FACTORS AFFECTING SUBMAXIMAL RUNNING ECONOMY IN CHILDREN

A thesis presented for the degree of Doctor of Philosophy

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ABSTRACT

The research conducted in this study has helped to clarify a number of important methodological and physiological questions in submaximal paediatric exercise physiology. The work was sub-divided into three major sections: methodological aspects of measuring submaximal running economy, factors affecting submaximal running economy and possible methods of manipulation of submaximal running economy.

The three major methodological concerns addressed were the validity and stability of measurements of submaximal performance and the suitability of submaximal paediatric exercise testing. Data obtained from the validation study demonstrated that it was possible to use a biological calibration to assess the validity of the S2900Z metabolic cart. Of the selected cardio-respiratory variables studied, FeCO2 represented the only variable to demonstrate any bias between the computerised data collection and the reference system (Douglas Bag). The confirmation of the validity of these measurements allowed the subsequent body of work to be developed.

For true treatment effects to be noted in the manipulation of submaximal running economy, the level of natural variability needed to be measured. Results from the second methodological study demonstrated the level of variability associated with repeated submaximal testing (standard error of the mean ± 1.25 ml/kg/min) and peak testing (standard error of the mean ±2.25 ml/kg/min). It was concluded that single economy test sessions were valid for estimating the group stability of running economy. However, if individual profiles were required then multiple submaximal and maximal exercise testing would be necessary.

The determination of the shortest submaximal steady state stage is important in the development of continuous submaximal protocols in children. Minimising the amount of time a child has to be on a treadmill lessens the overall stress placed upon the child at submaximal exercise intensities. The third methodological study addressed this issue. The results demonstrated that stable submaximal oxygen values were attained by the third minute of the steady state stage. Very little variation occurred between 3 and 6 minutes. Hence, the use of steady state stages between 3 and 6 minutes was considered acceptable.

Profiling the physiological differences between a group of run-trained and control boys indicated that some form of physiological adaptation had occurred, either as a result of pre-selection or training. At submaximal exercise intensities differences in blood lactate, fractional utilisation, ventilatory equivalent, heart rate, ventilation and respiratory exchange ratio were noted. Confounding data obtained in the run-trained group indicated that the submaximal oxygen cost of running appeared to be similar to the controls in one study and higher in the second study. Inferences with regard to enhanced free fatty acid oxidation in the trained boys were postulated. The influence of kinematic factors upon submaximal running economy was investigated and found to be minimal with no significant differences evident in gait characteristics between the two populations. It appeared that gait adjustment was a product of running velocity rather than training status. On the basis of these results the use of submaximal running economy as a marker for physiological differences between trained and untrained populations is valid.

The one clear index that differed throughout all the studies was peak $\dot{V}O_2$, with run-trained boys demonstrating superior aerobic power. The source of this difference could have been either as a result of training or as a consequence of genetic pre-selection for running. The nature of the studies undertaken prevent us from answering this question .

In an attempt to manipulate submaximal running economy, a high intensity aerobic training intervention study was conducted. Ergogenic manipulation of submaximal running economy was also attempted using an agent suggested to have ergogenic potential, a β2-agonist. The inhalation of a β2-agonist (Terbutaline), however, was found to have no effect upon submaximal running economy. In contrast, training led to striking improvements in submaximal running economy of the order of 7%. The possible sources of this improvement are many : increased glycolytic potential, enhanced cardiovascular and ventilatory responses, substrate utilisation shifts and possible body composition changes. The possibility of altering submaximal running economy through training remains the most striking aspect of this work into submaximal running economy. This work suggest that submaximal running economy is an appropriate and sensitive marker for assesing the impact of training in a pre-pubertal population.

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AUTHOR'S DECLARATION

All work conducted in this thesis represents my own work. However, the final section of this body of research: manipulation of submaximal running economy represents collaborative research. The conception of the project idea and the inception of the testing was conducted by myself. However, data collection during the test sessions was jointly accomplished by myself and students J. A. Timmons and K. J. Thomson respectively.

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GENERAL INTRODUCTION

INTRODUCTION

The energy efficiency of muscular work is defined as the ratio of work accomplished to the total amount of energy expended (Rowland *et al.* 1990). During treadmill running, efficiency is less readily defined, since the work load is more difficult to quantify. Body weight, elastic tendon recoil of leg muscle-tendon units, arm motion, transfer of energy between body segments and running gait all contribute to variability in the total work accomplished. Efficiency of movement during treadmill running has therefore been expressed as oxygen uptake at a given speed, so called running economy.

In 1985 a symposium entitled "The efficiency of human movement - a statement of the problem" was published in Medicine and Science in Sports and Exercise (Cavanagh and Kram, 1985). The relationship between running economy and a series of variables (biomechanical, psychological and physiological) was discussed. This forum represented the first collective attempt to synthesise factors affecting submaximal running performance. Given the performance implications associated with being an economical runner it was surprising how little attention this topic had received from exercise and sports scientists.

The concluding themes of the 1985 forum addressed three main areas: biomechanics, psychology and physiology. In the area of biomechanics more multi-disciplinary research on trained and untrained performers was needed in order to isolate both individual and global parameters of running style. Determining those factors responsible for a more efficient running style and implementing strategies that would help coaches and runners to improve efficiency was promoted as a major bio-mechanical directive. In order that the established relationship between cognitive activity and submaximal oxygen consumption could be developed further a significantly greater amount of research was also suggested within the psychological realm.

Two major questions were formulated with regard to the physiology of economy: (i) Why do certain runners consume less oxygen than others and (ii) can economy be positively modified through training?

It was interesting to note that even by 1991 an American College of Sports Medicine symposium on running economy was still addressing many of the similar questions that had been put forward in 1985. The aim of the 1991 symposia was to stimulate investigators to formulate testable hypotheses with regard to running economy. It was also hoped that a multi-disciplinary approach could be applied to the investigation of submaximal running economy. This type of approach would enhance the possibility of identifying and manipulating those variables associated with economical running. Through the process of identification and manipulation of those variables the aim was to identify precisely those mechanisms responsible for the development of an economical running pattern. It was somewhat surprising to note that by 1991 there still remained a general lack of consensus and a paucity of knowledge with regard to factors affecting submaximal running economy. A major directive issued by ACSM in 1991 was to attempt to determine which factors governing submaximal economy could be manipulated and which were innate properties of the individual.

Consequently, based upon the directives issued from the American College of Sports Medicine the current body of work was formulated. Determining the factors responsible for submaximal running performance while important in the adult population has an added significance for the paediatric population. The emergence of the elite pre-pubertal runner has led to the need to quantify the exercise response precisely in order to provide important feed-back to both athlete and coach. The physiological requirements of the coach remain specific and geared to the performance demands of the pre-pubertal athlete. Information from the paediatric sports scientist may assist in determining optimal intensity, frequency and duration of training. Helping to bring the elite pre-pubertal athlete to peak performance represents only one facet of the role of the paediatric sports scientist. Ensuring that the child remains in good physical health and minimising the risk of injury throughout a critical phase of development must have equal priority for both coach and scientist. In a wider context isolating those factors responsible for economical locomotion has longer term implications for children. If the ability to develop an economical pattern of locomotion in childhood can be sustained to adulthood then an array of physiological fitness benefits might accrue such as lower resting heart rate, reduced resting blood pressure, lower submaximal exercising heart rate and higher maximal oxygen carrying capacity.

The work described in this thesis falls in to three major sections:

1. Methodological concerns related to running economy.
2. Factors affecting submaximal running economy in pre-pubertal children and
3. Manipulation of submaximal running economy

Methodological concerns related to running economy

With the constant up-grading of computerised exercise testing equipment the need to be fully confident of the data generated is critical. Consequently, the development of a validation protocol that could be easily implemented and adapted to the specific demands of a paediatric population represented the first stage of the study.

A good deal of attention is focused upon research strategies designed to manipulate running economy. It is, therefore, of great interest to quantify normal variability in the assessment of submaximal running. The knowledge of within subject stability in running economy is also important in determining the number of tests required to obtain stable measurements. The measurement of stability of maximal and submaximal oxygen consumption, therefore, represented the second methodological concern addressed.

Within paediatric exercise testing a number of submaximal steady state protocols have been used. The third methodological aspect considered was the length of submaximal protocol most appropriate for the assessment required.

Having established the factors necessary to make valid and reproducible measurements in children the study proceeded to examine two questions relating to submaximal running economy in children.

Factors affecting submaximal running economy in pre-pubertal children

The emergence of the trained pre-pubertal runner was the basis for the subsequent body of work. A multi-disciplinary approach was used to investigate the factors affecting submaximal running between two groups of subjects. These groups were of similar age, height and weight, but differed in that one group had experienced formal running training. A series of 4 studies addressed the fundamental differences that exist between groups with respect to cardio-respiratory, kinematic, blood lactate and echocardiographic status of the children. The final study in this sequence investigated the association between selected laboratory variables and race performance.

Manipulation of submaximal running economy

In an attempt to challenge the hypothesis that submaximal running economy cannot be manipulated, two strategies were adopted: The first involved the implementation of a longitudinal training study in an attempt to see whether 10 weeks of high intensity aerobic training could improve submaximal running economy in a group of moderately trained runners. The second strategy attempted to assess the effect of drug manipulation upon submaximal running economy. A β2-agonist commonly used in the treatment of childhood asthma had been demonstrated to enhance submaximal running economy in asthmatic children (Zanconato *et al.* 1990). With the current wide-spread use of inhalers in children, it was considered appropriate to investigate the impact of a β2-agonist on submaximal running economy in normal healthy children.

One of the most critical and significant elements of research into performance is the homogeneity of the sample being studied. Studying pre-pubertal populations allows the researcher to unwind some of the physiological factors responsible for running performance at a time when the confounding effects of growth are less manifest .

This work, therefore, addresses a number of fundamental questions in paediatric exercise science. It is hoped that the results will provide the basis for future discussion and guidelines.

Hypotheses

Three major hypotheses formed the basis of this research:

1. Valid, reliable and appropriate exercise protocols can be developed for a pre-pubertal population.
2. Potential factors influencing submaximal running economy could be isolated in a pre-pubertal population.
3 Submaximal running economy has the capacity to be manipulated through training or ergogenic means.

Aims

Before investigating the above hypotheses it was necessary to establish that valid and reliable studies of exercise performance could be performed in pre-pubertal children. The first series of methodological studies were designed to investigate this. The aims of these studies were:

1. To determine the validity of the computerised data obtained by the Sensormedics (S2900Z) metabolic cart in children and to develop a validation protocol specific for this population.
2. To assess the stability of repeated submaximal and maximal exercise testing in children.
3. To determine the most appropriate steady state submaximal protocols applicable to a paediatric population.

Once it had been established that valid and reliable measurements were possible with the equipment available and in the targeted population. The aims of the investigations into factors affecting submaximal running economy were:

1. To assess whether kinematic differences existed between a group of moderately trained pre-pubertal boys and a group of control boys at submaximal running speeds.
2. To assess whether there were differences in submaximal economy between a group of moderately run-trained pre-pubertal boys and a group of control boys at submaximal running speeds.
3. To investigate the contribution of steady state lactate production to submaximal running economy in a group of moderately trained pre-pubertal runners.
4. To examine the relationship between running economy, peak oxygen consumption and fractional utilisation to running performance in run-trained pre-pubertal boys.

The final part of the study was designed to investigate whether submaximal running economy was amenable to manipulation either by training or by drugs:

1. To assess the impact of a 10 week high intensity aerobic training programme upon submaximal running economy.
2. To assess the effect of a β2-agonist upon submaximal running economy in a group of pre-pubertal boys.

Ethical Approval

All studies were approved by the Ethics Committee of the Royal Hospital for Sick Children, Yorkhill, Glasgow.

METHODOLOGICAL CONCERNS RELATED TO RUNNING ECONOMY

BIOLOGICAL VALIDATION OF EXERCISE TESTING SYSTEMS IN CHILDREN

Introduction

The development of the microprocessor has been of considerable benefit to the exercise specialist. These developments have led to the increased application of computerised on-line gas analysis systems in adult and, more recently, paediatric exercise testing. Two broad categories of exercise testing protocols are employed in these populations: (i) submaximal steady state testing and (ii) progressive incremental exercise tests. With the use of these systems it is necessary and important to ensure that data generated by these systems at both high and low exercise intensities are both valid and reliable.

Despite the steady development of on-line computerised exercise testing systems, the importance of quality control procedures appears to have been neglected. The need to make quality control, protocol and population specific is highlighted by the fact that using machines to simulate volumes and flows generated by children would never fully mimic their responses. Equally, asking an adult to work at low work outputs to mimic a paediatric response is also inadequate as ventilation, tidal volume, oxygen consumption and ventilatory efficiencies cannot be sustained in the way that a child would.

Jones (1984) developed confidence intervals for a micro-processor controlled exercise testing system (Horizon MMC metabolic cart) based on the measured accuracy of the computer measurement of oxygen consumption $\dot{V}O_2$, ventilation (Ve), fraction of expired oxygen (FeO2) and fraction of expired carbon dioxide

(FeCO2) compared to a reference system. In this study, Jones used a Douglas bag measurement technique as the reference system against which to compare the computer generated values. Based upon the results generated from this study a confidence interval of ± 3% was derived. For computer generated cardio-respiratory values to be considered valid, the percent difference between the Douglas bag values and the computer value had to lie within ± 3% of the Douglas bag generated value. Jones used adult subjects for his study. There are no similar data for children although their smaller size may place greater technical demands on a system. The Sensormedics S2900Z computerised exercise testing was tested using children as part of the present study.

The environment in which the exercise testing system is used should determine the type of validation that is employed. One of the aims of this study was to design a "biological" validation protocol using healthy children that could be implemented easily within paediatric exercise testing laboratories. "Biological" validation reduces the need for the employment of artificial systems to mimic the exercise response, but raises the problem of the natural variability associated with a biological calibration. However, this type of calibration is likely to be of far greater relevance to on-line exercise testing of children.

The aim of this study was to assess the validity of the cardio-respiratory variables generated by the S2900Z metabolic cart against those generated by a reference system (Douglas bag) in a group of children and in so doing develop and evaluate a biological validation protocol suitable for children.

Methods

Subjects

10 active healthy children volunteered to take part in the study. The subjects represented both sexes and a range of ages (Table 1.1). The study was approved by the Ethics committee of the Royal Hospital for Sick Children. Informed consent was obtained from the parents/guardians of the subjects. All testing took place in the Paediatric Respiratory Function Laboratory which has a controlled environment with a temperature of 22 degrees celsius and a relative humidity of 50%. Prior to the start of the testing, all the subjects were familiarised with walking and running on the treadmill and were introduced to all the equipment involved in the collection of cardio-respiratory data.

In order to assess the validity and reliability of the S2900Z across a range of ventilation rates that might be expected in children, two exercise protocols were generated: a Low Ventilation Rate (LVR) and a High Ventilation Rate (HVR). The length of each protocol (11minutes) was chosen on the expectation that both metabolic and cardiovascular steady state would be attained (Krahenbuhl *et al.* 1979). The two protocols were designed to ensure that the work intensities would represent approximately 60 and 80% respectively of the predicted heart rate maximum. The on-line S2900Z generated cardio-respiratory values were compared against values obtained by the Douglas bag technique for expired gas collection.

Exercise Protocols

(i) Low Ventilation Rate (LVR):

All children performed the LVR protocol on 2 separate occasions. This involved an 11 minute walk with gas collections taken from minutes 6 - 7 and 10 -11 using the Douglas bag collection technique and from minutes 8 - 9 using the metabolic cart. Heart rate data was monitored throughout. Eight of the children walked at a speed of 4.2 km/h at 0% gradient, the two youngest children at 3.7 km/h at 0%. Each child performed the test twice with a minimum of 48 hours separating each test.

(ii) High Ventilation Rate (HVR):

This involved an 11 minute run at a speed of 8 km/h and 0% gradient. Cardio-respiratory and heart rate data were measured at identical time intervals to that of the LVR protocol. 8 of the 10 children performed the HVR protocol on two occasions.

Experimental Procedure

During the period of exercise the subject was fitted with a nose clip and breathed through a mouthpiece connected to a low resistance paediatric valve. Interposed between the bag and one end of the plastic tubing was a three-way aluminium tap. This allowed the subject to expire either into the bag or to the atmosphere. Between 6 - 7 min and 10 - 11 min the subject's expired air was directed through a 25mm bore flexible plastic tube to the Douglas Bag.

After completion, a sample of expired air was introduced into the gas analysers of the reference system through a sample tube attached to the Douglas Bag. One minute was allowed for the reading on the analysers to stabilise. The displayed readings were recorded and were taken as representing the CO2 and

02 content of the expired air. The side valve was shut off and the volume of expired air was measured using the gas meter. The temperature of expired air was recorded using a thermistor attached to the gas meter. The volume of expired air (pulmonary ventilation) was then corrected for the amount of water vapour at STPD using a correction factor from a standard nomogram (Consolazio *et al.* 1963).

From minutes 8-9, while still breathing through the low resistance paediatric valve and mouthpiece, the expired air from the subject was directed through to the S2900Z via small bore paediatric tubing (25mm). Appropriate low dead space valves (16ml, Hans Rudolph 1410B) were used to minimise dead space ventilation during the gas collection phases. The cardiorespiratory variables measured were $\dot{V}O_2$, Ve(STPD), VCO2, FeO2 and FeCO2. Heart rate was monitored throughout by a Sport Tester PE3000 heart rate monitor (Kempe, Finland).

Test System

The S2900Z system uses a hot wire pneumotachograph to measure the mass of expired air. The relationship between mass of air and volume is non-linear. Therefore, subsequent linearisation of the output current generated from the mass-flow anemometer occurred to generate a volume of the expirate. Calibration of the volume output involved the delivery of a fixed volume using a calibration syringe (3 Litres), which was flow rate independent. This procedure was monitored by the microprocessor and adjustments for room temperature and pressure were made.

The S2900Z utilises an infra-red carbon dioxide analyser and a Zirconium Oxide oxygen analyser to measure expired 02 and CO2. The manufacturer's accuracy of the single beam non-dispersive infra-red analyser was stated to be ±

0.04%CO2 (within the range of 0 to 10%). The inherent accuracy of the O2 sensor was ±0.02%(within a O2 range of 0 to 25%). For calibration of the gas analysers the processor samples two calibration gases (26%O2, 0%CO2) and (16%O2, 4%CO2). The concentration of the calibration gases were verified by the manufacturers using the double Scholander technique The processor sets the zero and gain of the O2 and CO2 channels. These factors are used for the subsequent measurements.

Reference System

The reference system consisted of a turbine gas meter (Parkinson-Cowan Ltd, London, England) to measure the volume of air. The gas meter was calibrated from 50-150 litres/minute using a Tissot spirometer. During measurement of the expirate, a vacuum pump was used to ensure that a constant flow of air was drawn through the dry gas meter. Oxygen and Carbon Dioxide analysers (Paramagnetic O2 analyser, Servomex type 570 SYBRON, Servomex Ltd, Crowborough, Sussex, England; Infra-red CO2 analyser, P.K. Morgan Ltd, Chatham, Kent, England) were calibrated each day prior to the start of the test. They were first set at zero by introducing oxygen free nitrogen and then calibrated using standard gas mixtures (4.09%CO2, 16.03%O2 or 6.17%CO2 and 15.68%O2). All gas concentrations were analysed by the Scholander method to verify their composition. The span of the O2 analyser was set at 20.93% using fresh dried atmospheric air. Oxygen Free Nitrogen (OFN) was introduced again to reset the analysers at zero. The inherent accuracies of the two sensors were ±0.1% for the paramagnetic O2 analyser and ±1% over the range of reading for the infra-red CO2 analyser.

Statistical Methods

Initially, a general linear model was used to investigate whether or not there were significant biases between the S2900Z and Douglas Bag values as well as any order effects. This was achieved by means of a repeated measures analysis of variance. The biases were then quantified in terms of the percentage difference of the S2900Z value relative to the Douglas Bag value i.e. [100 *(S2900Z-Douglas Bag)/Douglas Bag). All data analysis was performed using Minitab version 8.

RESULTS

The S2900Z was tested against the reference system (Douglas Bag) using two exercise regimes: Low Ventilation Rate (LVR) and High Ventilation Rate (HVR). 10 children completed 2 visits at LVR and 8 completed 2 visits at (HVR). On each visit 3 readings were recorded at different time points for five cardio-respiratory variables ($\dot{V}O_2$,Ve(STPD), VCO2, FeO2 and FeCO2). At 6 and 10 minutes Douglas Bag (DB) readings were taken while at 8 minutes a S2900Z reading was recorded. There was a potential of 48 (6x8) readings per variable, but this number was not always achieved due to missing values. Three missing values existed for FeCO2 at LVR, two missing values for $\dot{V}O_2$, FeO2 and FeCO2 at HVR and three missing values for Ve and VCO2 at HVR.

(i) Low Ventilation Rates (LVR)

The study design raises the possibility of a possible confounding effect between testing the bias of the S2900Z and an order effect due to the timing of the reading. To investigate the possibility of such an order effect, an initial analysis was conducted comparing the first and second Douglas bag readings using a generalised linear model. Significant ($P<0.05$) subject effects were noted for Ve,VCO2, FeO2 and FeCO2 and a significant visit effect was noted for Ve. Having corrected for both subject and visit effects, fitted means for the Douglas Bag at low ventilation rates were generated (Table 1.2). There was no evidence to suggest an order effect for any variable at the low ventilation rates.

(ii) High Ventilation Rates (HVR)

A similar assessment of order effects was conducted for each variable at the HVR. Significant ($P<0.05$) subject effects were noted for all cardio-respiratory variables. Also significant ($P<0.05$) Douglas bag order effects were noted for

$\dot{V}O_2$ and Ve (i.e. the Douglas Bag values were significantly higher at 10 mins compared to 6 minutes) . Again, having corrected for subject and visit effects the fitted means at the HVR were calculated (Table 1.2). Evidence of an increase in $\dot{V}O_2$ and Ve between minutes 6 to 10 of the exercise at HVR were noted. Such an order effect in the Douglas Bag readings complicates the investigation of an S2900Z effect for $\dot{V}O_2$ and Ventilation. If a single discrete Douglas Bag reading were to be chosen to act as the reference, the increasing $\dot{V}O_2$ and Ve with time confounds this analysis. However, the rationale of the present analysis was based upon the presence of an S2900Z effect over and above the mean Douglas Bag reading.

Using a generalised linear model, tests of significance were made between the average Douglas Bag value and the S2900Z value. Having corrected for these biases fitted means were applied for the S2900Z values at both HVR and LVR (Table 2). Significant positive biases were noted for VCO2 (3.6%) and FeCO2 (6.2%) at HVR and at LVR a significant positive bias for FeCO2 (11.9%) and a negative bias for FeO2 (-1.9%). These estimates of bias are expressed relative to the average Douglas Bag reading. All estimates of bias are listed in Table1.3.

DISCUSSION

The rationale for the 11 minute protocols used in this study relied on the attainment of steady state from 6 -11 minutes during the period of exercise. The absence of an order effect between minutes 6 - 7 and 10 - 11 during the LVR protocol suggested that for the protocol used this assumption was true. However, at HVR an order effect did exist The intensity and the duration of the HVR protocol led to a slight cardiovascular drift with time. The effect was small and for $\dot{V}O_2$ from 6 to 10 minutes represented only a 4% overall increase. However, to compensate for this the analysis of the HVR data used the mean Douglas bag values and consequently the presence of this order effect had a negligible effect on the overall findings.

Based on the data generated from this study it appears that the Sensormedics System 2900Z is an adequate instrument for exercise testing of children. However, despite the general adequacy of the results a number of limited sources of variability were evident.

In the case of $\dot{V}O_2$ it would appear that any such errors were minimal and no systematic bias was noted between the two systems at either ventilation rate. The only source of variability with respect to oxygen analysis was the slight downscale drift in FeO2 (-1.8%) and this could be attributed to possible accumulated water vapour in the test system sample line not completely removed during transit through the drying tube. The bias subsequently generated is not of a sufficient magnitude to be of concern.

The only major source of bias between the two systems lay in the measurement of FeCO2 and this was reflected at both LVR (11.9%) and HVR (6.5%). In each instance the S2900Z systematically over-estimated the FeCO2 concentration. However, despite these biases minimal fluctuation in VCO2 was noted at the two workloads. The small systematic differences between the test and reference system for FeCO2 concentration measurements resulted in a systematic bias of measurement in VCO2 at HVR (3.7%). This positive bias in the measurement of VCO2 at HVR while significant, lay only marginally outside the ±3% confidence interval suggested by Jones (1984) .

The inability of the infra-red sensors to cope with the water vapour could have contributed to the greater variability in FeCO2. The manufacturers of the S2900Z claim that ventilation can be accurate to within ± 3% of the reading and the fraction of expired CO2 can be measured to within ± 0.05% across a concentration span of (0 to 10%). Yet these inherent specifications can themselves give rise to variability in VCO2 measurement.

Consider the following, single individual sample data for the S2900Z:

True VCO2 = (Ve x FeCO2) x10

True VCO2 = (14.8 x 4.09/100) x 10

TVCO2 = 605mls/min, but the potential range of data may lay from 579-631mls. This demonstrates the limitations that the S2900Z imposes in a study of this nature.

During mixed expired gas collection, gas collects in the baffled mixing chamber within the housing of the S2900Z and is sampled through one of three ports. Which sampling port is used, is based upon the ventilation rates. Sample port 1 is recruited for resting ventilation, port 2 is used for low ventilation rates and port 3 for high ventilation rates. With the progressive increase in ventilation the volume of the mixing chamber is increased. This enhances the mixing of gases, improves the optimal response time and should minimise O2 and CO2 fluctuations due to tidal volume. The pattern of response, demonstrating a higher CO2 concentration coupled with a lower O2 value is indicative of the analysis of an end-tidal volume sample. This pattern noted for FeO2 and FeCO2 specifically at LVR and possibly at HVR suggests that insufficient mixing of the expired gases may have occurred. Confirmation of this theory could be achieved by simultaneously collecting the Douglas Bag expirate at the exhaust port of the S2900Z (Rayfield Validation).

The reference system used in this study differed from other validation studies (Jones 1984). Douglas bag collections were taken at discrete intervals either side of the S2900Z analysis and air was not sampled simultaneously from the exhaust port of the S2900Z. Despite this difference in technique, the only major source of bias to arise from this study was in the measurement of FeCO2. It appears that the biological validation of exercise testing systems in children is both feasible and appropriate. Further, using this approach our data suggest that the Sensormedics S2900Z is suitable for use as an exercise testing system in children.

Tables

Gender	Age (yrs)	Height (cm)	Weight (kg)
F	8.1	136	31.6
F	9.3	136	30.2
M	10.6	152	42.3
F	16.4	156	46.4
M	11.6	154	41.4
M	12.3	141	36.5
M	9.2	136	29.0
F	11.1	141	31.3
M	13.4	184	68.0
M	13.6	164	52.3
MEAN	11.5	150	40.9
SD	2.33	14.7	11.62

Table 1.1: Demographic details of subjects studied

Protocol	LVR			HVR		
	DB 6min	DB 10 min	S2900 8min	DB 6min	DB 10 min	S2900 8min
VO2 (ml/kg/min)	15.89	15.90	15.75	36.35	37.78	36.22
Ve (l/min)	15.63	15.36	15.04	33.07	35.29	34.0
VCO2 (ml/min)	607	561	593	1414	1457	1488
FeO2 (%)	16.75	16.65	16.36	16.37	16.38	16.29
FeCO2 (%)	3.79	3.73	4.21	4.21	4.14	4.44

Table 1. 2: Fitted means for Douglas Bag and S2900Z at LVR and HVR

Variable	Protocol	Order Effect	Estimate of Bias	S2900Z bias
VO2 (ml/kg/min)	HVR	yes	2.3%	no
	LVR	no	-0.94%	no
Ve(STPD) (L/min)	HVR	yes	-0.53%	no
	LVR	no	-2.90%	no
VCO2 (ml/min)	HVR	no	3.69% *	yes
	LVR	no	1.36%	no
FeO2 (%)	HVR	no	-0.49%	no
	LVR	no	-1.79% *	yes
FeCO2 (%)	HVR	no	6.5% *	yes
	LVR	no	11.9% *	yes

* Denotes a bias significantly different from zero at the 5% significance level.

Table 1. 3: Analysis of results of cardiorespiratory variables for high and low ventilation rate protocols

REPRODUCIBILITY OF CARDIO-RESPIRATORY MEASUREMENTS

Introduction

The variability of cardio-respiratory measurements at submaximal and maximal exercise intensities is of considerable importance to the paediatric sports scientist and to the paediatrician. Intervention, rehabilitation and training strategies are based on data from physiological testing and a knowledge of the level of natural variability both between and within individuals is critical to an understanding of the efficacy of a treatment or training effect.

The variability of submaximal exercise performance in adults has been investigated in a number of studies (Armstrong and Costill 1985, Daniels *et al.* 1984, Morgan *et al.* 1987, Morgan *et al.* 1991 and Williams *et al.* 1991). These studies have found significant differences in the submaximal energy cost of running both between and within moderately and well trained runners on repeated submaximal exercise testing. A number of variables have been identified that could influence submaximal treadmill running performance including circadian variation, footwear, training status and treadmill accommodation (Morgan *et al.*1991).

Training status also has the capacity to influence the degree of variability associated with repeated submaximal testing. Williams *et al.* (1991) and Morgan *et al.* (1991) addressed this question in an assessment of submaximal running economy in runners. Their two studies indicated that the more highly trained subject the lower the variability between testing sessions. This led Morgan *et al.* (1991) to conclude that a stable measure of running economy could be obtained in a single data collection session involving trained, non-elite male runners if the testing environment was controlled to minimise non-biological variability.

The limited number of reproducibility studies in children has focused mainly on the reliability and reproducibility of maximal oxygen consumption tests. For example, Cunningham *et al.* 1976 demonstrated a reliability coefficient of 0.76 for two maximal oxygen consumption tests within a four week period where the reliability coefficient represents the proportion of the total variability explained by between subject variability This value is below the 0.90 value found in most adult studies (Morgan *et al.* 1991, Williams *et al.* 1991). However, the coefficient of variation in the paediatric studies was only 3%. Thus, while the coefficient of variation was low, the measurements were calculated to be reproducible average mean difference, 3%). This emphasises the general weakness of the use of the coefficient of variation, as it is incapable of accounting for the repeatability of a measurement.

No studies to date have assessed the stability of submaximal running performance in children. The primary aim of this study was to evaluate the variability of cardio-respiratory measurements at three submaximal exercise intensities in pre-pubertal children. For comparison, we also measured the variability associated with maximal treadmill exercise performance. A secondary aim of the study was to predict the optimal number of visits that would be necessary to obtain stable submaximal and peak oxygen consumption values.

Methods

Subjects

Ten boys were studied (age 10.7 ± 0.71yrs, mean ± SD, Table 2.6). All were pre-pubertal, Tanner stage 1, based on parental reporting . Of the 10 boys, 5 were rated as active and 5 very active on data obtained from a physical activity questionnaire completed.

Accommodation Visit

All subjects underwent an habituation / accommodation visit prior to the start of the testing, (Shephard 1984). At this visit all subjects were introduced to the treadmill with a short period of walking and running. In addition the children were familiarised with all the equipment to be used in the cardio-respiratory testing.

Measurement of cardio-respiratory parameters

Expired gas measurements were made using a computerised metabolic cart (Sensormedics S2900Z, Bilthoven, Netherlands). Measurement of cardio-respiratory variables were made every 20 seconds throughout the test collection period. The Sensormedics S2900Z uses a mass-flow anemometer for volume measurement. Pre-test calibration of the anemometer was achieved by the use of a three litre calibration syringe (Sensormedics, Bilthoven, Netherlands) . The oxygen and carbon dioxide analysers were calibrated by the introduction of two calibration gases. (26%O2, 0%CO2, balance Nitrogen) and (16%O2, 4%CO2, balance Nitrogen) both immediately prior to, and just after the completion of each exercise test. Previous work from this laboratory has demonstrated the validity of the Sensormedics S2900Z metabolic cart in paediatric exercise testing. (Unnithan *et al.* 1992).

To facilitate the expired gas analysis and minimise dead space ventilation, all subjects were tested using paediatric mouthpieces and valves (Hans-Rudolph 1410B, dead space 16mls, Hans-Rudolph Incorporated, Kansas City, USA). The valve and mouthpiece was supported by a head support (Hans-Rudolph , Model Number 1426). Small bore tubing assisted in minimising dead space ventilation between the outflow of the valve and the entry port of the S2900Z metabolic cart.

Heart rate data was obtained by means of the PE3000 Sport Tester heart rate monitor(Polar Sports Ltd, Kempe, Finland.). The treadmill (Power Jog M10, Cardinal Sports, Edinburgh) speed was calibrated for each submaximal steady state stage. The testing was carried out in an air conditioned laboratory with an environmental temperature between 21 and 26 degrees Celsius and a relative humidity of between 43 and 54%. In an attempt to control for possible circadian variations in submaximal running economy (Morgan *et al.* 1991), the time of testing remained constant for 8 of the ten subjects (i.e. submaximal and peak VO2 tests were conducted at the same time of day). All subjects were advised to wear the same footwear each visit and all testing was completed within a 2-4 week period.

Test Protocols

Submaximal economy runs:

Two submaximal economy tests were administered within a 2-4 week period. The tests consisted of 3 x 6 minute runs at 7.2, 8.0 and 8.8 km/h. Each 6 minute run was preceded by a 2 minute walk at 4.2 km/h in order to introduce gradually the subject to exercise at the onset and between submaximal exercise stages. It also provided an indication of any drift in baseline oxygen consumption as a result of external factors (temperature, fatigue and learning). In order to ensure that no residual effect existed between one submaximal economy stage and the next, the protocol was discontinuous in nature with passive recoveries of 8 minutes between each. On-line oxygen consumption measurements were taken throughout the 8 minute submaximal stages using the Sensormedics S2900Z metabolic cart (Bilthoven, Netherlands) and confirmed the return to baseline oxygen consumption. Based upon work generated in this laboratory (Unnithan *et al.* 1992, unpublished observations) cardio-respiratory steady state was found to be achieved between three and six minutes within submaximal exercise testing. Therefore, data from the final 20s in each 6 minute submaximal stage was used for the subsequent analysis.

Peak $\dot{V}O_2$ Test

Two peak $\dot{V}O_2$ tests were also administered within the 2 - 4 week period. The test protocol was a modified incremental test devised for paediatric testing (Unnithan and Eston 1990). After a 2 minute warm-up walk at 4.2 km/h and 0% gradient, the speed was then increased to 8.8 km/h at 0% gradient and recording on the Sport Tester receivers and S2900Z was initiated. Throughout the test the speed remained constant at 8.8 km/h, but the gradient was increased 2.5% every 2 minutes until volitional fatigue was achieved. The subjects were given extensive verbal encouragement to achieve their maximal exercising capacity. Attainment of peak $\dot{V}O_2$ was used as the maximal index (Williams and Armstrong 1991) and was judged to have been achieved when two of the four following criteria were attained: (i) Heart rate within 10bpm of 200bpm or a (ii) heart rate plateau (plateau was defined as less than a 5 beat increase from the penultimate to the final stage). (iii) Respiratory exchange ratio value of greater than 1.0. (iv) Approximate plateau for $\dot{V}O_2$ values (defined as the difference between the final $\dot{V}O_2$ value and the penultimate stage $\dot{V}O_2$ being less than or equal to the mean difference of the preceding stages). Practically, termination of the test occurred when, despite strong verbal encouragement from the researchers the subject was unwilling or unable to continue.

Statistical Methods

Standard descriptive statistics (mean and standard deviations) were used to summarise the data. A two way repeated measures analysis of variance statistics was used to test for visit and speed effects. After adjusting for significant visit, subject and speed effects the coefficient of reliability was calculated as follows:

Coefficient of Reliability (C.R.) = σ^2_B / $\sigma^2_B + \sigma^2_W$

Where σ^2_B = between patient variance and σ^2_W = within patient variance.

To provide the best estimate of the coefficient of reliability, the data were pooled across all three speeds for each boy. An hypothesis test was used to check that the same physiological trends existed across speeds for each boy, ensuring that this statistical manipulation was valid. All statistical calculations were performed using Minitab version 7.1 and a significance level of 0.05 was used.

Results

Submaximal Running Economy

The mean change in body mass of the 10 subjects over the 4 testing periods was 0.57 kg (Table 2.6). Accordingly, any variation in the submaximal energy cost of running was unlikely to be attributable to fluctuation in weight.

Four variables were measured across the three submaximal speeds: Oxygen consumption, ($\dot{V}O_2$, ml/kg/min), ventilation (Ve, l/min), heart rate (HR, bpm), and respiratory exchange ratio (RER). For all 4 variables there was a significant increase with increasing speed (Table 2.1). There was no evidence of a significant visit effect. Two variables, ventilatory equivalent for Oxygen (VeVO2) and fractional utilisation (FU), were measured only across the three submaximal running speeds . For both there was a significant drop in levels between visits 1 and 2 (VeVO2: 27.33 vs 26.56 and FU: 67.39 vs 64.01) indicating a possible learning effect. FU exhibited the expected increase with speed confirming the boys used a higher proportion of their peak $\dot{V}O_2$ at each submaximal work load.

Coefficient of reliability (CR) describes the relationship between two aspects of variance: between subject and within subject variance. In any assessment of variability the major expectation is that variability between subjects dominates over the variability within subjects for any given dependent variable . The coefficient of reliability describes the ratio of the between subject variance to the total variance. The CR percentages derived, express how much of the total variation is accounted for by between person variability.

It appeared based upon the data generated that between and within subject variances differed at maximal compared to submaximal work loads for different indices. Consequently, CR values were calculated separately. For submaximal speeds $\dot{V}O_2$, HR, VeVO2, and FU, were the most reliable with between subject variation accounting for over 2/3 of the total variance. Ventilation and RER appeared only moderately reliable accounting for less than half the total variance (Table 2.2, Figure 2.1).

Both an individual and an overall analysis were conducted for the submaximal running speeds. The overall analysis was undertaken to account for the particular variability of certain individual subjects. Since each speed involves fewer observations it was more likely to be affected by excessive random variability in a few subjects and hence distort the estimation of the coefficient of reliabilities for the group. At increasing submaximal running speeds, heart rate and RER coefficient of reliability progressively increased. In contrast, ventilation demonstrated a systematic decrease in the reliability coefficient with increasing running speed. Submaximal oxygen consumption demonstrated no significant trend with increased treadmill running speed. However, the highest coefficient of reliability (0.80) was noted at the first running speed (7.2 km/h, Table 2.3). At the three submaximal running speeds the coefficients of reliability for FU were 87.0%, 86.5% and 89.3% respectively.

Within subject differences were investigated for ventilation, heart rate and oxygen consumption at all three running speeds. At 7.2 km/h, the group mean difference in $\dot{V}O_2$, expressed as a percentage of each individual's mean $\dot{V}O_2$ calculated from the two visits, was 4.08%. However, this moderate fluctuation obscured a wide range of intra-individual variation (range = 0.67-7.99%). At 8.0 km/h the value was 5.61% (range 1.09 - 11.28%) and at 8.8 km/h , 5.75 (0.16 - 17.26%). Similar values were generated for Ve and HR (Table 2.4).

Based upon the results in this study, the accuracy for the mean $\dot{V}O_2$ level of an individual derived from a 2 test assessment would give a standard error of the mean of ±1.25 ml/kg/min. The standard error of the mean based upon a predicted 4 visits would be ±0.9ml/kg/min. This predicted value is derived from the formula:

k^2 = 12.07/n where n is the number of visits and k^2 represents the standard error of measurement.

Peak $\dot{V}O_2$ Analysis

At maximal exercise $\dot{V}O_2$, ventilation and time to exhaustion appeared to be the most reliable responses with between person variability accounting for approximately 2/3 of total variance (Table 2.5). The mean $\Delta\ \dot{V}O_2$ expressed as a percentage of the mean $\dot{V}O_2$ from visits 1 to 2 was 5.3%. However, this low intra-individual variation masked a high degree of between subject variation (range 0.17 - 17.78%) . Results from the analysis of peak ventilation demonstrated a similar range (ΔVe, mean= 10.27, range 1.94 to 19.48%). The same trend was noted with HR (mean = 3.15%, range from 0 to 14.14).

Of the 10 boys tested in this study 3 demonstrated plateaux at both peak $\dot{V}O_2$ tests. However, $\Delta\dot{V}O_2$ expressed as a percentage of the mean $\dot{V}O_2$ was low in one individual (0.58%) and high in the other two (11.63 and 12.2%). Of the remaining 7 boys, 6 demonstrated a plateau with respect to peak $\dot{V}O_2$ at one of the two visits. Their $\Delta\dot{V}O_2$ values expressed as a percentage of the mean $\dot{V}O_2$ was 4.97% (range 0.17 to 17.78). One subject failed to attain a plateau at either of the two visits, attaining a value of 0.79. Therefore, there appeared to be no significant pattern linking the presence or absence of a $\dot{V}O_2$ plateau with the test-retest reliability within an individual.

Within this testing environment a two visit assessment of an individual was capable of estimating the mean peak $\dot{V}O_2$ with a standard error of the mean of $\pm$ 2.28 ml/kg/min. To achieve an estimate of mean peak $\dot{V}O_2$ with a standard error of $\pm$ 0.5 ml/kg/min would require a predicted 40 peak $\dot{V}O_2$ assessments. The predicted number of visits was calculated in the same manner as for the submaximal assessment ($k^2 = 12.07/n$).

Discussion

Results from the submaximal running performance analysis demonstrated that $\dot{V}O_2$, HR, VeVO2 and FU were the most reliable submaximal parameters, accounting for over 67% of the total variance. Ventilation and RER were only moderately reliable accounting for less than half of the total variation. At maximal exercise $\dot{V}O_2$, ventilation and time to exhaustion appeared to be the most reliable measurements, each accounting for over 67% of the total variance. Between subject variability dominated in the assessment of these variables, accounting for approximately 67% of the total variance. In many adult studies coefficient of reliabilities of the order of 90% have been generated. It would be hoped that the variability between individuals would dominate over that seen within individuals. Hence, in the case of adults the ratio of between to within person variability is in the order of 9:1. In the present study the ratio of between to within person variability is approximately 2:1. A possible reason for this difference could be due to the homogeneity of the group being tested.

The homogeneous nature of the group with respect to submaximal and maximal running physiological criteria (i.e.Peak $\dot{V}O_2$) had a significant bearing upon the CRs generated. The smaller inter-individual distribution of physiological data resulted in a lower between subject variance. Consequently, the subsequent estimations of coefficients of reliabilities are likely to be underestimated (assuming within person variability stays the same) because of the homogeneous nature of the subject population being tested. In a wider fitness, spectrum the between person variability would have been larger and again assuming that within person variability remained constant this would have given rise to estimations of coefficients of reliability which would be too high. Accordingly, our conclusions on reliability of repeated submaximal and maximal exercise testing can only be applied to fairly homogeneous childhood populations . This highlights the need for each laboratory to determine the number of test sessions specific to the nature of their particular population.

Submaximal and maximal running performance is the product of both physiological and psychological interaction (Crews 1992) . The contribution of motivation towards physiological variation was not measured in this study. However, in attempt to control this variable all the boys were motivated in a similar manner throughout all the testing sessions.

A significant visit effect was noted for VeVO2 (Table 2.2). The pattern of breathing was more efficient at the second visit, possibly reflecting greater familiarity with the test apparatus. This suggests that despite careful and extensive efforts a degree of accommodation was occurring during the test procedures.

In the present study there was no pattern in the CRs for $\dot{V}O_2$ with increased treadmill running speed. These findings are consistent with the data generated by Morgan *et al.* (1987). Armstrong and Costill (1985) also demonstrated that certain submaximal treadmill speeds (Table 2.3) represented "inefficient" work loads for their specific population. It is possible that all the submaximal treadmill speeds selected for the boys in the present study represented relatively inefficient running speeds and that this bio-mechanical inefficiency contributed toward the lack of pattern in $\dot{V}O_2$ reliability.

The influence of training status on $\dot{V}O_2$ variability was considered by Katch *et al.* (1982) and Williams *et al.* (1991). These authors hypothesised that biological variation would be larger in untrained subjects due to the greater variation in both the transport and extraction of oxygen at the cellular level. The group of boys used in this study would be classed as active, but not highly run trained. Therefore, the greater variability compared to adult studies could arise as a product of their differing metabolic profiles during exercise or as a consequence of their lack of training. In keeping with the latter, Williams *et al.* (1991) calculated higher estimates of variability than those obtained by Morgan *et al.* (1991), who had used well trained runners.

The magnitude of coefficient of reliabilities generated in this present study at maximal exercise are of the same order as those obtained by Cunningham *et al.* 1976 and Cunningham *et al.* 1977. In the present study there was no evidence to link the presence (9 boys) or absence(1 boy) of a plateaux in $\dot{V}O_2$ with the reliability of peak $\dot{V}O_2$. This contradicts the data derived by Cunningham *et al.* 1977 who traced a greater reliability in peak $\dot{V}O_2$ to those subjects who reached a plateaux and attributed this greater reliability to those boys being more capable of generating energy from anaerobic sources. These authors hypothesised that the enhanced anaerobic capacity would allow a sustained work output at peak exercise.

Results from the present analysis of submaximal and maximal $\dot{V}O_2$ reliability also indicated that the degree of reliability was not related to the exercise intensity (See Tables 2.2 and 2.5). There is conflicting evidence with respect to the impact of exercise intensity upon the coefficient of reliability. Armstrong and Costill (1985) demonstrated that within subject day to day variation was lower at submaximal rather than maximal levels while Taylor 1944 reported the opposite. The possible psychological implications of attaining peak exercise intensities could have contributed to the differences between the two populations.

Ventilatory data generated from this present study is in agreement with that generated by Armstrong and Costill (1985) and Davies *et al.* (1970). Higher coefficient of reliabilities were obtained at maximal compared to submaximal exercise. Davies *et al.* 1970 hypothesised that an increased muscle mass recruitment at maximal exercise resulting in altered proprioceptive reflexes from joints and muscles generally led to more stable ventilation patterns at maximal exercise. However, in absolute terms the magnitude of the coefficient of reliabilities was low in agreement with Taylor (1944). He demonstrated low reliabilities for Ve at both submaximal and maximal workloads. RER demonstrated low coefficients of reliability at both maximal (38%) and submaximal exercise (45%) intensities due of the multiple substrate and ventilatory factors that influence this parameter. Consequently, it should not be regarded as a reliable index. The high CR(75%) of the derived variable VeVO2 at submaximal exercise intensities indicated that the ventilatory pattern remained stable. This lends support to the theory that the major source of $\dot{V}O_2$ variability lies at the level of oxygen extraction.

The lack of change in submaximal heart rate from visits1 to 2 (CR, 94%) imply that no apparent training effects have occurred in the circulatory system at submaximal exercise. Davies *et al.* (1970) demonstrated a decreased submaximal heart rate for constant $\dot{V}O_2$ with repeated testing mediated perhaps through adjustments in stroke volume and/or O2 extraction at the cellular level. This would not appear to be the case with the submaximal heart rate profiles obtained in the present study. The short duration of the project (2-4) weeks effectively controlled for any training effects that may have been present. However, the small number of maximal heart rate recordings obtained made any conclusions tentative.

The high coefficients of reliability obtained for fractional utilisation overall - (82%) and at the three submaximal speeds (87.0%, 86.5% and 89.3%) have significant implications. Exercise intensities are prescribed for both clinical and sporting assessments based upon treadmill testing. Therefore, the data from the present study indicate that prescribing an exercising range relative to a percentage of peak $\dot{V}O_2$ is a reasonably robust approach within a laboratory setting. The visit effect, while statistically significant, has minimal implications in the prescription of exercise intensities for laboratory based training and rehabilitation.

The aim of this study was to quantify the degree of reproducibility that exists with submaximal and maximal exercise testing and to predict the optimal and most practical number of visits that would be necessary to achieve stable physiological data. At the submaximal level, to achieve an estimate of submaximal $\dot{V}O_2$ with a standard error of $\pm$ 0.9 ml/kg/min 4 submaximal tests would be required for a given individual. This would be an impractical and unrealistic test schedule for most children. If the same rationale is applied to peak $\dot{V}O_2$ testing, to achieve an estimate of mean peak $\dot{V}O_2$ with a standard error of $\pm$ 0.5 ml/kg/min 40 peak $\dot{V}O_2$ tests would be required.

In conclusion , based upon the results single economy testing sessions are valid for estimating group stability of running economy in non-elite active boys. If individual profiles are required then multiple submaximal and maximal testing will be necessary.

Daniels (1984) stated " Even when controlling for the multiple external factors that influence running economy (circadian variation, footwear, training and length of treadmill accommodation), significant differences still exist in the aerobic demands of running between and within well trained runners." The need for a multi-disciplinary approach incorporating metabolic, structural and mechanical factors to explain fully within subject variation in paediatric running economy is clear.

Tables

	Speed km/h		
Variable	7.2	8.0	8.8
VO2 (ml/kg/min)	35.2	38.5	40.7
SD	2.59	2.65	3.53
Ve (l/min)	32.2	34.5	36.5
SD	3.8	2.84	3.73
HR (beats/min)	165	176	185
SD	20.9	18.9	16.2
RER	0.93	0.92	0.94
SD	0.046	0.033	0.047

Table 2.1: Mean values for cardio-respiratory variables at submaximal running speeds.

Variable	σ^2_B	σ^2_W	Coefficient of reliability
VO2 (ml /kg/min)	6.63	3.07	68%
Ve (l/min)	5.1	5.2	50%
RER	0.00075	0.00093	45%
HR (bpm)	397.8	27.6	94%
VeVO2	5.19	1.76	75%
FU (%)	68.4	15.5	82%

σ^2B between subject variance

σ^2W within subject variance

Table 2.2: Between and within subject variance and coefficient of reliability values for submaximal data.

	Speed (km/h)		
Variable	7.2	8.0	8.8
VO2 (ml/kg/min)	80%	61%	68%
Ve (l/min)	70%	68%	43%
HR (bpm)	69%	79%	93%
RER	28%	40%	78%

Table 2.3: Individual analysis of coefficient of reliabilities at submaximal intensities.

	7.2 km/h		8.0 km/h		8.8km/h	
Variable	Mean Difference	Range	Mean Difference	Range	Mean Difference	Range
VO2 (%)	4.08	0.67-0.99	5.61	1.09- 11.28	5.75	0.16-17.26
Ve (%)	9.07	1.45-20.29	6.17	1.04-20.09	3.74	0.95-5.49
HR (%)	8.42	0-25.53	5.73	0-17.50	3.74	0.95-5.49

Table 2.4: Mean differences expressed as a percentage of mean value generated over two visits and range for VO2, Ve and HR.

Variable	σ^2_B	σ^2_W	Coefficient of reliability
VO2 (ml/kg/min)	19.20	10.39	65%
Ve (l/min)	54.84	32.80	63%
RER	0.00093	0.00154	38%
HR (bpm)	15.9	50.2	24%
Time to exhaustion (mins)	1.298	0.747	63%

σ^2B between subject variance

σ^2W within subject variance

Table 2.5: Between and within subject variance and coefficient of reliability values for peak data.

Subjects	Age (yrs)	Height (cm)	Weight (kg)				Sum of Skinfolds (mm)
			Visit 1	Visit 2	Visit 3	Visit 4	
1	10.7	141	41.8	42.1	41.5	43	37.5
2	9.5	133	28.6	29.0	29.0	28.7	20.8
3	11.3	151	37.2	37.4	37.3	37.8	22.1
4	11.8	143	31.4	31.6	31.4	31.7	17.0
5	11.1	151	37.3	37.5	37.3	37.4	15.7
6	10.5	145	35.3	35.9	35.5	35.3	21.7
7	10.5	148	35.1	35.2	35.2	35.8	19.4
8	9.9	136	29.0	28.7	29.5	29.5	16.6
9	11.7	142	30.1	30.6	30.5	30.6	17.6
10	10.3	138	31.5	31.6	31.6	31.5	16.6
Mean	10.7	142	33.7	34.0	33.9	34.1	20.5
SD	0.71	5.79	4.08	4.13	3.89	4.28	6.08

Table 2.6: Demographic details of boys studied

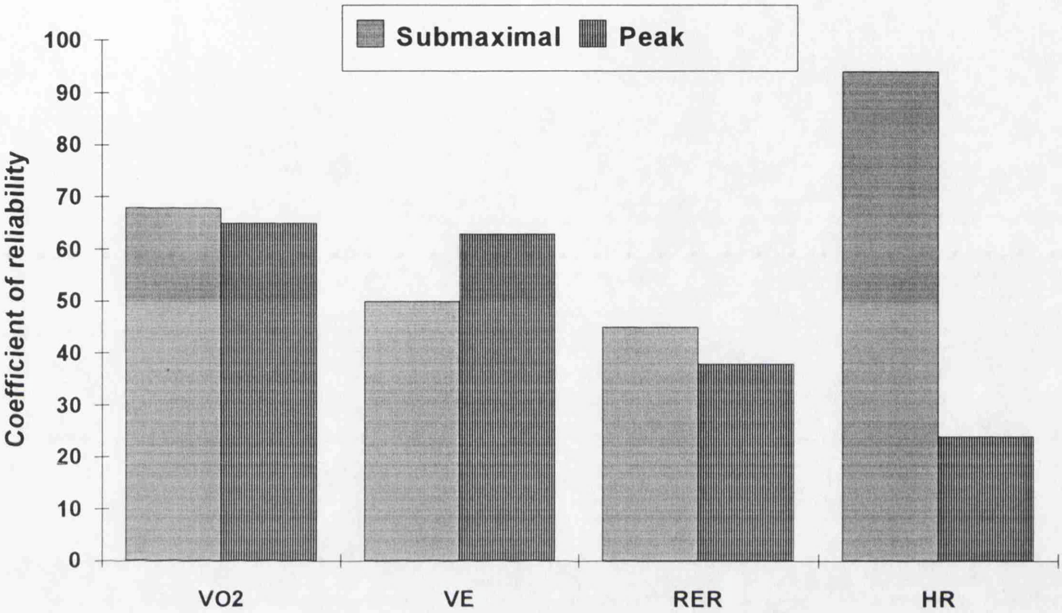

Figure 2.1: Coefficient of reliability at submaximal and peak exercise intensities

ATTAINMENT OF STEADY STATE DURING EXERCISE IN CHILDREN

Introduction

The duration of submaximal steady state protocols in paediatric exercise testing has been varied. Krahenbuhl *et al.* (1979) utilised a 6 minute protocol to obtain submaximal oxygen consumption data in children. whereas, Rowland *et al.* (1987), (1988) and Unnithan and Eston (1990) all utilised three minute protocols to estimate submaximal steady state oxygen consumption. Steady state was defined by Krahenbuhl *et al.* (1979) as stable readings in oxygen consumption and respiratory exchange ratio measured over the last two minutes of each run.

Three distinct phases have been identified in the oxygen consumption response to exercise. Phase I is the cardiodynamic phase and represents the rapid increase in oxygen consumption observed in the first 20 seconds of exercise. This increase has been associated with the sudden increase in cardiac output and specifically stroke volume at the onset of exercise (Whipp and Ward 1982). The phase II response represents the increase in cardiac output and a widening of the arterial-venous difference. Phase III represents the steady state response to a constant work load with response characteristics that appear linear and first order. Any drift in steady state oxygen consumption beyond three minutes is only noted at work loads above the anaerobic threshold of the individual.

(i) The primary aim of this study was to investigate the difference in submaximal oxygen consumption at 3 minutes and 6 minutes within a 6 minute protocol. Oxygen consumption kinetics were not considered and Phase III steady state values were the only values being assessed. The significance of attaining the optimal conditions for submaximal steady stage measurements in the shortest possible time is of considerable importance in most paediatric testing. Since in a progressive continuous submaximal protocol the shorter the submaximal stages the less stress is placed upon the child.

(ii) A secondary aim of the study was to determine whether the order of the speeds had any significant effect upon submaximal oxygen consumption.

Methods

Subjects

Ten boys were studied (age 12.5 ± 0.35yrs, mean ± SD, Table 3.1). Of the 10 boys , 8 were rated as active and 2 moderately active on data obtained from a physical activity questionnaire completed. All subjects underwent an habituation/accommodation visit prior to the start of the testing, Shephard (1984). At this visit all subjects were introduced to the treadmill (Powerjog M10, Cardinal Sports, Edinburgh) with a short period of walking and running. In addition the children were familiarised with all equipment to be used in the cardio-respiratory testing.

Measurement of Cardio-respiratory variables

Expired gas measurements were made using a computerised metabolic cart (Sensormedics S2900Z, Bilthoven, Netherlands). Measurement of cardio-respiratory variables were made using the pseudo -breath-by-breath option throughout the test collection period. The Sensormedics S2900Z uses a mass-flow anemometer for volume measurement. Pre-test calibration of the anemometer was achieved by the use of a 3 litre calibration syringe. The oxygen and carbon dioxide analysers were calibrated in breath-by-breath mode by the introduction of two calibration gases (26%O2 and 0%CO2) and (16%O2 and 4%CO2) both immediately prior to, and just after the completion of each exercise test. Previous work from this laboratory has addressed the validity of the Sensormedics S2900Z metabolic cart in paediatric exercise testing (Unnithan *et al.* 1992). To facilitate the breath by breath gas analysis and minimise dead space ventilation, all subjects were tested using paediatric mouthpieces and valves (Hans Rudolph 1410B). The valves were modified to accommodate the breath by breath line.

The treadmill speed was calibrated for each submaximal steady state stage. The testing was carried out in an air conditioned laboratory with an environmental temperature between 21 and 26 Celsius and a relative humidity of between 43 and 54%. All subjects were advised to wear the same footwear at each visit and all testing was completed in a four day period.

Study design

Test Protocols:- submaximal economy runs

One submaximal economy test was administered within the four day period. The test consisted of 2 x 6 minute runs at 7.2 and 8.0 km/h. The order of the speeds was randomised for each boy. Each 6 minute run was preceded by a 2 minute walk at 4.2 km/h in order to introduce the subject to exercise at the onset and between the two submaximal stages. This also served to provide an indication of any drift in baseline oxygen consumption as a result of external factors (temperature, fatigue and learning). In order to ensure that no residual effect existed between one submaximal economy stage and the next, the protocol was discontinuous in nature with a 10 minute passive recovery between each stage. On-line breath by breath oxygen consumption measurements were taken throughout the 6 minute submaximal stages using the S2900Z.

Peak $\dot{V}O_2$ test

One peak $\dot{V}O_2$ test was administered within the four day period. Using a modified version of the protocol designed by Unnithan and Eston (1990). The running speed was customised to fit the individual requirement of each child. Once baseline speed was established the gradient was increased 2.5% every 2 minutes until voluntary exhaustion was attained. submaximal testing. The child was judged to have reached peak $\dot{V}O_2$ when any two of the following four criteria were met (Williams and Armstrong, 1991): heart rate within 10 beats of 200 beats per minute or a heart rate plateau, respiratory exchange ratio value of greater than 1.0 and an approximate plateau of $\dot{V}O_2$ values.

Physiological Analysis

The S2900Z generated discrete data points for every breath during the gas collection phases. These discrete values were averaged to produce a mean value for minutes 2-3 and minutes 5-6. $\Delta\dot{V}O_2$ was calculated by subtracting $\dot{V}O_2$ at (5-6) from $\dot{V}O_2$(2-3). The calculation of the delta value provided an indirect estimation of the attainment of a plateau from minute 3.

Statistical Methods

Standard descriptive statistics (mean,SD) were used to summarise the data. Paired t-test statistics were used to assess the effect of time upon submaximal oxygen consumption. A paired t-test was also used to investigate the effect of speed order upon submaximal oxygen consumption. All statistical calculations were performed using Minitab version 7.1 and a significance level of 0.05 was used.

Results

The demographic, physical activity data and peak $\dot{V}O_2$ value (58.9± 5.14) demonstrated that all the boys in this study were of a good level of aerobic fitness (Table 3.1).

Paired t-test analysis demonstrated no significant difference in submaximal oxygen consumption at either 7.2 or 8.0 km/h (30.13±2.51 at 3 mins versus 30.45±3.49 at 6 mins @ 8 km/h,) and (28.04±2.07 at 3 mins versus 27.84±3.15 at 6 mins @ 7.2 km/h, mean±SD) (Table 3.2).

Within the context of the two submaximal speeds chosen , relative intensity appeared to have no effect upon submaximal oxygen consumption. For these boys, a speed of 7.2 km/h represented an approximate mean fractional utilisation of 48% while 8 km/h represented 51%. Further comparison of the absolute mean differences at 8 km/h and 7.2 km/h demonstrated no significant difference between absolute differences at the two speeds (-0.20±1.47 @ 7.2 km/h vs 0.31±1.65 @ 8.0 km/h) (Table 3.2). No systematic difference existed in the sign of the absolute differences at either submaximal running speed.

To assess the impact of order upon submaximal oxygen consumption a paired t-test was conducted using the absolute differences at 3 and 6 minutes. No significant difference was noted for speed order. These, results indicate that the order of speed had no impact upon submaximal oxygen consumption.

Discussion

The two speeds selected for this analysis represent two submaximal speeds within a range of speeds commonly used for submaximal exercise testing in children . For example, these two speeds had been previously used by Unnithan and Eston (1990) to assess submaximal running economy. The results from this study indicate that a range of optimal submaximal steady state stages could be employed. It would appear that no systematic or significant drift in submaximal oxygen consumption occurred from minutes three to minute 6. Therefore, the use of submaximal steady state stages ranging from three to six minutes appears to be valid.

Thee data from this study demonstrated that no apparent difference in submaximal oxygen consumption existed at 3 and 6 minutes at either running speed investigated. Even expression of the data as $\Delta\dot{V}O_2$(3-6)mins showed no significant difference across time and between the two seeds.

These data show that submaximal oxygen consumption is stable by three minutes of exercise in prepubertal boys and measurements can be made.

A limitation of this study is the fact that two speeds studied were quite close together. It is not therefore possible to comment on the effects of relative intensity upon the time to achieve steady state.

A number of submaximal protocols are commonly used within this laboratory. In order to assess the need to randomise the order of the speeds an assessment of the effect of speed was conducted. Results from the paired t-test demonstrated no significant order effect for the two submaximal work loads chosen. Therefore, it was concluded that an ascending order of speeds could be chosen for the submaximal protocols. The majority of the cardio-respiratory assessments performed in this laboratory employ mixed expired gas analysis. This type of analysis has the facility to smooth individual variability in submaximal oxygen consumption. The present study used breath by breath (averaged) in attempt to perform the most rigorous assessment of $\Delta\dot{V}O_2$ (3-6) minutes. This type of data collection exposes $\dot{V}O_2$ variability to its widest range, as discrete breath by breath measures vary far more significantly than the discrete 20 second measures generated by mixing chamber analysis. Within the context of the conditions that applied to this study (i.e. breath-by-breath analysis and a discontinuous protocol), the results obtained suggest that submaximal protocols ranging from three to six minutes are suitable for making measurements of steady state submaximal oxygen consumption.

Tables

Subject	Age (yrs)	Ht (cm)	Wt (kg)	Sum of Skinfolds (mm)	Peak VO2 (ml/kg/min)
1	12.8	161.0	51.8	32.6	49.4
2	12.9	181.0	64.1	20.0	64.9
3	12.0	139.0	35.2	-	57.7
4	12.1	150.0	44.5	39.1	54.9
5	12.7	161.0	50.0	24.4	58.1
6	12.9	158.0	47.5	-	62.6
7	12.2	147.6	38.2	-	65.1
8	12.4	149.4	39.7	26.3	59.6
9	12.9	155.8	38.9	18.2	62.7
10	12.2	146.0	38.2	24.9	53.8
Mean	12.5	154.9	44.8	26.5	58.9
SD	0.35	10.97	8.34	6.69	5.14

Table 3.1: Demographic and Peak $\dot{V}O_2$ data

	7.2km/h			8.0 km/h		
	3 minutes	6 minutes		3 minutes	6 minutes	
VO2 (ml/kg/min)	28.0	27.8	NS	30.1	30.4	NS
(SD)	2.07	3.15		2.51	3.15	
ΔVO2 (ml/kg/min)	-0.20			0.31		NS
(SD)	1.47			1.65		

Table 3.2: Summary of means and standard deviations of paired t-test analysis

FACTORS INFLUENCING RUNNING ECONOMY IN CHILDREN

KINEMATIC FACTORS

Introduction

It has long been thought that the combination and magnitude of stride frequency and stride length are important determinants of running economy. A number of authors (Cavanagh and Williams (1982), Hogberg (1952), Kaneko *et al.* (1987), Powers *et al.* (1982) and Knuttgen (1961)) have demonstrated a 'U' shaped quadratic relationship between running economy and stride length in adults. Minimising the submaximal energy cost of running has been linked with the selection of a freely chosen stride length and stride frequency combination for any individual at any given submaximal running speed. The closer the freely chosen stride length to that of the optimal stride length, the lower the energy cost of running (Cavanagh and Williams 1987).

Functional adaptations of the cardio-respiratory system that occur through long-term training have been well documented (Costill 1967, Costill *et al.* 1973 and Conley and Krahenbuhl (1980). However, there is a lack of data on the impact of long-term training upon simple kinematic factors. Stride length and running economy have been shown to differ between experienced and novice adult runners, with experienced runners possessing longer stride lengths and enhanced running economy (Bailey and Pate 1991). Whether the attainment of this optimal stride length-oxygen consumption relationship is a result of training or an inherent characteristic of the individual has yet to be evaluated in any longitudinal study with experienced athletes.

Cavanagh and Williams (1982), tested the hypothesis that running economy and optimisation of stride length could occur through training in a group of novice male runners and demonstrated that neither stride length nor running economy changed significantly over the seven week training period. If training adaptations are postulated to arise from an iterative process based upon perceived exertion and repeated physiological stimuli of high training intensities (Conley and Krahenbuhl 1980) such a process might occur over many years of training and be well beyond the scope of all of the studies conducted to date.

In the absence of evidence from long term studies, is there any proof that specific biomechanical training can alter or achieve the same result in a shorter time span? To date, results from 3 studies have failed to arrive at a consensus on how the effects of biomechanical training influence gait, economy and technique (Petray and Krahenbuhl 1985, Messier and Cirillo 1989 and Williams *et al.* 1991b). Further, cross-sectional analysis between good and elite adult runners has demonstrated no significant difference with respect to a range of gait descriptors including stride length, Cavanagh (1977). Only one of these studies investigated the impact of specific biomechanical training in children. Petray and Krahenbuhl (1985) demonstrated that after an eleven week instruction programme in running technique no significant improvements were observed in submaximal running economy or gait characteristics in a group of 10 year old boys.

These results appear to indicate that both general run training and specific bio-mechanical training have little impact upon gait characteristics and submaximal running performance. Little manipulation of gait appears to be required to match the freely chosen stride length with an optimal stride length in experienced adult runners.

The primary aim of this study was to asses whether differences in simple gait characteristic existed between a group of boys involved in long-term running training and a group of active but non run-trained controls at two submaximal running speeds and to determine how this related to submaximal running economy. A secondary aim of the study was to investigate whether the two groups responded to speed increments in a similar manner.

Methods

Subjects

Thirty three male pre-pubertal boys (Tanner stage 1) volunteered to take part in the study. The first group consisted of 15 run-trained subjects [age 11.7 ± 1.06 years, mean ± SD, Table 4.1]. The second group consisted of 18 control subjects [age 11.3 ±0.90 years, Table 4.2]. The two groups were similar in terms of age and height (Tables 4.1 and 4.2). Table 4.5 shows details of the training and race performance for the trained subjects. Within the context of this study, run training was defined as involvement in a formal, structured, training programme for a minimum of one year. The parents of the control subjects completed a physical activity questionnaire to allow determination of their children's physical activity profile. The level of the child's habitual physical activity was assessed as either; (A) Inactive, (B) Active, (C) Moderately active, (D) Active and (E) Very active (Appendix). Seven of the control subjects were rated as active and the remainder were rated as moderately active. None were taking part in regular training.

All but three of the subjects were familiar with exercise testing . Despite this, all subjects were asked to attend for a habituation visit to accustom them to the equipment being used for cardio-respiratory testing. At this visit the subjects were familiarised to the treadmill by a period of walking and running (Shephard,1984). i es e

Study Design

Two separate submaximal protocols were used for the trained and untrained groups with each submaximal protocol consisting of four submaximal running stages each of three minutes in duration. The four running speeds used for the trained group were 8, 9.6, 11.2 and 12.8 km/h. 7.2, 8.0, 8.8 and 9.6 km/h for the controls with the two overlapping speeds of 8.0 and 9.6 km/h allowing kinematic and physiological comparison.

All metabolic data measurements were made using a computerised metabolic cart (Sensormedics S2900Z, Bilthoven, Netherlands), which was calibrated prior to each test. This instrument has previously been validated for use in children (Unnithan *et al.*, 1992). A low dead space valve ((16ml, Hans-Rudolph 1410B) was used to minimise dead space ventilation during the gas collection phases. Heart rate was monitored using a Sport Tester PE3000 heart rate monitor (Kempe, Finland). Two Sport Tester watches were fixed, one on the subject and one attatched to the front bar of the treadmill. Two simultaneous recordings were obtained for each subject in order to asess accuracy of the heart rate measurements.

Kinematic and Physiological Analysis techniques

Stride frequency was measured during the final minute of each submaximal running stage using a JVC KY17 Camcorder positioned perpendicular to the treadmill. Calculation of stride length (SL), stride frequency (SF), oxygen cost per stride (O2/str), stride frequency/stride length and stride length/leg length ratios were derived from the following formulae:

$\dot{V}O_2$ per stride (ml/kg/stride) = $\dot{V}O2$ (ml/kg/min) / SF (Strides per second)

SL (metres) = Treadmill speed (metres/second) / SF (Strides per second)

Leg length was measured as the distance from the greater trochanter to the base of the calcaneus and SF was determined by video analysis using a right foot to right foot strike as one stride.

Statistical Methods

A two-tailed unpaired t-test was used to investigate between group differences at the two comparison speeds in each protocol (8 and 9.6 km/h). In addition, linear regression analysis was used to assess the trends of the kinematic variables with speed within each group. Statistics were performed using the statistical functions in Microsoft Excel version 4 and a significance level of 0.05 was used.

Results

Comparison of the demographic data demonstrated that no significant differences existed for height and weight between the run-trained and control groups. Only the skinfold measurements were significantly different between the two groups . Mean peak $\dot{V}O_2$ value for the run trained group was 60.5±3.3 ml/kg/min compared to 51.1±4.3 ml/kg/min for the control group , ($P<0.001$). Significant differences were found at 8 km/h between the trained and control groups for fractional utilisation ($\%\dot{V}O_2$max) and submaximal heart rate. At 9.6 km/h significant differences arose between the two groups for fractional utilisation ($\%\dot{V}O_2$max), submaximal heart rate and respiratory exchange ratio (RER). At both speeds and for all significant dependent variables the trained group generated significantly lower values (Table 4.3).

Despite the differences in cardio-respiratory variables, there were no significant differences between the two groups with respect to economy ($\dot{V}O_2$), oxygen cost per stride, stride length, stride frequency, SF/SL and SL/LL at the two common speeds (Table 4.3, Figures 4.1 and 4.2).

In order that the influence of speed increments upon stride length and stride frequency could be assessed, individual regression lines were generated for each boy across the four submaximal treadmill speeds. The gradients and intercepts of these individual regression lines were plotted for each boy. No evidence existed for differences between the two groups for both stride length and stride frequency. In effect the population was homogeneous with respect to these two variables. Based upon the results obtained from the linear regression analysis, ΔSL and ΔSF were calculated for both groups with respect to the speed increments. The control group had speed increments of 0.8 km/h and the run-trained 1.6 km/h across the four submaximal speeds. Therefore, the change in stride length and stride frequency from running stage to the next was expressed as a ratio of the increment of speed.

Unpaired t-test analyses demonstrated that no significant differences existed between groups with respect to ΔSL across the first three speeds in each group. However, significant differences existed in ΔSL across the final two submaximal running speeds. The run-trained group increased their stride length significantly to adjust to the increase in running speed from stage 3 to stage 4 (Figure 4.4). No significant differences between groups were noted for Δ SF with respect to speed increment across all four submaximal speeds (Table 4.4 and Figure 4.3).

The pattern for both groups was slightly different with respect to the combination of stride length and stride frequency across the speed continuum. The control group progressively increased stride length over the four submaximal speeds with a progressive decline in stride frequency, whereas the trained group had stable stride length values over the first 3 submaximal running speeds. The highest stride frequency was achieved at the transition from submaximal speeds 2 to 3 for both trained and control groups.

No significant correlations were obtained between stride length and/or stride frequency and submaximal running economy at both overlap submaximal running speeds for both the trained and untrained groups.

Discussion

Peak $\dot{V}O_2$, fractional utilisation, RER, submaximal heart rate (table 4.3) and performance criteria (Table 4.5) provided evidence the trained boys had a higher level of functional adaptation to exercise. Despite this, no significant differences were noted between groups with respect to any of the gait descriptors used in this study. Differences in submaximal gait do not therefore appear to contribute to submaximal performance in these boys.

Within the context of the present study the absences of any gait differences between the two groups might be attributed to several factors. If the enhanced biomechanics of running are coupled to height (Rowland *et al.* 1987) the absence of a significant difference in height between the two groups could account for the lack of kinematic differences. Also, the training undertaken in the runners was not specifically designed to promote or enhance running form in these junior athletes.

If the selection of optimal SL/SF combinations is an inherent, self-selective process then our results suggest that both groups had attained optimal SL/SF combinations. This view is substantiated by the lack of significant differences between the groups in the submaximal energy cost of running at the two comparison speeds.

The influence of stride length and stride frequency to running economy may be subtle and beyond the level of sensitivity used in this assessment. However, some evidence exists to suggest that stride length and stride frequency may be resistant to specific bio-mechanical training manipulation (Petray and Krahenbuhl 1985, Messier and Cirillo 1989 and Williams *et al.* 1991b). In addition, there is increasing evidence to suggest that the direct significance of these two determinants to running economy may be minimal. Cavanagh and Kram (1985), Williams and Cavanagh (1987), Martin and Morgan (1992) and Morgan and Martin (1986) all demonstrated that slight alterations from the freely chosen stride length/stride frequency had no effect upon the energy cost of submaximal walking and running. The SL/SF ratio had to vary greatly from optimal to cause an increase in the submaximal energy cost of running. In addition, day to day variations in stride length have also been shown not to account for day to day variations in running economy (Morgan *et al.* 1989a).

The criteria which dictate optimal stride lengths are unknown. A number of theories have been put forward to explain the optimisation of SL/SF. It may arise as a result of the relationship between the efficiency of muscular contraction and the velocity at which muscles contract (Cavanagh and Kram 1985). The elastic properties of muscle may also dictate the optimal SL and SF. McMahon (1984) demonstrated that the resonant frequency of the elastic component in kangaroo tendon determines the hopping speed in the kangaroo at which $\dot{V}O_2$ is minimised.

The linear regression analysis indicated that with respect to SL/SF adjustments to increased running velocity, the group was homogeneous. The SL/SF linear regression data represented a descriptor of a single speed continuum. Subsequent analysis of ΔSL and ΔSF confirmed this theory. At the lower end of the speed spectrum the control boys made adjustments through increased stride length and decreased stride frequency to increments in running speed that were not significantly different to those of the run-trained. Only at the upper end of the speed range did the run-trained boys exhibit significantly higher SL than the controls. Across the speed continuum, the pattern of adjustment to speed increments appeared to be through stride frequency at slow transitional speeds, a combination of SL/SF at intermediate speeds and primarily SL at the upper end. These adjustments appeared to be totally independent of training status and a product of running velocity alone.

Significant adjustments of stride length have been linked to enhanced submaximal running economy. The possible mechanisms underlying these adjustments were addressed by Kaneko *et al.* (1981). These authors noted the greater contribution from stride frequency as opposed to stride length to submaximal economy. At low stride frequencies, the muscles need to develop a high external power to achieve a longer stride length. Equally at high stride frequencies the mechanical power associated with moving limbs increases. At either extreme, greater reliance is placed upon less economical fast twitch fibres than at more intermediate stride length/stride frequency combinations. Increasing stride length with increased treadmill running speed is indicative of a greater contribution from eccentric muscle contraction and approximately 40% less oxygen is consumed than for an equivalent concentric muscle contraction minimising the submaximal energy cost of running.

In summary, despite a high level of aerobic fitness and running performance in the trained group, we found no evidence that at the same speed significant differences existed between the run-trained and control boys with respect to any of the gait descriptors analysed in this study. Also, despite the functional adaptations in the trained boys there appeared to be no interaction between the cardio-respiratory variables and the kinematic factors assessed. Both groups adjusted to increments in speed by optimising their stride length/stride frequency patterns.

A limitation of any gait analysis study in children is the inability to totally exclude habituation effects influencing performance. Thorough treadmill habituation and accommodation procedures were performed on all the children. However it is impossible to rule out that these factors could have had a confounding effect upon the kinematic factors generated. The data on pre-pubertal males points to the optimisation of stride length and stride frequency ratio being an inherent characteristic of a given individual and a product of running velocity rather than training status.

Tables

Subject	Age	Height (cm)	Weight (kg)	Sum of Skinfolds (mm)	Peak VO2 (ml/kg/min)
1	12.3	157.1	38.9	17.9	63.9
2	13.0	139.0	31.3	16.8	61.1
3	13.0	139.0	38.2	18.7	61.4
4	11.4	148.0	32.4	15.9	59.1
5	12.5	145.0	35.6	22.5	67.4
6	11.2	146.0	41.1	25.1	57.5
7	10.2	150.3	33.0	16.1	59.8
8	10.2	136.5	34.1	26.8	57.0
9	10.3	144.2	32.3	25.2	55.0
10	12.2	149.5	35.2	15.8	63.3
11	13.1	153.6	37.2	15.5	62.7
12	10.6	148.0	37.2	19.9	58.1
13	11.6	149.5	38.0	27.1	62.0
14	12.6	160.4	46.7	20.3	61.2
15	11.9	154.5	40.6	21.3	57.0
Mean	11.73	148	36.8	20.35	60.5
SD	1.06	6.77	4.09	4.17	3.26

Table 4.1: Demographic details of trained boys

Subject	Age	Height (cm)	Weight (kg)	Sum of Skinfolds (mm)	Peak VO2 (ml/kg/min)
1	12.1	153.0	42.2	34.0	49.89
2	11.3	145.0	56.5		48.64
3	11.6	149.0	37.8	30.9	46.89
4	12.3	161.0	45.1	22.9	51.64
5	11.0	146.0	38.2	31.3	48.91
6	10.5	155.4	46.2	32.9	50.12
7	11.1	138	28.0	29.4	48.04
8	11.8	131.3	30.0		60.94
9	10.5	139.0	31.1	21.3	58.06
10	10.3	142.0	43.8	39.9	46.6
11	12.2	152.0	38.6	21.5	57.51
12	10.1	145.0	38.1	27.6	50.38
13	10.0	141.8	35.8	37.3	47
14	12.0	146.0	32.7	22.5	55.43
15	13.3	165.0	54.0	35.0	46.79
16	11.3	145.0	44.7	36.1	49.53
17	10.4	143.0	38.8	37.5	52.98
18	11.1	137.0	31.3	22.0	49.99
Mean	11.3	146.4	39.6	30.1	51.07
SD	0.9	8.49	7.88	6.42	4.26

Table 4.2: Demographic details of control boys

	8 km/h			9.6km/h		
	Control	Trained		Control	Trained	
SL (metres)	1.55	1.56	NS	1.84	1.85	NS
SD	0.14	0.13		0.08	0.11	
SF (Strides/minute)	85	86	NS	87	87	NS
SD	4	5.3		4	5.3	
SF/SL	55	56	NS	48	47	NS
SD	6.8	7.4		4.3	5.8	
O2/stride (ml/kg/str)	0.44	0.45	NS	0.49	0.51	NS
SD	0.05	0.04		0.04	0.04	
VO2 (ml/kg/min)	36.98	38.45	NS	42.92	43.85	NS
SD	3.9	2.12		2.9	1.81	
HR (beats per min.)	179	161	P<0.01	194	177	P<0.05
SD	8.8	11.6		13.3	12.2	
RER	0.96	0.93	NS	1.02	0.96	P<0.05
SD	0.05	0.06		0.04	0.03	
FU (%)	73	64	P<0.01	85	73	P<0.05
SD	8	3		7	3	
Peak VO2	51.07	60.47	P<0.001			
SD	4.26	3.26				

Table 4.3: Kinematic and cardio-respiratory analysis at two comparison speeds

	Δ1			Δ2			Δ3		
	Trained		Control	Trained		Control	Trained		Control
ΔSF (Strides / min)	0.49	NS	2.40	0.67	NS	2.26	0.11	NS	1.15
SD	1.79		2.23	1.31		3.27	1.66		3.90
ΔSL (metres)	0.17	NS	0.12	0.17	NS	0.17	0.24	P<0.05	0.19
SD	0.05		0.18	0.03		0.20	0.04		0.05

Δ1,2 and 3 (Transition from submaximal speeds (1-2, 2-3 and 3-4)

Table 4.4: Δanalysis of stride length and stride frequency

Subject	Years Training	Months per year	Times per week	Hours per week	Number of years competing	Number of competitions	3000m personal best (mins)
1	3	9	3	5	1	2 per month	11:00
2	3	12	4	2	5	2 per month	11:01
3	3	10	2	3	3	1 per month	12:23
4	2	12	3	6.5	2	4 per month	12:02
5	3	12	2	2	3	2 per month	11:04
6	2.5	12	2	2	1.5	1 per month	13:58
7	2	12	1	1.5	1	4 per year	13:36
8	2	12	1	1.5	1	2 per year	13:57
9	1	6	1	1.5	0	0	14:04
10	3	12	2	5	0	1 per month	
11	1	12	2	4	1	2 per month	11:56
12	3	12	2	3	1	1 per month	13:01
13	1	12	2	3	1	0	13:22
14	1	12	1	0.5		0	13:04
15	3	12	2	5	3	2 per month	
Mean	2.2	11.3	2	3	1.9		12:51
SD	0.83	1.65	0.82	1.66	1.23		1.04

Table 4.5: Training, competition and performance details

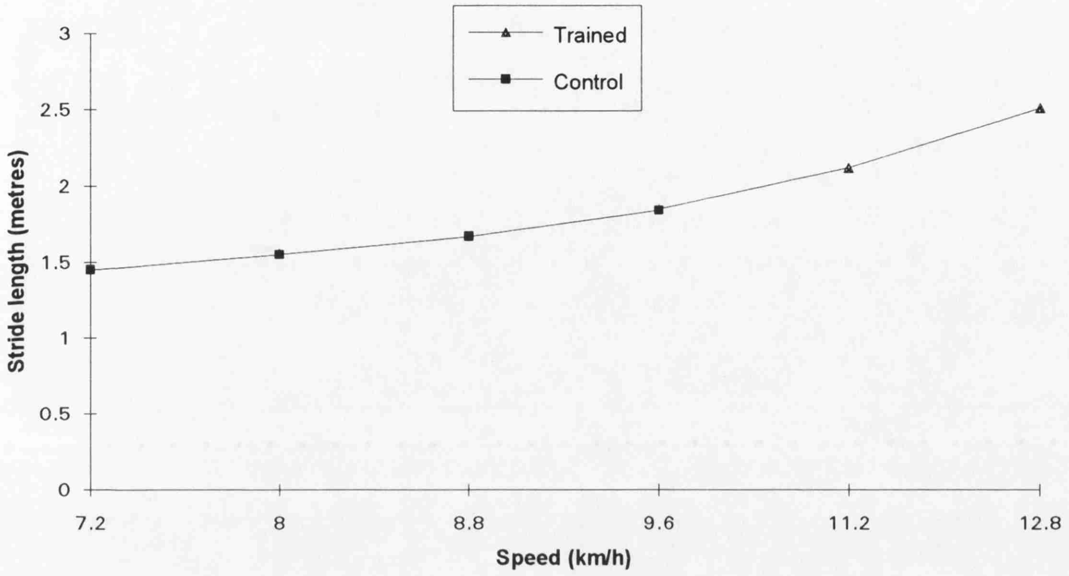

Figure 4.1: Relationship between stride length and submaximal running speeds for trained and control boys

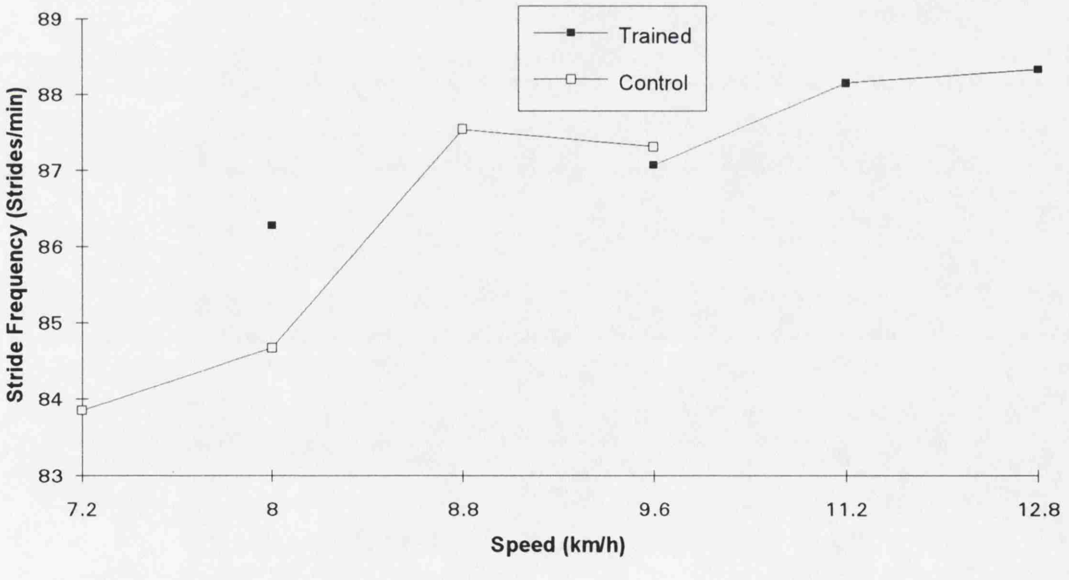

Figure 4.2: Relationship between stride frequency and submaximal running speeds for trained and control boys

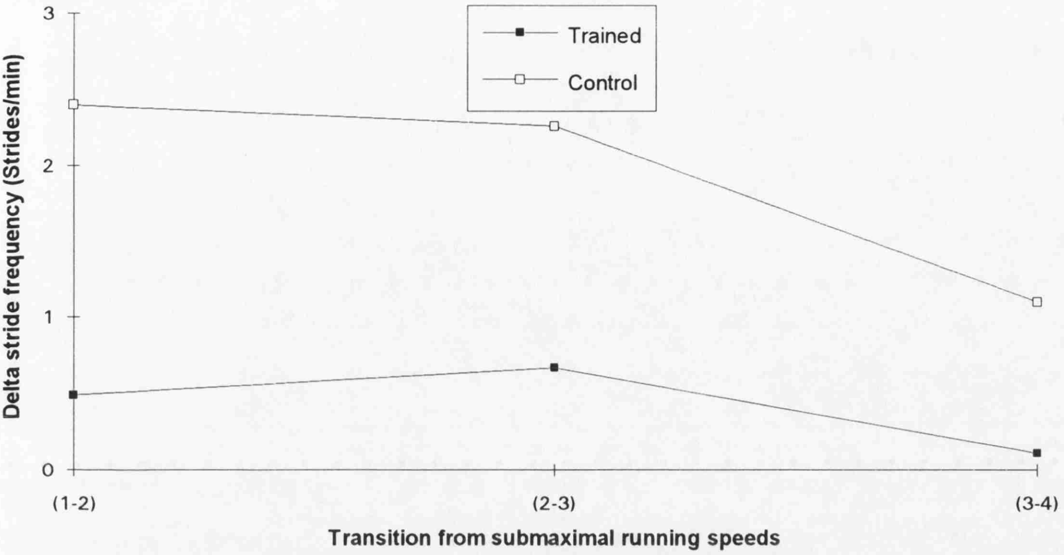

Figure 4.3: Relationship between delta stride frequency and transition from submaximal running speeds

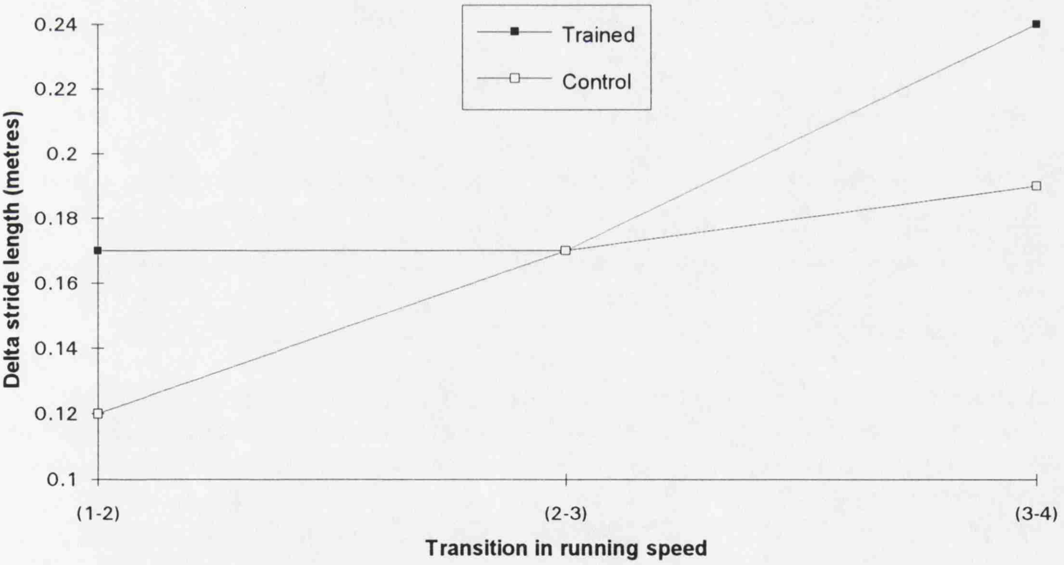

Figure 4.4: Relationship between delta stride length and transition from submaximal running speeds

SUBMAXIMAL RUNNING ECONOMY IN RUN-TRAINED CHILDREN

Introduction

Cross-sectional analyses of trained and untrained individuals allow physiological differences to be demonstrated, without necessarily apportioning the mechanism, source or nature of difference. Cross-sectional analyses can, therefore, present only a profile of two groups. Differences that are demonstrated between groups might potentially arise from three sources:

1. Genetic pre-disposition.
2. Accelerated development.
3. Training induced changes.

All factors affecting endurance performance are strongly influenced by genetic determinants including anatomical, biochemical, physiological and competitiveness and motivation (Cowart 1987). Current data suggest that the contribution of genetics to maximal oxygen consumption is approximately 50% and 70% for endurance performance (Bouchard 1986). Any individual may be a high or low responder to fitness training based upon this genetic endowment (Hamel *et al.* 1986). Two genetic prerequisites appear to be required for successful running performance, a high level of baseline aerobic fitness, and an the inherent capacity to respond optimally to exercise training.

In most cross-sectional analyses development or accelerated development is normally assessed through chronological age. However, chronological age appears to be a poor marker of biological maturity, as, at any given age, children may differ significantly in work capacity and motor proficiency. Skeletal age as indicated by bone X-ray is the most valid measure of biological maturity (Hebbelinck, 1978). Cumming *et al.* (1972) illustrated that bone age predicted running performance better than chronological age, height or weight. During biological development, factors that contribute to physical fitness mature and performance in exercise tests improves. The rate of exercise-related maturation does not parallel chronological age, consequently significant inter-subject variability can exist (Mirwald and Bailey, 1986). The ability to differentiate true training effects from the confounding effects of accelerated development represents a major limitation of any form of cross-sectional analysis. The possibility always exists that the "athletic group" merely represent children who may have matured early in factors responsible for efficient submaximal running.

Physiological differences profiled in cross-sectional studies may indeed be the product of training induced changes. In adult runners, the available data is contradictory as to whether improvements in $\dot{V}O_2$max and submaximal running economy can be obtained through training. A considerable number of both cross-sectional and longitudinal studies have been equivocal demonstrating that training has increased, left unchanged or decreased the submaximal energy cost of running. A wide range of improvements in submaximal oxygen consumption were noted in training studies that employed a combination of distance, interval and hill training over a wide spectrum of training periods (14 weeks to 5 years) (Conley *et al.* 1981, Conley *et al.* 1984, Daniels *et al.* 1978, Patton and Vogel 1977 and Svendenhag and Sjodin 1985)

Several researchers have demonstrated that physiological adaptation can occur across the spectrum of running fitness levels. For example, Conley *et al.* 1984, Daniels 1974 and Svendenhag and Sjodin 1985 all demonstrated improvements in submaximal running economy in elite, middle and long distance runners. In addition Ramsbottom *et al.* 1989 and Bransford and Howley 1977 demonstrated the capacity for improvement in recreational runners.

Whether the same level of physiological adaptation can occur through training in a pre-pubertal population has been addressed by a number of researchers. A number of cross-sectional studies have demonstrated that trained pre-pubertal boys have peak $\dot{V}O_2$ values beyond the normal expected values at this age range (Brown *et al.* 1972, Ekblom 1969, Kellet *et al.* 1978, Lussier & Buskirk 1977, Massicote & McNab 1974, Mayers and Gutin 1979, Sundberg and Elovainio 1982, Vaccaro *et al.* 1980 and Mirwald *et al.* 1981). However, the difference between the trained and untrained child with respect to peak $\dot{V}O_2$ is only 20-30% higher than the 70% plus seen in trained to untrained adult populations. The nature of the training stimuli has been demonstrated to dictate the capacity for improvement in peak $\dot{V}O_2$. Rowland (1985) stated that if adult exercise intensity criteria were applied to children the capacity to improve peak $\dot{V}O_2$ existed. However, in pre-pubertal athletes the impact of exercise training appears to be negligible (Daniels and Oldridge 1971).

Controversy exists as to the impact of training on submaximal running economy . In a cross-sectional study, Mayers and Gutin (1979) found that submaximal running economy was superior in a group of elite pre-pubertal runners compared to a group of control subjects at submaximal running speeds. However, when the oxygen consumption data were controlled for height no significant difference was seen between the groups for submaximal running economy. Short-term specific running training has also seemed to be ineffective in improving submaximal running economy (Petray and Krahenbuhl 1985). Krahenbuhl and Williams (1992) concluded that over the short-term little or no improvement in running economy would occur through training.

The stimulus of growth alone appears to be the major factor mediating improvements in submaximal running economy. Krahenbuhl, Morgan and Pangrazi (1989) demonstrated a 13% improvement in submaximal running economy with no change in peak oxygen consumption over a seven year period in a group of male subjects (mean age at start 9.9yrs, mean age at end 16.8years). This group of boys underwent no form of training in the seven years. Therefore, improvements in running economy were attributed to growth alone. To a lesser extent Daniels and Oldridge (1971) demonstrated similar findings. These authors concluded that a combination of growth and training contributed to improved submaximal running economy over a 22 month training period. These two studies remain to date the only two that attribute improvements in submaximal running economy to training and/ or growth.

The possibility exists that over a period of years, the augmentation of improved running economy achieved through growth could be assisted through participation in running training programmes.

The present study was undertaken to characterise the cardio-respiratory differences between a group of run-trained pre-pubertal boys and a group of control boys. It aimed to assess the influence that training, genetic pre-disposition and accelerated development had upon submaximal and maximal running performance in a group of moderately trained pre-pubertal boys.

Methods

Subjects

Thirty three male pre-pubertal boys (Tanner stage 1) volunteered to take part in the study. The subjects were in two groups: 15 run-trained subjects [age 11.7 ± 1.06years, mean ± SD, Table 4.1] and 18 control subjects [age 11.3 ±0.90years, Table 4.2]. The two groups were similar in terms of age, height, weight and skinfold measurements (biceps, triceps, subscapular and suprailliac). Table 4.5 shows details of the training and race performance for the trained subjects. Within the context of this study, run training was defined as involvement in a formal, structured, training programme for a minimum of one year. The parents of the control subjects completed a physical activity questionnaire to allow determination of their children's physical activity profile. Seven of the control subjects were rated as active and the remainder were rated as moderately active. None was taking part in regular running training. However, seven of these boys were involved in organised sports (football, rugby, basketball and karate).

All but three of the subjects were familiar with treadmill exercise testing. Despite this, all subjects were asked to attend for a habituation visit to accustom them to the equipment being used for cardio-respiratory testing. At this visit, the subjects were familiarised with the treadmill (Powerjog M10, Cardinal Sports, Edinburgh) by a period of walking and running (Shephard,1984).

Study Design

Two separate submaximal protocols were used for the trained and untrained groups. Each submaximal protocol consisted of four submaximal running stages each of three minutes in duration with running speeds of 8, 9.6, 11.2 and 12.8

km/h and 7.2, 8.0, 8.8 and 9.6 km/h for the controls with the two overlapping speeds (8.0 and 9.6 km/h) allowing kinematic and physiological comparison. At all submaximal treadmill speeds the treadmill belt was calibrated before use.

All the boys performed a peak $\dot{V}O_2$ test within seven days of the submaximal testing. The peak $\dot{V}O_2$ test involved running at a constant speed of 8.8 km/h for the control group and 9.6 km/h for the run-trained group with an increase in gradient of 2.5% every 2 minutes until voluntary exhaustion was attained. Heart rate and cardio-respiratory variables were measured throughout the test. The child was judged to have reached peak $\dot{V}O_2$ when any two of the following four criteria were met (Williams and Armstrong, 1991): i) heart rate within 10 beats per minute of 200 beats per minute or ii) a heart rate plateau, iii) respiratory exchange ratio value greater than 1.0 and iv) an approximate plateau of $\dot{V}O_2$ values.

Metabolic data measurements were made using a computerised metabolic cart (Sensormedics S2900Z, Bilthoven, Netherlands), which was calibrated prior to and following each test using two reference gases. This instrument has previously been validated for use in children (Unnithan *et al.*, 1992). A low dead space valve (16mls; Hans-Rudolph 1410B) was used to minimise dead space ventilation during the gas collection phases. Heart rate was monitored using a Sport Tester PE3000 heart rate monitor (Kempe, Finland).

Physiological Analysis

The S2900Z generated discrete data points every 20 seconds during the gas collection phases. These discrete values were averaged to produce a mean value for each minute of the submaximal running stages. The final minute of each submaximal running stage was taken to represent the steady state value. The following cardio-respiratory variables were assessed: relative oxygen consumption ($\dot{V}O_2$ rel), absolute oxygen consumption ($\dot{V}O_2$ abs), fractional utilisation (FU), ventilatory equivalent for oxygen (VeO2), ventilatory equivalent for carbon dioxide (VeCO2), heart rate (HR), tidal volume (T_V), respiratory rate (RR), respiratory exchange ratio (RER), ventilation (Ve abs) and rating of perceived exertion (RPE).

Statistical Methods

Data was summarised using standard descriptive indices for normally distributed data (mean, SD). Comparisons between the groups were made using a two-tailed unpaired t-test with a P value of <0.05 being regarded as significant. Statistics were performed using Microsoft Excel version 4.

Results

All boys taking part in the study were classified as pre-pubertal using the Tanner pubertal grading scale. There were no significant differences between the two groups of boys for age, height or weight. Only the skinfold measurements were significantly different between the two groups (P<0.05), with the run-trained boys possessing lower sum of skinfolds [Run-trained: 20.35±4.17 vs Control: 30.1± 6.42].

At the two comparison speeds selected, physiological differences existed between the two groups. At 8 km/h, FU and HR were significantly lower in the run trained group ((P<0.01, Table 5.1). At 9.6 km/h FU, VeO2, VeCO2, HR, RER, Ve and RPE were also all significantly lower in the run trained boys (Table 5.1). No significant differences were found in submaximal running economy ($\dot{V}O_2$rel) at either comparison speed (Table 5.1).

Comparisons of the two groups at peak exercise intensity demonstrated that significant differences only existed with respect to $\dot{V}O_2$(rel). Mean peak $\dot{V}O_2$ value for the run trained group was 60.5±3.3 ml/kg/min compared to 51.1±4.3 ml/kg/min (P<0.001) for the control subjects. All other cardio-respiratory variables did not differ significantly at peak exercise intensity (Table 5.2).

Discussion

Despite the absence of any significant differences in age, height or weight between the two groups significant physiological differences were present at both submaximal and peak exercise intensities (Tables 5.1 and 5.2).

During treadmill running efficiency is not readily used, as total work accomplished is difficult to quantify. Body weight, elastic tendon recoil, arm motion, transfer of energy between body segments and running gait all contribute to variability in work accomplished. Consequently, with respect to treadmill running, efficiency of movement is usually expressed simply as oxygen consumption at a given speed (running economy).

The mechanical efficiency of contracting skeletal muscle is determined by the fraction of energy released from the pyrophosphate bonds of ATP (phosphorylative coupling) and the percentage of the energy used by muscle to create external work (contraction coupling). Rowland *et al.* (1990) demonstrated that no significant difference existed in mechanical efficiency between a pre-pubertal and adult population suggesting that muscular efficiency would appear not to be a factor in submaximal economy differences between adults and children. The lack of differences in submaximal running economy within the present study probably demonstrates the fact that muscular efficiency is both independent of age and training status.

A number of factors can potentially influence submaximal running economy including: vertical displacement, lateral motion, stride length, fuel utilisation patterns, energy transfer between body segments, body composition, co-ordination, strength and muscle elasticity, muscle fibre types and vascularisation, pacing , heat dispersion and shoe factors. Within the context of the present study, the relationship of substrate utilisation, heart rate, ventilation and perception of effort to submaximal running economy were assessed.

The submaximal running economy results generated at the two comparison speeds demonstrated an interesting trend. The results from the present study agree with the majority of previous studies conducted which suggest that submaximal running economy does not differ on comparing run-trained and non run-trained individuals (Krahenbuhl *et al.* 1989, Petray and Krahenbuhl 1985 and Krahenbuhl and Williams 1992).

Heart rate and ventilation are two indices that reflect the oxygen supply to the active musculature. Pate *et al.* (1992) demonstrated that both variables were significantly and positively correlated with oxygen consumption . Bailey and Pate (1991) theorised that training induced reductions in submaximal heart rate and ventilation (Zauner 1989, Nudel 1989 and Bailey and Pate 1991) produce an overall lowering of submaximal aerobic demand. Based upon data extrapolated from animal studies, meaningful reductions in submaximal oxygen consumption arose primarily from decreases in ventilation resulting from a reduced respiratory rate and an increased tidal volume.

At 9.6 km/h significant differences existed with respect to ventilation between the two groups. The run-trained group demonstrated a significantly lower submaximal ventilation. No significant differences were noted with respect to the tidal volume and respiratory rate . However, respiratory rate was lower in the run-trained boys although not significantly so. Consequently, the product of respiratory rate and tidal volume generated a significantly lower submaximal ventilation in the run-trained boys.

At submaximal exercise intensities, maintenance of ventilation is achieved primarily through respiratory rate rather than tidal volume in children (Rowland and Green 1990). The respiratory rate/tidal volume combination is optimised to minimise the total ventilatory work required to achieve an appropriate ventilation and is determined primarily by limiting factors in the chest wall. Increasing tidal volume in children is prohibitively expensive as the ventilatory muscules are required to oppose the elastic recoil forces of the lung.

The choice of optimal respiratory rates rather than tidal volume in children is a direct result of the higher lung recoil forces. These forces are generated as a result of increased pulmonary elastic fibre density (Zapletal *et al.* 1971). Consequently, to sustain ventilation through tidal volume adjustments would require increased work by the ventilatory musculature. The mechanical disadvantage of optimising tidal volume would negate any saving in submaximal energy cost as described by Bailey and Pate (1991). Therefore, it was not surprising that no significant differences were noted in submaximal oxygen consumption at the two comparison speeds.

Bailey and Pate (1992) theorised that the lower blood lactate accumulation and higher blood pH in trained athletes could contribute to the reduced submaximal ventilation in trained athletes. At submaximal exercise the generation of less lactate ensures that the bicarbonate buffer system is less taxed and consequently less CO2 is removed leading to reduced stress on the ventilatory system. As, Millic-Emili *et al.* (1962) demonstrated the total work of ventilation constitutes 7-8% of the total energy cost of exercise. Therefore, minimising the ventilatory response at submaximal exercise may act to decrease the whole body oxygen cost. Whatever, the source of the ventilatory differences at 9.6 km/h, no significant differences in submaximal oxygen consumption existed between the two groups.

Significant differences also existed at 9.6 km/h with respect to VeO2 and VeCO2. For both variables, the run-trained group demonstrated lower ratios than the control group. Lower VeO2 responses in adult endurance athletes have been attributed to the high aerobic capacity of these individuals. This physiological adaptation enables the athlete to rely primarily on aerobic sources of energy, thereby reducing the contribution from anaerobic sources and the resulting reduction in respiratory metabolic stimuli.

The impact of training upon the submaximal heart rate response in exercise has been addressed by a number of authors (Bar-Or and Zwiren 1973, Stewart and Gutin 1976, Nudel *et al.* 1989) who all reported lower submaximal heart rates in good or elite child runners compared to non-runners. At 9.6 km/h in the present study, the run trained group demonstrated significantly lower (P<0.05) heart rates than the control group. Eriksson *et al.* (1973) demonstrated an increase in stroke volume after training in boys but theorised that this increase was less related to heart size and more likely caused by enhanced contractility or improved left ventricular filling.

Work in this laboratory (Rowland *et al.* 1993-Appendix1) demonstrated that no significant differences were seen in ECG intervals, axes and precordial voltages between the runners and controls at rest. No significant differences were noted between echocardiographic chamber sizes, wall thickness and mass indexed to body surface area. This study demonstrated overall no evidence of the "athlete's heart" at rest in the run-trained boys defined as cardiac enlargement, resting bradycardia, heart murmurs, third and fourth heart sounds and electrocardiographic alterations The results are in line with data obtained by other authors (Shepherd *et al.* 1988, Telford *et al.* 1988 and Nudel *et al.* 1989) on pre-pubescent athletes. Bielen *et al.* 1990 found no genetic effect upon left ventricular end diastolic dimension or wall thickness in a study of 6-8 year old twins. These authors concluded that the presence of the "athlete's heart" at rest was not an inherited factor and suggested that inheritance of aerobic power may be related to the genetic transmission of non-aerobic factors. However, the results from these studies tell us little with regard to cardiac dynamics during exercise. Further research is required to isolate factors responsible for the lower submaximal heart rates in trained boys during submaximal exercise.

Two assumptions underpin the relationship between submaximal running economy and heart rate and ventilation. If muscle oxygen extraction remains constant, then the differences that may arise in submaximal oxygen consumption may occur directly from heart rate and ventilation. However, if peripheral oxygen extraction varies the increase in heart rate, ventilation and oxygen consumption are secondary to the maintenance of an adequate oxygen gradient at the mitochondrial level.

Respiratory exchange ratio values were significantly lower in the run -trained boys. This might arise from preferential fat substrate utilisation in the trained boys. However, in the absence of any invasive measurements and with the confounding effects of possible hyperventilation, this interpretation remains speculative.

The perception of exercise stress for the run-trained boys was assessed by the rating of perceived exertion. At 8 km/h no significant difference was found with regard to the perception of effort. However, at 9.6 km/h the run-trained group perceived the effort to be significantly lower than the control group. It would be interesting to speculate that the impact of training at high exercise intensities enabled these run-trained boys to perceive the exercise stimulus as lower. The perceived exertion results are in line with the results obtained for fractional utilisation at 9.6 km/h. The run-trained group were exercising at a significantly lower percentage of their peak aerobic power for both comparison speeds. At present, the significance of fractional utilisation to submaximal running economy remains unclear in paediatric populations and it still remains unclear whether fractional utilisation in children represents anything more than an expression of relative exercise intensity.

Peak oxygen consumption reflects the combination of cardiac output and peripheral oxygen extraction. In well trained pre-pubertal athletes peak $\dot{V}O_2$ can be 20-25% higher than non-athletes (Rowland 1985). In the present study, peak $\dot{V}O_2$ of the run-trained boys was 18% higher than the controls. The values generated in the current study [Controls: 51.07±4.26 versus Run-trained: 60.47±3.26 ml/kg/min, mean±SD] are similar to those found in other studies (Nudel *et al.* 1989, Sundberg and Elovainio 1982, Mayers and Gutin 1979 and Krahenbuhl and Pangrazi 1983).

The cross-sectional nature of the present study prevents the partitioning of the training effect from the influence of hereditary factors. Thus, it may be equally true that a genetic pre-disposition towards participation in athletic events may account for the peak $\dot{V}O_2$ differences between the run-trained and control groups rather than any influence of training (Nikolic and Ilic 1992)
While it may not be possible to partition the genetic effect from the training effect with respect to peak oxygen consumption, considerable evidence exists to suggest that a background of regular physical activity cannot stimulate above average peak aerobic power (Rowland 1985). Cunningham *et al.* 1981 have also shown no association between daily activity and peak oxygen consumption. Gilliam *et al.* 1981 demonstrated over a 12 hour period of heart rate monitoring

the infrequency with which sustained exercise is maintained in a group of young children and concluded that moderately active children seldom exercise to levels sufficient to improve cardiovascular fitness. Thus habitual physical activity is unlikely to produce functional physiological adaptations.

The presence of well matched controls, adequate sample size, maturationally well-matched boys and fully laboratory habituated subjects has allowed us to demonstrate physiological differences between the two groups. The major limitation of a study of this nature is in the cross-sectional nature of the design. However, within the limitations of this design significant physiological differences were noted. The peak $\dot{V}O_2$ results obtained in this study parallel those obtained in the often quoted study of Mayers and Gutin 1979. Although, it was not possible to account for the genetic influence, results from the literature seem to indicate that the enhanced aerobic power seen in the present study could have resulted from the impact of training.

In summary, at peak exercise intensities the run-trained group exhibited superior aerobic power compared to the control group perhaps as a result of pre-selection, training or a combination of both. The run-trained group demonstrated no form of superior submaximal running economy at either comparison speed. . Yet, at 9.6 km/h measurable physiological differences existed between the run-trained and control groups. The lack of multiple physiological differences at 8.0 km/h was probably an artefact of the submaximal treadmill running speed chosen.

Despite the lack of difference in submaximal running economy between the two groups at the two comparison speeds, significant physiological functional adaptations appear to have occurred in the run-trained. The source of these differences is not clear but they may be related to training, to genetic pre-selection or to developmental differences.

More invasive analyses, such as free fatty acid and blood lactate analyses will be required to understand fully the metabolic effects of pre-selection or training upon submaximal running economy. Only applications of these techniques will allow us to determine whether submaximal running economy is an appropriate index to use to assess functional physiological differences between the trained and untrained.

Tables

speed	8.0 km/h			9.6 km/h		
	Control	Trained		Control	Trained	
VO2 (ml/kg/min)	36.9	38.4	NS	42.9	43.8	NS
(SD)	3.07	2.12+		2.9	1.81	
VO2 (ml/min)	1468	1408	NS	1692	1609	NS
(SD)	349	179		334	203	
FU (%)	73	64	P<0.01	85	73	P<0.05
(SD)	8	3		7	3	
VeO2	27	25	NS	30	26	P<0.05
(SD)	2.6	2.5		2.2	2.5	
VeCO2	28	27	NS	29	28	P<0.05
(SD)	2.3	2.5		1.9	2.3	
HR (bpm)	179	161	P<0.01	194	177	P<0.05
(SD)	8.8	11.6		13.3	12.2	
V_T	1.02	1.02	NS	1.07	1.02	NS
(SD)	0.31	0.35		0.3	0.29	
RR	40	39	NS	49	45	NS
(SD)	11	15.3		11.3	13.5	
RER	0.96	0.93	NS	1.02	0.96	P<0.05
(SD)	0.05	0.06		0.04	0.03	
Ve	39.6	35.6	NS	51.1	42.5	P<0.05
(SD)	9.4	4		10.1	5.8	
RPE	10.5	8	NS	12.9	9.9	P<0.05
(SD)	2.7	1.2		3	1.4	

Table 5.1: Cardio-respiratory analysis at two comparison speeds

	Control	Trained	
VO2 (ml/kg/min)	51.07	60.47	$P<0.001$
(SD)	4.26	3.26	
VO2 (ml/min)	2026	2234	NS
(SD)	352	276	
FU (%)	-	-	
(SD)	-	-	
VeO2	32	32	NS
(SD)	3.3	3	
VeCO2	29	29	NS
(SD)	2.6	2.6	
HR (bpm)	200	205	NS
(SD)	7.0	7.2	
V_T ***(litres)***	1.27	1.27	NS
(SD)	0.24	0.24	
RR	54	57	NS
(SD)	9.1	9.4	
RER	1.12	1.13	NS
(SD)	0.05	0.04	
Ve (litres)	64.7	71.43	NS
(SD)	8.97	9.19	
RPE	10.5	8	NS
(SD)	2.7	1.2	

Table 5.2: Peak data analysis

INFLUENCE OF STEADY STATE BLOOD LACTATE

Introduction

Endurance training studies in adults have in the main used changes in $\dot{V}O_2$max as an indicator of changes in endurance capacity. However, it is increasingly suggested that submaximal variables may be more valid indicators of training status (Daniels *et al.* 1978, Katch *et al.* 1978). The major criticism of the use of VO2max is its lack of sensitivity as a marker of adaptation to endurance training. In highly conditioned athletes, the lack of improvement in $\dot{V}O_2$max coupled with improved endurance performance has led to the use of the submaximal exercise model in an attempt to unwind factors responsible for enhanced running performance.

In the paediatric population lower lactate levels have been demonstrated compared to adults (Macek and Vavra 1985). Several theories have been projected to explain these findings. Astrand (1952) indicated these findings do not necessarily indicate any impairment of the anaerobic capacity but rather reflect the net result of accumulation and clearance. It is possible, for example, that reduced sympathetic activity in children allows significant blood flow to be maintained to the liver allowing the liver to remove lactate at higher rates than adults during exercise. Whether training is capable of modifying this lactate response in pre-pubertal athletes has yet to be evaluated. It is tempting to speculate that a combination of enhanced aerobic power and reduced sympathetic drive achieved through training could have implications for submaximal steady state lactate production.

Mayers and Gutin (1979) demonstrated no significant difference in submaximal running economy in a group of elite pre-pubertal runners compared to a group of control boys, but did not report any evidence of blood lactate levels in these trained runners. In this often quoted study there was no linking of submaximal running performance and submaximal blood lactate production.

In this study our aim was to investigate the relationship between steady state lactate production and submaximal oxygen consumption in a group of run-trained pre-pubertal compared to a group of healthy control boys not engaged in any formal run training.

Methods

Subjects

Twenty four pre-pubertal male subjects (based upon pubertal grading by physical examination (Tanner 1962), Table 1) volunteered to take part in the study. The subjects were divided into two groups. The first group consisted of 11 run-trained subjects [Table 6.1] while the second consisted of 13 control subjects [Table 6.1]. The two groups were similar in terms of age, height and weight (Table 6.1). Table 4.5 shows details of the training and race performance for the trained subjects. Within the context of this study, run training was defined as involvement in a formal, structured, training programme for a minimum of one year. The parents of the control subjects completed a physical activity questionnaire to allow determination of their children's physical activity profile. Of the control subjects,10 were rated as active and the remainder were rated as moderately active. None were taking part in regular training.

All but two of the subjects were familiar with the laboratory environment. Nevertheless, all subjects were asked to attend for a habituation visit to accustom them to the equipment being used for cardio-respiratory testing. At this visit, the subjects were familiarised with treadmill exercise (Powerjog M10, Cardinal Sports, Edinburgh) by a period of walking and running (Shephard,1984).

Study Rationale

Eleven of the 15 run-trained boys who took part in the previous investigation (Submaximal running economy in run-trained children) returned to take part in the present investigation. The present study was conducted at the mid-way point of the boys' winter training programme. The boys were all selected on the basis of their summer performance times and on their willingness to undergo further laboratory measurements. Based upon these two criteria a sub-set of 11 of the original 15 boys were studied in the present investigation.

Study Design

A single test session protocol was used for both the run-trained and control groups. The submaximal protocol differed for both the run-trained and the control group. The run trained group completed three four minute running stages at 9.6, 11.5 and 13.1 km/h. These absolute speeds corresponded to approximately 75, 85 and 95% peak $\dot{V}O_2$ for the run-trained group. The running stages were interspersed with 7 minutes of passive and 3 minutes of active recovery (walking at 4 km/h). The control group performed only one 4 minute submaximal stage at 9.6 km/h). One of the submaximal speeds overlapped, allowing lactate and cardio-respiratory comparison at 9.6 km/h. At all submaximal treadmill speeds the treadmill belt was calibrated.

All the boys performed a peak oxygen consumption test 20 minutes after the end of the final running stage using a modified version of the protocol designed by Unnithan and Eston (1990). The running speed was customised to fit the individual requirement of each child. Once baseline speed was established the gradient was increased 2.5% every 2 minutes until voluntary exhaustion was attained. The child was judged to have reached peak $\dot{V}O_2$ when any two of the following four criteria were met (Williams and Armstrong, 1991): i. heart rate within 10 beats per minute of the age predicted maximum or ii. a heart rate plateau or iii. respiratory exchange ratio value of greater than 1.0 an iv. an approximate plateau of $\dot{V}O_2$ values.

Metabolic data measurements were made using a computerised metabolic cart (Sensormedics S2900Z, Bilthoven, Netherlands), which was calibrated prior to and following each test using two reference gases. This instrument has previously been validated for use in children (Unnithan *et al.*, 1992). A low dead space valve (16mls; Hans-Rudolph 1410B) was used to minimise dead space ventilation during the gas collection phases. Heart rate was monitored using a Sport Tester PE3000 heart rate monitor (Kempe, Finland).

Physiological Analysis

The S2900Z generated discrete data points every 20 seconds during the gas collection phases. These discrete values were averaged to produce a mean value for each minute of the submaximal running stages. The final minute of each submaximal running stage was taken to represent the steady state value. At peak exercise intensity the average $\dot{V}O_2$ over the last three readings was taken to represent peak $\dot{V}O_2$ The following cardio-respiratory variables were assessed: relative oxygen consumption, ($\dot{V}O_2$)rel; fractional utilisation (FU); ventilatory equivalent for oxygen (VeO2); heart rate (HR); respiratory exchange ratio (RER) and Ventilation (Ve). In addition four site skinfold measurements were taken (bicep, tricep, subscapular and suprailliac).

Whole blood lactate samples were obtained from the fingertip at rest and 1 minute post exercise. The distal epidermal puncture was obtained using the Mumford Autolet-lite capillary blood sampler (AT0207). Duplicate blood samples were collected in heparinised 100µl whole blood analysis capillary tubes (GMRD-053) supplied by Analox Instruments, London, UK. The GM7 Analox lactate analyser was calibrated at the beginning and end of each test session with a range of lactate standards (2mMol/L-8mMol/L). All lactate values are expressed as Δlactate from rest for each individual subject.

Statistical Methods

A two-tailed unpaired t-test was used to investigate between group differences at the single comparison speed used in this study (9.6 km/h) and at peak exercise intensities. Statistics were performed using Microsoft Excel version 4 and a significance level of 0.05 was used.

Results

Comparison of the demographic data demonstrated that no significant differences existed for height, weight and age between the run-trained and control groups. Only the skinfold measurements were significantly different between the two groups', with the run-trained boys possessing lower sum of skinfolds. Based upon the physical examination and Tanner rating scale 23 of the boys were pre-pubertal, with only one boy in early puberty.

The submaximal lactate concentrations were 117% greater in the control group (control: 1.5mM/L vs run-trained: 0.69mM/L, P<0.03) than in the run-trained group. At the one comparison speed selected (9.6 km/h), the trained boys exhibited a significantly (P<0.01) higher submaximal energy cost of running with respect to the control boys. The trained boys were generating submaximal oxygen consumption values that were 5.84% higher than the controls. At the same comparison speed the trained boys also generated significantly (P<0.03) lower submaximal lactate, RER (P<0.05), FU (P<0.05) and submaximal heart rate values (P<0.01). No significant differences were noted for ventilation or VeO2 at the comparison speed (Table 6.2).

At peak exercise intensity a highly significant (P<0.0003) difference in aerobic power was noted between the two groups. The run-trained boys demonstrated higher peak oxygen consumption (control: 51.1 vs run-trained: 60.3 ml/kg/min). No significant (P>0.05) differences were noted with respect to any of the other cardio-respiratory variables at peak exercise intensity.

Discussion

Despite the absence of significant differences in height, weight and age between the two groups significant physiological differences existed at both submaximal and peak exercise intensities (Table 6.2). The submaximal running economy results generated at the comparison speed were particularly interesting . At 9.6 km/h the run-trained boys demonstrated 'poor' economy, manifest as a higher submaximal energy cost at a given submaximal workload.

Three theories have been postulated to account for these differences: limb segment theory, fat substrate theory and test protocol artefact.

The limb segment theory suggests that use of body weight may not be the most appropriate ratio standard for the expression of submaximal oxygen consumption. Body weight distribution varies from trunk to limbs and this distribution is not controlled for by the use of body weight as the ratio standard. Individuals who have a greater fraction of the body weight in the limbs (increased muscle mass per se) have a tendency to have a larger VO2max because of the recruitment of a greater active muscle mass. Equally, at submaximal exercise intensities the same individuals would have higher submaximal oxygen consumptions because of the extra cost of moving relatively heavier limbs. Both Cavanagh and Kram (1985) and Myers and Struedel (1985) suggested that runners with proportionately smaller body mass in the extremities (particularly legs) would perform less work moving these body segments during running than those with a greater proportion of body mass in the extremities.

The higher submaximal oxygen consumption values in the run-trained group suggest that more of the energy needs of the muscle are being met by aerobic metabolism. Within the context of the present study the lower RER and submaximal lactate values provide evidence to support this.

The fat substrate theory suggests that the increased oxygen consumption may reflect increased utilisation of free fatty acids or intramuscular triglycerides and/or a more efficient oxidation of blood borne and muscle carbohydrates. The lower RER values obtained in this study are in accord with data obtained by (Mayers and Gutin 1979 and Nudel *et al.* 1989).

Enhancement of the aerobic metabolism through training has been shown to occur through muscle morphology changes, enhanced muscle blood flow, enzymatic changes and preferential substrate utilisation. Du Plessis *et al.* (1985) demonstrated that adolescent boys have three times (13%) more transitional Type IIc fibres than adults (4%). Therefore, the potential for muscle morphological adaptation is present in adolescent populations. In fact specific sports training has been demonstrated to cause adaptation in muscle cell ultra-structure and metabolic capacity. However, the significance of muscle morphology to running performance in young athletes remains uncertain. Melichna *et al.* 1988 demonstrated that successful young 800m runners exhibited Type I muscle fibre distributions ranging from (23-83%). The most successful of these young athletes had fibre type ratios of 1:1 for Type I and Type II muscle fibres. Therefore, while evidence exists for muscle adaptation in this population, the relationship between muscle fibre composition and aerobic performance has yet to be established.

Similar equivocal evidence exists with regard to the role of enhanced muscle blood flow and its implications for enhanced aerobic metabolism. Koch (1974) demonstrated increased local muscle blood flow in children compared to adults. The capacity for adaptation through training in children is unknown, due to the invasive techniques required. Yost *et al.* (1981) have demonstrated an increased pulmonary capilliarisation with training in an animal model and hypothesised that this may parallel training induced capillary proliferation in muscle. The critical question is whether enhanced perfusion of muscle tissue either through capillary proliferation or enhanced muscle blood flow has any impact upon muscle cell substrate utilisation and ultimately aerobic performance. Some evidence from Eriksson (1980) in children with coarctation of the aorta suggests that the impact of blood perfusion upon substrate levels is minimal.

The enhancement of aerobic metabolism through enzyme changes with training was illustrated by Eriksson (1972). Phosphofructokinase levels and Succinate dehydrogenase levels were increased 83% and 30% respectively after 6 weeks of training in a group of 11 year old boys. NADH staining was more pronounced after training in this group of boys. However, despite the magnitude of these change only an 8% increase in $\dot{V}O_2$max was noted bringing into question the significance of the oxidative capacity of muscle on whole body oxygen consumption.

The question of preferential utilisation of fat as opposed to carbohydrate in children has been addressed by a number of authors. In contrast to adults, Berg & Keul 1980 demonstrated no significant difference in blood glucose concentrations during step-wise treadmill tests in 12-14 year olds. This enhanced glucose homeostasis was attributed to an increase in lipolysis and free fatty acid utilisation. Increased rates of lipolysis and elevated glycerol levels occurred at an earlier time threshold in the children. As Rowland *et al.* (1987) stated the utilisation of fatty acids in aerobic metabolism is reciprocally related to anaerobic glycolysis and lactate production. The enzymatic capacity of muscle tissue in children is designed for the breakdown of Acetyl-CoA compounds and can, through training be enhanced to maximise free fatty acid oxidation.

The 'poor' economy has also been attributed to an artefact of the specific test protocol chosen. Pate *et al.* 1992 theorised that runners with a high VO2max utilised a lower percentage of their VO2max at the submaximal speeds. This was demonstrated in the present study (control: 82.4% vs run-trained: 73.8%). If this intensity represented less than training pace the runners were less comfortable and subsequently less economical due to neural and mechanical factors. Within the context of the present study, the run-trained boys were exercising at around an average of 73% FU at 9.6 km/h. This exercise intensity represents the expected minimum boundary for training intensities for these runners. While the submaximal workload did represent a low exercise intensity for these runners a simple kinematic analysis indicated that there were no significant gait characteristic differences between the two groups at the comparison speed.

The impact of training upon the submaximal heart rate response in exercise has been addressed by a number of authors. (Bar-Or and Zwiren 1973, Stewart and Gutin 1976, Nudel *et al.* 1989) all reported lower submaximal heart rates in good or elite child runners compared to non-runners. At 9.6 km/h in the present study the run trained group demonstrated significantly lower ($P<0.01$) heart rates than the control group. Despite significantly lower FU and lactate values in the run-trained group compared to the control group, the two variables appear not to be related, as the within group correlations between FU and lactate were very weak.

The only significant variable at peak exercise intensity was relative oxygen consumption. The run-trained boys exhibited higher VO2(rel), demonstrating their superior aerobic power (Controls: 51.1 ± 3.3 versus Run-trained: 60.3 ± 2.8 ml/kg/min, mean±SD). These results are commensurate with those generated by other studies (Nudel *et al.* 1989, Sundberg and Elovainio 1982, Mayers and Gutin 1979 and Krahenbuhl and Pangrazi 1983).

In summary, the 'poor' economy demonstrated by the run-trained boys and the lower submaximal lactate and RER levels generated by these individuals lends credence to the theory that this 'poor' economy was most likely a reflection of enhanced Free Fatty Acid oxidation. If free fatty acid oxidation and glycolysis are reciprocally related then the superior aerobic power of the run-trained individuals allows them to monopolise fat as a primary energy source. Whether this is innate or arises as a consequence of long term moderate training remains to be determined.

The interpretation of a higher submaximal energy cost of running as 'poor' economy requires reviewing in light of the results generated in this study. Increased numbers of subjects and a longitudinal study design would help us to understand the mechanism which underpins this phenomenon.

Tables

	Trained (n=11)	Control (n=13)	
Age (yrs)	11.96	11.38	NS
(SD)	0.93	0.82	
Height (cm)	151.1	145.9	NS
(SD)	7.9	8.8	
Weight (kg)	39.01	38.83	NS
(SD)	5.3	8.6	
Tanner Grading			
Median	1	1	
Range	1-2	1-2	
Sum of Skinfolds (mm)	19.9	32.7	P<0.05

Tanner grading estimated from: Gen (Genitalia)
Ph (Pubic hair)
Tes (Testicular volume)

Table 6.1: Demographic details of trained and control boys.

	9.6 km/h			Peak Data		
	Control	Trained		Control	Trained	
ΔLa (mM/l)	1.5	0.69	P<0.03	3.98	3.5	NS
(SD)	0.96	0.69		1.6	1.5	
VO2 (ml/kg/min)	41.9	44.5	P<0.01	51.1	60.3	P<0.003
(SD)	1.95	2.6		3.3	2.8	
RER	0.98	0.95	P<0.05	1.08	1.08	NS
(SD)	0.05	0.04		0.05	0.05	
HR (bpm)	182	170	P<0.01	202	204	NS
(SD)	10	8		8	6.3	
FU (%)	82	74	P<0.05			
(SD)	51	4.12				
VeO2	28	25	NS			
(SD)	8.8	11.6				
Ve	45.1	42.8	NS			
(SD)	0.31	0.35				

Table 6.2: Cardio-respiratory and lactate analysis at submaximal and peak exercise intensities.

FACTORS INFLUENCING RUNNING PERFORMANCE

Introduction

In adults, three variables have been shown to influence success in distance running performance: running economy, peak oxygen consumption and fractional utilisation (defined as the percentage of peak aerobic power utilised at a given submaximal running speed). When differences in $\dot{V}O_2$ max values between athletes are narrow (Daniels and Daniels 1992, Morgan 1989a and Conley & Krahenbuhl 1980), differences in submaximal running economy may be important in distance running success. For example, Costill and Winrow (1970) attributed performance variability in 2 ultra-marathon runners with similar $\dot{V}O_2$max values to individual differences in running economy. Conley and Krahenbuhl (1980) and Fay *et al.* (1989) both obtained significant correlations between running economy and 10K and 16K performance times in trained adult runners. Differences in submaximal running economy were also thought to be responsible for almost identical 2 mile run times in 2 champion male distance runners whose $\dot{V}O_2$max values differed by greater than 10 ml/kg/min (Daniels 1974). However, some evidence is contradictory, demonstrating poor correlations between running economy and endurance performance. A number of studies have demonstrated poor correlations with respect to running economy and endurance performance (10k race times) within adult populations (Morgan (1987): r= 0.30, Morgan (1989b): r= 0.64 and Powers (1983), r= 0.51).

All the data in children refute the economy/performance relationship, except a single study of Rowland *et al.* (1988). These researchers related treadmill endurance time but not peak $\dot{V}O_2$ to running economy. Cunningham (1990b) demonstrated that running economy was poorly correlated (r=-0.05) to 5K race performance in a group of high school females. These results are in agreement with Krahenbuhl (1983) and Krahenbuhl *et al.* (1979) who demonstrated no correlation between submaximal aerobic economy and performance field tests.

Peak or maximal oxygen consumption has been demonstrated to correlate highly with adult endurance performance. Costill *et al.* (1967) and (1973) , Farell *et al.* (1979), Foster *et al.* (1977) and Maughan and Leiper (1983) have all demonstrated correlations in the range -.82 to -.91 between $\dot{V}O_2$max and endurance running performance in well trained experienced athletes. However, despite this evidence the influence of $\dot{V}O_2$max upon endurance running appears to be governed by the range of performance times and aerobic power ($\dot{V}O_2$max) within each subject group. Daniels and Daniels (1992) illustrated that $\dot{V}O_2$max correlates highly with distance running performance in a group who possess high $\dot{V}O_2$max values, but whose aerobic power and performance times vary across the group . The more homogeneous the group with respect to maximal aerobic power and running ability the lower the correlation between $\dot{V}O_2$max and distance running performance. This trend has been demonstrated in a number of studies. Conley and Krahenbuhl (1980), Morgan *et al.* (1989b), Powers (1983) and Tanaka (1984) all produced low correlations with running performance when the range of maximal aerobic power and performance times was narrow.

Fractional utilisation or the ability to sustain a high percentage of $\dot{V}O_2$max for a given period has been well related to race performance in adults (Conley *et al.* (1981). Costill *et al.* (1973), Pollock (1977), Sparling (1984) and Peronnet *et al.* (1987)). However, Cunningham (1990a) demonstrated that fractional utilisation at race pace was not linked to performance differences between male and female adolescent runners. This present investigation represents the first study of its kind to attempt to correlate laboratory based variables to running performance in a pre-pubertal population. Isolating those factors responsible for successful running performance at the pre-pubertal age could lay the foundation for the long term enhancement of successful running performance.

The primary aim of this study was to describe and relate the performances of run-trained pre-pubertal boys to these three major determinants of distance running success at both 3000m and 1500m

Methods

Subjects

Fifteen run-trained male pre-pubertal boys [age 11.7 ± 1.06yrs, mean ± SD, Table 7.3] volunteered to take part in a 3000m time trial and laboratory assessment. Within the context of this study, run training was defined as involvement in a formal, low intensity, aerobic training programme for a minimum of one year. The boys' training sessions had consisted primarily of endurance work with an element of interval training and amounted to 3 ± 1.66 hours per week. Ten boys returned for a 1500m time trial and laboratory assessment [age 11.9 ± 0.93yrs, Table 7.4]. Tables 7.3 and 7.4 give details of the demographic and race performance of the subjects. At both initial and return testing sessions, height, weight and skinfold measurements were taken.

The 3000m time trial was conducted at the end of the competitive racing season on a 200m indoor track at the Kelvin Hall International Sports Arena. The 1500m time trial was completed on the same track approximately half way through the winter season. For the time trials, the boys each had staggered starts. Thus while they were not competing directly against each other, they had the motivation of other boys being present during the run.

All but one of the subjects was familiar with exercise testing within the respiratory function laboratory. Despite this, all subjects were asked to attend for a habituation visit to accustom them to the equipment being used for cardio-respiratory testing. At this visit, the subjects were familiarised with the treadmill (Powerjog M10, Cardinal Sports, Edinburgh) by a period of walking and running (Shephard,1984).

Study Rationale

The initial study conducted in the summer racing season attempted to correlate submaximal and maximal physiological variables with 3000m race performance. This race distance was selected as one would tax the aerobic system of children of this age. Submaximal laboratory protocols were designed to attain steady state within each stage and allowed for the correlation of a range of submaximal speeds with race performance. Four submaximal speeds were selected for study representing a range of speeds from a slow submaximal run to approximate race pace.

In an attempt to partition factors responsible for successful pre-pubertal running performance at a slightly shorter distance (1500m), a second laboratory/performance investigation was undertaken. Adult 1500m running requires a significantly greater contribution from "anaerobic" sources. Consequently, in an attempt to quantify this contribution the intensity and duration of the submaximal protocols were re-structured. The length of each submaximal stage (4mins) and the treadmill speeds were re-designed to facilitate steady state lactate sampling. The 10 boys who took part in this second study were selected purely on the basis of their willingness to co-operate in further cardio-respiratory and capillary blood lactate sampling.

Study Design

The initial group of 15 run-trained boys underwent both a laboratory and field test. The laboratory based test consisted of submaximal and peak oxygen consumption tests. The submaximal protocol consisted of four running stages each of three minutes in duration with running speeds of 8, 9.6, 11.2 and 12.8 km/h respectively. The subjects then returned within seven days to complete a peak oxygen consumption test using a modified version of the protocol designed by Unnithan and Eston (1990). The running speed was customised to fit the individual requirement of each child. Once baseline speed was established the gradient was increased 2.5% every 2 minutes until voluntary exhaustion was attained. The child was judged to have reached peak $\dot{V}O_2$ when any two of the following four criteria were met (Williams and Armstrong, 1991):

1. Heart rate within 10 beats per minute of the age predicted maximum.
2. A heart rate plateau
3. Respiratory exchange ratio value greater than 1.0.
4. An approximate plateau of $\dot{V}O_2$ values

The field test consisted of an indoor 3000m time trial.

Ten of the boys returned to undergo further laboratory tests and the 1500m time trial. The laboratory based test again incorporated submaximal and peak oxygen consumption testing within the same session. The submaximal protocol consisted of three four minute stages at 9.6, 11.5 and 13.1 km/h These absolute speeds corresponded to approximately 75, 85 and 95% peak $\dot{V}O_2$ for the run-trained group. The running stages were interspersed with 7 minutes of passive and 3 minutes of active recovery (walking at 4 km/h) 20 minutes after the end of the final submaximal stage a peak oxygen consumption test was conducted. Whole blood capillary lactates were drawn at rest and 1-2 minutes following the end of each exercise stage including at the end of peak effort. Again a modified Unnithan and Eston (1990) protocol was used to achieve peak oxygen consumption. Criteria for the attainment of peak oxygen consumption as defined by Williams and Armstrong (1990) were used.

All laboratory based metabolic data measurements were made using a computerised metabolic cart (Sensormedics S2900Z, Bilthoven, Netherlands), which was calibrated prior to and following each test using two reference gases. This instrument has previously been validated for use in children (Unnithan *et al.*, 1992). A low dead space valve (16mls, Hans-Rudolph 1410B) was used to minimise dead space ventilation during the gas collection phases. Heart rate was monitored using a Sport Tester PE3000 heart rate monitor (Kempe, Finland). At all submaximal treadmill speeds the treadmill belt was calibrated by pre-marking the belt, measuring the belt length, noting the time taken for 20 revolutions and calculating the resulting speed.

Physiological Analysis

The S2900Z generated discrete data points every 20 seconds during the gas collection phases. These discrete values were averaged to produce a mean value for each minute of the submaximal running stages. The final minute of each submaximal running stage was taken to represent the steady state value. At peak exercise intensity, the average $\dot{V}O_2$ over the last minute was taken to represent peak $\dot{V}O_2$ The following cardio-respiratory variables were measured : relative oxygen consumption (VO2)rel, Fractional Utilisation(percentage of peak $\dot{V}O_2$) (FU), heart rate (HR), respiratory exchange ratio (RER).

Whole blood lactate samples were obtained from the fingertip at rest and 1 minute post exercise. The distal epidermal puncture was obtained using a capillary blood sampler (Mumford Autolet-lite, AT0207). Duplicate blood samples were collected in heparinised 100µl whole blood analysis capillary tubes (GMRD-053, Analox Instruments, London, UK). The GM7 Analox lactate analyser was calibrated at the beginning and end of each test session with a range of lactate standards (2mMol/L-8mMol/L). All lactate values are expressed as the change in lactate from rest for each individual subject (Δlactate).

Statistical Methods

Pearson Product Moment correlation coefficients were calculated for the selected physiological variables and performance times. Using a confidence interval of 5% and a two-tail analysis, r was considered to be significant ($r > 0.514$) Macin & Cambell (1987). Both simple and multiple linear regression analysis were used to analyse performance variability. Statistics were performed using the statistical functions in Microsoft Excel version 4 and a significance level of 0.05 was used throughout.

Results

3000m Analysis

The demographic characteristics of the run-trained group in the 3000m study are listed in Table 7.3. Two of the trained boys were unable to complete the 3000m time trial due to illness, hence times on 13 boys were available for analysis. Correlations between submaximal oxygen consumption and 3000m time ranged from -0.59 to -0.30 across the four submaximal running speeds. The only significant economy correlation was that between $\dot{V}O_2$ at 8 km/h and 3000m time trial (r= -0.59). In contrast, peak oxygen consumption was significantly correlated with 3000m run time (r= -0.83, Table 7.1, Figure 7.1). Submaximal running economy was found to be significantly correlated with peak oxygen consumption at three (8, 9.6 and 12.8 km/h) of the four submaximal speeds. However, although significant, the correlations were low, ranging from 0.52 to 0.66

Fractional utilisation was significantly but weakly correlated with running performance at the final two (11.2 and 12.8 km/h) submaximal running speeds (r= 0.61 and 0.67 respectively). Thus , the lower percentage peak $\dot{V}O_2$ utilised at these submaximal speeds the faster the finishing time on the time trial.

Submaximal HR was only significantly correlated with 3000m performance at 12.8 km/h (r= 0.59). HR at peak effort was also significantly correlated with 3000m performance time (Table 7.1).

Multiple linear regression analysis for the five most highly correlated variables ($\dot{V}O_2$ at 8 km/h, Peak HR, Peak $\dot{V}O_2$, FU at 12.8 km/h and HR at 12.8 km/h) was conducted to try to explain the source of variability in 3000m race performance time. The coefficient of determination (R^2) illustrated that the combined variances of all five variables accounted for 73% of the total variability in 3000m race performance. However, single linear regression analysis for peak $\dot{V}O_2$ alone accounted for 69% of the variance. It would appear that, with respect to 3000m race performance time, $\dot{V}O_2$max accounts for the majority of variability in running performance in this group.

1500m Analysis

Physiological correlates of 1500m race performance were assessed in the second study of ten boys (age 11.9± 0.93yrs, ht 151.1± 7.74cm, wt 38.7± 5.04 kg). Table 7.2 details the correlations obtained at submaximal and peak exercise intensities. VeO2 and VeCO2 at 9.6 km/h were significantly correlated with 1500m time. At 11.5 km/h Δ[La]blood, RER, HR and VeCO2, VeO2 and RPE were all significantly correlated with 1500m time. At the final submaximal running speed (13.1 km/h) the Δ [La] blood, RER, HR, VeCO2, VeO2 and RPE variables were all significantly correlated with 1500m race time. Again, peak $\dot{V}O_2$ was highly correlated with 1500m race performance (r = -.78).

Discussion

Running economy defined as the submaximal energy cost of running was only significantly correlated with 3000m performance time at one of the submaximal running speeds (8 km/h r = -.59) indicating that the higher the submaximal oxygen consumption the lower (ie faster) the 3000m performance time. This relationship might arise from enhanced oxidation of intra-muscular tri-glycerides or more efficient oxidation of blood borne carbohydrates in these trained runners. The greater energy cost of fat oxidation could have contributed to the higher submaximal energy cost of running but the resulting increase inefficiency of substrate utilisation could enhance 3000m race performance. However, multiple and single linear regression analysis illustrated that $\dot{V}O_2$ at 8 km/h contributed minimally to the variability in 3000m race performance (coefficient of determination, R^2= 35%). The low but significant correlations between submaximal oxygen consumption and $\dot{V}O_2$max at three (8, 9.6 and 12.8 km/h) of the four submaximal speeds indicates that those runners having a high $\dot{V}O_2$max are less economical at the submaximal speeds. This lends further support to the idea of enhanced aerobic power being coupled to a shift in substrate utilisation.

Several further theories have been postulated to explain the lack of correlation between running economy and performance time. The runners in this group were reasonably homogeneous in terms of age, running ability and training, all variables thought to influence running economy. Consequently, homogeneity amongst factors thought to relate to running economy would negate any possible relationship with running performance. The most critical factor appears to be the wide range of $\dot{V}O_2$max (55 to 67 ml/kg/min). Daniels (1985), Morgan *et al.* (1989b), Noakes (1988) and Sjodin and Svendenhag (1985) all reported that when performance levels were reasonably homogeneous, high $\dot{V}O_2$max values were associated with poor running economy. Equally, it was noticed that runners with lower $\dot{V}O_2$max values compensated by reducing their submaximal energy costs of running. The only other comparable paediatric performance research was conducted by Cunningham 1990b. He demonstrated that running economy was not correlated with running time at 5000m race distance in a group of female cross-country runners (age 15.9 yrs).

Conley and Krahenbuhl (1980) demonstrated similar performance times in a 10k race among highly trained experienced adult male runners. The association between race times and submaximal oxygen consumption ranged from 79 to .83. Fay (1989) demonstrated increasing correlation coefficients (-.40, -.55 and -.62) at 12.9 km/h for submaximal oxygen consumption and race times at 5, 10 and 16k. This suggests that running economy may be more important for longer distance races. In keeping with this, Svendenhag and Sjodin (1984) demonstrated that running economy was important for success at marathon running levels.

$\dot{V}O_2$max in the present study was found to correlate very highly with distance running time at 3000m (r= -0.83). These data are in line with the r values of -0.78 to -0.91 obtained by a number of authors (Costill *et al.* 1973, Farell *et al.* 1979, Foster *et al.* 1977, Maughan and Leiper 1983 and Sjodin and Svendenhag 1985) when the range of abilities within each subject pool was large. When running abilities were narrowed little relation with running performance was noted (r= 0.01 to 0.355) (Sjodin and Svendenhag 1985, Conley and Krahenbuhl 1980 and Tanaka and Matsuura 1984). Cunningham 1990b also demonstrated a significant relationship between running time and $\dot{V}O_2$max (r= -.69) in a group of female adolescent cross country runners. On the basis of multiple linear regression analysis $\dot{V}O_2$ peak accounted for 69% of the total multiple linear regression variance (73%) and is therefore the single most important characteristic associated with running success in moderately trained pre-pubertal runners.

Fractional utilisation is the ability to sustain a high percentage of $\dot{V}O_2$ for a given period and is another variable that has been associated with running performance (Costill *et al.* 1973). In the present study FU was poorly correlated to 3000m time trial at the lower two submaximal running speeds. Multiple and single linear regression analysis demonstrated that FU contributed minimally to 3000m performance variance. These results are in agreement with Cunningham (1990b) who demonstrated a poor association between FU and actual running time in female high school runners (r=0.18). To date the ability to sustain a high proportion of $\dot{V}O_2$max has been linked to successful running performance only in adults (Costill *et al.* 1973, Pollock 1977, Sparling 1984 and Peronnet *et al.* 1987].

Submaximal HR at 12.8 km/h and at HR at peak exercise were both significantly correlated with 3000m race performance. It is tempting to speculate that the high correlation between peak HR and 3000m race performance is an artefact of the high correlation between $\dot{V}O_2$max and race performance . This relationship could also reflect an enhanced peripheral oxygen extraction in the faster runner. Multiple linear regression analysis indicated that HR (submax and max) accounted for only a small part of the total 3000m performance variability.

In an attempt to determine other possible determinants of endurance performance a 1500m time trial was conducted. Consistent with the results generated from the 3000m study, submaximal oxygen consumption was poorly correlated with 1500m race time. Peak $\dot{V}O_2$ was significantly correlated with race performance. However, the magnitude of the correlation was slightly lower (r=-.78) . RER, HR, [La]blood, VeO2, VeCO2 and RPE were all highly correlated to 1500m race performance. Both the positive RER and [La]blood correlations at submaximal exercise indicate that successful 1500m race performance could be mediated by two possible mechanisms : the ability to oxidise blood borne carbohydrates more efficiently or to metabolise lactate more effectively. Palgi *et al.* (1984) examined physiologic correlates of 2k run-times in 10-14 year old children. Anaerobic capacity measured by the Wingate test was the most highly correlated variable accounting for 60% of the variance in 2k time in this study.

Two other variables demonstrated a significant relationship with running performance, rating of perceived exertion and Ventilatory equivalent for oxygen and carbon dioxide. The faster runners perceived the intensity of submaximal exercise to be lower at submaximal running speeds. This lower perception of effort could be coupled to the ability to withstand high levels of stress as a result of training or might be related to the lower lactate levels generated in the faster runner (0.7mM vs 1.75mM, fastest vs slowest 3k time trialist at 9.6km/h). Ventilatory equivalent data is compatible with the possibility that as a result of the enhanced aerobic power of the trained individual less anaerobic metabolic stimuli were applied to the respiratory system.

The evidence from both the 3000m and 1500m profiles indicates that children do have the metabolic capacity to adopt to the different demands of specialised running distances. Of the three major determinants of distance running performance examined in this study, $\dot{V}O_2$max appears to be the single most important factor for superior performance at either 1500m or 3000m.

Tables

Speed km/hr	8.0	9.6	11.2	12.8	Peak
VO2 (ml/kg/min)	-.59*	-.50	-.24	-.30	-.83*
FU (%)	0.21	0.49	0.61*	0.67*	
HR (bpm)	0.49	0.51	0.36	0.59*	0.60*

* (P<0.05)

Table 7.1: Pearson correlation coefficients for selected physiological variables and 3000m race time.

Speed km/hr	9.6	11.5	13.1	Peak
VO2	-.44	-.16	-.47	-.78*
RER	0.69*	0.85*	0.72*	0.33
HR	0.65*	0.78*	0.75*	0.21
[La]blood	0.19	0.74*	0.78*	0.18
VeO2	0.81*	0.85*	0.82*	
VeCO2	0.74*	0.65*	0.72*	
RPE	0.59*	0.75*	0.79*	

* (P<0.05)

Table 7.2:. Pearson Correlation co-efficients for selected physiological variables and 1500m race time.

Subject	Age (yrs)	Height (cm)	Weight (kg)	Sum of Skinfolds (mm)	Peak VO2 (ml/kg/min)	3000m Time (mins)
1	12.3	157.1	38.9	17.9	63.9	11:00
2	13.0	139.0	31.3	16.8	61.1	11:01
3	13.0	139.0	38.2	18.7	61.4	12:23
4	11.4	148.0	32.4	15.9	59.1	12:02
5	12.5	145.0	35.6	22.5	67.4	11:04
6	11.2	146.0	41.1	25.1	57.5	13.58
7	10.2	150.3	33.0	16.1	59.8	13.36
8	10.2	136.5	34.1	26.8	57.0	13:57
9	10.3	144.2	32.3	25.2	55.0	14:04
10	12.2	149.5	35.2	15.8	63.3	-
11	13.1	153.6	37.2	15.5	62.7	11:56
12	10.6	148.0	37.2	19.9	58.1	13:01
13	11.6	149.5	38.0	27.1	62.0	13:22
14	12.6	160.4	46.7	20.3	61.2	13:04
15	11.9	154.5	40.6	21.3	57.0	-
Mean	11.73	148	36.8	20.35	60.5	12:51
SD	1.06	6.77	4.09	4.17	3.26	1.05

Table 7.3: Demographic and performance details of 3000m time trialists

Subject	Age (yrs)	Height (cm)	Weight (kg)	Sum of Skinfolds (mm)	Peak VO2 (ml/kg/min)	1500m Time (mins)
1	12.5	159.4	40.2	18.0	62.9	5:26
2	13.0	141.9	33.3	18.0	65.8	5:32
3	13.3	153.9	39.2	17.8	57.1	5:36
4	11.7	148.0	33.6	18.0	60.1	5:45
6	11.5	146.9	43.8	28.4	53.9	6:39
16	10.7	160.6	45.3	23.4	62.0	5:35
8	10.5	137.1	34.2	21.6	57.0	6:29
10	12.6	152.1	37.4	15.3	57.1	6:00
12	10.6	148.2	37.8	20.5	59.5	6:06
14	12.8	162.6	49.4	20.7	61.9	5:34
Mean	11.9	151.4	38.7	19.9	60.3	5:40
SD	0.93	7.74	5.04	3.67	2.81	0.42

Table 7.4: Demographic and performance details of 1500m time trialists.

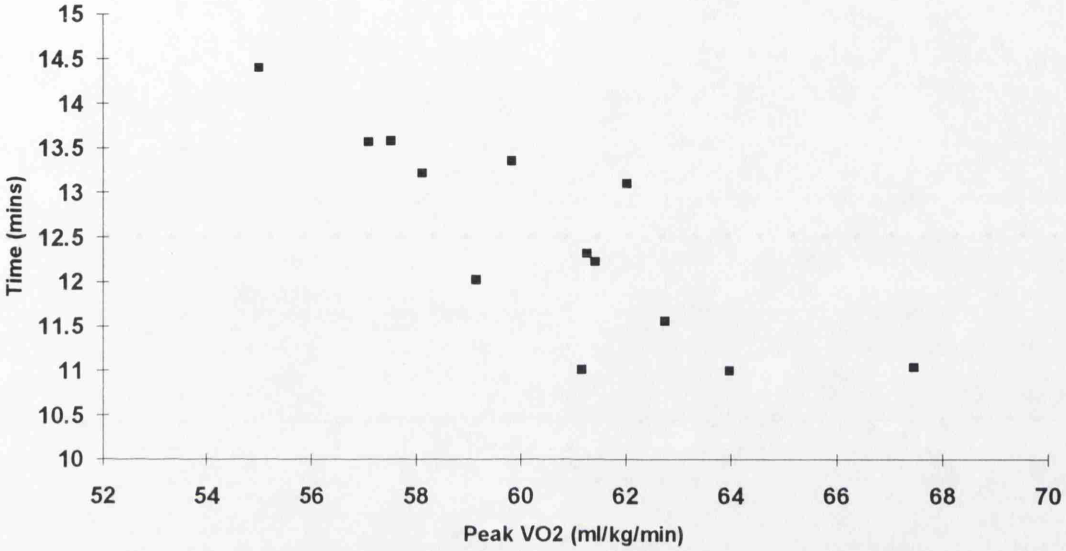

Figure 7.1: Relationship between peak $\dot{V}O_2$ and 3000m performance time

MANIPULATION OF SUBMAXIMAL RUNNING ECONOMY

LONGITUDINAL TRAINING STUDY

Introduction

Longitudinal training studies provide one of the most powerful methods of unravelling factors responsible for running economy in adults and children. However, studies of this nature are fraught with problems. Common weaknesses of previous studies in this field have included : inadequate sample sizes (Rowland 1985), the lack of assessment of intra-individual variability (Rowland 1985) and a failure to control potential factors which can affect running economy, such as fatigue, training status, circadian variation and treadmill accommodation (Morgan (1989a)). Consequently, many such studies do little more than "profile" differences between two groups of subjects. Even in cross-sectional studies , major sources of error can arise. The heterogeneity of selected sample populations can quickly confound subsequent data collection. Similarly, the absence of adequate control subjects, inadequate sample sizes and improperly designed testing protocols can all contribute to the misinterpretation of cross-sectional data.

The criteria for subject selection into both control and run-trained groups were the most difficult aspects of these studies. The criteria for selection into a run-trained group is normally based upon previous running history and race performance, which can be difficult to precisely quantify (Shephard 1992).

However, Daniels *et al.* (1978) demonstrated no change in submaximal running economy in 15 adult recreational runners over a shorter 8 week time period. Patton and Vogel (1977) demonstrated a significant improvement in a shorter time frame (6 months), in a group of fit (non run-trained) military personnel. Svendenhag and Sjodin (1985), Sjodin *et al.* 1982 and Conley *et al.* (1981) all demonstrated significant improvements in running economy in even elite athletes over 22 months, 14 weeks and 18 weeks respectively. This suggests a capacity for improvement in running economy even in well-trained subjects.

Results from several studies have demonstrated that high intensity aerobic training is necessary to bring about improvements in running economy. Conley *et al.* (1981) & (1984), Svendenhag and Sjodin (1985) and Sjodin *et al.* (1982) all included components of high intensity aerobic training as part of their training programmes. In the case of Conley *et al.* (1981) most of the improvements in running economy were noted during or immediately after a period of increased interval training. The major benefit of interval training is the promotion of economical running at the pace demands of competition.

In children, Daniels and Oldridge (1971) using a group of male athletes aged 10-15 years with previous running experience demonstrated improved submaximal running economy over a two year period. The only study that has attempted to directly manipulate submaximal running economy in children was conducted by Petray and Krahenbuhl (1985). No significant difference was noted in submaximal running economy following an 11 week training programme that involved steady state running training and biomechanical running instruction. This has led to a general consensus that, in children, submaximal running economy is resistant to manipulation through training (Krahenbuhl *et al.* 1989 and Krahenbuhl and Williams 1992).

We hypothesised that a high intensity training programme would promote an improvement in submaximal running economy within a pre-pubertal population and that failure to observe this in previous studies arose because of a failure to control for potential confounding factors. The primary aim of this study was to complete a longitudinal training study of 10 weeks in duration in a group of moderately trained pre-pubertal runners. The impact of growth upon selected cardio-respiratory variables was assessed by the physiological investigation at week 0 and week 10 in a comparison group of boys.

Methods

Subjects

Twenty boys volunteered to take part in this study (Appendix 2). The subjects were in two groups. The first group consisted of 10 run-trained subjects [age: 11.8 ± 1.03yrs, mean ± SD, Ht: 150.9 ± 8.25 cm and Wt: 39.5 ± 5.25 kg, Table 8.1]. For comparison a second group consisting of 10 subjects was studied [age: 11.3 ± 0.78 yrs, mean ± SD, Ht: 146.5 ± 8.56 cm and Wt: 39.3 ± 8.4 kg, Table 8.1]. The run trained subjects had each undergone on average one year of structured running training prior to the commencement of the present training study. The parents of the comparison subjects completed a physical activity questionnaire to allow determination of their children's physical activity profile (Appendix 3). Seven were rated as moderately active, but none was taking part in regular running training. All the boys taking part in the study were experienced in exercise testing having taken part previously in maximal and submaximal testing within the exercise laboratory. Despite this, all subjects were asked to attend for a habituation visit to re-accustom them to the equipment being used for cardio-respiratory testing. At this visit, the subjects were re-familiarised to the treadmill (Powerjog M10, Cardinal Sports, Edinburgh) by a period of walking and running (Shephard, 1984).

Study design

Prior to the commencement of the 10 week training study both groups of boys (comparison and run-trained) attended the laboratory for a physical examination and physiological testing. Pubertal status was assessed using pubic hair, genital development and testicular size (Tanner 1962). Four site skinfold measurements were measured (biceps, triceps, subscapular and supra-iliac). Pubertal gradings and growth measurements were repeated in both groups at week 10. One of the major limitations of a study of this nature is the choice of the control subjects. The control boys who volunteered for this study were very physically active, despite being non run-trained. Hence, the use of the term comparison rather than control group represented a more accurate description of the boys who took part in this study.

Training details

The boys in the training group trained three times a week with each session lasting 1 hour. To ensure full compliance with the training programme and to maintain enthusiasm and motivation, all training sessions were supervised by a senior British Amateur Athletic Federation coach. The composition of each session followed a similar pattern each week:

1. A 15 minute warm-up run was followed by 10 minutes of stretching and callanetics. The next stage was a hill session of 4 sets of 5 repetitions up a 60 metre incline, with a jog recovery. Four minutes rest was allowed between each set. The repetitions were designed in the main to be maximal efforts. The session was concluded by a 10 minute cool down run.

2. Session 2 was preceded by the standard warm-up run and Callanetics. This was followed by a 300m/500m/300m session with adequate recovery periods between each. Short recovery relays were conducted for a further 15 minutes and a 10 minute cool down run concluded the one hour session.

3. The third session of the week took the form of a race or a 30 minute fartlek run. Heart rates were palpated during the session in order to assess the approximate training intensity. Heart rates in the range (180-190 beats per minute) were recorded.

A 1500m time trial was conducted at week 0 and week 10 to assess improvements in performance after the training.

Test protocols

A single test session protocol was used for both the run-trained and comparison groups. The submaximal protocol differed for both the two groups. The run trained group completed three four minute running stages at 9.6, 11.5 and 13.1 km/h, corresponding to approximately 75, 85 and 95% peak $\dot{V}O_2$. The three running stages were interspersed with 7 minutes of passive and 3 minutes of active recovery (walking at 4 km/h). The comparison group performed only one 4 minute submaximal stage at 9.6 km/h). The treadmill belt speed was calibrated at each submaximal speed.

All the boys also performed a peak oxygen consumption test 20 minutes after the end of the final running stage using a modified version of a protocol designed by Unnithan and Eston (1990). In this protocol, the running speed was customised to each child . Once baseline speed was established the gradient was increased 2.5% every 2 minutes until voluntary exhaustion was attained. Each child was judged to have reached peak $\dot{V}O_2$ when any two of the following four criteria were met (Williams and Armstrong, 1991): 1. heart rate within 10 beats per minute of the age predicted maximum or 2. a heart rate plateau; 3. respiratory exchange ratio value of greater than 1.0 or 4. an approximate plateau of $\dot{V}O_2$ values.

Metabolic data measurements were made using a computerised metabolic cart (Sensormedics S2900Z, Bilthoven, Netherlands), which was calibrated prior to, and following each test using two reference gases. This instrument has previously been validated for use in children (Unnithan *et al.*, 1992). A low dead space valve (Hans-Rudolph 1410B) was used to minimise dead space ventilation during the gas collection phases. Heart rate was monitored using a Sport Tester PE3000 heart rate monitor (Kempe, Finland).

Physiological analysis

The S2900Z generated discrete data points every 20 seconds during the gas collection phases. These discrete values were averaged to produce a mean value for each minute of the submaximal running stages. The final minute of each submaximal running stage was taken to represent the steady state value. At peak exercise intensity the average $\dot{V}O_2$ over the last three readings was taken to represent peak $\dot{V}O_2$ and the following cardio-respiratory variables were measured : relative oxygen consumption ($\dot{V}O_2$)rel, fractional utilisation (FU), heart rate (HR), respiratory exchange ratio (RER) and ventilation (Ve) at both submaximal and peak exercise intensities.

Whole blood lactate samples were obtained from the fingertip at rest and 1 minute post exercise. The distal epidermal puncture was obtained using a capillary blood sampler (Mumford Autolet-lite AT0207). Duplicate blood samples were collected in heparinised 100µl whole blood analysis capillary tubes (GMRD-053, Analox Instruments, London, UK). The lactate analyser (GM7 Analox) was calibrated at the beginning and end of each test session with a range of lactate standards (2mMol/L-8mMol/L). All lactate values were expressed as Δlactate from rest for each individual subject.

Statistical methods

A two-tailed paired t-test was used to investigate the difference in pre- and post training variables within the run-trained group. A similar analysis was conducted with the comparison group in order to assess the influence of growth over the same time period. The power of the t-test enabled us to examine the delta(Δ) change in variables with training. A cross sectional between groups analysis was conducted in the section " Influence of Steady State Lactate". Statistics were performed using Microsoft Excel version 4 and a significance level of 0.05 was used.

Results

Demographic comparison of the run-trained and comparison boys from week 0 to week 10 indicated that no change in maturational status had occurred over the ten weeks for any of the boys. There was also no significant increase in height over the period of study for either group. However, statistically significant differences ($P<0.05$) were noted for Δweight and Δsum of skinfolds in the trained boys. The trained boys became significantly heavier than the comparison boys and this was also associated with a significant reduction in the sum of skinfold measurements over the ten week period (Tables 8.2, 8.3 and 8. 4).

In order to control for the effects of growth upon submaximal running economy both groups were tested at an overlap speed of 9.6 km/h at week 0 and week 10. No significant differences were noted for any of the selected physiological variables measured (Table 8.5).

Previous work produced in this laboratory (Reproducibility of cardio-respiratory measurements) measured within subject variability for submaximal exercise testing. Mean variability in submaximal oxygen consumption from test 1 to test 2 for a group of 10 pre-pubertal boys was 5.75% at 8.8 km/h. For both ventilation and heart rate the mean test-retest variability was 3.74%. Within the context of the present study three trained boys were selected to be tested twice at the start of the study. Submaximal oxygen consumption varied by a mean of 2.1% across the three speeds and ventilation by 3.9%. Consequently, both variables lay within the previously measured range of normal variability for submaximal testing. Within the context of the present study improvements in submaximal oxygen cost of economy of 7.6% at 9.6 km/h, 5.9%at 11.5 km/h and 7.2% at 13.1 km/h were noted. These improvements are well above the normal level of variability and indicate a systematic improvement. No effect was observed in the comparison group. The training schedule used, therefore, appeared to have brought about a significant improvement in submaximal economy.

Of the three submaximal speeds used, the smallest effects over the 10 weeks training were noted at 9.6 km/h. Nevertheless significant reductions in relative oxygen consumption ($P<0.01$, Figure 8.1), absolute oxygen consumption, submaximal heart rate and fractional utilisation were all present (Table 8.6). At 11.5 km/h significant reductions also occurred in ΔLactate, $\dot{V}O_2$(abs) and FU ($P<0.01$) along with $\dot{V}O_2$(rel); Figure 8.2 and HR ($P<0.05$) over the ten weeks of the study. The same variables including $\dot{V}O_2$(rel), Figure 8.3 were also significant at the final submaximal running speed (13.1 km/h). RER at any of the three running speeds did not change over the course of the training. The only variable to demonstrate a more significant reduction was FU ($P<0.01$). In light of the significant reductions in the other related physiological variables, the lack of change in RER should be treated with caution.

At peak exercise intensity, no significant difference was noted for any of the selected variables (ΔLactate, Peak $\dot{V}O_2$(rel) and Peak $\dot{V}O_2$(abs) from week 0 to week 10 (Table 8.7) for either the trained or the comparison group.

Discussion

Three important findings were noted in this longitudinal study: ten weeks of high intensity aerobic/interval training stimulated an improvement in submaximal running economy, reduced blood lactate accumulation but had no effect upon peak aerobic power.

That the changes observed were the result of training rather than growth was supported by two lines of evidence. Firstly, the lack of change in the cardio-respiratory and lactate data within the comparison group provided powerful evidence that the significant physiological adaptations seen in the trained group resulted from the training undertaken. Further, quantification of intra-individual variability within the trained group established clearly that significant physiological change beyond normal test-retest variability had occurred .

The sources of improvements in submaximal running economy were potentially multiple and complex as relationships exist between submaximal running economy and a number of variables including heart rate, ventilation, substrate utilisation and lean body mass.

Two variables that have previously been shown to be significantly related to running economy are heart rate and ventilation. Pate *et al.* 1992 demonstrated positive relationships between heart rate and ventilation with running economy. However, within the context of the present study, significant reductions in ventilation following training were only noted at 13.1 km/h. It would appear that any "training effect" for ventilation manifested itself only at the final submaximal running speed. Ventilation has been demonstrated to be 7 to 8% of the total oxygen cost of exercise (Milic-Emili *et al.* 1962). The potential, therefore, exists that a manipulation of ventilation could alter overall running economy. The enhanced buffering capacity, reduced lactate production and higher blood pH adaptations to training (Koch and Rocker 1980) all could contribute to a reduced metabolic ventilatory demand and the energy saved by reduced metabolic demand may act to decrease the whole body oxygen cost. The evidence from the present study suggests that in practise, the contribution to sub-maximal economy is minimal.

Significant reductions in submaximal heart rates following training were noted. Such improvements have potentially been linked to a reduction in whole body oxygen consumption through a reduction in myocardial oxygen consumption which constitutes a significant fraction of whole body oxygen consumption during exercise (Kitamura 1972). Again reductions in myocardial oxygen consumption could theoretically reduce whole body oxygen consumption and therefore improve running economy. Assuming that haemoglobin concentrations, haematocrit and oxygen demand of the muscles remain constant the rate at which blood is supplied to the working muscles and cardiac output would be constant at a given submaximal workload. Any reduction in myocardial oxygen consumption would then result from a reduced heart rate and increased stroke volume.

Evidence exists in animal models that if cardiac output is held constant, myocardial oxygen consumption is reduced in isolated canine hearts when the heart rate was slowed. Manipulation of heart rate and it's effect on whole body oxygen consumption has been assessed in humans by the use of β-blockers. Kalis *et al.* (1988) demonstrated that a reduction of submaximal heart rate of 35 beats per minute was associated with a reduction in whole body oxygen consumption of 0.1l/min. However, the interpretation of the β-blockade response is masked by the complexity of its multiple interactions. β-blockers have the capacity to inhibit lipolysis leading to a greater carbohydrate contribution to energy. This effect in itself could reduce submaximal oxygen consumption. The preceding line of argument indicates that the manipulation of submaximal heart rate could have implications for submaximal running economy. Training adaptations noted in the present study demonstrate a significant reduction in submaximal heart rate across all three speeds following training of the order of 8 bpm. Whether this training induced reduced submaximal heart rate response is the result of a training stimulated enhanced contractility or enhanced left ventricular filling response remains to be investigated and its contribution to the improved submaximal running economy has yet to be fully established.

Another theoretical mechanism potentially capable of altering submaximal running economy is the alteration of substrate utilisation. When carbohydrate is used as a primary substrate 5.05 kcal of energy are generated for every litre of oxygen consumed; fats, in contrast, generate 4.70 kcal per litre of oxygen. The preferential usage of carbohydrates as a primary substrate for exercise is also linked to the more direct and faster functioning pathway for carbohydrate metabolism. In addition, Acetyl-CoA generated from carbohydrate metabolism also acts to inhibit β-oxidation (Brookes and Fahey 1984).

Consequently, the manipulation of substrate utilisation through diet or training should contribute to a reduced submaximal oxygen cost of running. However, Davis *et al.* (1988) demonstrated that carbohydrate dietary manipulation had no significant effect upon submaximal running economy in adults . It has been documented that children have lower concentrations of the glycolytic rate limiting step enzyme, Phosphofructokinase (PFK) (Rutenfranz 1986). This bio-chemical difference in children would alter the balance towards fat oxidation in preference to carbohydrate metabolism.

Only one study has demonstrated the capacity to alter the glycolytic potential in children through training. 6 weeks of interval training in 11 year old boys stimulated an 83% increase in PFK, a 30% increase in Succinate dehydrogenase and an overall higher lactacid capacity(Errikson *et al.* 1973). It is tempting to speculate that the high intensity aerobic training conducted in the present study increased the glycolytic capacity of the trained boys and this increased glycolytic potential then contributed to the reduced submaximal running economy seen following training.

The increased potential glycolytic capacity and the reduced submaximal blood lactate levels post training might at first appear contradictory. However, it has been well documented that children possess several physiological adaptations that allow for more effective clearance of blood lactate, adaptations which may possibly be enhanced through training. Sympathetic activity during exercise is less in pre-pubertal children, consequently lessened hepatic vasoconstriction might allow for more rapid liver metabolism of lactate (Macek 1986). Higher local muscle blood flow might also contribute to enhanced lactate clearance (Koch & Rocker 1980). Reported changes as a result of aerobic training, such as capillary and mitochondria proliferation, both would assist in enhancing lactate clearance Brookes & Fahey (1984).

The relationship between submaximal running economy, training and enzyme profiles were demonstrated by Sjodin *et al.* 1982. These researchers documented illustrated increases in heart specific Lactate dehydrogenase (H-LDH) enzyme in adult middle and long distance runners . Improvements in submaximal running economy were found to be highly correlated with increased levels H-LDH. It has been demonstrated that H-LDH bound to the inner membrane of the mitochondria will facilitate the oxidative translocation lactate in the presence of NAD (Skilleter and Kun 1972). The net result of this adaptation would be lower blood lactate accumulation at absolute or relative exercise intensities. The possibility of such a change in the present study is speculative but it highlights questions that future paediatric training studies may need to address using magnetic resonance spectroscopy (Zanconato et al 1993).

The alterations noted in the body composition of the trained boys could also contribute to enhanced submaximal running economy. Body weight increased over the ten week training period by a mean of 1.44 kg accompanied by a reduction in mean skinfold measurements of -0.71 mm could have subtle influences upon submaximal running economy. An increase in weight coupled with a reduction in sum of skinfolds implies an increase in lean body mass (muscle mass). Improved muscular efficiency as a result of increased muscle mass recruitment could have the capacity to improve submaximal running economy.

The lack of change in peak $\dot{V}O_2$ following the ten week training programme has been addressed by a number of authors. Pate and Ward (1990) stated that as in adults paediatric subjects with high fitness levels might not demonstrate a large improvement in peak oxygen consumption with training. In fact, Koch & Rocker (1980) suggested that the upper limit of trainability for maximal oxygen consumption is 60 ml/kg/min in boys aged 12-15 years. While initial fitness levels may be a determinant of the capacity to improve maximal oxygen consumption, so too is the nature of the training programme. Krahenbuhl & Williams 1992 reviewed several studies in which pre-pubertal children improved running performance times with little or no improvement in maximal oxygen consumption. In 5 of these studies there was little or no steady state endurance running. Consequently, the lack of change in peak $\dot{V}O_2$ may reflect both the high fitness levels of our subjects and the lack of significant endurance component in their ten week training programme.

In summary, we would speculate that the improvements in submaximal running economy seen in the present study could be the product of improved mechanical and biochemical efficiency stimulated through training. Incorporation of pre and post training kinematic and kinetic analyses would have allowed us to assess any improvement in mechanical efficiency. Daniels *et al.* (1978) suggested that factors representing local muscular metabolic characteristics should be considered when attempting to evaluate the adaptation to training in trained subjects. This has particular relevance in instances where no significant alterations in peak oxygen consumption were noticed.

Whatever the origin, stimulating improvements in running economy through training manipulations appears to be a most productive path to follow. More research experimenting with different combinations of training stimuli will help to refine the nature of the most appropriate stimuli.

Tables

	Run-Trained			Comparison Group		
Subject	Age (yrs)	Ht (cm)	Wt (kg)	Age (yrs)	Ht (cm)	Wt (kg)
1	12.5	159.4	40.2	11.9	152.6	39.9
2	13.0	141.9	33.3	11.4	148.8	41.4
3	13.3	153.9	39.2	12.6	152.2	39.4
4	11.7	148.0	33.6	10.6	146.8	38.7
5	11.5	146.9	43.8	10.8	144.5	46.2
6	10.7	160.6	45.3	11.7	146.6	48.4
7	10.5	137.1	34.2	11.0	157.5	50.0
8	10.6	148.2	37.8	11.6	140.0	28.6
9	12.8	162.6	49.4	9.70	124.9	20.8
10	-			11.94	151.9	40.0
Mean	11.8	150.9	39.5	11.3	146.5	39.3
SD	1.03	8.25	5.25	0.78	8.56	8.40

Table 8.1: Demographic details of run-trained and comparison subjects

Subject	Age (yrs)	ΔHt (cm)	ΔWt (kg)	ΔSum of Skinfolds (mm)
2	13	0.0	0.2	0.80
14	12.8	3.0	2.8	0.66
12	10.6	0.7	2.3	-2.00
1	12.5	1.6	0.3	0.30
16	10.7	1.3	1.0	0.93
3	13.3	0.0	1.3	0.00
4	11.7	1.7	1.1	0.40
8	10.5	1.6	0.8	-2.00
6	11.2	0.6	2.2	-3.60
Mean	11.8	1.17	1.33	-0.71
SD	1.03	0.96	0.91	1.53

Table 8.2: Demographic characteristics of the trained boys expressed as delta variables from week 0 to week 10.

Subject	Age (yrs)	ΔHt (cm)	ΔWt (kg)	ΔSum of Skinfolds (mm)
1	11.9	1.2	0.8	3.9
2	11.4	1.4	1.2	2.3
3	12.6	1.8	1.8	3.3
4	10.6	0.9	0.6	2.3
5	10.8	0.0	0.8	-2.4
6	11.7	0.0	1.1	-1.6
7	11.0	2.4	-0.2	7.3
8	11.6	0.9	-0.4	-2.9
9	09.7	0.5	-0.2	7.9
10	11.9	1.8	-0.2	2.7
Mean	11.3	1.01	0.61	2.28
SD	0.78	0.79	0.75	3.72

Table 8.3: Demographic characteristics of the comparison boys expressed as a change in variables from week 0 to week 10.

Variable	Trained	Comparison	
Δheight (cm)	1.17	1.01	NS
(SD)	0.96	0.79	
Δweight (kg)	1.33	0.61	P<0.05
(SD)	0.91	0.75	
Δsum of skinfolds	-0.71	2.28	P<0.05
(SD)	1.53	3.72	
Tanner grade	8 Stage1,1 stage2	10 stage 1	

Table 8. 4: Summary of demographic changes from week 0 to week 10 for trained and comparison boys.

	9.6 km/h		
	Week 0	Week 10	
ΔLactate (Mmol/l)	1.65	1.63	NS
SD	1.00	0.65	
VO2(rel) (ml/kg/min)	42.04	43.02	NS
SD	2.21	3.32	
VO2(abs) (ml/min)	1641	1696	NS
(SD)	319	324	
FU	84	83	NS
(SD)	5.19	3.97	
RER	0.99	1.0	NS
(SD)	0.05	0.05	
HR (beats per min)	183	185	NS
(SD)	9.35	7.8	

Table 8.5: Summary of physiological data for comparison boys from week 0 to week 10 at submaximal exercise intensities.

	9.6 km/h			11.5 km/h			13.1 km/h		
	0 wk	10 wk	P value	0 wk	10 wk	P value	0 wk	10 wk	P value
ΔLactate (Mmol/l)	0.82	0.58	NS	1.48	0.78	<0.05	2.66	1.61	<0.05
(SD)	0.78	0.28		0.96	0.33		1.52	0.75	
VO2 (ml/kg/min)	44.0	40.63	<0.05	49.53	46.60	<0.01	56.16	52.14	<0.01
(SD)	2.81	2.66		2.31	1.44		2.46	2.0	
VO2(abs) (l/min)	1745	1650	<0.01	1963	1905	<0.05	2227	2128	<0.05
(SD)	302	261		328	319		388	335	
FU (%)	73	68	<0.05	83	78	<0.05	94	87	<0.01
(SD)	4.43	4.89		5.48	4.51		5.02	3.28	
RER	0.94	0.95	NS	0.98	0.98	NS	1.01	1.01	NS
(SD)	0.03	0.03		0.04	0.03		0.05	0.04	
HR (bpm)	169	164	<0.05	182	174	<0.01	195	186	<0.01
(SD)	10.42	7.98		5.53	5.66		9.42	8.62	

Table 8.6: Summary of physiological data for trained boys from week 0 to week 10 at submaximal intensities.

	Week 0	Week 10	
Peak ΔLactate (Mmol/l)	3.49	3.58	NS
(SD)	1.53	0.65	
Peak VO2 (ml/kg/min)	60.12	59.84	NS
(SD)	3.61	3.93	
Peak VO2(abs) (l/min)	2375	2440	NS
(SD)	363	416	

Table 8.7: Summary of physiological data for trained boys from week 0 to week 10 at maximal exercise intensities.

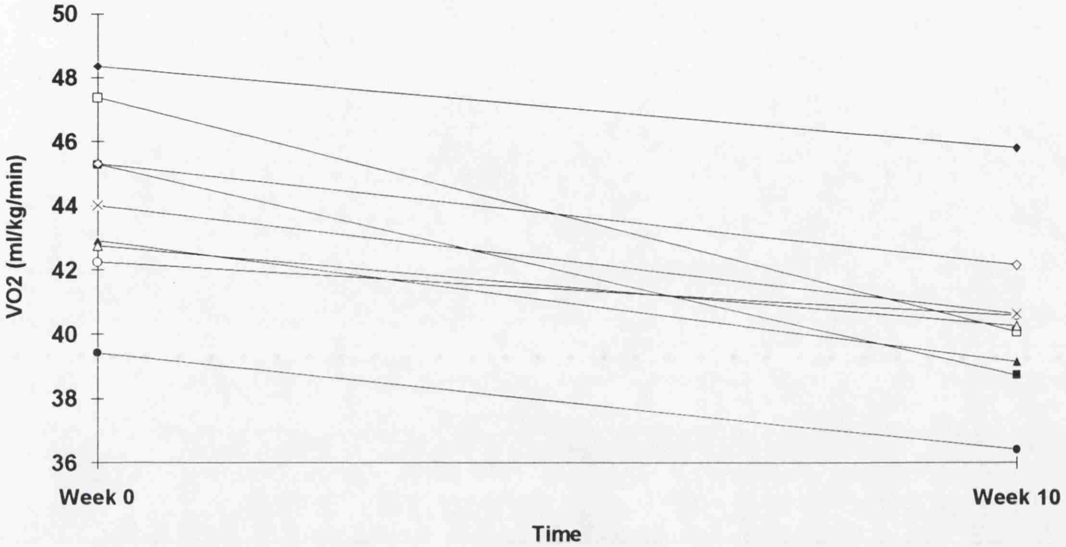

Figure 8.1: Impact of a 10 week training programme on submaximal running economy at 9.6 km/h

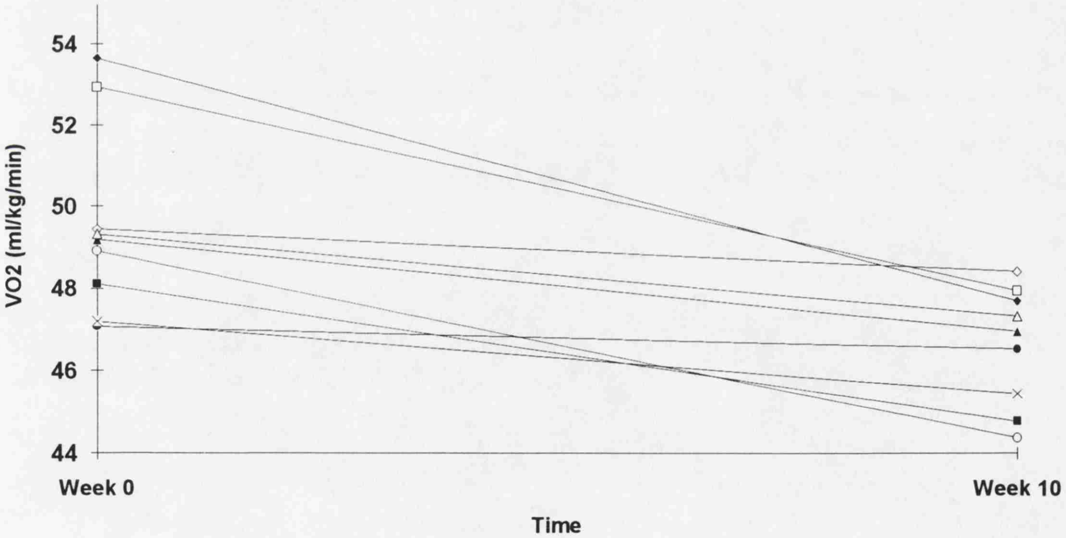

Figure 8.2: Impact of a 10 week training programme on submaximal running economy at 11.5 km/h

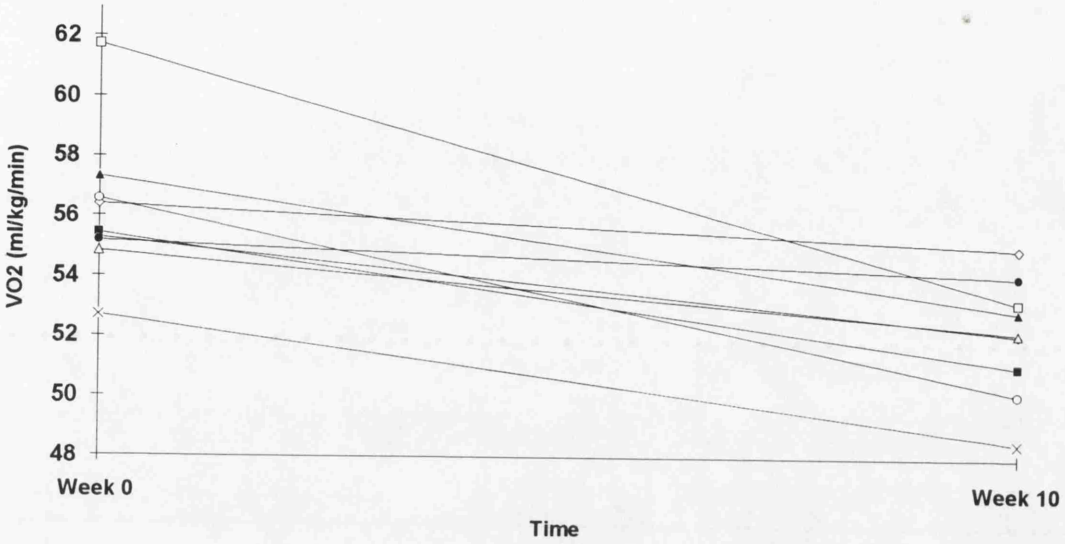

Figure 8.3: Impact of a 10 week training programme on submaximal running economy at 13.1 km/h

BETA 2- AGONISTS AND RUNNING PERFORMANCE

Introduction

Two key components of submaximal running economy are heart rate and ventilation. Bailey and Pate (1991) demonstrated that the two were positively correlated with running economy (i.e. an increase in submaximal oxygen consumption was accompanied by an increase in heart rate and ventilation). Consequently, the hypothesis was framed that any variation in submaximal heart rate and ventilation could have implications for whole body submaximal oxygen consumption. In an attempt to test this hypothesis, we administered inhaled therapeutic dosages of a β2-agonist (Terbutaline) in a group of normal healthy pre-pubertal boys.

Recently, there has been concern that β2-agonists may be ergogenic and actually improve athletic performance (Bedi *et al.* 1988 and Signorile *et al.* 1991.) In asthmatic adults, the possible ergogenic effect of β2-agonists have been addressed in a number of studies. These studies have shown that the β2-agonist Salbutamol did not alter the $\dot{V}O_2$max in trained asthmatics (Freeman *et al.* 1989). In this particular study, the dosage administered was described as the regular metered dosage for each individual from an aerosol inhaler. Trained non-asthmatics were also non-responders to β2 stimulation (McKenzie *et al.* 1983). In untrained asthmatics a dosage of 5mg in 2ml of saline produced no enhancement of $\dot{V}O_2$max again using an aerosol inhaler (Ingerman-Hanson *et al.* 1980). Schmidt *et al.* (1988) assessed the response in normal non-asthmatic adults and again found no significant differences with respect to maximal oxygen consumption, ventilation, lactate threshold and total run time. In adults, therefore, it appears, that pre-medication with approximately physiological doses of β2-agonists leads to no significant improvement in maximal exercise performance in either asthmatic or non-asthmatic, trained or untrained adults.

In children, there is some evidence that the response to β2-agonists may be different. Zanconato *et al.* (1990) examined the effects of pre-treatment with a β 2-agonist (Salbutamol) on the energy cost of running at submaximal and maximal intensities in a group of asthmatic children. Pre-medication with 200μg of salbutamol via a metered dose inhaler led to lower maximal ventilation and a lower energy cost of running at submaximal stages compared to placebo. These data suggested that pre-medication enhanced the submaximal running performance of an asthmatic child. The use of this drug has other implications in the light of evidence that suggested that this group of drugs may have ergogenic properties in children. Asthmatic children are encouraged to participate in a wide range of sporting activities. However, their ability to take part fully in sport often depends upon pre-medication with β2-agonists. Removing its use in competitive sport would prevent the participation of considerable numbers of junior competitors.

To date, no studies have assessed the possible ergogenic effects of β2-agonists in normal children. This is of importance because β2-agonists have been demonstrated to be safe, effective and easily administered. The aim of this study was to attempt to manipulate submaximal running economy through the administration of a standard pharmacological dosage of a β2-agonist (Terbutaline) in normal non-asthmatic pre-pubertal boys and evaluate any possible ergogenic effects.

Methods

Subjects

10 pre-pubertal boys (Tanner stage 1) volunteered to take part in the study (age 10.4± 0.48yrs, mean ± SD, Table 9.1) The study was approved by the Ethics Committee of the Royal Hospital for Sick Children and informed consent was obtained from the parents or guardians before the start of the study.
All testing took place in the Respiratory Function Laboratory of the Royal Hospital for Sick Children. A preliminary familiarisation visit was organised before the first test. At this visit the subjects were introduced to treadmill walking and running in order to reduce subsequent test anxiety.

Study Design

The study was a single blind study, with subjects randomly assigned to either a drug or a placebo group before their first test. Prior to each exercise test, 2 puffs (500µg) of Terbutaline or placebo were administered via a Nebuhaler (Astra, Herts) using a standard "five breath" technique. The submaximal exercise protocol was performed first and peak $\dot{V}O_2$ testing was conducted second with 48 hours separating each session. The sequence was paired for both drug and placebo.

All metabolic data measurements were made using a computerised metabolic cart (Sensormedics S2900Z , Bilthoven, Netherlands), which was calibrated prior to each test. This instrument has previously been validated for use in children (Unnithan *et al.* 1992). Low dead space valves (Hans-Rudolph 1410B) and narrow bore tubing were used to minimise dead space ventilation during the gas collection phases. Heart rate was monitored using a Sport Tester PE 3000 heart rate monitor (Kempe, Finland). The laboratory temperature was maintained at 21 Celsius and 50% relative humidity for the duration of the study.

Submaximal Economy Testing

All ten boys performed two submaximal economy runs over a 4 week period. The submaximal protocol involved exercise at 3 submaximal running speeds (7.2, 8.0 and 8.8 km/h). The submaximal exercise test was discontinuous in nature. With each 6 minute running stage ended with an 8 minute passive recovery.

Peak Oxygen Consumption testing

The ten boys also performed two peak $\dot{V}O_2$ tests within the four week period with drug or placebo administered in the same way as for the submaximal testing. The peak $\dot{V}O_2$ test involved running at a constant speed of 8.8 km/h with an increase in gradient of 2.5% every 2 minutes until voluntary exhaustion was attained. Heart rate and cardio-respiratory variables were measured throughout the test. The child was judged to have reached peak $\dot{V}O_2$ when any two of the following four criteria were met (Williams and Armstrong (1991):heart rate within 10 beats per minute of the age predicted maximum, a heart rate plateau, respiratory exchange ratio value of greater than 1.0 and an approximate plateau of $\dot{V}O_2$ values.

Pulmonary Function Tests

Pulmonary function tests (PFT) were performed using a calibrated pneumotach system (Screenmate, Jaeger, Germany). Each subject performed three trials for the assessment of FEV_1. PEFR was measured using a Wright peak flow meter. All PFT's were measured prior to the administration of drug or placebo, immediately post-administration and 2, 8 and 15 minutes post exercise for both submaximal and maximal exercise testing.

Statistical Methods

The sample size was determined by a power calculation based upon an assumed magnitude of standardised expected differences in oxygen consumption between treatments of 0.85 and a significance level of 0.05 for a 2-sided test. Standardised differences (0.85), two-sided alpha error of 0.05 and a chosen power of 70% determined the selection of 10 subjects for the study (Statistical Tables for the Design of Clinical trials, Machin and Campbell 1987). Data were summarised using standard descriptive measures (mean and standard deviations). Analysis of Variance (ANOVA) was used to investigate any drug and or speed effects for each variable separately and to compare the selected variables. Statistics were performed using Minitab version 7 and a significance level of 0.05 was used.

Results

Cardio-respiratory Variables

No significant differences were found after pre-medication for $\dot{V}O_2g$ and heart rate at both submaximal and maximal exercise intensities (Table 9.2, Figures 9.1 and 9.2). Further ANOVA analysis demonstrated no significant visit effect . A treatment effect was noted, as pre-medication with Terbutaline resulted in higher Respiratory Exchange Ratio (drug: 0.94, 0.93, and 0.94 vs placebo: 0.91, 0.92 and 0.91, $P<0.05$, Figure 9.3). Fractional utilisation values at submaximal intensities were also elevated with pre-medication (drug: 66, 72 and 77% vs placebo: 63, 69 and 75%, $P<0.05$, Figure 9.4).

Pulmonary Function Tests (PFT's)

All children demonstrated normal lung function profiles confirming the absence of any exercise induced asthmatics within the subjects. Terbutaline and placebo produced a small but significant pre to post exercise increase in FEV_1 ($P<0.001$). The small but significant increase in FEV_1 was not dependent upon the exercise intensity. (Table 9.3)

Pre-treatment with Terbutaline produced a small but significant increase ($P<0.001$) in the post-exercise PEFR values. This increase was intensity dependent: post-maximal values were significantly higher ($P<0.001$) than post sub-maximal values. Analysis of the two main effects demonstrated no drug effect, but a significant visit effect was noted. The PEFR values were consistently lower at the first visit (all submaximal) than at the second visit (maximal tests, Table 9.3).

Discussion

In this single blind placebo controlled study, a normal pharmacological dose (500 µg) of Terbutaline had no effect upon the maximal exercise capacity of the non-asthmatic child. In addition, inhalation of the drug produced only small changes in the cardio-respiratory responses to submaximal steady state exercise.

No significant differences were noted with respect to oxygen consumption at any of the submaximal running stages. Thus, running economy defined as the energy cost at a given submaximal work load was unaffected by the inhalation of the drug. Lung function data generated by this study demonstrated that all children had normal lung function and pre-medication produced no physiologically significant enhancement of PEFR and FEV_1.

The increased RER in the absence of any significant ventilatory changes with pre-medication could be attributed to a possible shift in substrate utilisation. An increased relative contribution of carbohydrate (Persson *et al.* 1970) could have led to the elevation in the RER. The use of RER as an estimation of substrate utilisation is a crude index. However, in the absence of blood analysis and with the lack of ventilatory change, only tentative substrate inferences can be made. Terbutaline has the capacity to stimulate both lipolysis and to enhance glycogenolysis in the liver. It also has the capacity to influence potassium uptake into the cells. The higher RER values demonstrated with pre-medication might, therefore, indicate a possible shift towards an increased carbohydrate contribution in exercise. This would have been expected to be associated with a lower oxygen consumption at submaximal exercise (Bailey and Pate (1991). While statistical significance was obtained for the RER shift, the magnitude of these changes are small, therefore the interpretation of substrate changes should be treated with caution.

Direct manipulation of carbohydrate levels during exercise were conducted by Davis *et al.* (1988), who demonstrated, that an increased carbohydrate ingestion during submaximal exercise while increasing the RER had no significant effect upon reducing the submaximal oxygen consumption. Alternatively, increased recruitment of fast-twitch fibres would lead to greater glycogen depletion and hence an elevated RER. However, it would appear unlikely that a change in muscle fibre recruitment could be stimulated by the acute administration of a β2-agonist.

Fractional utilisation has been found to be closely related to running performance in adults (Conley & Krahenbuhl 1980), but its significance in children is not yet established. Consequently, the elevated fractional utilisation values with pre-medication are of uncertain significance with respect to running performance in children. The cause of this increased fractional utilisation may be due to the impact of the drug elevating resting metabolic rate. Imai *et al.* (1975) stated that the cardiovascular changes seen with the inhalation of a β2-agonist in situ or in isolation would have minimal significance under the normal physiologic conditions of exercise. as the response would be completely masked by the systemic response of the body to an increased oxygen demand. Consequently, a rigorous analysis of resting metabolism would be required to fully understand the mechanisms of the observed changes.

Whether chronic long-term usage of the drug would systematically alter the child's response has yet to be evaluated. The improved submaximal energy cost of running seen with pre-medication with Albuterol in mild asthmatics, Zanconato *et al.* (1990). could have been influenced by the fact that several subjects were on long-term medication. The impact that these drugs may have upon long-term metabolic adaptations to exercise have yet to be elucidated. However, McKenzie *et al.* (1983) demonstrated that a 1 week administration of inhaled salbutamol produced no improvement in VO2max or pulmonary function in non-asthmatic adults.

It was not possible to estimate the effective dosage of the of the drug administered. However, it is clearly documented in the literature that the nebuhaled route of administration has the greatest local effect and the least systemic toxicity Katzung (1989). Terbutaline also has a longer duration of action than other sympathiomimetics. Therefore it is assumed that optimal effective dosages were attained for all the children.

It would appear based upon cardio-respiratory and pulmonary function data that Terbutaline was not capable of modifying whole body oxygen consumption. The use of a β2-agonist enabled us to re-examine the relationship established by Zanconato *et al.* 1990 between enhanced submaximal performance and the administration of the drug in asthmatic children. Based upon the relationship established by Bailey and Pate (1991) the expected outcome for the administration of a β2-agonist should have been a higher energy cost of running. This was not achieved in the present study, possibly as a result of the less systemic nature of the drug.

The lack of change in heart rate and ventilation following pre-medication could have been a product of the specific nature of the drug. Consequently, the use of a more systemic, less specific β2-agonist could potentially have modified heart rate and ventilation responses. The absence of any change in submaximal running economy following pre-medication may be an indication of the robustness of this variable to manipulation. Alternatively it may indicate the subtle interplay of variables such as heart rate, ventilation and substrate utilisation.

From the evidence of this study it appears that the acute use of a β2-agonist pre-exercise confers no significant ergogenic benefits on submaximal and maximal running performance in non-asthmatic children. However, further investigations utilising more invasive techniques (blood substrate analysis) will be necessary to fully understand the mechanism of action of this drug and its interaction with children and exercise.

Tables

Subject	Age (yrs)	Height (cm)	Weight (kg)	Sum of Skinfolds (mm)
1	10.0	136.0	29.3	21.0
2	10.2	148.7	35.2	38.5
3	10.2	149.0	35	28.3
4	10.2	141.0	31.7	21.8
5	10.1	144.5	54.8	70.8
6	10.9	143.0	38.1	23.3
7	10.5	135.7	31	21.4
8	10.6	140	35.2	20.3
9	10.7	134.6	26.7	20.5
10	10.7	136.7	32.7	32.0
Mean	10.4	142.8	38.7	42.8
SD	0.48	7.8	7.5	20.5

Table 9.1: Demographic characteristics of boys

	Submaximal						Maximal	
	Terbutaline			Placebo			Terbutaline	Placebo
Speed (km/h)	7.2	8.0	8.8	7.2	8.0	8.8	-	-
VO2 (ml/min)	1388	1530	1617	1384	1487	1605	2135	2129
(SD)	81	92	100	139	135	112	228	223
VO2 (ml/kg/min)	35.8	39.5	41.8	35.7	38.4	41.4	55.1	55.0
(SD)	2.1	2.4	2.6	3.6	3.5	2.9	5.9	5.8
HR (b/ min)	161	174	181	168	174	180	204	203
(SD)	13	13.7	10.4	6.4	6.6	6.1	3	4
FU (%)	65.6*	72.4*	76.5*	63.4	69.1	74.6	-	-
(SD)	7.2	7.8	8.5	6.4	6.6	6.1	-	-
RER	0.94*	0.93*	0.94*	0.91	0.92	0.91	-	-
(SD)	0.03	0.03	0.03	0.03	0.03	0.03	-	-
Run Time (min)	-	-	-	-	-	-	7.81	7.5
(SD)	-	-	-	-	-	–	1.62	1.57

* (P<0.05)

Table 9.2: Summary of cardio-respiratory data at submaximal and maximal exercise intensities

	Placebo					Terbutaline				
	Pre-Exer		Post-Exer			Pre-Exer		Post-Exer		
Time (min)	Pre-Ad	Post-Ad	2	8	15	Pre-Ad	Post-Ad	2	8	15
Smax FEV1	109	109	107	110*	111*	100	104	108	110*	111*
Max FEV1	106	103	104	111*	109*	106	109	110	113*	115*
Smax PEFR	99	98	95	100	100	99	105	104	111*	112*
Max PEFR	105	105	103	105	106	107	110	111	113*	114*

* Significant increase from post-administration value ($P<0.05$)

All values expressed as percentage of predicted.

Table 9.3: Summary of pulmonary function data at submaximal and maximal exercise intensities.

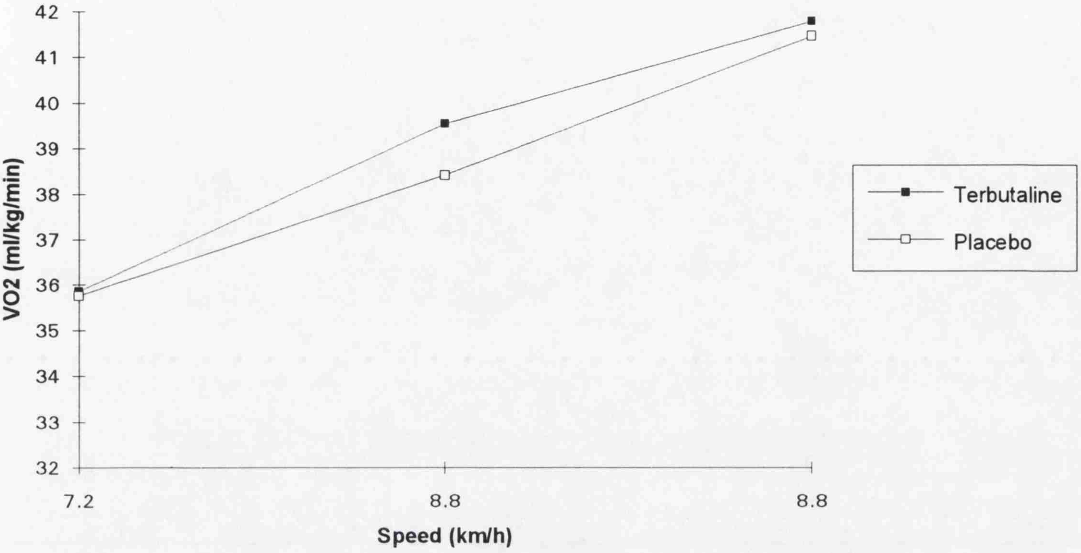

Figure 9.1: Effect of drug and placebo upon oxygen consumption at submaximal intensities

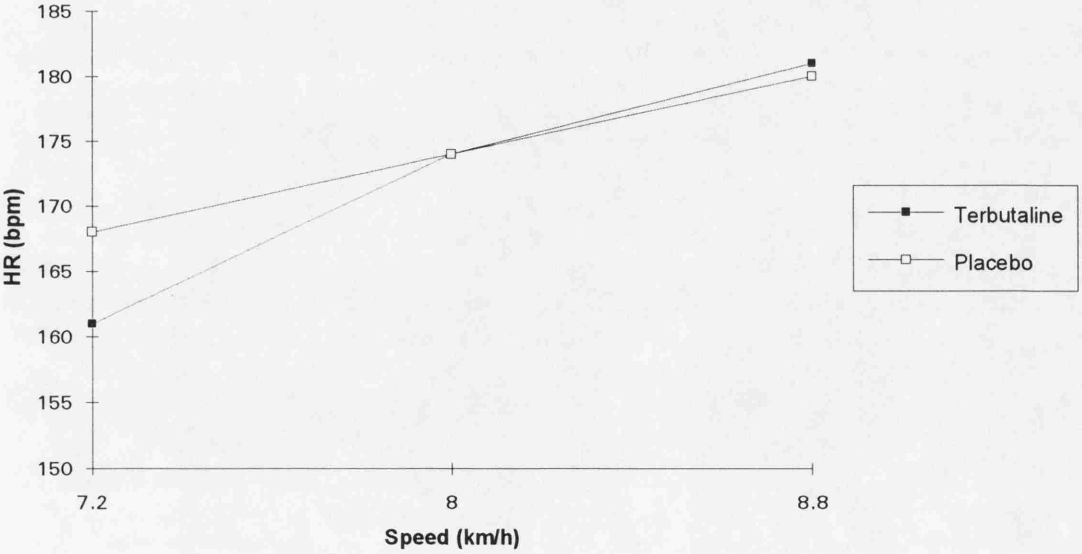

Figure 9.2: Effect of drug and placebo upon heart rate at submaximal intensities

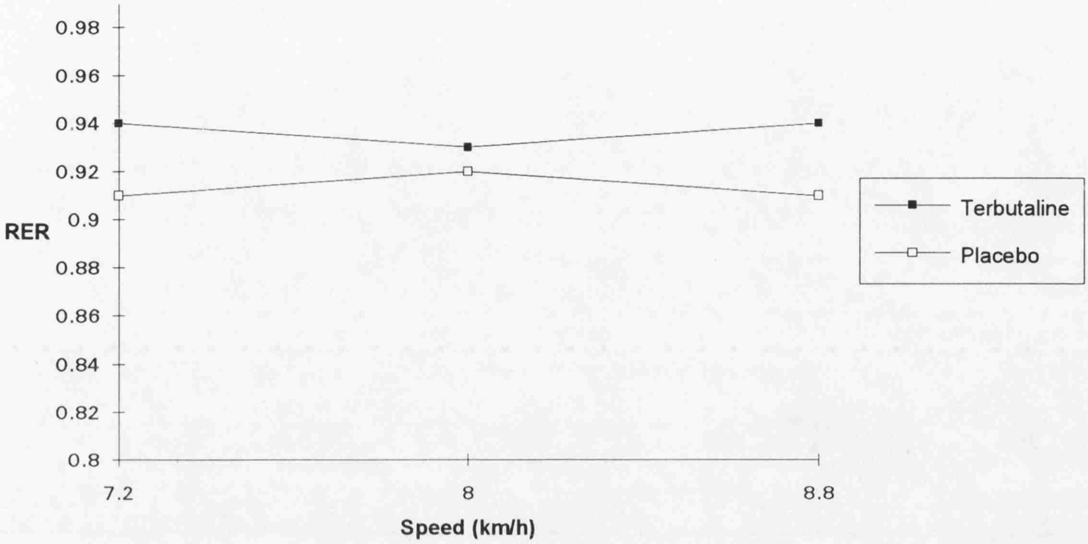

Figure 9.3: Effect of drug and placebo upon RER at submaximal intensities

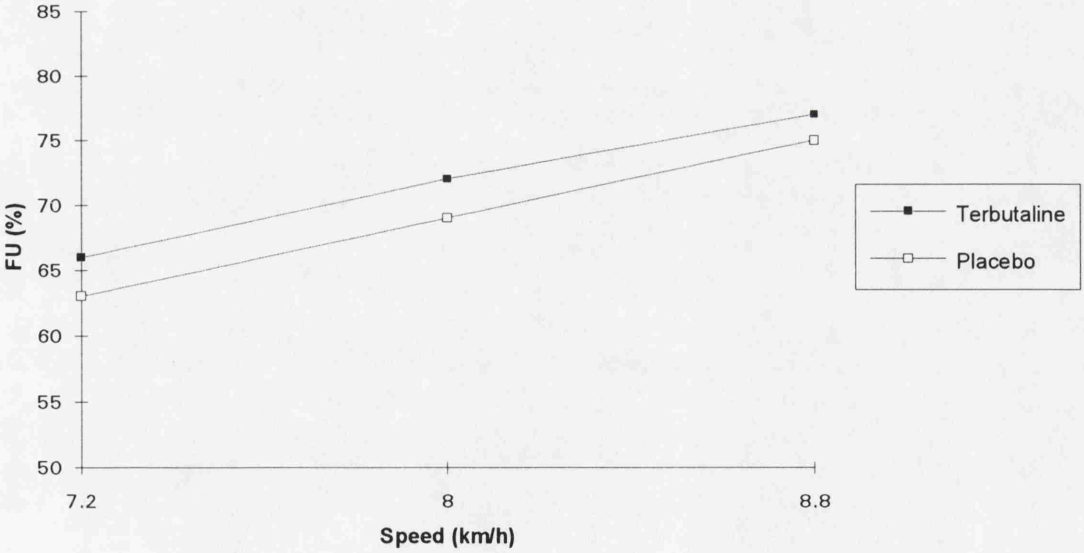

Figure 9.4: Effect of drug and placebo upon fractional utilisation at submaximal running speeds.

GENERAL DISCUSSION

GENERAL DISCUSSION

With greater numbers of children competing in competitive sport at an early age the benefits of a physiological approach for the athlete and coach may be important. A better understanding of the physiological response to exercise may enable both the coach and the athlete to develop strategies to enhance performance. More significantly, research in paediatric exercise science may help in understanding factors of importance for development and growth and long-term health. The real significance of paediatric exercise science research lies in the unwinding of potential factors that govern long-term health and development.

A great deal of debate exists as to the significance and relevance of measuring the pre-pubertal performance at peak exercise. The use of peak measurements as a single index of performance can be misleading. In addition, peak exercise intensity represents a level of exercise intensity infrequently attained even in competitive pre-pubertal athletes. Therefore, assessing performance at intensities more commonly encountered represents a more realistic path to understanding the physiology of the pre-pubertal child.

The research conducted in this study has helped to clarify a number of important methodological and physiological questions in submaximal paediatric exercise physiology. The work was sub-divided into three major sections: methodological aspects of measuring submaximal running economy, factors affecting submaximal running economy and possible methods of manipulation of submaximal running economy.

The three major methodological concerns addressed were the validity and stability of measurements of submaximal performance and the suitability of submaximal paediatric exercise testing. Data obtained from the validation study demonstrated that it was possible to use a biological calibration to assess the validity of the S2900Z metabolic cart. Of the selected cardio-respiratory variables studied, FeCO2 represented the only variable to demonstrate any bias between the computerised data collection and the reference system (Douglas Bag). The confirmation of the validity of these measurements allowed the subsequent body of work to be developed.

For true treatment effects to be noted in the manipulation of submaximal running economy, the level of natural variability needed to be measured. Results from the second methodological study demonstrated the level of variability associated with repeated submaximal testing (standard error of the mean ± 1.25 ml/kg/min) and peak testing (standard error of the mean ±2.25 ml/kg/min). It was concluded that single economy test sessions were valid for estimating the group stability of running economy. However, if individual profiles were required then multiple submaximal and maximal exercise testing would be necessary.

The determination of the shortest submaximal steady state stage is important in the development of continuous submaximal protocols in children. The minimum amount of time the child has to be on the treadmill lessens the overall stress placed upon the child at submaximal exercise intensities. The third methodological study addressed this issue. The results demonstrated that stable submaximal oxygen values were attained by the third minute of the steady state stage. Very little variation occurred between 3 and 6 minutes. Hence, the use of steady state stages between 3 and 6 minutes was considered acceptable.

Profiling the physiological differences between a group of run-trained and control boys indicated that some form of physiological adaptation had occurred, either as a result of pre-selection or training. At submaximal exercise intensities differences in blood lactate, fractional utilisation, ventilatory equivalent, heart rate, ventilation and respiratory exchange ratio were noted. Confounding data obtained in the run-trained group indicated that the submaximal oxygen cost of running appeared to be similar to the controls in one study and higher in the second study. Inferences with regard to enhanced free fatty acid oxidation in the trained boys were postulated. The influence of kinematic factors upon submaximal running economy was investigated and found to be minimal with no significant differences evident in gait characteristics between the two populations. It appeared that gait adjustment was a product of running velocity rather the training status. On the basis of these results, the use of submaximal running economy as a marker for physiological differences between trained and untrained populations is valid. One limitation of the profile studies conducted in this thesis lay in the composition of the groups. The control boys in this study represented very active boys and the run-trained boys varied in their training history. Thus, there is the possibility of physiological overlap between the two groups. Consequently, negative findings on subsequent statistical findings must be treated with caution.

The one clear index that differed throughout all the studies was peak $\dot{V}O_2$, with run-trained boys demonstrating superior aerobic power. The source of this difference could have been as a result of training or a consequence of genetic pre-selection for running. The nature of these studies undertaken prevent us from answering this question fully.

In an attempt to manipulate submaximal running economy, a high intensity aerobic training intervention study was conducted. Ergogenic manipulation of submaximal running economy was also attempted using an agent whose ergogenic potential has been suggested. The inhalation of a β2-agonist (Terbutaline), however, was found to have no effect upon submaximal running economy. In contrast, the training led to striking improvements in submaximal running economy of the order of 7%. The possible sources of this improvement are many: increased glycolytic potential, enhanced cardiovascular and ventilatory responses, substrate utilisation shifts and possible body composition changes. The possibility of altering submaximal running economy through training remains the most striking aspect of this work into submaximal running economy. Following training, the indications are that submaximal running economy is an appropriate and sensitive marker to assess the impact of training in a pre-pubertal population.

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APPENDICES

APPENDIX 1

CLINICAL MANIFESTATIONS OF THE "ATHLETE'S HEART" IN PREPUBERTAL MALE RUNNERS

T. W. Rowland, V. B. Unnithan, N. G. MacFarlane, N. Gibson, J.Y. Paton, Baystate Medical Center, Springfield, Ma and Royal Hospital for Sick Children, Glasgow, Scotland.

Cardiac findings in adult endurance athletes are well characterised, but data regarding the "athlete's heart" in children are limited. This study evaluated physical examination, EKG and echocardiogram in 15 male distance runners (R) ages 10-13 years compared to 18 physically active but untrained boys (C).

Mean $\dot{V}O_2$ max values on treadmill testing for the two groups were 60.5 (3.3) and 51.1 (4.3) ml/kg/min, respectively. The runners had been training for an average of 1.9 years with a mean current 3 km indoor race time of 12:42. No significant differences in the frequency of carotid bruits, cervical venous hums, heart murmurs or third and fourth heart sounds were observed between the groups. Mean resting heart rate was 70 (11) bpm for R and 73 (8) bpm for C (P>0.05). Average supine blood pressure values were systolic 110 (7) and 106 (11), diastolic 64 (7) and 65 (7) for R and C respectively (P> 0.05). No significant differences were observed in EKG intervals, axes or precordial voltages between the two groups and mean echocardiographic variables indexed to body surface area were also similar (P>0.05):

	Vent. septum (cm)	LV posterior wall (cm)	LV dias (cm)	LV sys (cm)	Shortening fraction (%)
R	0.69(0.20)	0.58(0.08)	3.39(0.34)	2.22(0.33)	34.2(8.7)
C	0.61(0.10)	0.51(0.09)	3.35(0.28)	2.27(0.40)	32.0(6.4)

This study failed to identify clinical features of the "athletes heart" in competitive child endurance runners compared to non-trained subjects.

APPENDIX 2

INFORMED CONSENT FOR PARTICIPATION IN A STUDY OF THE EFFECTS OF A PERIOD OF TRAINING ON MODERATE AND MAXIMUM RUNNING.

Investigators: Mr. Viswanath B. Unnithan MSc. (Extn 4729 / 4238)
Dr J. Y. Paton

Title of the study:

A COMPARISON OF THE RUNNING ECONOMY BETWEEN CHILDREN INVOLVED IN RUNNING TRAINING AND NORMAL CHILDREN AT 3 SUBMAXIMAL TREADMILL RUNNING SPEEDS.

Background and Purpose of the Study

In this study we want to compare the efficiency of running in children before and after a period of running training and a group of control children.

Your participation will involve four separate visits to the laboratory over a period of two months.

The following tests will be completed :

1. During the four visits to the laboratory, data will be collected during periods of light exercise and during short periods of the maximum exercise your child can achieve. For all exercise tests, chest electrodes will be attached to monitor your child's heart rate. Your child will be fitted with a snorkel type mouthpiece to obtain the air that he breathes out while doing the running to allow us to make the necessary measurements.

During the periods of light exercise, he will have to run at three different speeds at the same incline on the treadmill. For the maximal exercise test, the speed will be increased until your child is running on the treadmill, and then held constant. The incline will be gradually increased every 3 minutes with a 1 minute rest between each incline raise. The test will be terminated when the child feels that he cannot run any longer or further. At this point the study stops although we continue to take readings until you are back to normal breathing, about 5 minutes later.

In addition, during the exercise studies small finger prick blood samples will be taken from the tip of your child's fingers. These samples will be taken at rest, three times during the light exercise and at 3 minute intervals during the maximal exercise test.

Potential Benefits of the study

If your child takes part in the study we will be able to give you and them an estimate of their fitness . Otherwise the results of the study will be of no direct benefit to your child. This information may allow us to design better exercise programmes for children involved in running training and normal healthy children.

Potential Risks of the study

During the testing an occasional child may feel light headed, become short of breath, or even may develop slight irregularities of the heart beat. There will be a small amount of discomfort in the fingertips as a result of the finger prick blood sampling. In the event of an emergency there will be members of staff present available, capable of dealing with any problems.

Confidentiality

Case histories, the results of treatment, laboratory data, photograps and X-rays may be published for scientific purposes, but neither your child's nor your identity will be disclosed and confidentiality will be maintained.

You are free to withdraw from this project at any time without any penalty. We do not expect any unusual risks as a direct result of this project. Should an unforeseen physical injury occur, appropriate medical treatment will be provided, but no financial compensation will be given.

I, ______________________________, agree that my child

____
Parent/Guardian

may participate in the study as detailed above. I understand that I may withdraw my consent at any time.

____
Parent's Signature

____
Witness' Signature

____
Investigator's Signature

__/___/____
Date

APPENDIX 3

PHYSICAL ACTIVITY QUESTIONNAIRE

Child's Name:____

1. During the past three months , what would best describe your child's usual level of

physical activity ? (circle letter)

A. INACTIVE

watches television, reads, or does homework after school, has a ride to school; no sports outside school.

B. OCCASIONALLY ACTIVE

prefers sedentary activities, but sometimes plays outside.

C. MODERATELY ACTIVE

takes opportunities to become involved in physical activity when available and enjoys it.

D. ACTIVE

takes initiative to participate in physical exercise and prefers this to sitting activities; at least three times a week involved in vigorous exercise.

E. VERY ACTIVE

participates regularly in out of school sports; great deal of energy ;
dislikes sitting activities.

2. During the last six months was your child involved in an organised sports or exercise programme (Youth Club, Rugby, Football and Athletics leagues, gymnastics, dancing classes, etc.) outside of regular physical education ?

Yes_______ Describe______________________________

No________

3. During the last six months was your child involved in regular athletic training running, bicycling, swimming, etc. ?

Yes_______ Describe______________________________
No________

4. Has your child ever had any serious medical / surgical illness ?

Yes_______ Describe______________________________
No________

5. Is your child taking any medications ?
Yes_______ List__________________________________

No________