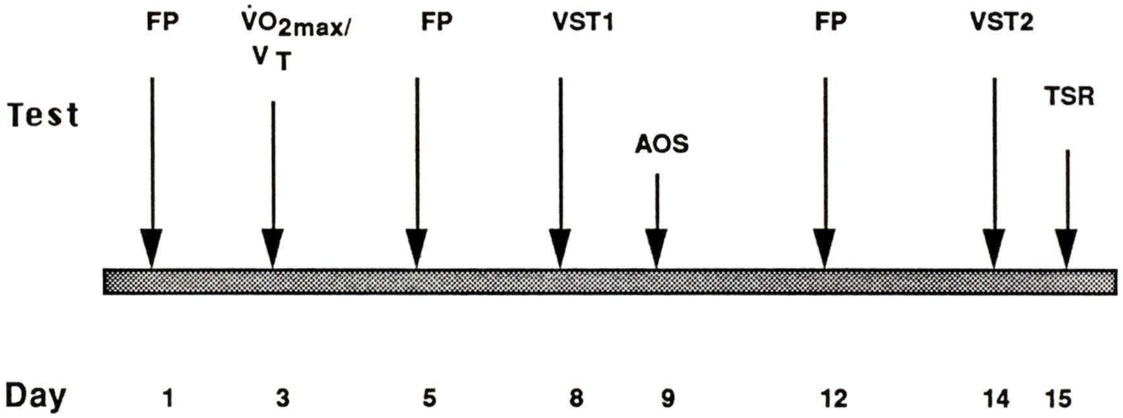
Blood samples from an antecubital vein were taken 5 minutes prior to the AOS and TSR , immediately after , and at intervals of 3 , 6 , 9 and 12 minutes after both performances. Venous blood samples were stored in EDTA solution and analysed using the YSI lactate analyser (model 23A). In addition , 25 µl of blood was immediately centrifuged and analysed for haematocrit to determine plasma lactate from whole blood samples.

Statistical Analyses

SAS-Forward and SAS-R^2 multiple regression , as well as SAS linear regression procedures (SAS Institute, 1987) were used to determine the relationships between the performance and physiological/metabolic variables. A SAS paired t-test was used to determine differences between the $[BLa^-_{max}]$ variables. The significance level was set at $p < 0.05$.

Figure 1

Time schedule of testing sessions.

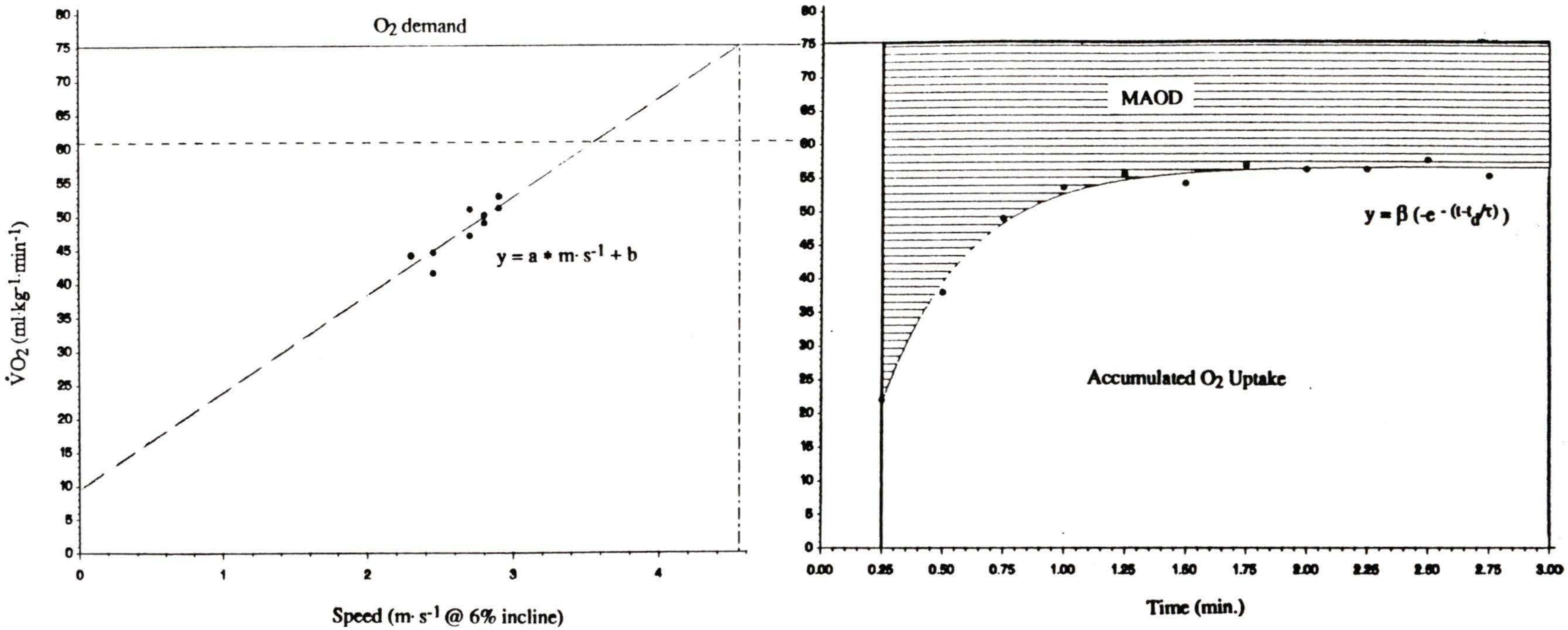


FP = Field Performance
VST = $\dot{V}O_{2SS}$-Speed Test
AOS = All-out Sprint
TSR = Treadmill Sprint Run

Table 1

Physical characteristics of the subjects

Variable	n	$\bar{x}$	SD	range
Age (yrs)	20	22.5	3.5	16-30
Weight (kg)	20	73.7	10.4	57.5-101.5
Height (m)	20	1.79	7.8	1.66-1.94
%Body Fat	20	12.6	4.0	7.5-23.2
Σskinfolds (mm)	20	29.7	8.4	19.2-47.6
LBM (kg)	20	64.7	7.5	50.8-82.9

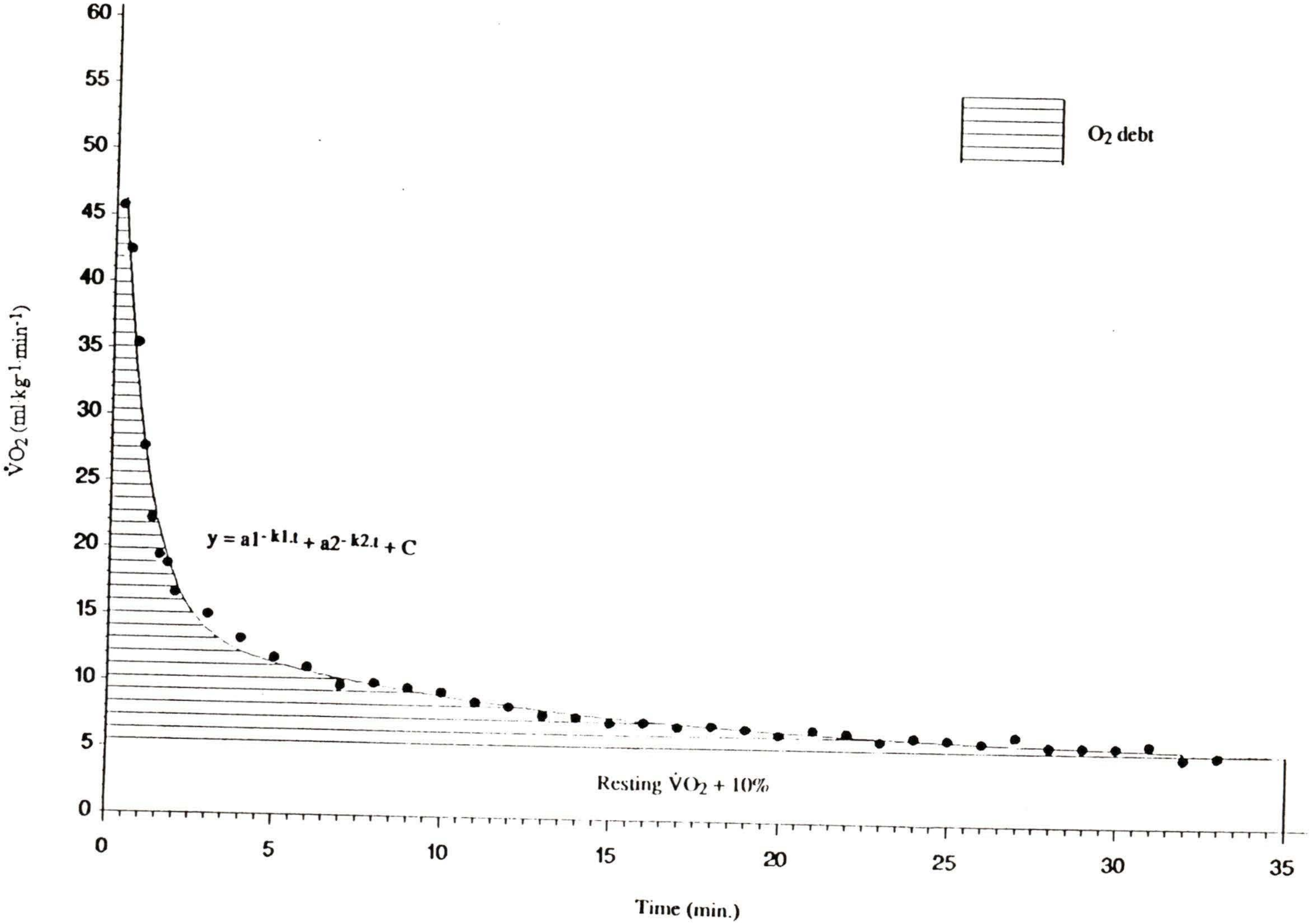


Figures 2a & 2b

Method for determining MAOD: 2a (left). Relationship between VO_{2ss} and treadmill speed; 2b(right). MAOD is calculated as the difference between the accumulated O_2 demand and the accumulated O_2 uptake over t=15 s to the time to exhaustion. Subject SH ran for 3 min. @ 4.44 $m{\cdot}s^{-1}$ which corresponded to an accumulated O_2 demand of 227.1 $mL{\cdot}kg^{-1}$ (75.2 $mL{\cdot}kg^{-1}$ * 3 min.) and an accumulated O_2 uptake of 143.8 $mL{\cdot}kg^{-1}$: MAOD = 83.2 $mL{\cdot}kg^{-1}$.

Figure 3

Graphical representation of the $\dot{V}O_2$-recovery curve and the determination of the O_2 debt (see text for explanation)



Operational Definitions

$\dot{V}O_{2max}$ (maximal aerobic power): is the highest rate of oxygen uptake ($L \cdot min^{-1}$ or $mL \cdot kg^{-1} \cdot min^{-1}$) that the individual can attain during physical work while breathing air at sea-level (Åstrand & Rodahl, 1977).

V_T (ventilatory threshold): During exercise of increasing power output , ventilation ($\dot{V}_E$) increases linearly with $\dot{V}O_2$. However , as a 'critical' power output is achieved and then surpassed , the $\dot{V}_E$ is observed to 'break away' from $\dot{V}O_2$ such that the $\dot{V}_E$ vs $\dot{V}O_2$ curve increases non-linearly. The power output at which this non-linear increase in the $\dot{V}_E$ vs $\dot{V}O_2$ relationship occurs has been termed the Ventilatory Threshold (V_T) (Jones & Ehrsam, 1982).

Supra-$\dot{V}O_{2max}$ power output: describes exercise performed at a power output which is greater than that which elicits $\dot{V}O_{2max}$.

All-out Sprint (AOS): a running sprint during which the individual is required to exert and maintain a maximal effort over a distance of 400m on a synthetic running track.

Accumulated O_2 uptake: is equal to the measured O_2 uptake ($\dot{V}O_2$) integrated over the time of the exercise.

Delimitations

1. All subjects participating in the study were male athletes attending the University of Victoria.

2. The sample size was equal to 21.

3. All subjects regularly participated (> twice/week) in an activity which involved running as the primary form of locomotion.

4. Subjects only engaged in a sufficient volume of physical activity required to maintain maximum levels of physiological function during the testing period.

5. Subjects did not smoke or consume food 3 hours prior to , or have exercised 24 hours prior to testing.

Limitations

1. The results of this study were applicable only to the population from which the subjects were selected.

2. Dietary patterns of subjects prior to and during the testing period could not be controlled , therefore , variations in muscle glycogen stores prior to each test may have occurred.

3. There may have existed inter-individual differences in response to motivation during the performance tests , therefore , test performances may not have been maximal.

4. The small sample number (n = 21) for descriptive research.

Assumptions

1. All variables were normally distributed.

2. The subjects understood and followed all instructions that applied during the testing period.

3. There was no training effect over the testing period.

4. The variables were linearly related , or may have been transformed so that non-linear relationships between variables may have been detected using a linear regression model.

Results

Simple statistics

The mean , standard deviation and range values of all performance variables are displayed in Table 2. The corresponding descriptive statistics for the aerobic and anaerobic variables are displayed in Tables 3 & 4.

The determination of MAOD for each subject was based on the individual $\dot{V}O_{2ss}$-Speed regression line and the estimated O_2 demand (Fig. 2a) , as well as the mono-exponential curve describing the $\dot{V}O_2$ response during the TSR (Fig. 2b). Linear regression analysis of the pooled $\dot{V}O_{2ss}$-Speed data collected from all subjects revealed a common regression line which had a slope of 15.47 $mL{\cdot}kg^{-1}{\cdot}min^{-1}{\cdot}m^{-1}$. The slopes of the individual $\dot{V}O_{2ss}$-Speed regression lines ranged from 11.4-21.2 (mean SEE = 2.9) $mL{\cdot}kg^{-1}{\cdot}min^{-1}{\cdot}m^{-1}$ reflecting a 63% range about the common slope. Also , the y-intercepts averaged 3.7 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ with the individual y-intercepts ranging from -8.7-15.4 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ (mean SEE = 8.1 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$) which is equivalent to a 651% range about the common y-intercept. Furthermore , the individual O_2 demands estimated using the regression lines derived from sub-V_T $\dot{V}O_2$ measures measured during the first , and the second VST were not significantly correlated ($r = 0.20$). The mean MAOD value determined using the VST 1 regression line (77.0 ± 39.0 $mL{\cdot}kg^{-1}$) was 10.5% greater than the MAOD value determined using the VST 2 regression line (69.7 ± 25.4 $mL{\cdot}kg^{-1}$).

Quasi-Newton non-linear regression analysis of the $\dot{V}O_2$ during the TSR revealed that the function $\dot{V}O_2(t) = \beta\ (1\text{-}e^{-(t-t_d/\tau)})$ best described the data. The mean parameter estimates of the function were: $\beta = 61.0$ (+/- 5.7) mL·kg^{-1} , $t_d = -0.09$ (+/- 0.37) seconds and $\tau = 24.6$ (+/- 16.2) seconds. The mean $t_{1/2}$ response ($t_{1/2} = \tau * 0.693$) was 17.0 seconds.

The mean (& range) values for the TSR duration and speed were 173.5 s (143.0-256.0 s) and 4.25 m·s^{-1} (3.89-4.88 m·s^{-1}) , respectively. The mean vertical work output generated during the TSR was 31.99 kJ (6342.3 kg·m).

Following the TSR , the individual $\dot{V}O_2$ response was measured and the resultant $\dot{V}O_2$-recovery curves were best described (mean $SS_{RES} = 47.9$) by the bi-exponential function $\dot{V}O_2(t) = a1^{-k1.t} + a2^{-k2.t} + C$ (Fig. 3). The mean parameter estimates of the $\dot{V}O_2$-recovery curve were: $a1 = 54.2$ mL·kg^{-1} (3.99 L) , $k1 = 1.40$, $a2 = 14.8$ mL·kg^{-1} (1.09 L) , $k2 = 0.08$ and $C = 4.5$ mL·kg^{-1} (0.33 L). The $t_{1/2}$ responses of the 'fast' and 'slow' components were 29.7 seconds and 519.3 seconds (8.66 min) , respectively. The mean O_2 debt and alactic O_2 debt was 114.4 mL·kg^{-1} (8.43 L) and 54.7 mL·kg^{-1} (4.03 L) , respectively , whereas the O_2 debt : MAOD ratio was 1.63 : 1.

The mean values of [BLa$^{-}_{max}$] following the TSR (14.8 mmol·L^{-1}) and the AOS (12.8 mmol·L^{-1}) were significantly different ($p < 0.05$).

Correlation coefficients (Pearson r)

Pearson product-moment correlation coefficients describing the relationships between the performance , anthropometric , aerobic and anaerobic variables are displayed in Tables 5a , 5b and 5c. Scatterplots of observed and predicted values for each variable were analysed for non-linear relationships between variables , as well as for outliers. A single outlier was detected for MAOD but was not omitted

omitted from subsequent analyses since the physiological range of MAOD has not been adequately established , and also , the removal of this outlier failed to significantly alter the relationships between MAOD and all other variables.

The magnitude of the Pearson r between all aerobic variables and each of the four performance criteria progressively increased with an increase in the distance run (Table 5a). When expressed in units of $mL{\cdot}kg^{-1}{\cdot}min^{-1}$, $\dot{V}O_{2max}$ ($r = -0.62$, $R^2 = 0.38$) and V_T ($r = -0.49$, $R^2 = 0.24$) were correlated ($p < 0.05$) with 800m , but were not significantly correlated with either the AOS400m or 400m performances. In contrast , $\dot{V}O_{2max}$ ($m{\cdot}s^{-1}$) and V_T ($m{\cdot}s^{-1}$) accounted for 44% ($r = -0.70$, $p < 0.001$) and 64% ($r = -0.80$, $p < 0.001$) of the variance in the 1500m performance. With the exception of $\dot{V}O_{2max}$ ($m{\cdot}s^{-1}$) and V_T ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$) , all aerobic variables were found to be correlated with each other ($p < 0.05 - 0.001$). LBM was correlated ($p < 0.001$) with $\dot{V}O_{2max}$ ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$) and V_T ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$) , but was not significantly related to any other variable.

The correlations between the performance variables (Table 5a) demonstrated that AOS400m and 400m , 400m and 800m , as well as 800m and 1500m were significantly related.

The correlation coefficients for the performance and anaerobic variables are displayed in Table 5b. O_2 debt was found to be correlated with AOS400m performance ($r = 0.62$) , however , no other anaerobic variable was significantly correlated with a performance variable. Furthermore , with the exception of AOS[BLa^-_{max}] and AOS400m , the sign of all correlations between the anaerobic variables and performance criteria was positive. The correlations anaerobic variables demonstrated that only AOS[BLa^-_{max}] and MAOD were significantly correlated ($r = 0.70$) , whereas TSR[BLa^-_{max}] was not significantly correlated with either AOS[BLa^-_{max}] ($r = 0.20$) or MAOD ($r = 0.09$). O_2 debt was not significantly related to any other anaerobic variable.

The Pearson r values describing the relationships between the aerobic and anaerobic variables are displayed in Table 5c. TSR[BLa^-_{max}] and AOS[BLa^-_{max}] were correlated ($p < 0.05$) with $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) and $\dot{V}O_{2max}$ ($m \cdot s^{-1}$) , respectively. All other correlations between the aerobic and anaerobic variables were not significant.

Multiple Regression Analysis

The multiple regression statistics are displayed in Table 6. In almost all cases , the aerobic variables accounted for the greatest portion of variance (adjusted partial R^2) in all four performance criteria , and were thus entered into the regression model as first predictors. For each performance criterion , only the aerobic variable that yielded the highest R^2 for the one-predictor regression model was included in Table 6 to demonstrate the effects of the subsequent entry of the second predictor on the total R^2 value. Therefore , to facilitate a comparison of the effect of each anaerobic variable on prediction (adjusted partial R^2) of each performance , the first predictor was held constant as each anaerobic variable was entered to form a two-predictor regression model.

Although O_2 debt accounted for the greatest portion of the explained variance in AOS400m performance , it was included as a second predictor since: all other anaerobic variables were entered into the regression model as second predictors and thus the contribution that O_2 debt made to prediction of performance could be directly compared with these variables , and; the physiological significance of a positive relationship with AOS400m performance was not clear. $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) , $\dot{V}O_{2max}$ ($m \cdot s^{-1}$) and V_T ($m \cdot s^{-1}$) accounted for the greatest portion of the total variance in the AOS400m (2-37%) and 800m (33-41%) , 400m (6-64%) , and 1500m (56-74%) performances, respectively. The magnitude and the level of significance of the partial R^2 values varied according to the sample size of the two-predictor model , such that for the AOS400m and 400m the levels of significance of the aerobic predictors varied from non-significant to $p < 0.001$. In contrast , $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) was a significant predictor of 800m performance for 3 of the 4 two-predictor models , whilst V_T ($m \cdot s^{-1}$) accounted for a significant portion of the variance in 1500m performance for all two-predictor models.

The entry of each anaerobic variable into the regression model predicting each of the four performances failed to significantly increase the total R^2 value. As a result , in the majority of cases the variance in the performances accounted for by the various 2-predictor models was almost entirely attributed to the aerobic variable. Subsequent regression analysis (SAS R^2) of all possible 2 and 3-predictor regression models failed to demonstrate a significant contribution by the anaerobic variables to the explained variance in any performance.

Split-group analysis

The sample was divided into two groups based on whether the subjects were track athletes (Track) or non-track athletes [soccer , rugby , recreational sport]

(Non-Track). Analysis of the Track group data was not reported since the low sample size ($n = 4$-7) made statistical interpretation difficult. Although the Non-Track group was also characterised by a relatively small sample size , analysis of these data allowed differences in relationships between variables due to modifed sample characteristics to be identified.

The correlational statistics for the Non-Track group are displayed in Tables 7a , 7b and 7c (Appendix A). In general , the aerobic variables were still correlated with 400m , 800m and 1500m performance ($p < 0.05$) , as well as between each other ($p < 0.05$ - 0.001). V_T ($m \cdot s^{-1}$) accounted for the greatest amount of variance in 800m (45%) and 1500m performance (61%) , whereas $\dot{V}O_{2max}$ ($m \cdot s^{-1}$) and V_T ($mL \cdot kg^{-1} \cdot min^{-1}$) accounted for 36% and 4% of the variance in 400m and AOS400m performance , respectively. The correlations between the performance variables demonstrated that only 800m and 1500m were significantly correlated ($r = 0.74$, $R^2 = 0.55$).

In comparison to the whole-group analysis , only MAOD and TSR[BLa^-_{max}] demonstrated a consistent 'shift' from positive to negative (non-significant) correlations with most performances. A moderate correlation between MAOD and the 1500m ($r = - 0.58$, $p = 0.08$) performance was found , yet , MAOD was also found to be significantly correlated with V_T ($m \cdot s^{-1}$).

The multiple regression statistics are displayed in Table 8 (Appendix A). As for the whole-group analysis , the aerobic variables were entered into the four regression models as first predictors. Again , the subsequent entry of the anaerobic variables failed to significantly increase the total R^2. Although MAOD was moderately related to 1500m performance , when MAOD was incorporated into the two-predictor model its contribution to the R^2 value was minimal since it was also significantly correlated with V_T (m·s^{-1}).

Table 2

Descriptive characteristics of the performance variables

Variable	n	$\bar{x}$	SD	range
AOS400m (s)	18	58.9	2.1	55.5-62.9
400m (s)	20	59.4	3.3	52.8-64.4
800m (s)	18	137.5	9.8	119.7-151.2
1500m (s)	18	290.8	26.1	250.4-336.0

Table 3

Descriptive characteristics of the aerobic variables

Variable	n	$\bar{x}$	SD	range
$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	20	60.1	4.4	52.0-68.7
$\dot{V}O_{2max}$ ($m \cdot s^{-1}$)	20	4.1	0.3	3.6-4.9
V_T ($mL \cdot kg^{-1} \cdot min^{-1}$)	20	51.3	4.9	42.0-60.6
V_T ($m \cdot s^{-1}$)	20	3.2	0.3	2.7-3.8

Table 4

Descriptive characteristics of the anaerobic variables

Variable	n	$\bar{x}$	SD	range
MAOD ($mL \cdot kg^{-1}$)	15	70.2	25.2	38.9-135.5
O_2 debt ($mL \cdot kg^{-1}$)	17	114.4	25.9	76.3-152.3
TSR [BLa^-_{max}] ($mmol \cdot L^{-1}$)	19	14.8	3.4	9.1-21.1
AOS [BLa^-_{max}] ($mmol \cdot L^{-1}$)	15	12.8	3.0	8.8-18.1

Table 5a

Correlation coefficient matrix of selected anthropometric , aerobic and performance variables

Variable	1	2	3	4	5	6	7	8	9
1. LBM	1.00								
2. $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	-0.66** (20)	1.00							
3. $\dot{V}O_{2max}$ (m·s^{-1})	-0.18 (20)	0.60* (20)	1.00						
4. V_T (mL·kg^{-1}·min^{-1})	-0.77** (20)	0.88** (20)	0.38 (20)	1.00					
5. V_T (m·s^{-1})	-0.32 (20)	0.58* (20)	0.76** (20)	0.62* (20)	1.00				
6. AOS400m (s)	0.07 (17)	-0.30 (17)	-0.15 (17)	-0.11 (17)	-0.11 (17)	1.00			
7. 400m (s)	0.01 (20)	-0.43 (20)	-0.27 (20)	-0.24 (20)	0.03 (20)	0.76** (17)	1.00		
8. 800m (s)	0.17 (18)	-0.62* (18)	-0.43 (18)	-0.49* (18)	-0.45 (18)	0.27 (16)	0.54* (18)	1.00	
9. 1500m (s)	.24 (18)	-0.66* (18)	-0.70** (18)	-0.56* (18)	-0.80** (18)	0.19 (15)	0.23 (18)	0.77** (17)	1.00

* - significant at $p < 0.05$

** - significant at $p < 0.001$

note: sample number is displayed in parentheses

Table 5b

Correlation coefficient matrix of selected anthropometric , anaerobic and performance variables

Variable	1	2	3	4	5
1. LBM	1.00	-	-	-	-
2. MAOD	-0.37 (15)	1.00	-	-	-
3. O_2 debt	0.17 (18)	0.20 (14)	1.00	-	-
4. AOS $[BLa^{-}_{max}]$	0.20 (15)	0.70* (12)	0.28 (13)	1.00	-
5. TSR $[BLa^{-}_{max}]$	0.36 (19)	0.09 (14)	0.48 (16)	0.20 (15)	1.00
6. AOS400m	0.07 (17)	0.17 (13)	0.62* (15)	-0.14 (14)	0.19 (16)
7. 400m	0.01 (20)	0.21 (15)	0.13 (18)	0.12 (15)	0.09 (19)
8. 800m	0.17 (18)	0.10 (14)	0.26 (15)	0.46 (14)	0.13 (17)
9. 1500m	0.24 (18)	0.05 (14)	0.18 (15)	0.35 (14)	0.28 (17)

* - significant at $p < 0.05$
note : sample number is displayed in parentheses ( )

Table 5c

Correlation coefficient matrix for the aerobic and anaerobic variables

Variable	$\dot{V}O_{2max}$ $mL \cdot kg^{-1} \cdot min^{-1}$	$\dot{V}O_{2max}$ $m \cdot s^{-1}$	V_T $mL \cdot kg^{-1} \cdot min^{-1}$	V_T $m \cdot s^{-1}$
MAOD	-0.13 (15)	-0.19 (15)	0.2 (15)	0.26 (15)
O_2 debt	-0.07 (17)	-0.01 (17)	-0.14 (17)	-0.01 (17)
TSR[BLa$^-$ max]	-0.54* (19)	-0.31 (19)	-0.42 (19)	-0.22 (19)
AOS[BLa$^-$ max]	-0.35 (15)	-0.57* (15)	-0.32 (15)	-0.39 (15)

* - significant at $p < 0.05$

Table 6

Multiple Regression Statistics (whole group)

Criterion Variable	1st Predictor	Partial R^2	2nd Predictor	Partial R^2	df	Total R^2
AOS400m	$\dot{V}O_{2max}$ $mL \cdot kg^{-1} \cdot min^{-1}$	0.37*	MAOD	0.02	12	0.39
		0.03	O_2 debt	0.16	15	0.19
	"	0.05	TSR[BLa]	< 0.01	15	0.05
		0.02	AOS[BLa]	0.01	13	0.03
400m	$\dot{V}O_{2max}$ $m \cdot s^{-1}$	0.64**	MAOD	< 0.01	14	0.64*
	"	0.49*	O_2 debt	0.14	16	0.63*
	"	0.06	TSR[BLa]	< 0.01	18	0.06
	"	0.31*	AOS[BLa]	0.06	13	0.37
800m	$\dot{V}O_{2max}$ $mL \cdot kg^{-1} \cdot min^{-1}$	0.41*	MAOD	< 0.01	13	0.42*
		0.41*	O_2 debt	0.03	13	0.44*
	"	0.33*	TSR[BLa]	0.02	16	0.35*
	"	0.24	AOS[BLa]	0.08	13	0.32
1500m	V_T $m \cdot s^{-1}$	0.56**	MAOD	0.07	13	0.63*
	"	0.74**	O_2 debt	0.02	14	0.76**
	"	0.69**	TSR[BLa]	0.01	16	0.70**
	"	0.74**	AOS[BLa]	< 0.01	13	0.74**

* - significant at $p < 0.05$ ** - significant at $p < 0.001$

Discussion

Aerobic variables

The mean $\dot{V}O_{2max}$ (60.1 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$) and V_T (51.3 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$) values lie within the range previously reported for well-trained athletic populations (Powers et al., 1985; Rhodes et al., 1986). However , since the sample assessed in this study was mainly composed of track athletes , soccer and rugby players , the range values of the aerobic variables were wider than those reported for samples composed of only rugby players (Maud & Schultz , 1984) , soccer players (Rhodes et al., 1986) or middle-long distance runners (Bulbulian et al., 1986; Costill & Winrow, 1970).

As reported previously (Berg & Keul, 1984) , this study demonstrated that the r value describing the relationship between the aerobic variables and performance increased concomitantly with an increase in the distance run. That $\dot{V}O_{2max}$ was significantly related to performances over 800m or 1500m has been supported by Berg & Keul (1984) who reported that $\dot{V}O_{2max}$ significantly predicted running performances which lasted longer than 2 minutes.

The importance of $\dot{V}O_{2max}$ to endurance performance has been acknowledged (Wilmore & Costill, 1988) , yet , the anaerobic (lactate) threshold has also been shown to be a useful predictor of endurance performance (Kindermann et al., 1979). Although there exists a lack of agreement on whether the anaerobic threshold and V_T reflect the same physiological construct (M^c Lelland & Gass, 1989; Neary et al., 1985) , in this study V_T was assumed to approximate the anaerobic threshold. Regardless of its physiological nature , V_T was a significant predictor of both 800m and 1500m performance. V_T has also been found to account for 88% of the variance in 10km performance time (Powers et al., 1985) , but was not significantly correlated (r = -.51) with 8km cross-country run time (Bulbulian et al., 1986). The variance in the predictive capabilities of V_T reported in these different studies may be partially attributed to the different samples.

MAOD

This is the first reported study to use nonlinear regression curve analysis to determine MAOD. The common function $\dot{V}O_2(t) = \beta(1- e^{-(t - t_d)/\tau})$ used to describe the data was consistent with the common function previously reported for supra-$\dot{V}O_{2max}$ exercise (Katch, 1973). The mean values were also similar to those reported by Katch (1973) for the $\dot{V}O_2$ response during a 60 second cycle sprint. When the time constant , τ, was expressed as the $t_{1/2}$ response , the mean value of 17.0 seconds fell within the 15-30 second range previously reported for submaximal exercise (Cerretelli et al., 1979; Powers et al., 1985; Whipp & Wasserman, 1972) and was similar to the 18.4 seconds reported by Katch (1973).

In this study , values for MAOD were knowingly underestimated since the O_2 deficit accumulated over the initial 15 seconds of the TSR was eliminated from the calculations. This procedure eliminated the requirement to subtract from MAOD the O_2 equivalent of the haemoglobin and myoglobin O_2 stores that are utilised as energy sources during this initial period (Åstrand et al., 1986). Although direct evidence is lacking , the individual variation in both the magnitude of the depletion of these O_2 stores (~ 0.4-0.6 l: Medbø et al.,1988) and the $\dot{V}O_2$ response during this initial period were considered to have minimal impact on the MAOD calculated over appoximately 3 minutes.

Despite this underestimate , the mean value of MAOD (70.2 mL·kg^{-1}) was consistent with corresponding values reported for supra-$\dot{V}O_{2max}$ treadmill running of a similar duration (Medbø et al., 1988) , but higher than those values recalculated from the original data for exhaustive supra-$\dot{V}O_{2max}$ cycle ergometer exercise (Åstrand et al., 1986; Medbø & Tabata, 1989). In the latter study (Medbø & Tabata, 1989) the data was recalculated based on a mean body weight (74 kg) similar to that found in the present study. Medbø & Tabata (1989) reported 30% higher MAOD values for treadmill running (Medbø et al., 1988) as compared to cycle ergometer exercise and attributed this difference to variations in the muscle mass used during these two activities. In addition to differences in sample characteristics between studies, a similar reason may account for the higher MAOD values reported in this study as compared to studies using the cycle ergometer (Åstrand et al. 1986; Medbø & Tabata, 1989).

In comparison to the MAOD range (52-90 mL·kg^{-1}) reported by Medbø et al. (1988) , the range in the present study was larger (38.9-135.5 mL·kg^{-1}). Approximately 37% of the total sample elicited MAOD values which fell outside the range reported by Medbø et al. (1988). Since both the exercise protocols and the samples were similar in both studies , differences in MAOD values were probably not attributed to these factors. Considering that the physiogical range of MAOD has not been adequately established , it is not clear whether the larger range reported in this study reflects individual differences in maximal O_2 deficits at the tissue level.

To date , correlation or regression statistics between MAOD and running performance have not been reported. The low [and positive] correlation coefficients and partial R^2 values describing the relationship between MAOD and the four performance variables demonstrated that MAOD was a poor predictor of short-term running performance. The positive r values were also theoretically inconsistent with the assumption that an increased anaerobic capacity will result in a decreased performance time , given that all other measured predictors were held constant.

As previously stated (Medbø et al., 1988; Vandewalle et al., 1989) , the validity of MAOD is based upon two primary assumptions: 1) the O_2 demand (energy expenditure) is constant during exercise and; 2) the O_2 demand of supra-$\dot{V}O_{2max}$ exercise can be extrapolated from submaximal $\dot{V}O_2$ measurements.

With respect to the first assumption , O_2 demand is not likely to remain constant during the TSR since a transient increase in cardiac and ventilatory work after the onset of exercise (Weismann et al., 1983) , will require a concomitant increase in energy requirement without an increase in external work output. Also , the observed changes in gait that occurred during the latter portion of the TSR would have also required an increased energy input.

In consideration of the second assumption , the maintenance of constant efficiency throughout the range of power outputs used in this study is also not likely since: a) running speeds at which individuals will work most efficiently will vary according to biomechanical and anatomical function (Cavanagh & Kaneko, 1977); b) an increased energy cost per unit of work has been associated with greater power outputs (> AT) as compared to lower power outputs (Hansen et al., 1988; Luhtanen et al., 1987), and; c) the O_2 cost of ventilation would have been greater at higher power outputs resulting in an increased O_2 requirement per unit of work performed (Shephard, 1966).

The tenuous nature of the two basic assumptions has been acknowleged , yet , the use of MAOD as an accurate estimate of anaerobic capacity has been recently supported (Medbø et al., 1988; Medbø & Tabata, 1989). Although MAOD may be useful in estimating the contribution of anaerobic ATP production to supra-$\dot{V}O_{2max}$ exercise performance of different durations (Medbø & Tabata, 1989) , its utility as an accurate estimate of anaerobic capacity in athletic populations was not supported by the present findings.

Due to practical considerations , the $\dot{V}O_{2SS}$-Speed regression line was derived from data collected during two , 25 minute tests as opposed to multiple (> 2) sessions (Åstrand et al., 1986; Medbø et al., 1988; Medbø & Tabata, 1989). Two VST trials were used in an attempt to demonstrate the reliability of a single test to estimate the O_2 demand. Since a low correlation coefficient ($r = 0.20$) was found between the O_2 demands determined using the two regression equations (VST trials 1 & 2) , the reliability with which the $\dot{V}O_{2SS}$-Speed relationship provided an estimate of individual treadmill running efficiency was poor. Furthermore , the 63% and 651% variation in the regression line slope , and Y-intercept , respectively , was found to be higher than the corresponding variances reported by Medbø et al. (1988).

This variance in the submaximal $\dot{V}O_2$ response at a given submaximal power output may be explained by: 1) differences in levels of anxiety which may alter the ventilatory response , and therefore , the O_2 cost of ventilation during the submaximal test. This is supported by subjective reports of greater discomfort during , and 'nervousness' prior to the first VST , despite that all subjects were familiarised with treadmill running prior to the first VST; 2) the possibility that some subjects became progressively more efficient over the testing period. The higher estimated O_2 demands based on the first VST trial support both 1) and 2); 3) although it is not clear , an intra-individual variation in $\dot{V}O_2$ response may have been influenced by differences in acute levels of fatigue induced by varying training loads during the testing period. Kuipers et al. (1985) have demonstrated that variations in gross mechanical efficiency were associated with day-day variations in performance and subjective assessments of fatigue , and; 4) biological variability (Coggan & Costill, 1984). Furthermore , the larger variances in the $\dot{V}O_{2SS}$-Speed regression parameters reported in this study may also be influenced by the smaller range of speeds across which $\dot{V}O_2$ values were measured , since similar deviations in $\dot{V}O_2$ values at corresponding speeds will alter regression parameters to a greater degree when the range of the independent variable (i.e. speed) is smaller (Myers, 1990).

Even though the 10% difference in the mean MAOD values estimated using the VST 1 and VST 2 regression lines demonstrated considerable error was incurred in determining MAOD based upon estimations of submaximal efficiency , the finding that MAOD was poorly related to all performance variables may also be explained on the basis that the aerobic variables were good predictors of 800m and 1500m performance. Since those individuals who displayed the highest level of aerobic function were middle-long distance runners (Track group) and were observed to be more highly skilled runners in comparison to the other subjects (Non-Track group) , it is probable that a portion of the unexplained variance in the performances would have been attributed to a skill-related factor. In an attempt to reduce the influence of wide variations in skill , the original sample was partitioned and the data for the Non-track group was analysed (see p 23 for explanation). Although no significant correlations were found , a shift in the direction of the correlations between MAOD and all performances was observed (Table 7b). This suggested that a skill factor may have been a major confounding variable in the whole-group analysis. Furthermore , the anaerobic capacities of the Track group may have differed little , or have been inferior to those athletes who compete in sports which require a substantial energetic contribution from anaerobic sources (Rhodes et al., 1986). Therefore , it is plausible that anaerobic capacity was not a major determinant of the running performances used in this study.

Blood Lactate

The AOS [BLa^-_{max}] values reported in this study fell within the ranges previously reported for exercise of similar mode , intensity and duration (Fujitsuka et al., 1982; Hermansen & Medbø, 1984; Ohkuwa et al., 1984). The mean and range values for TSR [BLa^-_{max}] were also consistent with previous studies using similar protocols and well-trained samples (Schnabel & Kindermann, 1983; Schnabel et al., 1979) , but lower than those reported for elite 400m and 800m runners (Parkhouse et al., 1985).

In comparison to AOS [BLa^-_{max}] , the TSR [BLa^-_{max}] mean value was found to be significantly greater which is consistent with previous reports that have demonstrated that BLa^- values elicited following exhaustive exercise lasting 2-4 minutes were greater than those BLa^- values following exercise causing exhaustion within one minute (Karlsson & Saltin, 1971; Medbø et al., 1988). Assuming that the La^- kinetics were similar following the AOS and TSR , the higher $[BLa^-_{max}]$ suggests that a greater volume of ATP was regenerated via anaerobic-glycolysis during the TSR. However , the lack of relationship between TSR $[BLa^-_{max}]$ and AOS $[BLa^-_{max}]$ ($r = 0.20$, $p > 0.05$) demonstrated considerable individual variation in the BLa^- response following the two activities. Since 5-10% of this unexplained variance may be attributed to biological variability (Coggan & Costill, 1984) , a considerable portion of this variance must be attributed to unidentified sources.

It has been demonstrated that $[BLa^-_{max}]$ is influenced by pre-exercise intramuscular glycogen concentrations (Fric et al., 1988; Klausen, Piehl & Saltin, 1973) and acid-base changes induced by prior exercise (Kindermann & Kullmer, 1985; Klausen et al., 1972). Fric et al. (1988) reported that changes in exercise training loads resulted in poor reproducibility of the maximal BLa^- response following exhaustive treadmill exercise , and attributed these findings to differences in pre-test muscle glycogen levels. Although the AOS and TSR were performed at least 24 hours prior to a previous training session , many of the subjects used in this study were regularly involved in sport-specific training programs and weekly competition. Therefore , it was possible that the training volume of some of these athletes (i.e. soccer , rugby) may have resulted in inadequate replenishment of glycogen stores during recovery periods which was of sufficient magnitude to elicit an altered BLa^- response.

The BLa^- response after supra-$\dot{V}O_{2max}$ exercise has also been found to closely parallel the changes in blood volume (Hermansen et al., 1984). Although the extent to which the post-exercise blood volume response differed between the AOS and

TSR was not determined , it was possible that variations in the BLa^- response were partially attributed to differences in the blood volume following the two tests.

The kinetics of La^- is dependent upon the rate of La^- production , the rate of La^- efflux from muscle to blood and other tissue , and the rate at which it is subsequently removed from the blood (Freund et al., 1989). Post-exercise La^- kinetics and $[BLa^-_{max}]$ have been reported to be influenced by the power output and duration of the activity (Freund et al., 1989 , 1986; Mazzeo et al., 1986). In addition , the major determinants of La^- kinetics have been reported to be highly related to both the level of aerobic function (Freund et al.,1989; Simon et al., 1986; Stanley et al., 1986) and mechanisms associated with the aerobic status of skeletal muscle such as the % of ST fibres within the active muscle (Bonen et al., 1978; Tesch et al., 1981) , as well as the capillary supply to the working muscle (Tesch & Wright, 1983). Although these findings have been demonstrated following submaximal exercise , it is tempting to speculate that these factors may also influence BLa^- kinetics following supra-$\dot{V}O_{2max}$ exercise. The correlations found between $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) and TSR$[BLa^-_{max}]$ (Table 5c), and $\dot{V}O_{2max}$ ($m \cdot s^{-1}$) and AOS$[BLa^-_{max}]$ (Table 5c) demonstrated that mechanisms associated with both $\dot{V}O_{2max}$ and the appearance of La^- within the blood following supra-$\dot{V}O_{2max}$ exercise were related. As yet though , the causal mechanisms underlying the basis of this relationship are still not clear.

The low correlation coefficients (Tables 5b &7b) and partial R^2 values (Tables 6 & 8) demonstrated that AOS $[BLa^-_{max}]$ and TSR $[BLa^-_{max}]$ accounted for minimal variance in all performances for either the whole-group or Non-Track group. These findings have been corroborated by Ohkuwa et al. (1984) for elite sprinters and 400m performance , but the r values reported in this study were lower than those reported for endurance-trained or untrained groups and 400m performance (Fujitsuka et al., 1982). As previously discussed , this may be partially explained by the possibility that anaerobic capacity was not a major determinant of the performances used in this study. However , since the mechanisms which influence the $[BLa^-_{max}]$ may not necessarily be related to La^- production within the exercised muscle , the accuracy with which BLa^- accurately quantifies anaerobic-glycolytic ATP production is questionable. Since training-induced changes in anaerobic capacity in well-trained athletes may be small (Vandewalle et al., 1987) , it is important that measures of anaerobic capacity are of sufficient accuracy to detect such changes that occur. Considering that the reliability of $[BLa^-_{max}]$ is poor (Fric et al., 1988; Graham & Andrew, 1973) , and that this study failed to demonstrate that either of the $[BLa^-_{max}]$ variables significantly predicted running performance despite the change in sample characteristics , $[BLa^-_{max}]$ does not appear to provide an accurate estimate of anaerobic capacity in highly trained athletic populations.

O_2 debt

The degree to which the bi-exponential function $\dot{V}O_2(t) = a1^{-k1.t} + a2^{-k2.t} + C$ described the data supports the previous use (Katch, 1973; Roberts & Morton, 1978) of this function to 'best' describe the $\dot{V}O_2$ response following supra-$\dot{V}O_{2max}$ exercise. The mean values of the rate constants , k1 (1.40) and k2 (0.08) , and the parameter C (0.33 l) were almost identical to those previously reported (Katch, 1973; Roberts & Morton, 1978). In contrast , the mean values of the amplitudes , a1 (54.2 mL·kg^{-1} , 3.99 L) and a2 (14.8 mL·kg^{-1} , 1.09 L) were considerably higher when compared to the corresponding values reported by these same investigators. Since the size of the O_2 debt is partially dependent upon the magnitude of the parameters a1 and a2 , the O_2 debt was also higher than the O_2 debts reported by Katch (1973) and Roberts & Morton (1978).

In comparison to Roberts & Morton (1978) , the higher O_2 debt values found in this study (Table 4) were likely due to factors other than differences in the procedures used to determine O_2 debt , since the procedure followed in both studies was identical. Firstly , the $\dot{V}O_{2max}$ values achieved during the TSR were likely to be higher than those achieved during the 25-40 second treadmill sprint used by Roberts & Morton (1978). The $\dot{V}O_2$ at the termination of the exercise would mainly influence the alactic ('fast') component of the O_2 debt. Also , this $\dot{V}O_2$ value corresponded closely with the parameter a1 (i.e. $\cong \dot{V}O_2$ at t=15 s post-exercise) which in conjunction with the rate constant k1 , defined the alactic component of the $\dot{V}O_2$-recovery curve. Since the mean alactic debt (54.7 mL·kg^{-1} , 4.03 l) was approximately 37% higher than the corresponding value reported by Roberts & Morton (1978) , it seems likely that the magnitude of the alactic debt , and consequently the magnitude of the O_2 debt was influenced by the $\dot{V}O_2$ at the termination of the exercise.

Secondly , Roberts & Morton (1978) have demonstrated that the O_2 debt was dependent upon the total vertical work output accomplished during the test. The total vertical work outputs (mean = 6342.3 kg·m) generated by the subjects having performed the TSR were greater than those reported by Roberts & Morton (1978). Since the treadmill incline used in the present study was lower than the 20% incline used in the study of Roberts & Morton (1978) , the horizontal work outputs generated in the present study would have also been greater. Therefore , it is probable that differences in work outputs between these two studies would have accounted for a major portion of the difference in O_2 debts reported. Despite the relatively high O_2 debt values (114.4 $mL \cdot kg^{-1}$) found in this study , they were similar to values reported following $\dot{V}O_{2max}$ treadmill tests (Graham & Andrew, 1973). In addition , the O_2 debt : MAOD ratio (1.63 : 1) fell within the O_2 debt : O_2 deficit ranges previously reported for human (Hughson, 1984) and animal species (Rose et al., 1988; Powers et al., 1987).

Until present , the relationship between O_2 debt and track running performance had not been determined. With the exception of AOS400m , no performance was significantly related to , or predicted by O_2 debt for either the whole-group or split-group analysis. Despite the finding that O_2 debt was a significant predictor of AOS400m performance , the physiological significance of this relationship cannot be explained since O_2 debt was positively related to performance , whereas it should have been negatively related assuming that an inverse relationship between anaerobic capacity and the performances assessed in this study existed.

On the basis of more recent findings , the valid use of O_2 debt to quantify the anaerobic capacity has not been substantiated since its magnitude has been purported to be influenced by: a greater release of catecholamines into the circulation than that which occurs at rest (Harris, 1980; Maron et al., 1977); a prolonged increase in body temperature following exercise (Brooks & Gaesser, 1980; Chad & Wenger, 1988); the substrate used during recovery (Chad & Wenger, 1988); a post-exercise elevation in substrate cycling and mitochondrial respiration (Gaesser & Brooks, 1984) and; the ventilatory response following exercise (Welch et al., 1970). These mechanisms are likely to be influenced by the power output-time characteristics of the exercise , which have also been shown to affect the $\dot{V}O_2$ response following submaximal exercise (Chad & Wenger, 1988; Segal & Brooks, 1979). In addition , the resynthesis of La^- to glycogen that occurs following heavy exercise (Åstrand et al., 1986; Brooks & Gaesser, 1980; Hermansen & Vaage, 1977) is performed at an energetic cost approximately twice that released during La^- formation (Martin, 1987). Although the fate of La^- following exercise is controversial , the energetic cost of glycogen resynthesis appears to be greater than the energy generated via La^- oxidation during recovery (Segal & Brooks, 1979). As a result , the O_2 debt will overestimate the anaerobic energy release that occurred during the TSR , and furthermore , the finding that the O_2 debt was 60% greater than MAOD also suggests that the anaerobic capacity was overestimated by the O_2 debt.

As for any physiological/performance variable derived from an exhaustive work test , maximal values of the three anaerobic variables (MAOD , TSR $[BLa^-_{max}]$ & O_2 debt) derived from the TSR were dependent upon the ability of the individual to exert a maximal effort on this test. Furthermore , in accounting for the poor predictive capabilities of the three anaerobic variables , it is speculated that differences in the metabolic requirements between treadmill (inclined) and track running would also alter the degree to which the metabolic measures predict running performance on a flat grade.

Conclusion

This study demonstrated that the four measures assumed to describe anaerobic capacity accounted for minimal variance in the short-distance running performances. Therefore , either anaerobic capacity was not a major predictor of the running performances assessed or , these measures are not useful estimates of anaerobic capacity in well-trained athletic populations. That the four anaerobic variables were generally not related with one another suggests that the metabolic bases of these measures differed , and as a result , do not describe the same metabolic construct.

Suggestions for Future Investigation

1. Further develop procedures (i.e. NMR) which will accurately quantify anaerobic ATP production , energy liberation and consumption.

2. Develop procedures which will accurately estimate work efficiency at supra-$\dot{V}O_{2max}$ power outputs.

3. Re-examine the common assumption that anaerobic capacity is an invariant construct when measures of anaerobic capacity are derived from work tasks > 2 min. duration.

4. Further development and recognition of anaerobic capacity tests which assess anaerobic capacity under 'sport-specific' conditions.

5. Examine the effects of various training programs on anaerobic capacity.

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Table 7a

Correlation coefficient matrix of aerobic and performance variables (Non-Track group)

Variable	1	2	3	4	5	6	7	8
1. $\dot{V}O_{2max}$ (mL·kg^{-1}min^{-1})	1.00							
2. $\dot{V}O_{2max}$ (m·s^{-1})	0.71* (13)	1.00						
3. V_T (mL·kg^{-1}min^{-1})	0.89* (13)	0.56* (13)	1.00					
4. V_T (m·s^{-1})	0.69* (13)	0.66* (13)	0.79** (13)	1.00				
5. AOS400m	-0.07 (11)	0.26 (11)	-0.21 (11)	-0.12 (11)	1.00			
6. 400m	-0.23 (13)	-0.60* (13)	-0.16 (13)	-0.37 (13)	0.32 (11)	1.00		
7. 800m	-0.37 (11)	-0.30 (11)	-0.48 (11)	-0.67* (11)	-0.08 (11)	-0.05 (11)	1.00	
8. 1500m	-0.55 (11)	-0.41 (11)	-0.67* (11)	-0.78* (11)	0.19 (9)	0.08 (11)	0.74* (10)	1.00

* - significant at $p < 0.05$
** - significant at $p < 0.001$
note: sample number in parentheses

Table 7b

Correlation coefficient matrix of anaerobic and performance variables (Non-Track group)

Variable	1	2	3	4	5	6	7	8
1. MAOD	1.00							
2. O_2 debt	0.27 (9)	1.00						
3. TSR $[BLa^-_{max}]$	-0.14 (11)	-0.20 (11)	1.00					
4. AOS $[BLa^-_{max}]$	0.69* (10)	0.25 (9)	-0.08 (11)	1.00				
5. AOS400m	-0.26 (9)	0.57 (9)	0.07 (11)	-0.22 (10)	1.00			
6. 400m	-0.06 (11)	-0.08 (11)	-0.43 (13)	0.04 (11)	0.32 (11)	1.00		
7. 800m	-0.49 (10)	0.11 (9)	-0.37 (11)	0.14 (10)	-0.08 (11)	-0.05 (11)	1.00	
8.1500m	-0.58 (10)	-0.10 (9)	-0.15 (11)	-0.20 (10)	0.19 (9)	0.08 (11)	0.74* (10)	1.00

* - significant at $p < 0.05$
note: sample number in parentheses

Table 7c

Correlation coefficient matrix for the aerobic and anaerobic variables (Non-Track group)

Variable	$\dot{V}O_{2max}$ $mL \cdot kg^{-1} \cdot min^{-1}$	$\dot{V}O_{2max}$ $m \cdot s^{-1}$	V_T $mL \cdot kg^{-1} \cdot min^{-1}$	V_T $m \cdot s^{-1}$
MAOD	0.56 (11)	0.21 (11)	0.58 (11)	0.72* (11)
O_2 debt	0.44 (11)	0.42 (11)	0.26 (11)	0.28 (11)
TSR[BLa^-_{max}]	-0.18 (13)	0.06 (13)	0.06 (13)	0.20 (13)
AOS[BLa^-_{max}]	-0.12 (11)	-0.31 (11)	-0.14 (11)	-0.01 (11)

* - significant at $p < 0.05$

Table 8

Multiple Regression Statistics (Non-Track group)

Criterion Variable	1st Predictor	Partial R^2	2nd Predictor	Partial R^2	df	Total R^2
AOS400m	V_T mL·kg^{-1} ·min^{-1}	0.27	MAOD	<0.01	8	0.27
		0.05	O_2 debt	0.33	8	0.38
	"	0.05	TSR[BLa]	0.01	10	0.06
		0.06	AOS[BLa]	0.05	9	0.11
400m	$\dot{V}O_{2max}$ m·s^{-1}	0.56*	MAOD	0.01	10	0.57*
	"	0.38*	O_2 debt	0.03	10	0.41
	"	0.35*	TSR[BLa]	0.16	12	0.51*
	"	0.38*	AOS[BLa]	0.03	10	0.41
800m	V_T m·s^{-1}	0.35	MAOD	0.02	9	0.37
	"	0.52*	O_2 debt	0.02	8	0.54
	"	0.45*	TSR[BLa]	0.03	10	0.48
		0.45*	AOS[BLa]	0.01	9	0.46
1500m	V_T m·s^{-1}	0.55*	MAOD	< 0.01	9	0.55
	"	0.89**	O_2 debt	0.01	8	0.90**
	"	0.61*	TSR[BLa]	< 0.01	10	0.61*
	"	0.61*	AOS[BLa]	0.05	9	0.66*

* - significant at $p < 0.05$

** - significant at $p < 0.001$

Table 9

Temperature and wind velocity data

Day	Time	Temp (°C)	Wind Velocity (m·s^{-1} @ °North)
15/9	8.50 am	13.0	0.2 @ 090°
	10.00 am	16.0	"
24/9	9.00 am	14.0	2.0 @ 300°
	10.00 am	16.0	2.4 @ 310°
27/9	2.00 pm	18.7	4.3 @ 030°
	3.00 pm	18.8	4.3 @ 060°
	4.00 pm	18.1	3.2 @ 110°
	5.00 pm	17.7	2.1 @ 110°
28/9	2.30 pm	19.9	3.6 @ 010°
	3.00 pm	21.1	1.8 @ 010°
	4.00 pm	19.9	2.0 @ 010°
	5.00 pm	19.3	2.0 @ 010°
30/9	9.00 am	14.5	3.1 @ 310°
	10.00 am	15.2	2.1 @ 280°
1/10	9.00 am	11.3	2.1 @ 280°
	10.00 am	12.2	1.5 @ 270°
7/10	9.00 am	11.1	1.0 @ 140°
17/10	3.00 pm	11.7	1.0 @ 050°
	4.00 pm	11.9	1.0 @ 080°
	5.00 pm	12.5	1.5 @ 050°
	6.00 pm	11.0	0.5 @ 330°
18/10	4.00 pm	12.0	8.4 @ 160°
21/10	9.00 am	10.9	4.2 @ 160°
	10.00 am	10.1	calm

Appendix B

Method of Determining TSR speed

On the basis of pilot study work , the treadmill speed (@ 6% incline) required to exhaust subjects within 2.5-3.5 minutes was approximately 1.5-2.0 $m \cdot s^{-1}$ less than the 800m average speed for each subject. It was also observed that the subjects with smaller mass (< 75 kg) were capable of TSR speeds that approximated the 800m speeds closer as compared to subjects of greater mass (> 75 kg). Although this procedure is crude at best , it did allow an approximation of the TSR speed based on 800m speed and body weight. For example , a subject weighing 74 kg and an 800m speed of 6.0 $m \cdot s^{-1}$ would be prescribed a TSR speed of 4.5 $m \cdot s^{-1}$.

To ensure that performance on the TSR could be maintained for at least 2 minutes during this study (thesis) , following the VST2 , each subject completed a 2 minute run at the TSR speed determined according to the method previously described. In all cases subjects completed the 2 minute trial run. Necessary adjustments were made to the TSR speed according to subjective comments received from subjects following the trial run , and observations of visual signs of acute stress and gait patterns. It is emphasised that all subjects were briefed on the importance , and requirements of a maximal performance during the TSR.

Appendix C

Informed consent for Physiological Assessment

In order to assess your physiological function the following laboratory tests will be performed:

Lab Initial Subject Initial

_____ _____

Anaerobic Function

You will be required to exert a maximal effort over the course of a 400m Δ , 800m Δ , 1500m Δ , all-out 400m Δ or a treadmill sprint Δ.
The following measures will be taken:

ventilatory __ blood sample __ muscle sample __
heart rate ___ work output ___

_____ _____

Maximal Cardio-Respiratory Function

You will exercise on a treadmill with progressively increasing speeds to elicit maximal responses in the following indicated variables:

oxygen consumption ___ heart rate ___
ventilation ____
other ____

_____ _____

Blood Chemistry

Blood samples will be taken prior to Δ , during Δ and/or post-exercise Δ by:

venipuncture Δ finger-tip prick Δ ear-lobe Δ

_____ _____

Anthropometry

Percent body fat and lean body mass will be assessed by:skinfold measures Δ other __________

_____ _____

Submaximal Exercise

You will exercise at 5 submaximal speeds for a total time of 25 min.whilst the following variables will be assessed: ventilatory Δ

Informed Consent

Purpose: To determine the relationship between physiological descriptors of anaerobic capacity and running performance.

Procedure: You will be asked to perform 6 maximal and 2 submaximal exercise tests over the course of 3 weeks. the time-line of the testing period will be as follows:

Day 1 - Field Performance 1
Day 3 - $\dot{V}O_{2max}$ / V_T test
Day 5- Field Performance 2
Day 8 - Submaximal test
Day 9 - All-out 400m sprint
Day 12 - Field Performance 3
Day 14 - Submaximal test
Day 15 - Treadmill Sprint Run

Tests will be administered by qualified personnel under the direct supervision of the investigator(s). Blood samples will be taken from a vein (antecubital) in the forearm by a registered nurse. Although there is always some risk of infection associated with the removal of blood , the procedure is considered safe with little risk of complication.

Whilst it is unlikely that a subject should be injured or taken ill during a test , lab personnel are trained in emergency procedures and emergency equipment is on-site at all times. All laboratory activity will be completed proximal to medical and/or paramedical assistance.

The maximal loads imposed will not exceed those which might be expected of an athlete during sports performance.

I will be assured anonymity of all results gathered in this research study.

I have read the above and volunteer to participate in this research project at my own risk. I confirm that I have been advised that I may ask for a further explanation and/or demonstration of such procedures at any time. I also acknowledge that I have been advised that I may terminate participation in any or all of the procedures as a matter of my own personal discretion or volition. I hereby waive and disclaim any entitlement against the University of Victoria , the personnel involved in this research study , the research investigators , or any other person in respect of liability that may arise from my participation as a research subject in this study.

Name: ______________________________ Date: ______________

Signature: ____________________________

Guardian's Signature (under 18 years): ____________________________

Appendix D

Review of Literature

To perform work requires the expenditure of energy. To develop tension , contract and perform work , human skeletal muscle requires energy that is liberated via the hydrolysis of adenosine triphosphate (ATP) to adenosine diphosphate (ADP) and phosphate (Pi) (Åstrand, 1981). Immediately following the onset of exercise , the required ATP input is primarily maintained via the breakdown of CrP (alactic) stores , the use of the anaerobic glycolytic pathway with the production of lactic acid , as well as oxidative phosphorylation (Gollnick & Hermansen, 1973). The relative contributions of these three metabolic pathways to ATP production is dependent upon the intensity and duration of the exercise (Åstrand, 1981).

In performing supra-$\dot{V}O_{2max}$ exercise , there is a requirement for a large volume of ATP supplied at rapid rates (Newsholme, 1981). As the intensity of exercise exceeds that which can be maintained almost entirely by aerobic metabolism , energy output from anaerobic sources becomes increasingly important to maintain the required power output (Gollnick & Hermansen, 1973). Exercise that requires energy supplied primarily from anaerobic sources has been classified as anaerobic exercise (Bar-Or, 1987). The total volume of energy supplied by the anaerobic systems to perform muscular exercise has been defined as the anaerobic capacity (Bouchard et al., 1982). This is an energetic definition and is distinct from the same term commonly applied to ergometric measures. When an ergometric measure and the corresponding work output is used to reflect anaerobic capacity , it would seem appropriate to use the term , anaerobic work capacity.

Anaerobic capacity is determined by:

1) the volume of CrP (alactic) stores (Vandewalle et al., 1987);

2) total production of ATP from anaerobic glycolysis , which is primarily dependent upon the buffering capacity of skeletal muscle and blood (Sahlin, 1978). The relative importance of these buffering mechanisms depends on the rate of lactate (La^-) and hydrogen (H^+) ion production within contracting muscle;

3) the rate of La^- and H^+ ion efflux from active muscle to the extracellular space (Benadé & Heisler, 1978) and;

4) the rate of blood La^- and blood H^+ ion removal from the muscle site (Hermansen & Vaage, 1977).

1. Volume of CrP stores (alactic capacity)

The volume of ATP resynthesised via the degradation of CrP , otherwise defined as the alactic capacity (di Prampero , 1981) , contributes to the total anaerobic ATP output within the working muscle (Åstrand, 1981). The total store of CrP within the active muscle mass is approximately 18 mmoles (Newsholme, 1981) , providing a rapid supply of energy for 5-7 seconds of maximal work (Hirvonen et al., 1987).

Meyer & Terjung (1979) demonstrated that fast twitch (FT) fibres contain 60-70% more CrP stores than slow twitch (ST) fibres. Greater power outputs over brief durations (≤ 10 seconds) have also been demonstrated in both isolated muscle bundles (Faulkner et al., 1986) and humans (Komi et al., 1977) that possess a higher proportion of FT fibres. Further , the hydrolysis of CrP may also play an important role in the intramuscular buffering of H^+ ions (Costill et al., 1984) , thereby facilitating the ATP output via anaerobic glycolysis by diminishing the fatigue-inducing effects of a reduced intramuscular pH. Therefore , it appears that the alactic capacity is influenced by the fibre-type characteristics of the working musculature , and that the alactic capacity of skeletal muscle may contribute directly to the anaerobic capacity and/or indirectly via its potential buffering mechanism.

2a). Anaerobic glycolytic ATP production (lactic capacity)

Under conditions of anaerobiosis , the use of glycogen as a fuel source results in the production of lactic acid which dissociates rapidly to La^- and H^+ ions (Hultman & Sahlin, 1980). Therefore , measurement of La^- within previously exercised muscle following exercise has been used to reflect the extent to which anaerobic glycolysis contributes to ATP supply (Gollnick & Hermansen, 1973).

Lactate production within skeletal muscle has been assessed using the biopsy technique (Bergstrom, 1962) or magnetic resonance spectroscopy (MRS) (Boden et al., 1986). The application of MRS to muscle energetics is relatively new , and therefore , the muscle biopsy procedure has been more often used to assess metabolic function in exercising humans. However , the applications of this method have been limited during multiple and/or serial testing of athletic populations , so previous investigators (Margaria et al., 1964; di Prampero, 1981) have calculated total lactate production based on blood La^- concentrations and assumptions regarding the distribution of La^- throughout the various body compartments following exercise. Since the validity of this method is suspect , studies using maximal blood La^- ($[BLa^-_{max}]$) as an index of total La^- production will not be discussed in this section.

During maximal work bouts of approximately 10-50 seconds duration , the primary source of ATP supply occurs via the anaerobic glycolytic pathway (Cheetham et al., 1986; Newsholme, 1981). It has been demonstrated that peak post-exercise muscle lactate concentrations ($[MLa^{-}_{max}]$) and performance times (50-120 seconds) on an exhaustive treadmill test , were significantly greater in sprint-trained athletes when compared to endurance athletes or untrained subjects (Parkhouse et al., 1985). Following a 30 second maximal cycling bout , male subjects demonstrated significantly greater mean power outputs and $[MLa^{-}_{max}]$ when compared to female subjects (Jacobs et al., 1983).

This apparent relationship between short-term maximal work outputs and $[MLa^{-}_{max}]$ is associated with the metabolic characteristics of the different skeletal muscle fibre types (Green, 1986). The ability to generate both La^{-} and supra-$\dot{V}O_{2max}$ power outputs , as well as to sustain these high power outputs is enhanced by possession of a greater proportion of FT glycolytic (Faulkner et al., 1986; Komi et al., 1977; Thorstensson et al., 1977) and FT oxidative fibres (Faulkner et al., 1986) , respectively. The greater La^{-} accumulation in FT fibres following repeated maximal contractions over 30-60 seconds (Essen & Haggmark, 1975; Tesch et al., 1978) and exhaustive cycling performance over 1-2 minutes (Tesch, 1980) has been related to higher activity levels of the glycolytic enzymes , phosphofructokinase (PFK) and phosphorylase (Essen et al., 1975) , as well as lactate dehydrogenase (Thorstensson et al., 1977).

It has been speculated that ST fibres may also contribute to the maintenance of supra-$\dot{V}O_{2max}$ power outputs via their ability to oxidize La^{-} at high rates (Tesch et al., 1981). Intuitively , it would seem that as the duration of supra-$\dot{V}O_{2max}$ work increases , greater reliance on FT oxidative and ST fibres to meet the immediate metabolic requirements would occur. Since these fibres also possess the capability to produce La^- and possibly oxidize it as fuel substrate almost instantaneously (Stanley et al., 1986) , the use of common invasive techniques to assess La^- production during longer exercise tasks may fail to detect the total quantity of La^- produced during the exercise. Although this quantity may be small in comparison with total La^- production , the fraction of {La^- oxidized/ La^- produced} may not only increase with the duration of the exercise , but may also be higher in individuals who possess a greater proportion of FT oxidative and ST fibres.

2b. Substrate Availability

Since ATP production via anaerobic glycolysis is dependent on the breakdown of glycogen , is the intramuscular glycogen concentration likely to limit anaerobic capacity ?

Klausen , Piehl & Saltin (1975) demonstrated a significant relationship between the magnitude of muscle glycogen depletion and the reduction in [MLa^-_{max}] and [BLa^-_{max}] following repeated bouts of supra-$\dot{V}O_{2max}$ exercise. After administering dietary/exercise regimens to manipuate intramuscular glycogen stores prior to a one minute maximal work bout , Jacobs (1981) demonstrated that a reduction in pre-exercise glycogen concentrations to approximately 40 mmol. glucosyl units per kg (wet weight) , resulted in significantly lower [MLa^-_{max}] following the exercise bout when compared to the normal condition (96.2 mmol glucosyl units per kg ww.). Further , regimens involving dietary (Greenhaff et al., 1987) or exercise/dietary manipulation (Maughan & Poole, 1981) assumed to deplete intramuscular glycogen stores have resulted in significant reductions in supra-$\dot{V}O_{2max}$ work output during 4-8 minutes of continuous , or intermittent activity , respectively. These findings suggest that both La$^-$ production and supra-$\dot{V}O_{2max}$ work outputs are reduced when glycogen concentrations have been reduced to critically low levels. However , it is not clear whether anaerobic capacity as determined over longer durations (> 4 min.) will be limited by normal intramuscular concentrations of glycogen. Since relatively small reductions (18.5-25%) in glycogen stores have been reported following 30 second maximal exercise bouts (Boobis et al., 1983; Cheetham & Williams, 1987; Kowalchuk, 1985) , normal glycogen concentrations are not likely to result in significantly lower La$^-$ production and power outputs over this shorter duration.

3. Buffering capacity of skeletal muscle and blood

The ability of the buffering systems of the body to sequester H^+ ions and thus resist the decline in pH is termed buffering capacity (Hultman & Sahlin, 1980). Excessive H^+ ion accumulation and the subsequent fall in pH has been linked with an inhibition of glycolytic energy production at the level of PFK (Sutton et al., 1981) , a decrease in maximum tension developed by skeletal muscle (Sahlin, 1978) and exhaustion in short-term maximal effort (Costill et al., 1983; Sahlin et al., 1978; Sutton et al., 1981).

The two important volatile buffer systems that operate within mammalian blood are the $NH4^+/NH3$ and $CO2/HCO3^-$ systems. Ammonia ($NH4^+$) is toxic for the organism and the concentration of this substance is so low that it has little importance in the buffering processes (Hultman & Sahlin, 1980). In contrast , the

CO_2/HCO_3^- system is vital in controlling acid-base homeostasis in the body (Hultman & Sahlin, 1980). It has been speculated that an increased $[HCO_3^-]$ in the blood may increase H^+ ion and La^- removal from the blood via an increased La^- diffusion gradient from muscle to blood (Mainwood & Worsley-Brown, 1975). The ability to demonstrate an ergogenic effect by orally ingesting $NaHCO_3$ is dependent upon the administered dose (Sutton et al., 1981) , as well as the duration of the exercise (Costill et al., 1984). In studies that have used doses >= 0.2g $NaHCO_3$/kg BW , a significant ergogenic effect was observed during intermittent (Costill et al., 1984) and continuous exercise (Wilkes et al., 1983) that produced exhaustion within 1.75-5 minutes. These observations support the concept that an increased blood $[HCO_3^-]$ facilitates the efflux of H^+ ions from the muscle (Mainwood & Worsley-Brown, 1975) during exercise. However , heredity or training-induced differences in the buffering capacity of the blood in human subjects have yet to be reported (Hermansen et al., 1984; Medbø & Sejersted, 1985; Sharp et al., 1982).

Within skeletal muscle , H^+ ions may be buffered by physico-chemical or metabolic buffering processes. During exercise in man , few buffering systems have any impact on the ability to buffer free H^+ ions (Hultman & Sahlin, 1980). Of the metabolic processes , the hydrolysis of CrP accounts for the major portion of the buffering of H^+ ions. Although unclear , it has been proposed that CrP may act as a buffer of H^+ ions during high intensity exercise (Sharp et al., 1986).

Of the physico-chemical processes , the phosphate compounds demonstrate minimal buffering effect in skeletal muscle (Dawson et al., 1978). The findings of recent studies suggest that the histidine-related compound , carnosine , is an important intramuscular buffer during supra-$\dot{V}O_{2max}$ exercise (Bell & Wenger, 1989; Parkhouse et al., 1985). Training-induced adaptations in intramuscular buffering capacity , carnosine levels and La^- production (Bell & Wenger, 1989; Sharp et al., 1986) have been associated with improvement in supra-$\dot{V}O_{2max}$ power outputs.

The previous findings suggest that the buffering capacity of skeletal muscle and blood does influence the body's ability to tolerate rapid rates of H^+ ion production within muscle , and as a result , mediates the muscular power output which can be sustained at supra-$\dot{V}O_{2max}$ power outputs.

4. Lactate and H^+ ion efflux during exercise

Studies in man have shown that corresponding amounts of La^- and H^+ ions accumulate in the muscle and to a lesser extent the blood following exercise (Sahlin et al., 1976; Sahlin et al., 1978). Consequently , a concentration gradient is observed between the muscle and blood (Karlsson, 1971) , as well as between different fibre types (Tesch et al., 1978) which facilitates the movement of the two metabolites from intracellular areas of high concentration. Following an initial period during post-exercise recovery the rate of efflux of both La^- and H^+ ions out of the muscle were found to be similar (Sahlin et al., 1976). Therefore , it has been suggested that the analysis of La^- kinetics provides insight into the movement of H^+ ions after exercise (Hultman & Sahlin, 1980).

The mechanisms associated with La^- kinetics are not well understood. Previous findings have suggested that the efflux of La^- and H^+ ions may occur via passive diffusion of the undissociated molecule , lactic acid , through porous membrane channels (Hultman & Sahlin, 1980) , via passive mediated transport utilizing a membrane-bound protein with specific binding sites for La^- or lactic acid (Jorfeldt et al., 1978) , and/or La^- diffusion may be restricted by the degree of muscle swelling during exercise (Eggleton et al., 1928). Since La^- efflux from active canine gracilis muscle (Karlsson , Rosell & Saltin, 1972) and in human quadriceps during bicycle exercise (Jorfeldt et al., 1978) has been observed to achieve saturation levels , it was suggested that a trans-membrane transport mechanism may influence the movement of intracellular La^- to the blood (Hultman & Sahlin, 1980). However , significant correlations between $[MLa^-_{max}]$ and $[BLa^-_{max}]$ (Schreiner, 1989; Cheetham et al., 1986) observed during post-exercise recovery suggested that the rate of La^- efflux may also be influenced by passive diffusion.

Since anaerobic glycolysis is inhibited by a decline in pH to critically low levels (Sutton et al., 1981) , conditions which facilitate La^- and H^+ ion efflux from the working muscle will increase ATP output from anaerobic glycolysis. The pH levels (Hultman & Sahlin, 1980; McCartney et al., 1983) , $[HCO3^-]$ (Costill et al., 1984; Mainwood & Worseley-Brown, 1975; Sutton et al., 1981) , $[La^-]$ (Jorfeldt et al., 1978) and electrolyte concentrations (Medbø & Sejersted, 1985) of the extracellular fluid , as well as the fibre type (Bonen et al., 1978) , are all reported to influence the rate of La^- and H^+ ion efflux. Concentrations of La^- , H^+ and $HCO3^-$ ions in the blood can be influenced by the amount of blood flow across the muscle membrane (Tesch & Wright, 1983). It has been suggested that an increase in the blood flow to the working muscle will remove diffusing metabolites at a faster rate , thereby maintaining a muscle-blood concentration gradient which facilitates a rapid efflux of metabolites from the muscle (Tesch & Wright, 1983). This is supported by the study of Tesch & Wright (1983) which reported significant relationships between capillary density and $[BLa^-_{max}]$, as well as an inverse relationship between capillary density and the rate of decrease in maximal torque output over 50 repetitive maximal contractions of the knee extensors.

Measurement of anaerobic capacity

On the basis of previous research , the measurement of anaerobic capacity can be classified into two major categories:

1. **Invasive (blood-borne)** and **non-invasive (gas-exchange)** measures used to quantify anaerobic capacity. These measures are commonly expressed in kJ , kcal or $mL \cdot kg^{-1}$.

2. **Work tests** , from which work outputs (joules) are used to qualitatively describe anaerobic capacity.

1a). Peak post-exercise blood lactate concentration ($[BLa^-_{max}]$)

Appearance of lactate within the vascular space is dependent upon the rates of production within contracting muscle , removal into , and elimination from the vascular space (Freund & Gendry, 1978). Margaria et al. (1933) first used BLa^- curves recorded during post-exercise rest to estimate anaerobic glycolytic energy expenditure. Margaria et al. (1964) modified this method to account for the estimated distribution volumes of La^- in the various tissue compartments. On the basis of this method and data previously reported (di Prampero, 1981) , an energy equivalent of BLa^- was determined to be approximately 2.7-3.3 kJ per $mmol \cdot L^{-1}$, thus allowing an energetic equivalent of $[BLa^-_{max}]$ to be calculated. Di Prampero (1981) proposed that $[BLa^-_{max}]$ provided an accurate and reliable estimate of lactic capacity , as long as the same conditions applied with respect to diffusion , distribution and removal of La^- occur , and that the recovery mode and site of blood sampling are standardized. Since $[BLa^-_{max}]$ may also be influenced by pre-exercise glycogen concentrations (Fric et al., 1988; Greenhaff et al., 1987; Klausen , Piehl & Saltin, 1973) and acid-base balance changes induced by prior exercise (Kindermann & Kullmer, 1985; Klausen et al., 1972) , there exists a further requirement to standardize for pre-test dietary and exercise patterns.

$[BLa^-_{max}]$ has been used to provide both a qualitative (Paterson et al., 1986) and quantitative measure (Berg, Jakob & Keul, 1989; Mero, 1988; Ohkuwa et al., 1984) of anaerobic capacity in athletic and non-athletic populations. Previous studies have demonstrated significant relationships between $[BLa^-_{max}]$ and supra-$\dot{V}O_{2max}$ performances such as 400m sprint running (Berg & Keul, 1985; Fujitsuka et al., 1982; Ohkuwa et al., 1984) , treadmill running over 30-60 seconds (Cheetham et al., 1986; Cheetham & Williams, 1987; Fujitsuka et al., 1982) and the Wingate test (Tamayo et al., 1984). Furthermore , $[BLa^-_{max}]$ has been shown to improve as a result of supra-$\dot{V}O_{2max}$ training regimens (Cunningham & Faulkner, 1969) and seasonal competition (Green & Houston, 1975).

Despite these findings , the validity of $[BLa^-_{max}]$ is controversial , and the accuracy with which it reflects anaerobic capacity in elite athletes has been questioned (Schnabel et al., 1979). Non-significant relationships between $[BLa^-$

$_{max}$] and mean power output on the Wingate test (Goslin & Graham, 1985; Taunton et al., 1981) , and [BLa$^-_{max}$] and supra-$\dot{V}O_{2max}$ performance in elite athletic populations (Ohkuwa et al., 1984) demonstrated that [BLa$^-_{max}$] may not be of sufficient accuracy to detect differences in anaerobic capacity in elite , homogeneous athletic populations. Why?

During post-exercise recovery , BLa$^-$ concentrations can be reliably described using the bi-exponential function : $La(t) = La(0) + A1(1- \exp^{-\gamma 1.t}) + A2(1- \exp^{-\gamma 2.t})$ (Freund et al., 1989). Intuitively , this function indicates that the peak value is dependent upon the two rate constants , $\gamma 1$ and $\gamma 2$, and their amplitudes , A1 and A2 , respectively. Freund et al. (1989, 1986) proposed that the rate constants , $\gamma 1$ and $\gamma 2$, quantitatively reflect the functional ability of the tissues to exchange La$^-$ between the previously exercised muscles and the total La$^-$ space (La$^-$ efflux) , and the functional ability of the body to eliminate La$^-$ from the blood via metabolic processes , respectively. Consequently , [BLa$^-_{max}$] will be influenced by rates of La$^-$ efflux and elimination , mechanisms not necessarily related to the muscular ability to produce La$^-$.

The rates of La$^-$ production , efflux and elimination may be modified according to the exercise duration (Freund et al., 1989) and power output (Freund et al., 1986) , as well as the aerobic functional ability of the individual (Freund et al., 1989; Simon et al., 1986). The rate at which La$^-$ is eliminated from the blood has been found to be related to $\dot{V}O_{2max}$ (Freund et al., 1989) , has been reported to be faster in endurance-trained as compared to sprint-trained athletes (Medbø & Sejersted, 1985) , and is increased as a result of endurance training (Donovan & Brooks, 1983). Therefore , it is likely that the post-exercise kinetics of [BLa$^-$] are influenced by physiological factors independent of total La^- production , as well as influenced by the nature of the exercise and the individual. The variant correlations aforementioned between $[BLa^-_{max}]$ and supra-$\dot{V}O_{2max}$ performances that vary in duration and intensity may be partially explained on this basis.

1b) O_2 debt

The $\dot{V}O_2$-recovery curve describes the decline in $\dot{V}O_2$ towards a resting level following exercise (Roberts & Morton, 1978). Following supra-$\dot{V}O_{2max}$ activity , the $\dot{V}O_2$-recovery curves previously reported (Katch, 1973; Roberts & Morton, 1978) are consistently described by the function $\dot{V}O_2(t) = a1(\exp^{-k1.t}) + a2(\exp^{-k2.t}) + C$. The first two terms in the equation have been referred to as the 'fast' and 'slow' components , respectively (Cerretelli, 1984; Margaria et al., 1964). The integral between the $\dot{V}O_2$-recovery curve and a predetermined baseline (ie. resting $\dot{V}O_2$) is the O_2 debt (Hill et al., 1924).

O_2 debt was first observed and defined by A.V. Hill (1924) , and later confirmed by Margaria et al. (1933). These investigators suggested that the 'fast' and 'slow' components of the $\dot{V}O_2$-recovery curve reflected the energetic repayment of the alactic , and lactic stores , respectively. The validity of the alactic component has received support from recent studies , which demonstrated a close relationship between the time-courses of the $\dot{V}O_2$-recovery curve and ~P resynthesis in canine gastrocnemius muscle (Piiper & Spiller, 1970) and human quadriceps muscle (Hultman et al., 1967). Its use as a reliable estimate of alactic capacity in man has been confirmed (Roberts & Morton, 1978; Sawka et al.,1980) , although it has been recognised that a constant portion of the 'fast' component includes the replenishment of the O_2 stores bound to haemoglobin and myoglobin (Hermansen et al., 1984).

Margaria et al. (1933) observed that after $[BLa^-_{max}]$ was achieved 3-7 minutes post-exercise , the $[BLa^-]$ decreases exponentially with a half time of a similar magnitude to the $\dot{V}O_2$ 'slow' component. As a result , Margaria et al. (1933) interpreted this 'slow' component as reflecting the lactic debt that was built up during exercise , and thus would provide a quantitative estimate of anaerobic glycolytic energy expenditure. Although the primary fate of La^- is oxidation and is therefore included in the total O_2 debt (Stanley et al., 1986; Brooks & Gaesser, 1980) , the remaining La^- enters the Cori-cycle and is resynthesised to glycogen (Åstrand et al., 1986; Brooks & Gaesser, 1980; Hermansen & Vaage, 1977) at an energetic cost twice that released during La^- formation (Martin, 1987). In addition , the magnitude of the O_2 debt may be influenced by the release of catecholamines (Harris, 1980; Maron et al., 1977) , elevated substrate cycling and mitochondrial respiration following exercise (Gaesser & Brooks, 1984) , tissue temperature via the Q_{10} effect (Brooks & Gaesser, 1980; Chad & Wenger, 1988) and the substrate used (Chad & Wenger, 1988). On the basis of these findings the validity of the O_2 debt is questionable. Further , a high coefficient of variation (21.4%) reported for repeated measurements of O_2 debt also suggested it was not a reliable measure (Graham & Andrew, 1973)

1c) O_2 deficit

At submaximal intensities , the steady-state O_2 uptake is assumed to reflect the total rate of energy release during exercise (Åstrand, 1981). Based on the assumption that the energy requirement (O_2 demand) increases linearly with increasing exercise intensity , the O_2 demand at supra-$\dot{V}O_{2max}$ power outputs can be estimated (Hermansen & Medbø , 1984). During supra-$\dot{V}O_{2max}$ exercise , the area between the O_2 demand and $\dot{V}O_2$ curves represents the total volume of energy derived from anaerobic metabolism , and has been termed the O_2 deficit (Hermansen, 1969).

The accumulated O_2 deficit has been determined in several studies to quantify anaerobic ATP output during supra-$\dot{V}O_{2max}$ cycle (Karlsson & Saltin, 1970, 1971; Pate et al., 1983; Szogy & Cheribetieu, 1974) and treadmill exercise (Hermansen & Medbø , 1984; Medbø et al., 1988; Medbø & Sejersted, 1985). Work output on a 1 minute all-out cycle test was found to be highly correlated with O_2 deficit (Szogy & Cheribetieu, 1974) , whilst sprint-trained athletes displayed greater O_2 deficits and running speeds than endurance-trained athletes on a 1 minute exhaustive treadmill test (Medbø & Sejersted, 1985).

In previous studies (Karlsson & Saltin, 1970, 1971; Pate et al., 1983; Szogy & Cheribetieu, 1974) , an assumed mechanical efficiency (19.5-22.5%) was used to determine the O_2 demand of the exercise. It has since been demonstrated that individual efficiency values may vary as much as 16% , suggesting a high degree of error may be incurred when determining O_2 deficit using a common efficiency. Medbø et al. (1988) suggested that the O_2 demand should be estimated according to the individual $\dot{V}O_2$-power output relationship. Using this method , these investigators demonstrated that the maximal accumulated O_2 deficit (MAOD) was achieved after 2-3 minutes of exhaustive , constant-paced running , with further increases in duration failing to increase the MAOD. A 4% error in determining

MAOD was reported in this study , and it was concluded that MAOD provided an accurate estimate of anaerobic capacity.

This claim has yet to be corroborated and the reliability of MAOD is not known. Also the method used to estimate efficiency in the study of Medbø et al. (1988) is very time-consuming , therefore , an alternative method using a common y-intercept (5 $mL \cdot kg^{-1} \cdot min^{-1}$) and a single $\dot{V}O_2$ measured at a speed equal to 90%$\dot{V}O_{2max}$ was recommended. However , substantial lactic acid production at this power output would have likely occurred in most subjects and as a result , diminished the accuracy with which $\dot{V}O_2$ reflected the O_2 demand.

1d) Prediction from running performance

Based upon [BLa^{-}_{max}] measured following four maximal treadmill runs lasting 15-60 seconds , Thomson & Garvie (1981) had proposed a method of calculating anaerobic capacity. Using this method , Thomson (1981) correlated the anaerobic capacities of highly trained subjects with their respective running speeds over different intervals of a 400m sprint. Although it was revealed that sprinting time to 256m , and average speed between 256 and 329m accounted for the greatest variance in anaerobic capacity ($R^2 = 0.70$) , this finding is difficult to interpret due to the questionable validity and reliability of [BLa^{-}_{max}] , and the failure of the investigators to provide sufficient methodological detail.

2. Work tests

Considering the time and expense required in using invasive and non-invasive measures , work output measured on an ergometric test has provided an easier method of assessing the physiological capabilities of athletes. To date , performance variables measured on the treadmill and cycle ergometer have been used to provide a qualitative assessment of anaerobic capacity , or more appropriately , anaerobic work capacity. Vandewalle et al. (1987) have classified work tests as either 'constant-load' or 'all-out' tests.

2a). Constant-load work tests (treadmill and cycle)

Treadmill work tests which use a motorised treadmill have been classified as constant-load tests (Vandewalle et al., 1987). In developing treadmill tests designed to measure anaerobic work capacity , a variety of protocols incorporating different gradients and speeds have been used. To exhaust subjects within 45-70 seconds , gradients ranging from 8-20% and speeds of 12.9-22 km·hr^{-1} have been selected (Cunningham & Faulkner, 1969; Medbø et al., 1988; Schnabel & Kindermann, 1983). Anaerobic work capacity has been previously been reported in units of joules (Paterson et al., 1986) , seconds (Berg & Keul, 1985; Houston & Thomson, 1977; Parkhouse et al., 1985) or units of velocity (Medbø & Sejersted, 1985; Thomson & Garvie, 1981). Due to the differences in protocol followed and work units expressed , inter-study comparisons were not possible. Also , procedures required to determine an appropriate workload for different populations increases the time required when using the motorised treadmill.

In comparison with constant-load tests , it has been suggested that all-out work tests are less time consuming and provide more information concerning anaerobic function (Vandewalle et al., 1987). Although a non-motorised treadmill has been used to assess metabolic function during sprint-running (Cheetham et al., 1986, 1985; Cheetham & Williams, 1987) , an anaerobic work capacity test using this apparatus has yet to be developed.

Constant-load tests have also been developed using the friction-loaded cycle ergometer , during which subjects are required to pedal against a set resistance maintaining a predetermined pedal rate (Debruyn-Prevost & Sturbois, 1984; Hebellink, 1969). However , the problems associated with this type of work are similar to those experienced using the motorised treadmill. In addition , the low test-retest coefficient (r = 0.77) reported for a constant-load cycle test (Heyters & Poortmans, 1977) demonstrated that this type of test may not be reliable , and it also reflects the difficulty in determining the precise moment of exhaustion during constant-load tests

2b). All-out work tests (cycle)

Friction-loaded cycle ergometers have been most often used in all-out work tests of anaerobic capacity. Total work outputs (or mean power output) measured on all-out work tests of 30 (Ayalon et al., 1974; Patton et al., 1985) , 60 (McKenna et al., 1987) and 90 seconds (Simoneau et al., 1983) have previously been used to assess anaerobic capacity , and have been shown to vary in reliability (r = 0.74 - 0.99). Since maximal work outputs are used to reflect anaerobic capacity , the appropriate duration and force-velocity characteristics of the test have to be considered. As yet , the power output-time characteristics of a work test which 'best' reflects anaerobic capacity have not been identified.

Duration

All-out cycle ergometer tests purported to measure anaerobic capacity range from 30-120 seconds in duration. Since the relationship between maximal work outputs over these durations and accurate biochemical measures of anaerobic metabolism have not been described , the accuracy with which these work outputs reflect the various anaerobic constructs is unclear. The 30 second Wingate test (WT) (Bar-Or, 1977) has often been used to assess anaerobic function. There exists a lack of agreement on whether the WT measures anaerobic power (Bar-Or, 1987; Goslin & Graham, 1985; Vandewalle et al., 1987) or anaerobic capacity (Bouchard et al., 1982). High correlations between mean power output on the WT , and 500m skate speed ($r = 0.76$) (Thompson et al., 1986) as well as 300m cycling time ($r = 0.75$) (Perez et al., 1986) suggest the physiological bases of these performances were similar. However , these findings do not not necessarily provide insight into the validity of the test as a work estimate of anaerobic capacity. Since the power output at the end of a 30 second work bout may approximate twice that generated at $\dot{V}O_{2max}$, it has been suggested that this duration is not sufficient to exhaust the anaerobic capacity (Katch, 1973; Vandewalle et al., 1989).

The bases on which the 40 (Katch et al., 1977) , 45 (Vandewalle et al., 1985) , 60 (McKenna et al., 1987; Szogy & Cheribetieu, 1974) , 90 (Simoneau et al., 1983) and 120 (Katch & Weltman, 1979) second tests were established were also not clear. Katch & Weltman (1979) attributed individual differences in maximal work output over 120 seconds to anaerobic function. Evidence supporting this claim was lacking , and since maximal effort over 60-120 seconds is maintained primarily by aerobic metabolism (Hermansen & Medbø , 1984; Katch, 1973) , it is possible that differences in aerobic function may have influenced work output over these latter durations. Positive correlations between $\dot{V}O2_{max}$ and maximal work output over 90 seconds (r = 0.81) (Boulay et al., 1985) and 120 seconds (r = 0.27) (Katch & Weltman, 1979) suggested that mechanisms associated with $\dot{V}O2_{max}$ and work output over these durations are not independent.

Force-Velocity Relationship

True maximal power is a product of instantaneous values of force and velocity (di Prampero & Mognoni, 1981). It has been demonstrated that the magnitude of the maximal power output is dependent upon the force-velocity characteristics of the movement. A parabolic relationship has been described between force (applied resistance) and maximal work output over a 30-45 second cycling bout (Dotan & Bar-Or, 1983; Mannion & Jakeman, 1986; Vandewalle et al., 1985) , with maximal work outputs elicited using applied resistances of 0.853 - 1 N. kg^{-1} BW for males , and 0.844 - 0.9 N. kg^{-1} BW for females (Dotan & Bar-Or, 1983; Vandewalle et al., 1985). Vandewalle et al. (1985) speculated that variation in optimal resistances identified in these studies may have been due to differences in equipment , subjects or protocol.

The use of the friction-loaded cycle ergometer incurs certain limitations. Forces and velocities measured on a friction-loaded cycle ergometer are mean values calculated each second (di Prampero & Mognoni, 1981) as opposed to the isokinetic cycle which allows instantaneous values of force and velocity to be determined (Sargeant et al., 1984). As a result , mean power output measured during each revolution is 50-60% less than that measured on an isokinetic cycle

(Sargeant et al., 1984) resulting in lower work outputs over 30 seconds (M^{c}Cartney et al., 1983). Further , the continual acceleration and deceleration that occurs during cycling limits the time for which the muscle maintains an optimal velocity (M^{c}Cartney et al., 1983). Since pedalling speeds may vary as much as 160 rpm's during a 30 second test depending on the resistance applied (Mannion & Jakeman, 1986) , it is likely that portions of the test are performed at less than optimal velocities. This is supported by studies which have used lower resistances for 90 second (Simoneau et al., 1983) and 120 second tests (Katch & Weltman, 1979).

Despite these limitations , work output measured using the friction-loaded cycle ergometer will reflect the functional state of the performer. It is important that the applied resistance be selected according to body weight , thereby allowing each individual to work at near-optimal velocities. However , caution must be expressed if attempting to quantify anaerobic capacity based on work outputs , since the work outputs generated using a friction-loaded ergometer are not 'truly' maximal (di Prampero & Mognoni, 1981).

2c) Time-work tests (treadmill and cycle)

In assessing the performance at various supra-$\dot{V}O_{2max}$ power outputs , the relationship between the total amount of work performed (W_{lim}) and the time corresponding to exhaustion (t_{lim}) has been studied (Monod & Scherrer, 1965; Moritani et al., 1981; Vandewalle et al., 1989). This relationship can be written as follows: $W_{lim} = a + b.t_{lim}$, where the slope b has the dimension of a critical power which is aerobic in nature , and the intercept [a] has the dimension of an anaerobic energy store (Moritani et al., 1981). The lack of effect that ischaemia

(Scherrer et al., 1954) and hypoxia (Moritani et al., 1981) have on the intercept [a] appear to confirm its anaerobic nature. More recently , this parameter has been used as an estimate of anaerobic work capacity and was shown to be a significant predictor of 8km running performance (Bulbulian et al., 1986). However , Vandewalle et al. (1989) reported that this same parameter underestimated a theoretical value of anaerobic capacity , and suggested that it was not a valid estimate of anaerobic capacity.

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June 15, 1990