THE INFLUENCE OF TRAINING ON SUBMAXIMAL ENDURANCE IN MAN

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By

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ABSTRACT

The purpose of this study was to develop a 30-minute endurance test on the cycle ergometer (T30min) which could be used to determine an individual's ability to sustain a high proportion of their maximum oxygen uptake ($\dot{V}O_2max$) and to identify the physiological characteristics associated with this ability.

Examination of the repoducibility of the test revealed strong test re-test reliability for cumulative average work rate (CAWR), the relative exercise intensity ($\%\dot{V}O_2max$) sustained during T30min and the cardiorespiratory responses during the test.

When endurance performance was compared between endurance-trained athletes and sprint-trained athletes, the results showed that endurance-trained athletes were characterised by the ability to exercise at a higher absolute and relative work rate than sprint-trained athletes before the onset of blood lactate accumulation occurred ($OBLA_w$ and OBLA% respectively). In addition, they were able to sustain a higher absolute and relative exercise intensity during T30min. The study also revealed strong correlations between OBLA and endurance performance when expressed in both absolute and relative terms.

The comparison of OBLA and endurance performance between the sexes revealed no difference in either the ability to exercise at a high relative exercise intensity or the relative exercise intensity at which OBLA occurred. This was in spite of the fact that the males recorded significantly higher CAWR, $OBLA_w$, and $\dot{V}O_2max$ values.

Six weeks of endurance training on a cycle ergometer did not enhance the ability to exercise at high relative exercise intensity but did result in a 24% increase in $\dot{V}O_2max$, a 26% increase in $OBLA_w$, a 12% increase in CAWR during T30min and a 347% increase in exercise time to exhaustion at 80% $\dot{V}O_2max$.

The experiments revealed that the ability to exercise at a high absolute work rate is strongly related to both $\dot{V}O_2max$ and the ability to delay the accumulation of blood lactate. The ability to sustain a high $\%\dot{V}O_2max$ appears to be independent of $\dot{V}O_2max$ but strongly related to OBLA%. Whilst long-term endurance-trained athletes are characterised by being able to exercise at a high $\%\dot{V}O_2max$ the effect of short-term training on this ability appears to be largely influenced by the magnitude of the training-induced change in $\dot{V}O_2max$.

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PUBLICATIONS

Unless otherwise indicated by acknowledgement or reference to published literature the work contained in this thesis is that of the author. Part of this work has been reported in the following publications:

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SPECIFIC DEFININTIONS

$\dot{V}O_2max$	Maximum oxygen uptake i.e., the highest oxygen uptake an individual can attain during physical work while breathing air at sea level (Astrand and Rodahl, 1977)
$\%\dot{V}O_2max$	Relative exercise intensity i.e., oxygen uptake relative to the subject's $\dot{V}O_2max$
OBLA	Onset of blood lactate accumulation Equivalent to a blood lactate concentration of 4 $mmol.l^{-1}$
$OBLA_w$	The work rate, in watts, required to elicit OBLA
OBLA%	The relative exercise intensity at which OBLA is achieved
T30min	The 30-minute endurance test
T80%	The 80% $\dot{V}O_2max$ endurance test
AWR	Average work rate i.e., total work done divided by time
CAWR	Cumulative average work rate i.e., the average work rate of the subjects during T30min or, $\frac{AWR\ minute\ 1 + AWR_2 + AWR_3 + ...AWR_{30}}{30}$
$\%\dot{V}O_2max_E$	The estimated relative exercise intensity of the subjects during T30min i.e., the estimated $\dot{V}O_2$ that would be elicited by a work rate equivalent to CAWR, expressed relative to $\dot{V}O_2max$

1. INTRODUCTION

In recent years there has been growing awareness of the importance of physical fitness for successful participation in sporting competition. It is now apparent that sportsmen and women who take part in either team games or individual sports can no longer rely solely on their basic skills to bring them success. For many, physical fitness is now as important if not more important than their level of skill.

In addition, the health benefits of being fit and leading an active lifestyle are now more readily appreciated. As a result of this, the opportunity for individuals to engage in activities that will improve their fitness, other than participation in competitive sport, has increased. For many of these individuals fitness is a personal challenge, can they run further or faster than last time? Participation in events such as fun runs provides many individuals who will never achieve elite standing in athletic performance with an opportunity to direct their training towards a specific goal, whether it be to improve on a previous performance or simply to complete the distance. Despite the fact that the standards of the elite athlete are unattainable for the majority, many will have trained as hard as the elite athletes and would rightly claim to be as fit.

Until recently such a claim was not substantiated by the accepted criterion used to define and measure endurance fitness. The ability of the individual to exercise at a high work rate, i.e. to run, swim or cycle fast is dependent on the individual's capacity to take up and utilise oxygen. Consequently it has become a well established fact that individuals who excel at endurance events, i.e. the elite athletes, are characterised by the possesion of a high maximum oxygen uptake ($\dot{V}O_2max$) (Saltin and Astrand, 1967).

Because the elite athlete also participates in rigorous training regimens, and are thus known to possess the quality of fitness, an association has arisen between $\dot{V}O_2max$ and endurance fitness. This assumption is based on the belief that the high $\dot{V}O_2max$ values are a direct consequence of the training regimens. As a result of this

assumption $\dot{V}O_2max$ has often been referred to as the single most important determinant of endurance fitness (Shephard et al., 1968; Sharkey, 1977). This notion has been reiterated by authorities such as Astrand and Rodahl who state:

> "During prolonged heavy work physical work, the individual's performance capacity depends largely on the ability to take up, transport and deliver oxygen to the working muscle. Consequently maximum oxygen uptake is probably the best measure of endurance fitness."
> (Astrand and Rodahl, 1977)

In recent years studies examining the influence of heredity on $\dot{V}O_2max$ have shown that an individual's $\dot{V}O_2max$ is largely dependent upon natural endowment (Klissouras, 1971) and can thus only be improved within genetically predetermined limits. Therefore, the adoption of $\dot{V}O_2max$ as an indicator of endurance fitness presuppposes that, irrespective of their training status, individuals with low or modest $\dot{V}O_2max$ values do not possess the same degree of fitness as those with high $\dot{V}O_2max$ values.

Empirical evidence has shown that this is clearly not the case. Mass paticipation in activites such as fun runs has identified that individuals with moderate or low $\dot{V}O_2max$ values are capable of attaining fitness levels, i.e stamina and endurance fitness, previously believed to be the domain of the elite athlete.

This observation, together with the recognition of the important hereditary component, questions the use of $\dot{V}O_2max$ as an index of endurance fitness. In addition, studies have reported that endurance performance may continue to improve despite an absence in change of $\dot{V}O_2max$ (Daniels, Yarbrough and Foster, 1978b). Since an index of fitness must be sensitive to increased training such findings suggest that $\dot{V}O_2max$ is an inadequate index and that some measurement of submaximal endurance may provide a more informative picture of training status. This notion is supported by the research findings of Davies and coworkers. They reported that muscle oxidative capacity in rats was the primary determinant of endurance, and that $\dot{V}O_2max$ was not limited by the muscle oxidative capacity (Davies, Packer and Brooks, 1981, 1982).

However, the measurement of submaximal performance by tests that

measure endurance in absolute terms does not reflect adequately an individual's training status since performance on these tests is largely dependent on the subject's $\dot{V}O_2max$. Nevertheless, changes in performance as a result of training do provide insight into changes in fitness for a given individual, since an improvement in the absolute work rate at which an individual can exercise, i.e. can he or she run faster?, is ultimately what the athlete strives for.

An alternative method of assessing fitness is to assess the ability of an individual to sustain a high relative exercise intensity. Such a measure not only reflects the oxidative capacity of the skeletal muscle more acurately than $\dot{V}O_2max$ but also allows the direct comparison of endurance performance between individuals with largely different $\dot{V}O_2max$ values.

The purpose of the series of studies reported in this thesis, therefore, was to develop a performance test on a cycle ergometer which could be used to assess the ability of an individual to sustain a high proportion of their $\dot{V}O_2max$ during endurance exercise, and to identify the characteristics which confer this ability.

1.1 ORGANISATION OF THE THESIS

Four studies are included in this thesis. The first study examines the reproducibility of a 30-minute test on a cycle ergometer as a means of assessing endurance performance. The study also highlights the relationship between this method of evaluating endurance performance and $\dot{V}O_2max$.

The second study adopts a cross-sectional approach, utlising sprint-trained and endurance-trained athletes, to examine the influence of long-term training on the ability to exercise at a high relative exercise intensity. The relationship between submaximal accumulation of blood lactate and performance is also examined.

The third study re-examines the data from the first two studies to examine whether the sex of the subject is an important determinant

of endurance performance.

The final study takes a longitudinal approach to examine the effect of short-term endurance training (6 weeks) on submaximal blood lactate concentration and two measures of endurance performance. Endurance performance in this study is determined by the 30-minute test and by exercise time to exhaustion at a work rate equivalnet to 80% of the subject's $\dot{V}O_2max$. In addition the relationship between changes in $\dot{V}O_2max$, submaximal blood lactate concentration and endurance performance is examined.

2. REVIEW OF LITERATURE

This review is divided into six sections. The first two examine the relationship between $\dot{V}O_2max$ and endurance performance and the extent to which $\dot{V}O_2max$ changes as a result of training. These two sections also identify two major reasons why the adoption of $\dot{V}O_2max$ as an index of endurance fitness has been questioned, namely, the strong hereditary influence and its insensitivity to further training in already well-trained individuals.

Having identified the shortcomings of $\dot{V}O_2max$ as an indicator of endurance fitness, section three of the review highlights some of the different methods used to measure endurance performance. The effect of training on endurance performance, as measured by these tests, and the independence of submaximal endurance and $\dot{V}O_2max$ is then reviewed in section four.

Section five examines the relationship between endurance performance and the accumulation of blood lactate during submaximal exercise and identifies the various criteria utilised for such purposes. The effect of training on submaximal blood lactate accumulation is then reviewed in the final section.

2.1 THE RELATIONSHIP BETWEEN MAXIMUM OXYGEN UPTAKE AND ENDURANCE PERFORMANCE

Successful performance in endurance events has been largely attributed to the individual's ability to consume oxygen maximally ($\dot{V}O_2max$). This assumption is based upon the fact that there exists a linear relationship between the rate of energy expenditure and oxygen utilization and, therefore, a high $\dot{V}O_2max$ is a necessary prerequisite for high speed running, cycling or swimming. Various studies designed to identify the key factors that influence endurance performance have revealed strong relationships between $\dot{V}O_2max$ and successful endurance performance, and $\dot{V}O_2max$ and elite endurance performers.

One of the first investigations to report a strong relationship

between $\dot{V}O_2max$ and endurance performance was carried out by Costill in 1967. He examined a battery of 16 test items and correlated them with the time to run a 4.7 mile cross-country course. The most conclusive finding from the study was the direct relationship between $\dot{V}O_2max$ ($ml.kg^{-1}min^{-1}$) and distance running performance ($r=0.83$). Since this initial study by Costill the relationship between $\dot{V}O_2max$ and endurance performance over distances ranging from 1 mile to marathon and ultra-marathon has been rigorously examined.

A slightly higher correlation than that found by Costill in 1967 was reported by Costill, Thomason and Roberts (1973) who correlated $\dot{V}O_2max$ ($ml.kg^{-1}min^{-1}$) with the performance time of 16 trained distance runners in a 10 mile "test race" and found a correlation coefficient of $r=-0.91$.

In an investigation examining the relationship between muscle enzyme activity, muscle fibre composition and $\dot{V}O_2max$ to performance in middle and long distance running, Foster and coworkers found that performance times for 1, 2 and 6 mile races were most strongly related to $\dot{V}O_2max$ ($r=-0.84$, $r=-0.87$ and $r=-0.88$ respectively) (Foster, Costill, Daniels and Fink, 1978). Davies and Thompson (1979) found similar correlations for 13 male ultra-marathon runners when they correlated $\dot{V}O_2max$ with their performance times in events ranging in distance from 5km to 84.64km. Their findings revealed that 5km time correlated well with $\dot{V}O_2max$ ($r=-0.85$) however, with increasing distance, the association with performance diminished ($r=-0.72$, 84.64km). Farrell and coworkers found the reverse of this when they correlated $\dot{V}O_2max$ (amongst other variables) with performance at several race distances for 18 male distance runners. Their findings revealed that the relationship between $\dot{V}O_2max$ and the time to run a given distance increased with an increase in distance from $r=0.83$ for 3.2km to $r=0.91$ for 42.2km (Farrell, Wilmore, Coyle, Billing and Costill, 1979).

In a later study by Foster (1983) high correlations were again found between $\dot{V}O_2max$ and running performance over a variety of different distances. The study examined the relative importance of $\dot{V}O_2max$, training volume and training intensity for running performances over distances ranging from 1.0 to 26.2 miles. For the

sample group of 78 well-trained runners correlations of r=-0.91, -0.92, -0.94, -0.96, -0.95 and -0.96 were found between $\dot{V}O_2max$ and 1.0, 2.0, 3.0, 6.0, 10.0, and 26.2 miles respectively.

With the upsurge in events such as fun runs, half-marathons and marathons researchers have been able to move away from the elite athlete as a focus of attention and assess the relationships between physiological characteristics of recreational runners and endurance performance. These studies have established that the strong relationship between $\dot{V}O_2max$ and endurance performance is not restricted to the elite performers.

Maughan and Leiper (1983) reported that, for a group of 28 subjects who were "not elite competitors, but represented a cross section of the individuals taking part in a major city marathon race" a linear relationship was found to exist between marathon performance and aerobic capacity ($\dot{V}O_2max$) (r=0.88, males; r=0.63, females). Williams and Nute (1983) also found a strong correlation between $\dot{V}O_2max$ and performance time for a half-marathon race where the subjects were 10 recreational runners (r=-0.81). Strong correlations were also found between $\dot{V}O_2max$ and 30 km running performance by Brewer (1986) in a study involving 18 "recreational standard" runners (r=-0.75), whilst Ramsbottom (1986) observed a relationship of r=0.91 when the $\dot{V}O_2max$ of 94 physical education students was correlated with average running speed over 5km.

Although there have been extensive studies of the relationship between $\dot{V}O_2max$ and endurance performance, as measured by some kind of running test, few studies have examined this relationship when endurance is measured on a cycle ergometer.

In 1969 Wilmore examined the relationship of $\dot{V}O_2max$ to a work capacity test on a cycle ergometer. The work capacity test involved exercising for 5 minutes at a work rate of 720 $kgm.min^{-1}$ and then exercising to exhaustion at a work rate of 1620 $kgm.min^{-1}$. Total work performed and total exercise time were both used as criteria for endurance performance. The results revealed a strong correlation between $\dot{V}O_2max$ and both work output (r=0.84) and ride time (r=0.81).

Katch (1973) also examined the relationship between $\dot{V}O_2max$ and performance on a cycle ergometer endurance test and found a statistically significant correlation of r=0.78 between $\dot{V}O_2max$ and the subject's average work rate during the 12-minute test.

If endurance performance is strongly related to $\dot{V}O_2max$ one would expect elite endurance athletes to possess high values. This is indeed the case. Costill and Fox (1969), Costill and Winrow (1970a), Davies and Thompson (1979), and Svedenhag and Sjödin (1984) have all reported $\dot{V}O_2max$ values in excess of 70 $ml.kg^{-1}min^{-1}$ for elite male endurance runners, whilst values in excess of 80 $ml.kg^{-1}min^{-1}$ have been reported by Robinson, Edwards and Dill (1937), Astrand (1955), Saltin and Astrand (1967), Costill, Thomason and Roberts (1973) and Hagan, Strathman, Strathman and Gettman (1980).

High $\dot{V}O_2max$ values have also been reported for elite female athletes. Values in excess of 60 $ml.kg^{-1}min^{-1}$ have been reported by Saltin and Astrand (1967), Brown, Harrower and Decter (1972), and Davies and Thompson (1979), whilst Wilmore and Brown (1974) recorded a value of 71.1 $ml.kg^{-1}min^{-1}$ for a female, who at that time held the world best marathon time for females.

As a consequence of these extensive studies of the physiological characteristics of successful endurance athletes a strong association evolved between $\dot{V}O_2max$ and endurance capacity such that $\dot{V}O_2max$ alone was used as an indicator of endurance capacity or endurance fitness. This association between endurance fitness and $\dot{V}O_2max$ evolved due to the assumption that the high $\dot{V}O_2max$ values of the elite performers were the direct consequence of their rigorous training regimens. It was hypothesised, therefore, that increases in fitness as a consequence of training could be reflected by the magnitude of the subject's $\dot{V}O_2max$. For these reasons $\dot{V}O_2max$ has often been used as a reference standard for fitness when comparisons are made between different individuals, and when the effects of endurance training on an individual are examined.

In the 1970's, however, a series of studies were reported that identified a strong hereditary influence on the magnitude of $\dot{V}O_2max$. These studies increased awareness of the fact that changes in $\dot{V}O_2max$

were, to a large extent, constrained by heredity and therefore suggested that $\dot{V}O_2max$ was an inappropriate measure of fitness.

Much of the early work on the influence of heredity was undertaken by Klissouras. Although aware of the influence of factors such as training, bed rest, age and sex on $\dot{V}O_2max$, the wide interindividual variability of Maximum Aerobic Power in a population, led Klissouras to examine the extent to which genetic difference accounted for existing differences. The proportional contribution of heredity to differences in $\dot{V}O_2max$ was estimated based on intra-pair differences observed in monozygous (MZ) and dizygous (DZ) twins. It was concluded that heredity alone accounted almost entirely for existing differences in a fairly homogeneous group of individuals (Klissouras, 1971).

Klissouras and coworkers confirmed these earlier findings in 1973 when they examined the intra-pair differences in $\dot{V}O_2max$ for 23 MZ and 16 DZ pairs of twins. They found that the average intra-pair difference in $\dot{V}O_2max$ was 16 times greater in the DZ twins than in the MZ twins. They concluded that, regardless of age, the existing differences in $\dot{V}O_2max$ could be attributed to heredity (Klissouras, Piranay and Petit, 1973).

Futher assessment of the hereditary influence on $\dot{V}O_2max$ was reported by Weber, Kartodihardjo and Klissouras in 1976. Using 12 sets of male identical twins they imposed a strenuous 10-week training programme on one twin whilst the other acted as a control. They found that inspite of the strenuous training the main cause of the total variation in $\dot{V}O_2max$ was still the genetic predisposition, however, its relative contribution to the total variance was reduced to about 50%.

Moving away from studies of twins Montoye and Gayle (1978) found a relationship of $r=0.66$ when the father-son relationship for directly measured $\dot{V}O_2max$ was correlated. However, when the $\dot{V}O_2max$ of 70 pairs of brothers was examined the relationship was not statistically significant.

Lortie and coworkers attributed Montoye and Gayle's rather modest resemblances between first degree biological relatives to the modest

sample size used. In their study 607 subjects from 160 families were measured for maximal aerobic power (MAP). The results revealed the presence of significant familial concentrations for MAP adjusted for age, sex, current energy expenditure and weekly participation in aerobic activities. Inter-class correlation analysis revealed significant covariation between parents and their children and between children of the same sibships. Their results suggested that heredity did contribute to the variation in MAP (35%), but that the hereditary influence was much less than was previously reported from twin studies. In an attempt to clarify this difference Lortie and coworkers claimed that the twin studies were performed sometimes with little control over the dimensions that may be associated with an inflated genetic effect, i.e. the unequal effects of age and/or sex (Lortie, Bouchard, LeBlanc, Tremblay, Simoneau, Theirault and Savoie 1982).

Aware of the sources of bias that had affected some of the previous findings concerning the influence of heredity on $\dot{V}O_2max$, Bouchard and coworkers conducted a study to examine the influence of heredity on both $\dot{V}O_2max$ and endurance performance (90-minute work output test). Based on dizygotic and monozygotic twin data they reported a significant genetic effect on both $\dot{V}O_2$ max (about 40%) and 90-minute work output performance (70%). They concluded from their results that endurance performance was more affected by hereditary factors than $\dot{V}O_2max$ was (Bouchard, Lesage, Lortie, Simoneau, Hamel, Boulay, Perusse, Theriault and LeBlanc, 1986).

With substantial evidence indicating that $\dot{V}O_2max$ is to a certain extent genetically predetermined, its adoption as an indicator of endurance fitness has been questioned. This is because its adoption assumes that those individuals with low or moderate $\dot{V}O_2max$ values may never attain high levels of fitness, irrespective of their training status, because their $\dot{V}O_2max$ is constrained by heredity. This argument is especially pertinent when comparisons are made between males and females. Studies reported in the literature investigating the differences in $\dot{V}O_2max$ between males and females have repeatedly demonstrated that males are superior in this parameter to females (eg. MacNab, Conger and Taylor, 1969; Drinkwater, 1973; Wilmore and Brown, 1974), due mainly to their lower relative body fat, higher lean body mass, and higher haemoglobin levels (Astrand and Rodahl, 1977). As has

been previously highlighted in this section of the review, even well-trained and world class female athletes demonstrate lower $\dot{V}O_2max$ values than men. The adoption of $\dot{V}O_2max$ as an indicator of aerobic fitness, therefore, automatically categorises the females as less fit than their male counterparts, irrespective of their training status. The upsurge in fun runs, half-marathons and full marathons, however, has clearly shown that recreational runners, both male and female, who possess only low or modest $\dot{V}O_2max$ values, *are* capable of performing endurance events that demand a relatively high level of endurance fitness and, therefore, $\dot{V}O_2max$ alone cannot be used as the sole indicator of endurance fitness or the sole determinant of endurance performance.

Just as some of the early studies which showed strong correlations between endurance performance and $\dot{V}O_2max$ did much to initiate and support the view-point that $\dot{V}O_2max$ could be used as an indicator of endurance fitness, other studies that have found only a poor relationship between these two variables have supported the belief initiated by the twin studies that this is not the case.

Costill and coworkers were one of the first groups of researchers to identify that $\dot{V}O_2max$ is not a good performance discriminator between athletes who all possess $\dot{V}O_2max$ values well above average. They examined 27 marathon runners and found no relationship between $\dot{V}O_2max$ and their best marathon performance ($r=0.08$) (Costill, Branam, Eddy and Sparks, 1971).

Kearney and Brynes (1974) also found that the relationship between performance and $\dot{V}O_2max$ was not strong for subjects of similar athletic abilities. They examined the relationship between $\dot{V}O_2max$, as predicted by the Astrand cycle ergometer test, and 12-minute run time for a group of 34 subjects of ranging abilities. The relationship between estimated $\dot{V}O_2max$ and 12 minute run time was $r=0.63$ for the group as a whole. However, when the group was divided into ability sub-groups a decreased relationship of $r=0.28$ was found between the two variables for a group of varsity cross-country runners who were more homogeneous in ability.

The use of a homogeneous group of athletes to examine the

relationship between $\dot{V}O_2max$ and endurance performance was examined further by Briggs in 1977. Ten male subjects with $\dot{V}O_2max$ values ranging from 67.2 - 76.3 $ml.kg^{-1}min^{-1}$ performed a 2 mile time trial and a treadmill run to exhaustion at a work rate equivalent to 95% $\dot{V}O_2max$. The relationship between $\dot{V}O_2max$ and both performance variables was found to be non-significant ($r=-0.38$ and $r=-0.56$ respectively). They concluded that with a homogeneous group of middle distance runners $\dot{V}O_2max$ did not discriminate between those with the fastest and slowest performances.

In a study set-up to examine the relationship between running economy and distance running performance Conley and Krahenbuhl (1980) determined the relationship between $\dot{V}O_2max$ and 10km race time for 12 highly trained and experienced distance runners of comparable ability. They too found a poor relationship between $\dot{V}O_2max$ and performance ($r=-0.12$). Although the $\dot{V}O_2max$ values, race times and distances were little different from other studies which reported correlations of $r=-0.85$ and above (eg. Costill, 1967; Foster, Daniels and Yarbrough 1977; Farrell, Wilmore, Coyle, Billing and Costill, 1979), the subject group used in this study was much more homogeneous in both performance and $\dot{V}O_2max$ than subjects previously studied.

Kenny and Hodgson (1985) worked with a group of athletes who were fairly homogeneous in both physiological characteristics and performance times (5000m and 3000m steeplechase). The 13 male athletes were all in training for the 1984 Olympics at the time of the study. The relationships found between $\dot{V}O_2max$ and performance time for 5000m and 3000m steeplechasers were again fairly low ($r=0.28$ and $r=0.40$ respectively).

Briggs, Conley and Krahenbuhl and Kenny and Hodgeson all summarised their findings with the same message. Although $\dot{V}O_2max$ could not discriminate between performance capacities amongst elite subjects the possession of the high $\dot{V}O_2max$ helped each subject gain membership in the elite group of athletes. For this reason alone one cannot belittle the importance of $\dot{V}O_2max$ for the competitive endurance athlete.

To summarise, the studies reviewed in this section have clearly

shown that a high $\dot{V}O_2max$ is a necessary prerequisite for successful endurance performance in competetive athletic events. This has been confirmed by the strong relationships between $\dot{V}O_2max$ and endurance performance, and the possession of very high $\dot{V}O_2max$ values by the elite athletes. The adoption of $\dot{V}O_2max$ as an indicator of endurance fitness, however, has its failings, since factors other than training, i.e. genetics and sex, are largely influential in predetermining not only the magnitude of the subject's $\dot{V}O_2max$, but the extent to which it is likely to change.

2.2 THE INFLUENCE OF ENDURANCE TRAINING ON MAXIMUM OXYGEN UPTAKE

Numerous studies in the literature have shown that $\dot{V}O_2max$ can be increased by short- or long-term training. Two of the earliest studies to demonstrate this increase were conducted by Robinson and Harmon (1941) and Knehr, Dill and Neufeld (1942). Both studies were set up simultaneously to examine the effect of training on non-athletic men. Robinson and Harmon revealed an average increase of 16% in $\dot{V}O_2max$ for 9 men who trained for 26 weeks, whilst Knehr and coworkers found a 6-7% increase in the transport of the oxygen to the tissue for a group of 14 men who trained for the same period of time.

Since these initial studies the training-induced changes in $\dot{V}O_2max$ reported in the literature have been varied. Some studies have found changes as high as 95% (Cureton and Phillips, 1964) whilst others have found no change at all (Daniels, Yarbrough and Foster, 1978b, Henritze, Weltman, Schurrer and Barlow, 1985). Whilst the majority of the studies have reported changes in the range of 10 - 20% a number of studies have shown changes in excess of 25%.

One of the largest percentage changes in $\dot{V}O_2max$ was reported by Cureton and Philips (1964). Following a 24-week training programme $\dot{V}O_2max$ increased 95% from 26.5 $ml.kg^{-1}min^{-1}$ to 50.2 $ml.kg^{-1}min^{-1}$ for a group of 6 "out of condition" males. Large percentage increases were also found in the much reported bed rest study by Saltin, Blomqvist, Mitchell, Johnson, Wildenthal and Chapman, (1968). They studied the

effect of bed rest followed by heavy training on a group of 5 young normal subjects. Two of the subjects regularly engaged in competitive sport whilst the remaining 3 participated in a minimal degree of college sporting activity. The effect of 20 days bed rest led to a pronounced decrease in the $\dot{V}O_2max$ of the subjects whilst the 55 days training that immediately followed the bed rest resulted in a 4% increase in the previously trained subjects' $\dot{V}O_2max$ (when pre-bed rest and post-training $\dot{V}O_2max$ was compared), and a 33% increase for the 3 sedentary subjects. When the post-bed rest and post-training $\dot{V}O_2max$ values were compared the increase in $\dot{V}O_2max$ was much higher, i.e. 34% for the 2 trained subjects and 100% for the 3 sedentary subjects.

In a study examining the effect of physical training on circulation during submaximal and maximal exercise in previously untrained male adults Ekblom (1969) reported an increase in $\dot{V}O_2max$ of 44% for one of the subjects who trained for 51 months. This large increase may have been due more to the length of the training study than to the subject's initial fitness since his $\dot{V}O_2max$ (3.07 $l.min^{-1}$ or 45.8 $ml.kg^{-1}min^{-1}$) was not as low as those reported in other studies where the magnitude in change has been similar.

A slightly higher increase in $\dot{V}O_2max$ was reported by Kavanagh, Shephard and Pandit (1974). They trained 8 post-coronary patients for 8-12 months to run in the Boston marathon. Pre-training the predicted $\dot{V}O_2max$ was only 72% of the normal for Toronto men of the same age (26 $ml.kg^{-1}min^{-1}$, range 21.4 - 31.8 $ml.kg^{-1}min^{-1}$). After training the average value was 113% of normal (45.6 $ml.kg^{-1}min^{-1}$, measured on the treadmill). This large percentage increase, like the one shown by Cureton and Philips, was probably a function of the exceptionally low pre-training predicted $\dot{V}O_2max$ (both studies had very similar pre-training values, i.e. 26.0 and 26.5 $ml.kg^{-1}min^{-1}$ respectively).

The rate and magnitude of the adaptive increases in $\dot{V}O_2max$ was examined by Hickson and coworkers, who trained 8 healthy subjects 6 days a week for 10 weeks (Hickson, Bomze and Holloszy, 1977). They reported a rather suprising finding that average $\dot{V}O_2max$ increased linearly during the entire 10 weeks of training without showing a tendency to level off. At the end of the study total increase in $\dot{V}O_2max$ for the 8 subjects averaged 39% when measured in $l.min^{-1}$ and

44% when measured in $ml.kg^{-1}min^{-1}$. The largest percentage increases in $\dot{V}O_2max$ (52% and 53%) were shown by 2 individuals who had been very sedentary for years and had very low initial $\dot{V}O_2max$ values. Of these 2 individuals, one continued to train hard for an additional 3 weeks by the end of which his $\dot{V}O_2max$ was 77% higher than his pre-training value of $1.68\ l.min^{-1}$. This initial value, however, was extremely low for a healthy individual, in fact even lower than the group mean reported by Kavanagh and coworkers for post-coronary patients (Kavanagh et al., 1974). In the conclusion to their study, Hickson and coworkers stated that, as a result of the linear increase in $\dot{V}O_2max$ with time, and the larger than expected changes in $\dot{V}O_2max$, the ability of normal individuals to increase their aerobic work capacity in response to training was considerably greater than had generally been thought.

The factors that appear to be important in determining the magnitude in change in $\dot{V}O_2max$ were assessed by Davis, Frank, Whipp and Wasserman (1979) who examined the effect of 9-weeks endurance training on 9 previously sedentary middle-aged men. They attributed the 25% increase in $\dot{V}O_2max$ to a combination of three factors - the low initial fitness level of the subjects, the same mode of exercise used for testing and training and the training intensity being above the anaerobic threshold throughout the study.

All the studies cited thus far have used male subjects. Cunningham and Hill (1975) revealed that the large magnitude in change in $\dot{V}O_2max$ is also apparent in females. In their study 17 "very unfit" females participated in a training programme divided into an initial 9 week period and a subsequent 52 week period, during which time 6 subjects continued to exercise while the remainder de-trained. During the initial 9 week period predicted $\dot{V}O_2max$ increased by 34% whilst the improvement over the next 52 weeks was only 5%. Cunningham and Hill concluded that women who are very unfit apparently adapt to the initial training with a central change (increase in $\dot{V}O_2max$) followed by a much stronger peripheral adaption during a longer training period.

While various studies have used either male or female subjects to highlight that the response of $\dot{V}O_2max$ to training does not differ between the sexes, Lortie and coworkers examined the effect of

training on both males and females. They examined the individual differences in $\dot{V}O_2max$ in response to a 20-week endurance programme for 13 female and 11 male sedentary subjects. They found a similar response to training for both sexes, with a 35% increase in $\dot{V}O_2max$ for the females and a 31% increase for the males. Within the groups the largest percentage increases were 87% for a female and 46% for a male. The initial $\dot{V}O_2max$ values for these two subjects were however, very low, i.e. 1.1 and 2.3 $l.min^{-1}$ respectively (Lortie, Simoneau, Hamel, Boulay, Landry and Bouchard, 1984).

The large percentage increases in $\dot{V}O_2max$ cited in the above studies can be largely attributed to a combination of two factors; the characteristics of the experimental subjects, i.e. their initial level of fitness, and the characteristics of the training programme, i.e. duration, frequency and intensity. The concept that the percentage improvement in physiological parameters is related to one's initial degree of fitness has been in evidence since the work of Muller in 1962. He concluded, in a series of experiments on strength gains, that the percentage increase in strength was directly related to the initial value, and its relative distance from a possible end-point in improvement. Since this end-point of improvement for $\dot{V}O_2max$ may well be the genetically constrained limit Muller's theory holds true when examining changes in $\dot{V}O_2max$. Pollock (1973), in reviewing a number of studies showing changes in $\dot{V}O_2max$, reported that those studies which showed the largest percentage improvement included subjects who began at the lower initial values. This also holds true for many of the studies cited above where the percentage change has been largely due to the very low initial $\dot{V}O_2max$ values.

Various factors concerning the characteristics of the training programmes have also been influential in the changes reported in $\dot{V}O_2max$. Many of the studies reported above were long in duration; only 2 were less than 9 weeks whilst the longest was 56 weeks. The importance of this time span on the changes in $\dot{V}O_2max$ varies, however, between investigations. Cunningham and Hill (1975) reported that the greatest percentage change is likely to occur within the first 9 weeks of training, whilst Hickson and coworkers report that $\dot{V}O_2max$ is still increasing linearly at week 10 of training (Hickson et al., 1977).

More important perhaps than the duration of the studies is the intensity of the training. All the studies cited in this section have included a training intensity that has increased as the subjects have improved in performance. As a result the intensity has been provocative enough to elicit physiological changes. Hickson and coworkers stressed the importance of increasing the intensity when they examined the time course of the increase in $\dot{V}O_2max$ in response to a constant training pattern. Nine active but untrained subjects trained at a constant work rate for 4 weeks and then at an increased work rate, again constant, for a further 5 weeks. During both training periods $\dot{V}O_2max$ increased for the first 3 weeks (14% and 8% respectively) and then remained constant for the remaining weeks. Their results indicated that without an increase in the training stimulus daily exercise did not result in a further increase in VO_2max (Hickson, Hagberg, Ehsani and Holloszy, 1981).

It is these large changes in $\dot{V}O_2max$ that originally led to the belief that $\dot{V}O_2max$ provided a good measure of endurance fitness. As has been previously highlighted, this belief arose from the logical conclusion that, because training increased the subject's fitness, and training also increased the subject's $\dot{V}O_2max$, changes in $\dot{V}O_2max$ would reflect changes in fitness. Reports of changes in $\dot{V}O_2max$ above 25% are not, however, a consistent finding in the literature. Many more training studies have reported increases of between 5% and 20%, while some have reported no increase at all.

Although the use of unfit inactive subjects has often been one of the main reasons for large changes in $\dot{V}O_2max$, other studies have found only modest changes despite using subjects from a similar sample population. Wilmore and coworkers studied the physiological changes as a result of a 20-week conditioning programme of bicycling, tennis and jogging on 38 sedentary middle-aged volunteers (Wilmore, Davis, O'Brien, Vodak, Walder and Amsterdam, 1980). Their results revealed a significant increase in treadmill $\dot{V}O_2max$ for subjects who trained on the cycle ergometer (15%) and on the treadmill (13%), whilst there was only a small improvement of 6% for the tennis group. Hoppeler, Claassen and Howald (1983) observed a similar increase in $\dot{V}O_2max$ (14%) in a group of 10 untrained subjects who trained for 6 weeks, 5 times a

week, at an intensity corresponding to a blood lactate concentration of 4 mmol.l^{-1}. In neither of these studies was the exercise intensity or frequency any lower than those reported in the previous section. This would imply that the smaller percentage change in $\dot{V}O_2max$ may be in part accounted for by the slightly higher initial values recorded by these subjects.

Because of the nature of many of the tests involved in these studies, and because much of the research is done at establishments of higher education, many studies have used students or active individuals as their subjects. As a result of this many of these subjects already have modest $\dot{V}O_2max$ values at the start of the studies and this, therefore, influences the percentage gains achieved as a result of training.

In a study assessing the specificity of cardiorespiratory adaption to bicycle and treadmill training, Pechar and coworkers examined the effect of 8 weeks training on 60 college men. They found that treadmill-trained subjects $\dot{V}O_2max$ increased by 6.8% and 6.9% when tested on the treadmill and cycle ergometer respectively, compared with the 2.6% and 7.8% increases for the group who trained on the cycle ergometer. Their results strongly suggested a specificity of the $\dot{V}O_2max$ response to cycle ergometer training (Pechar, McArdle, Katch, Mage and DeLuca, 1974).

Small but significant increases in $\dot{V}O_2max$ were found by Moffatt and coworkers when they compared the effects of interval training and continuous training on $\dot{V}O_2max$. Forty-six male undergraduates trained for 10 weeks, 12 minutes per session, twice a week. A 12% increase in $\dot{V}O_2max$ was recorded for the interval trained group while an 8% increase was seen for the continuosly trained group (Moffat, Stamford, Weltman and Cuddihee, 1977).

Changes in $\dot{V}O_2max$ of a similar magnitude were reported by Daniels, Yarbrough and Foster (1978b) who studied the response of $\dot{V}O_2max$ and running performance (805m and 3218m) after 4 and 8 weeks training in 12 previously untrained physical education students. Maximum oxygen uptake increased significantly by 9% during the first 4 weeks of training but failed to increase further, even in the presence

of an increased training load. Running performance, however, improved throughout the training period. These results indicated that not all the improvements in running performance were attributed to changes in $\dot{V}O_2max$.

As can be assessed from the studies cited thus far the effects of training on man's cardiorespiratory response to maximal exercise is well documented. In comparison, relatively little is known of the female response to training, and it is only in the last two decades that the physiological responses of women to exercise have been more actively researched. In a study of women ranging in age from 19-64 years, Kilbom (1971) reported an 11-12% increase in $\dot{V}O_2max$ following training at 70% $\dot{V}O_2max$. A similar increase in $\dot{V}O_2max$ was reported by Flint, Drinkwater and Horvath (1974), who trained 7 women on a treadmill (walking) for 6 weeks, 3 times a week. They found that, $\dot{V}O_2max$ (predicted from the Astrand nomogram and corrected for overestimation) increased by 12% as a result of the training regimen. Kearney and coworkers reported slightly higher increases in $\dot{V}O_2max$ for 27 sedentary college women who trained on a treadmill 3 times a week for 9 weeks (Kearney, Stull, Ewing and Strein, 1976). Mean $\dot{V}O_2max$ increased by 15% for those subjects who trained at 60% of maximum heart rate and 24% for those who trained at 65% of maximum heart rate.

In a study examining the effects of training, de-training and re-training Pedersen and Jorgensen (1978) trained 6 young healthy sedentary females over 2, 7-week periods and found increases in $\dot{V}O_2max$ of 10-14%, whilst smaller changes in $\dot{V}O_2max$ were reported by Williams and Nute (1986) who trained 10 female games players at 95% $\dot{V}O_2max$ for 6 weeks and found a 5% increase in $\dot{V}O_2max$.

Examination of the results of studies involving females has clearly shown that changes in parameters such as $\dot{V}O_2max$ are commensurate with those much more frequently documented in males.

The studies reviewed above are just a selection of a vast number that have reported only modest changes in $\dot{V}O_2max$. In such instances the changes in $\dot{V}O_2max$ have been only modest despite the intensity and duration of the training being of a similar magnitude to studies where

much larger percentage increases have been cited. One of the reasons that may account for this may again be the initial magnitude of $\dot{V}O_2max$. As Muller (1962) stated, the percentage increase in a subject's performance is related to the relative distance from an end-point. Since most of the subjects cited above were either active or healthy, and assuming there is a genetically predetermined ceiling for $\dot{V}O_2max$, these subjects would be far closer to their end point than the unfit or sedentary subjects.

While the studies reviewed thus far have reported changes in $\dot{V}O_2max$ ranging from 5% to 95% several other studies have reported cases where there has been minimal change, a plateau in change, or even no change at all.

In their bed-rest study Saltin and coworkers examined the time required after a period of bed-rest to reach pre-bed-rest, or control, $\dot{V}O_2max$ values. For 2 subjects who had previously been active 30-40 days were required to attain control $\dot{V}O_2max$ values. In addition, their highest $\dot{V}O_2max$ values recorded during this post-bed-rest phase of the study were not appreciably higher than their control values despite the fact that training was more vigorous than they had ever undergone before (Saltin, Blomqvist, Mitchell, Johnson, Wildenthal and Chapman, 1968).

Daniels, Oldridge, Nagel and White (1978a) examined the changes in $\dot{V}O_2max$ and endurance performance of 20 middle distance runners over a period ranging from 2-4 years. They established that $\dot{V}O_2max$ ($ml.kg^{-1}min^{-1}$) did not change significantly during the study period due to the parallel changes in body weight and $\dot{V}O_2max$ $l.min^{-1}$. Race times for 1 and 2 miles did, however, significantly improve, suggesting that factors other than $\dot{V}O_2max$ were to account for the increase in performance time. Daniels, Yarbrough and Foster (1978b) also confirmed these findings. They studied 15 previously well-trained runners before and after 4 and 8 weeks controlled training. Maximum oxygen uptake remained unchanged throughout the experimental period whilst running performance (805m and 3218m) continuously improved.

Puhl and Rungan (1980) studied 11 women cross-country runners during their 10 week competitive season. They found that although

training distance increased from 40-50 miles to 50-60 miles per week $\dot{V}O_2max$ did not change significantly during the competitive season. Whilst Henritze and coworkers also found that despite 12 weeks' training, 5 days a week, at or above lactate threshold 33 college women showed no significant increase in $\dot{V}O_2max$ during the training period (Henritze, Weltman, Schurrer and Barlow, 1985).

This final set of studies further confirms that various factors preclude the adoption of $\dot{V}O_2max$ as an accurate indicator of endurance fitness. These and other studies not reviewed here, indicate that the magnitude of $\dot{V}O_2max$ may not always change despite significant changes in training intensity and frequency. In addition, as will be highlighted later, even when $\dot{V}O_2max$ does increase as a result of training not only are these changes often only modest but the changes in endurance performance (as measured by some other variable) may be larger and also independent of the genetically constrained changes in $\dot{V}O_2max$. What is clearly evident from this and the previous section is that $\dot{V}O_2max$ is not the sole determinant of endurance performance, nor does it describe adequately a subject's state of conditioning. As Londeree and Ames (1975) state:

> "..for a given $\dot{V}O_2max$ it is impossible to know whether a subject has a lot of ability and is 'out of shape', if he has little ability and is in 'good shape', or if possesses an intermediate level of ability and is in 'moderately good shape'."

However, the importance of $\dot{V}O_2max$ lies in the fact that it provides an indication of the individual's potential to perform endurance work, and as Londeree and Ames go on to state:

> "..although $\dot{V}O_2max$ may not be a valid measure of state of conditioning this does not preclude the fact that changes in $\dot{V}O_2max$ resulting from regular exercise may serve well as an index in change in conditioning."

2.3 MEASUREMENT OF ENDURANCE PERFORMANCE

Many studies reported in the literature have attempted to quantify endurance performance, and more especially endurance fitness. Initially, studies set up to examine the physiological characteristics of elite

performers concluded that, since all elite athletes possessed high or very high $\dot{V}O_2max$ values, $\dot{V}O_2max$ represented the best single indicator of endurance fitness. Subsequent studies, however (as reviewed in the last section), have revealed that $\dot{V}O_2max$ is not the sole determinant of successful endurance performance, it does not reflect the state of conditioning of the subject, nor does it necessarily change with training. As a result of this the inclusion of some other measure of endurance performance is common in studies reported in the literature. While some of these studies include performance data from the $\dot{V}O_2max$ test itself to indicate endurance, or to quantify the change in performance, others advocate specifically designed endurance tests.

One of the first studies to include a measure of performance from a $\dot{V}O_2max$ test (other than $\dot{V}O_2max$) was Knehr, Dill and Neufeld (1942). They used both $\dot{V}O_2max$ run time and the treadmill gradient required to exhaust the subject as measures that could be used to assess training-induced changes in endurance performance. Subsequently, several other studies have also used various $\dot{V}O_2max$ indices as performance measures. Ekblom and coworkers measured the total work output that could be performed at the work rate that led to exhaustion within 3-5 minutes (Ekblom, Astrand, Saltin, Sternberg and Wallstrom, 1968). Geijsel (1980) measured exercise time at the $\dot{V}O_2max$ maximal work rate, whilst Wilmore measured the maximum power attained during the $\dot{V}O_2max$ test (Wilmore, Davis, O'Brien, Vodak, Walder and Amsterdam, 1980).

Although these and other studies have used $\dot{V}O_2max$ test variables, in conjunction with $\dot{V}O_2max$, to describe changes that may occur in performance as a result of training, the lack of standardisation of the test procedures and work loads administered do not permit cross-study comparisons on these measures, and they are therefore only useful within the study themselves. In addition, these measures are often only obtained as a by-product of the determination of $\dot{V}O_2max$ itself.

More commonly, the capacity to perform endurance work has been measured through distance running performances such as timed races. This has arisen because distance runners have often been the focus of

attention of physiological investigation. Many of these distance runs, however, have been performed as a yardstick against which other performance variables are correlated, and not as a direct performance measure to be used for comparisons between individuals.

Costill (1967), Costill, Thomason and Roberts (1973), Foster, Costill, Daniels and Fink (1978), Conley and Krahenbuhl (1980) and Kenny and Hodgson (1985), all looked at the relationship between physiological variables and performance times in races up to 10 miles, whilst Davies and Thompson (1979), Maughan and Leiper (1983) and Brewer (1986) assessed performance in distances from 30km to marathon.

Other studies have used distance running performance as a yardstick with which to assess the effect of a specific training regimen on endurance performance. Daniels, Yarbrough, and Foster (1978b) used 805m and 3218m race times to determine the response of running performance to training. Daniels, Oldridge, Nagel and White (1978a) used 1 and 2 mile times in a longitudinal study examining changes in $\dot{V}O_2max$ and endurance performance with age. Bland (1982) examined the effect of training on 2 mile time, whilst Ramsbottom (1986) examined the effect of training on 5km time.

Whilst many of these previous studies have used performance measures in conjunction with various physiological variables, these performance measures have not been included as a direct means of evaluating endurance fitness or endurance capacity. Running performances have, however, been used as direct indicators of endurance fitness by researchers such as Cooper (1968). He claimed that the distance covered in a 12 minute time period could be used to determine the 'Physical Fitness Category' of a subject. By measuring the distance covered in this time period the $\dot{V}O_2max$ of the subject could be estimated and according to this the subject could be categorised into a fitness level. Other performance tests have been based on the same principle. Tests such as the 1.5 mile Balke Field Test, the Eurofit Test, and the Harvard Step Test all assess performance and equate it to an estimated $\dot{V}O_2max$ value. However, as has already been previewed, $\dot{V}O_2max$ alone does not indicate an individual's fitness level and thus it can be argued that such tests do not adequately describe an individual's training status.

As a result of the desire to quantify endurance, more specific and controlled laboratory tests have been used by a number of researchers. The specific measurement of endurance dates back to the 1930's. Flannagan (1935) and Henry and Kleeberger (1938) set up independent studies to establish a method by which an index of endurance could be established. According to their criteria endurance was defined as the ability to maintain a high work rate of physical work output for a relatively long period of time without decrement. Both studies established their index of endurance as the degree to which a subject maintained, in 220 yards, the speed they established in a 60 yard dash. This index was thus the ratio of the time for the 220 yard run to the 60 yard run. Henry and Kleeberger contended, however, that these index scores were a better index of endurance if the influence of the runners ability was statistically partialled out, since the faster runners were originally getting the better scores.

Henry and Farmer (1949) went on to expand on the measurement of drop-off in performance as a measure of endurance. They concluded that if subjects were required to maintain some pre-determined pace, for a constant duration of time, until they were forced to slow down, the decrement in speed or rate of reduction would serve as the endurance index.

These initial ideas were later adapted to a cycle ergometer test by Katch and Katch (1972). Their idea was to ask subjects to try to maintain some pre-determined pace on a cycle ergometer for a constant period of time. As the subjects were forced to slow down due to fatigue those who slowed down the most would accomplish the least amount of work and would thus be lowest in endurance. Since all the subjects would perform work for the same period of time, the total amount of work done by each subject would be the mathematical integral of the area under the performance or drop-off curve. Their initial work examined the drop off in performance of 34 subjects who exercised at an initial work rate of 1,512 $kgm.min^{-1}$ for 10 minutes on 2 occasions. Their results revealed that the average drop-off was 17.5% whilst test re-test reliability of the endurance scores, defined as cumulated work done, was good ($r=0.87$).

Katch (1973) also used a similar test protocol when determining the optimal duration of endurance performance on the cycle ergometer. Fifty subjects exercised at the same work rate of 1,656 kgm.min^{-1} for 12 minutes. Results revealed a 25% drop-off in performance during the 12 minute test and a correlation of r=0.78 between the subjects' $\dot{V}O_2$max values and their cumulated work rate values.

A shortened version of the test was adopted by Weltman, Stamford and Fulco (1979) who examined the effect of differing recovery patterns following maximal exercise on blood lactate disappearance and subsequent performance. The performance test used in this study required the subjects to exercise for 5 minutes at a work rate equivalent to the highest work rate attained on the $\dot{V}O_2$max test. Their results revealed that, whilst the clearance of lactate from the blood was affected by the recovery activity (sitting or cycling), elevated levels of blood lactate concentration did not affect performance on a second 5-minute test repeated 20 minutes after the first.

Other studies which have used performance tests as a criterion of endurance performance have used constant load performance tests as opposed to drop-off tests. The constant load test requires that the subject exercises at a constant work rate to exhaustion. This type of test has been used routinely to examine both the physiological responses to exercise and the effects of training on performance. One of the earliest reports of this type of test was by Karpovich and Pestrecov (1941) who included a constant load submaximal test as a means of assessing changes in endurance performance after training.

In a study investigating the relationship between $\dot{V}O_2$max and the capacity for endurance performance, Wilmore (1969) incorporated a performance test whereby subjects exercised for 5 minutes at 720 kgm.min^{-1}, and then 1620 kgm.min^{-1} for the remainder of the test. The test was terminated when the subjects could no longer maintain a pedal frequency of 60rpm. Endurance performance was measured by the total work performed during the test and the total exercise time. The results indicated a good relationship between $\dot{V}O_2$max and both work output (r=0.84) and riding time (r=0.81).

Hickson, Bomze and Holloszy (1977) measured endurance performance

as the exercise time to exhaustion at a work rate which resulted in exhaustion within 2-5 minutes. Like Wilmore, the test was terminated when the subjects could no longer maintain a prescribed pedal frequency (60rpm). In addition, like Wilmore, they found a good correlation between endurance time and $\dot{V}O_2max$ (r=0.97).

The reliability of constant load maximal endurance performance was studied by Weltman and Regan in 1982. In their study the subjects were required to exercise to exhaustion at a work load 0.5kg above the highest work load maintained for 3 minutes during the $\dot{V}O_2max$ test. Each subject performed the test on two occasions with the test being terminated when the pedal frequency dropped below 60rpm for 3, 6 second time intervals. Weltman and Regan found a reliability coefficient of r=0.92 between test 1 and test 2 for pedal revolutions and performance time indicating that the test was highly reproducible.

Many of the studies reviewed in this section have employed endurance tests that measure the ability of the subject to perform work at a maximal or supra-maximal level. These tests may not necessarily, however, reflect the subject's ability to perform submaximal endurance exercise. For this reason tests that require the subject to exercise at a submaximal work rate are also a common finding. In 1984 Boulay and coworkers set up a study to describe and test a specifically designed "maximal aerobic capacity test" (Boulay, Hamel, Simoneau, Lortie, Prud'homme and Bouchard, 1984). Maximal aerobic capacity was defined as the total work output during a 90-minute non-stop period. Performed on a modified Monark cycle ergometer the starting work load was calculated to elicit a heart rate approximately 10 beats lower than the subjects ventilatory anaerobic threshold. The aim of the test was to maintain the highest possible work output during the 90 minutes. The authors not only reported a high level of reproducibility for the test (test re-test correlation of r=0.99 for total work performed), but also commented on its ease of administration, and its ability to monitor the improved capacity to perform work when improvements in parameters such as $\dot{V}O_2max$ had plateaued off.

Lortie and coworkers went on to examine the relationship between performance scores on this test and $\dot{V}O_2max$ when they assessed the

responses of maximal aerobic power and capacity to endurance training (Lortie, Simoneau, Hamel, Boulay, Landry and Bouchard, 1984). Twenty-four subjects performed a $\dot{V}O_2max$ test and the endurance performance test (as described above) before and after training. In both instances there was a significant correlation between VO_2max and endurance performance ($r=0.74$ vs $r=0.89$).

The studies cited above involve performance tests that require the subject to exercise at a given absolute work rate. Since cardiovascular and metabolic responses to exercise occur in relation to the relative exercise intensity, i.e. the oxygen cost of the activity in relation to each subject's $\dot{V}O_2max$ (Hermansen and Saltin 1967, Rowell 1974) the relative stress of the activity in these tests will vary greatly between individuals with varying $\dot{V}O_2max$ values. Therefore, subjects with a higher $\dot{V}O_2max$ can sustain the higher work rate with relatively less discomfort than the subjects with lower $\dot{V}O_2max$ values. As a result of this, endurance scores may be more a function of $\dot{V}O_2max$ than level of fitness, and may thus account for the high relationships found between successful performance on the tests and $\dot{V}O_2max$. Aware of this, a number of studies measuring endurance performance now administer tests where the relative exercise intensity is the same for all subjects. In these studies the endurance tests used generally require that the subject either exercise to exhaustion at a given relative exercise intensity or, exercise for a given time at as high a relative exercise intensity as possible.

In a study examining the effect of work-rest schedules on the repeated testing of endurance time Gleser and Vogel (1971) defined and measured endurance time as the exercise time to exhaustion at a work rate equivalent to 75% of the subjects $\dot{V}O_2max$. In a subsequent study Gleser and Vogel (1973) suggested that an individual's endurance capacity to do prolonged work may be defined by the locus of points of their endurance times when plotted against varying exercise intensities. They attempted to describe endurance capacity as a simple function of the measurement of endurance time at 6 different relative work loads. They found that the relationship between endurance time (t) and relative load (load/VO_2max) (Lr) could be expressed in the logarithmic form

$$\log (t) = A * Lr + B,$$

where A and B were parameters that could be determined for each subject singly or for all subjects as a group. They claimed that this equation could be used to describe an individual's ability to perform prolonged work over a wide range of loads and to make comparisons between individuals.

Bland (1982), like Gleser and Vogel (1971), used a more straightforward method of assessing endurance capacity. She defined endurance capacity as the ability of an individual to utilise a large proportion of his or her $\dot{V}O_2max$ for prolonged periods of time, and measured it as the exercise time to exhaustion at a work rate equivalent to 75% of the subject's $\dot{V}O_2max$. Hardman, Williams and Wootton (1986) also defined endurance performance as the time to exhaustion at a given $\%\dot{V}O_2max$. In a study examining the influence of short term endurance training on the capacity to perform maximal exercise a performance test requiring the subjects to exercise to exhaustion at an average work rate equivalent to 83% $\dot{V}O_2max$ was included in the study. Hardman (1984) included the same test protocol when examining the effect of endurance training on $\dot{V}O_2max$ and endurance performance. In this study subjects were required to exercise to exhaustion on a cycle ergometer at a work rate equivalent to 80% $\dot{V}O_2max$.

A slightly different approach to the measurement of endurance was adopted by Hoppeler and Lindstedt (1983). Aware of the shortcomings of $\dot{V}O_2max$ as a predictor of endurance capacity they devised a test whereby the subject was required to exercise for 30 minutes at a work load adjusted such that exhaustion occurred by the end of the test. By dividing the power delivered during the 30 minutes by $\dot{V}O_2max$ they calculated each individual's "useful aerobic efficiency" for this particular type of exercise ($J.ml^{-1}O_2$). If measured both pre- and post-training they claimed this variable would take into account both the actual physical performance capacity and the change in $\dot{V}O_2max$ and would yield relevant additional information about the fitness of the individual with regard to a specific exercise intensity.

All the studies mentioned thus far have been performed on the cycle ergometer. Other studies have used treadmill or track running to examine the ability of the individual to run at a given relative

exercise intensity. Williams and Nute (1983, 1986) measured run time to exhaustion at 90% $\dot{V}O_2max$, whilst Brewer (1986) did likewise but at 70% $\dot{V}O_2max$. In addition, researchers have recorded times for a given distance and estimated from the relationship between submaximal oxygen upake and work rate what $\%\dot{V}O_2max$ the subjects were exercising at (Davies and Thompson, 1979; Maughan and Leiper, 1983 and Ramsbottom, 1986).

To summarise, to date no standard endurance test has been accepted which describes adequately an individual's endurance fitness. Many studies have used variables within the $\dot{V}O_2max$ test itself to demonstrate changes that occur as a result of training, whilst others have used maximal load tests. These tests do not, however, reflect the subject's ability to work at a submaximal rate. The last 2 decades, however, has seen the emergence, and partial acceptance, of constant load tests at a given relative exercise intensity and tests that require the subject to perform as much work as possible in a given time period as more sensitive methods of assessing endurance capacity or endurance fitness.

2.4 THE EFFECT OF TRAINING ON ENDURANCE PERFORMANCE

Many of the tests reviewed in the previous section have been used to examine the effect of training on endurance performance. In so doing these studies have established that changes in endurance performance are not always of the same magnitude as the changes in VO_2max, nor are they necessarily dependent upon the changes in VO_2max.

In a study by Knehr, Dill and Neufeld in 1941 the effect of 6 months' training on $\dot{V}O_2max$, $\dot{V}O_2max$ test run time and treadmill gradient at exhaustion was reported. In order to exhaust the subjects within 5 minutes of exercise, a 13% increase in treadmill gradient was required in the post-training $\dot{V}O_2max$ test whilst the amount of work done before exhaustion occurred increased by 60%. This percentage increase in the capacity to exercise at the maximal level was much greater than the modest 7% increase in $\dot{V}O_2max$ itself. Findings of a similar order were made by Ekblom and coworkers who found that 16

weeks of endurance training led to an average increase of 50% in total mechanical work performed on a cycle ergometer during maximal exercise ($\dot{V}O_2max$ test) whilst the group mean $\dot{V}O_2max$ increased by only 16% (Ekblom, Astrand, Saltin, Sternberg and Wallstrom, 1968).

Other studies that have examined the effect of training on performance, as measured by some variable in the $\dot{V}O_2max$ test, have reported changes of a smaller magnitude to those reported by Knehr and coworkers and Ekblom and coworkers. Davis, Frank, Whipp and Wasserman (1979) reported that 9 weeks of training on a cycle ergometer increased $\dot{V}O_2max$ by 25% whilst $\dot{V}O_2max$ work rate increased by 28%. In a more thorough examination of changes in $\dot{V}O_2max$ test variables as a result of training on a cycle ergometer, Bland reported that 6 weeks of training led to a 7% increase in $\dot{V}O_2max$ whilst exercise time increased by 30%, work rate required to elicit $\dot{V}O_2max$ increased by 18% and total work performed during the test increased by 26% (Bland, 1982).

Although there is a tendency for the training-induced change in $\dot{V}O_2max$ to be smaller than the change in the performance variable measured, Karlsson, Nordesjo, Jordfeldt and Saltin (1972) and Hoppeler, Claasen and Howald (1983) both reported instances where the increases in $\dot{V}O_2max$ were greater than the increases in performance. Karlsson and coworkers reported that $\dot{V}O_2max$ increased by 24% as a result of 7 months' training whilst the work rate required to elicit $\dot{V}O_2max$ increased by 17%. Hoppeler and coworkers found a 14% increase in $\dot{V}O_2max$ after 6 weeks' training but only an 11% increase in "aerobic power" (as defined by work output).

Modest changes in both endurance performance and $\dot{V}O_2max$ have also been reported in studies where endurance performance has been measured by a timed run. In a study examining the effect of 5 months' training on 2 mile run time, Ribisl (1969) reported a 17% improvement in endurance time and a 10% increase in $\dot{V}O_2max$ ($l.min^{-1}$). whilst Moffatt and coworkers found a 12% increase in both $\dot{V}O_2max$ and endurance performance, when endurance performance was assessed as the distance run in 12 minutes (Moffatt, Stamford, Weltman and Cuddihee, 1977).

Moving from running performance tests to cycle ergometer tests

Hoppeler and Lindstedt (1983) reported on the "aerobic efficiency" of a group of subjects before and after 6 weeks' training. Aerobic efficiency was evaluated by dividing the total work done in a 30-minute time period by the subject's $\dot{V}O_2max$. They found that, as a result of the training, aerobic efficiency increased by 10% compared with a 14% increase in $\dot{V}O_2max$. This increase in aerobic efficiency improved to 30%, however, when the training period was extended to 6 months (n=2).

Lortie and coworkers measured the effect of a 20-week aerobic training programme on the capacity to perform as much work as possible during a 90-minute maximal cycle ergometer test. The results for 24 sedentary subjects revealed a significant increase of 33% for $\dot{V}O_2max$ whilst work rate during the 90-minute test increased by 51% (Lortie, Simoneau, Hamel, Boulay, Landry and Bouchard, 1984).

Studies involving endurance tests whereby the subject exercises post-training at a submaximal work rate have found larger increases in endurance performance than those reviewed thus far. One of the largest percentage increases in endurance performance was reported in 1941 by Karpovich and Pestrecov. They trained 12 county jail inmates, 5 times a week for 17-22 weeks. Measurement of endurance performance, both pre- and post-training was made on a cycle ergometer endurance test to exhaustion at a predetermined work rate. Results revealed an increase in performance ranging from 75% to 4420%, with 2 of the subjects exercising for over 6 hours in the post-training test.

In a study examining the effect of training, i.e. repeated performance of the same test, on endurance time Gleser and Vogel (1971) defined endurance as the length of time the subjects could exercise for at a work rate equivalent to 75% of their $\dot{V}O_2max$. Eight subjects performed the endurance test once a week for 13 weeks. Their results revealed that whilst $\dot{V}O_2max$ had increased by 8% endurance time had increased by over 100% by the end of only the 5th week. In addition, they reported no correlation between increase in $\dot{V}O_2max$ and endurance time. Gleser and Vogel (1973) used the same test when they examined the relationship between endurance time and exercise intensity. In a study lasting 16 weeks 8 subjects performed endurance tests of varying intensities for 10 weeks, followed by 3 weeks of

heavy training, after which the endurance tests were repeated. Maximum oxygen uptake increased by 12% between weeks 1 and 14 whilst endurance time, as measured by exercise time to exhaustion at 75% $\dot{V}O_2max$, increased by over 200%.

Bland (1982) examined the influence of short-term training on $\dot{V}O_2max$ and endurance capacity. Endurance capacity in this study was defined as the exercise time to exhaustion on a cycle ergometer at a work rate equivalent to approximately 75% pre-training $\dot{V}O_2max$. Eight subjects trained for 6 weeks, 3 times a week, at 75% $\dot{V}O_2max$. Training increased $\dot{V}O_2max$ by 7% while both endurance time and total work done during the test increased by 478%. Hardman (1984) also found large changes in endurance performance after training 13 male subjects on a cycle ergometer, 3 times a week, for 6 weeks. Results of the post-training tests revealed a 16% increase in $\dot{V}O_2max$ compared with a 250% increase in exercise time to exhaustion at approximately 80% $\dot{V}O_2max$.

A similar test protocol was used by Williams and Nute (1986) who examined the effect of 6 weeks of high intensity training on $\dot{V}O_2max$ and endurance capacity. Ten female games players trained by running to exhaustion at approximately 90% $\dot{V}O_2max$, 3 times a week, for 6 weeks. These workers found that $\dot{V}O_2max$ increased by 5% while exercise time to exhaustion at 90% $\dot{V}O_2max$ improved by 168%.

Many of these latter studies reveal that the training-induced improvements in endurance performance are not adequately reflected by the modest increases in $\dot{V}O_2max$. In addition, other training studies have highlighted occasions where $\dot{V}O_2max$ remains constant during and after training despite a continued improvement in endurance performance, thus suggesting that not all improvements in endurance performance subsequent to training are attributable to changes in $\dot{V}O_2max$. Daniels and coworkers have reported two such cases. In 1978 they reported that $\dot{V}O_2max$ ($ml.kg^{-1}min^{-1}$) remained unchanged in 10-18 year olds involved in a longitudinal study lasting 2-5 years despite a significant improvement in 1 and 2 mile race times (Daniels, Oldridge, Nagel and White, 1978a). Whilst in the same year Daniels, Yarbrough and Foster reported a study where running performance (805m and 3218m) continually improved during and after 8 weeks' training despite $\dot{V}O_2max$

remaining unchanged throughout this time period.

Work by Davies, Packer and Brooks (1981, 1982), although dealing with animals, has been significant in identifying the dissociation of endurance capacity from $\dot{V}O_2max$. In a 10-week endurance training programme on rats (1981) they found muscle oxidase activity increased by 403% whilst whole animal $\dot{V}O_2max$ only increased by 14%. From the results of this study they concluded that, muscle oxidative capacity was the primary determinant of endurance performance, rat $\dot{V}O_2max$ was not limited by muscle oxidative activity capacity, and therefore, $\dot{V}O_2max$ was an unreliable predictor of endurance. In a follow-up study in 1982 these suppositions were confirmed. As a result of a 4-week sprint training programme $\dot{V}O_2max$ increased by 15% (relative to controls), however, no improvements in either muscle oxidase capacities or endurance capacity were observed. These results demonstrated, therefore, that $\dot{V}O_2max$ was not limited by muscle oxidase activity, but that endurance capacity and muscle oxidative capacity were closely coupled.

From the studies reported it can be clearly seen that, when assessing an individual's level of conditioning or fitness, or when trying to identify physiological changes in endurance capacity as a result of training, the need for the inclusion of a performance test, other than the $\dot{V}O_2max$ test, is apparent. This does not, however, belittle the importance of $\dot{V}O_2max$. Maximum oxygen uptake, or changes in $\dot{V}O_2max$, not only reflect the subject's potential to perform maximal work but also reflect gross body adaptationsthat have occurred as a result of training (i.e. cardiovascular changes). However, since $\dot{V}O_2max$ tells us little about the subject's ability to exercise at a submaximal level changes at the metabolic level (as a result of training) may not necessarily be reflected by the changes in $\dot{V}O_2max$, and therefore, some other measure to monitor this change is required.

Care must be taken, however, when interpreting changes in endurance in the light of the percentage changes found in performance. Where subjects are required to exercise at a maximal rate, i.e. perform as much work as possible in a given time, or cover a specific distance as quickly as possible, the percentage change in performance

is relatively small. However, when post-training tests require that the subjects exercise at a submaximal work rate, usually for as long as possible, endurance time increases may be of the magnitude of several hundred percent, although the physiological changes that have occurred may not be dissimilar to those in the previous example. This phenomenon may inpart be explained by the exponential relationship between the intensity of the activity and its duration, i.e. the harder the activity the less able the subject is to continue it for a long period of time. Therefore, post-training tests that require maximal effort will not result in as large increases in performance as those that require submaximal effort.

This relationship between intensity, duration and percentage increase may also be seen in the studies already reviewed by Bland (1982), Hardman (1984) and Williams and Nute (1986). Bland reported a 478% increases in exercise time post-training at a work rate that required 75% of the subjects pre-training $\dot{V}O_2max$. Hardman reported a smaller increase of 250% when subjects were required to exercise at a pre-training work rate of 80% $\dot{V}O_2max$, whilst Williams and Nute reported the smallest percentage change (168%) when the subjects were required to exercise at a pre-training work rate of 90% $\dot{V}O_2max$. As long as care is taken in interpreting changes in performance results, the use of a test where the subject exercises at the same absolute work load both pre- and post-training provides valuable information concerning changes in endurance capacity.

Although several studies have included endurance tests, where the subject is required to exercise at a given $\%\dot{V}O_2max$, reports on the effect of training on the ability to tolerate the same relative exercise both pre-and post-training are scarce. Saltin and coworkers, in their classic bed-rest study, reported one of the few cases where the subjects' relative exercise intensity was adjusted post-training according to their new $\dot{V}O_2max$ (Saltin et al., 1968). They found no significant difference in exercise time to exhaustion at 80% $\dot{V}O_2max$ pre-bed-rest, post-bed-rest and post-training. More commonly, studies infer that training leads to the ability to tolerate a higher $\%\dot{V}O_2max$ either from studies that have identified this characterisic in endurance trained subjects (Costill and Fox, 1969; Costill et al. 1979; Davies and Thompson, 1979), or studies that have focussed upon the

training-induced changes in the relative exercise intensity at which blood lactate concentration occurs during submaximal exercise (Davis, Frank, Wasserman and Whipp, 1979; Hurley, Hagberg, Allen, Seals, Young, Cuddihee and Holloszy, 1984).

In summary, the changes in endurance performance that occur as a result of training have been measured in a number of different ways in recent years. In so doing, it has become apparent that the changes in endurance performance are, to a large extent, independent of both the training-induced changes in $\dot{V}O_2max$, and $\dot{V}O_2max$ *per se*. Such findings have implied, therefore, that the physiological mechanisms responsible for the changes in endurance are different to those responsible for changes in $\dot{V}O_2max$. While it is well documented, through use of the tests reviewed, that training leads to an increase in the ability to exercise at a given absolute work rate, few studies have examined the changes in the ability to exercise at a relative exercise intensity that occur as a result of training. This is a surprising finding since the ability to tolerate a high $\%\dot{V}O_2max$ reflects to a certain extent the metabolic characteristics of the skeletal muscle and their capacity to cover energy demands aerobically. Since changes in the skeletal muscle oxidative capacity may be one of the major factors influencing endurance performance, especially in individuals who show no change in $\dot{V}O_2max$, the need to assess these changes seems apparent.

2.5 THE RELATIONSHIP BETWEEN SUBMAXIMAL BLOOD LACTATE CONCENTRATION AND ENDURANCE PERFORMANCE

It is a well established and recognised fact that exercise at both submaximal and maximal levels will result in the accumulation of lactic acid in the muscles and blood. In addition this accumulation of lactic acid has been directly or indirectly related to fatigue. Whatever the physiological reasons for this accumulation (not reviewed here) researchers are in agreement that, as exercise intensity increases a point is reached at which an increase in the concentration of lactate becomes evident. The intensity of exercise that elicits this rise in concentration is highly variable, but once reached, if exercise intensity continues to increase the rise in lactate

concentration becomes exponential.

Many of the more recent studies examining the accumulation of blood lactate as a result of submaximal exercise have sought to investigate the relationship between endurance performance and the intensity at which this exponential increase occurs. The reference point against which performance is correlated, however, tends to vary from one laboratory to the next, not only in name but also in its detection procedures. Some studies have used ventilatory procedures to indirectly detect a blood lactate threshold while others have used the direct measurement of blood and muscle lactate concentration.

Wasserman and McIlroy (1964) were one of the first research teams to use breath-by-breath ventilatory changes as a method of detecting the initial increase in blood lactate. They termed the point where ventilation increased out of proportion to $\dot{V}O_2$ as the "anaerobic threshold" and assumed that the accumulation of muscle and blood lactate and the fall in pH was the cause of the changes in ventilation. In later work Wasserman and his colleagues further refined the non-invasive measurement of the anaerobic threshold (Wasserman, Whipp, Koyal and Beaver, 1973; Davis et al., 1979).

The direct determination of a blood lactate reference point was made by Williams, Wyndham, Kok and Rahden (1967) in a study investigating the effect of training on $\dot{V}O_2max$ and anaerobic metabolism in man. They refered to the accumulation of lactate in the blood during exercise as "excess lactate", stating that this excess lactate represented the start of anaerobic metabolism. In addition, through plotting excess lactate against $\dot{V}O_2$, they were able to clearly identify a turning point in the curve where lactate began to rise exponentially. This turning point was thus used as the reference point for comparisons between individuals and within individuals (pre- and post-training).

In a study examining the relationship between state of conditioning and relative maximal steady-state oxygen consumption, Londeree and Ames (1975) identified this as the relative $\dot{V}O_2$ needed to achieve a blood lactate concentration of 2.2 $mmol.l^{-1}$ and 4.4 $mmol.l^{-1}$. The rationale for their selection of these two

concentrations was based on the results of investigations that had reported plasma lactate levels of near 2.2 mmol.l^{-1} in runners immediately following races at various distances. While lactate levels of 4.4 mmol.$^{-1}$ had been found for submaximal speeds comparable to racing pace over distances ranging from 10km to the marathon.

Major changes in the classification of the various reference thresholds was made in 1979, when Kindermann, Simon and Keul revised and renamed the anaerobic and aerobic-anaerobic thresholds that had been previously identified by Wasserman and coworkers (1964, 1973) and Mader and coworkers (Mader, Liesen, Heck, Phillipi, Rost, Schurch and Hollmann, 1976). Wasserman and coworkers had previously suggested that the first increase in lactate above pre-exercise level occurred at approximately 2 mmol.l^{-1}, and this they defined as the anaerobic threshold, whilst Mader and coworkers, had defined the aerobic-anaerobic threshold as a lactate concentration of 4 mmol.l^{-1}. Exercise at this intensity it was claimed, would not result in a further increase in blood lactate concentration, whilst exercise intensities above this threshold would lead to a gradual increase in accumulation. Mader and coworkers, therefore, accepted 4 mmol.l^{-1} as representing the limit between exercise intensities which were predominantly anaerobic or aerobic in nature with regard to energy supply. In their study, Kindermann and coworkers examined the significance of the aerobic-anaerobic transition for the determimation of work load intensities during endurance training. As a result of their findings they identified optimal load intensities for training based on the thresholds previously identified. They reported that training in the range of 4 mmol.l^{-1} lactate would lead to high stimulation of oxidative metabolism in the skeletal muscle cells and thus increase endurance capacity, whilst training at an exercise intensity corresponding to 2 mmol.l^{-1} or below would allow exercise to be maintained for several hours (thus maintaining state of conditioning) but the stimulus would not be sufficient to achieve adaptions in muscle cells, both morphologically and metabolically. They concluded that for didactic reasons and efficiency, the known concepts of thresholds, derived from energy metabolism, should be rearranged. The anaerobic threshold, occurring at a blood lactate concentration of approximately 2 mmol.l^{-1}, was renamed the aerobic threshold. The aerobic-anaerobic threshold, occurring at a blood

lactate concentration of approximately 4 mmol.l^{-1}, was renamed the anaerobic threshold. Whilst the intensities between these two reference concentrations (2 mmol.l^{-1} - 4 mmol.l^{-1}) was called the aerobic-anaerobic transition.

Farrell, Wilmore, Coyle, Billing and Costill (1979) were one of the first groups of researchers to investigate the relationship between the onset of plasma lactate accumulation (OPLA) and performance. They concluded that OPLA did not represent the onset of anaerobiosis but rather reflected that the accumulation of lactate in the muscle had increased to that concentration which overcomes the gradient between muscle and blood. In addition, they also claimed that, due to sampling difficulties, no respiratory parameters were used as indicators of OPLA, and since other investigations had shown a pronounced ventilatory response to OPLA and had termed this phenomenon the anaerobic threshold, OPLA in their study was not necessarily synonymous with the anaerobic threshold.

In an attempt to clarify controversial issues about the transition from aerobic to anaerobic metabolism a hypothetical model was proposed in 1980 by Skinner and McLellan. Like Kindermann, Simon and Keul (1979) they were in agreement with the suggested terminology that the initial rise in lactate be designated the aerobic threshold (approximately 2 mmol.l^{-1}) whilst the sharp rise and exponential increase in lactate at approximately 4 mmol.l^{-1} be called the anaerobic threshold. They added a note of warning, however, stating that, although some of the literature and their own hypothetical model proposed values of 2 and 4 mmol.l^{-1} of blood lactate for the aerobic and anaerobic thresholds respectively these were arbitrary values that did not necessarily apply to each individual. They cited an unreferenced study by Mader who tested sprinters who had lactate concentrations greater than 4 mmol.l^{-1} at 50-60% $\dot{V}O_2max$ compared with highly trained endurance runners who had a lactate concentrations of around 1 mmol.l^{-1} at intensities of 80-90% $\dot{V}O_2max$. In these cases an arbitrary concentration of 4 mmol.l^{-1} would not necessarily reflect accurately the anaerobic threshold in both cases.

In a study examining the relationship between muscle histological and metabolical features and exercise performance Sjödin and Jacobs

(1981) refered to the exercise intensity corresponding to the point at which blood lactate concentration began to increase exponentially as the "exercise intensity at OBLA", OBLA refering to the "onset of blood lactate accumulation". They, like other researchers, adopted a blood lactate concentration of 4 $mmol.l^{-1}$ as their reference point.

In spite of the lack of universal agreement as to a) the physiological mechanisms underlying the various thresholds, b) the method of detection of this threshold or c) the adoption of the same reference point, there is a growing use of lactate concentration directly or indirectly during submaximal exercise. In addition, most of the studies that have examined endurance performance and blood lactate accumulation have have found the two to be significantly related irrespective of the reference point adopted.

In the last decade numerous studies have been set up to examine the relationship between blood lactate concentration, $\dot{V}O_2max$ and endurance performance. Weltman, Katch, Sady and Freedson (1978) were one of the first groups of researchers to identify the fact that the onset of metabolic acidosis could be a better measure than $\dot{V}O_2max$ by which to evaluate submaximum fitness. In a study where subjects were matched with respect to their $\dot{V}O_2max$ Weltman and coworkers found significant differences in the $\dot{V}O_2$ at anaerobic threshold, as determined by expired air analysis.

In 1979, Weltman and Katch examined the relationship between $\dot{V}O_2max$ and the onset of metabolic acidosis. They hypothesised that those individuals with a greater ability to deliver oxygen to the working muscles, i.e. possessing a high $\dot{V}O_2max$, should be able to complete more incremental exercise aerobically before the onset of metabolic acidosis than those with a low $\dot{V}O_2max$ and thus, their anaerobic threshold would presumably be quite high. Their results confirmed these findings, revealing a strong relationship between $\dot{V}O_2max$ and $\dot{V}O_2$ at the anaerobic threshold ($r=0.85$), as determined by expired air analysis.

The relationship between $\dot{V}O_2max$ and the anaerobic threshold was further examined by Rusko and Rhakila in 1982. They found a

statistically significant correlation of r=0.84 between the two variables for a group of 75 biathletes and cross-country skiers. In this study the anaerobic threshold was determined through the analysis of both expired air and blood lactate concentration.

One of the first studies to examine the relationship between a given blood lactate concentration and the state of conditioning or level of fitness of the subject was reported in 1975 by Londeree and Ames. They claimed that previous studies that had sought to examine differences in lactate production between fit and unfit subjects failed to differentiate adequately between sample groups, often using $\dot{V}O_2max$ as an indicator of fitness, and thus the results were misleading. Using a sample of 13 subjects Londeree and Ames divided their group into 3 categories of fitness. These fitness categories were inferred from an activity recall record of the previous 6 months. Individuals who seldom exercised were classified as "low fit"; those who exercised approximately 3 times a week were classified as "medium fit"; and those who exercised at least 5 times a week were considered "high fit". This classification procedure, therefore, took into consideration frequency, quantity and intensity of recent exercise. They then set out to determine which one of several steady state criteria was the best predictor of level of conditioning or fitness. Results revealed that heart rate at 2.2 $mmol.l^{-1}$ lactate discriminated between all three levels of fitness, while $\dot{V}O_2$ at 2.2 $mmol.l^{-1}$ lactate discriminated between the high and low fitness groups.

Farrell and coworkers also examined the relationship between endurance performance and the metabolic characteristics of their subjects. They obtained performance data on 18 male distance runners for distances ranging from 3.2km to marathon, and correlated it with $\dot{V}O_2max$, treadmill velocity corresponding to OPLA and $\dot{V}O_2$ corrresponding to OPLA. All three variables were significantly related to performance at all distances, however, multiple regression analysis showed that the treadmill velocity and $\dot{V}O_2$ corresponding to OPLA were more closely related to performance (both r=0.91) than $\dot{V}O_2max$ (r=0.83). They concluded that the subjects appeared to set a race pace that allowed the largest possible $\dot{V}O_2$ while just avoiding the exponential rise in plasma lacate (Farrell, Wilmore, Coyle, Billing and Costill, 1979).

The relationship between treadmill velocity and a specific blood lactate concentration was also examined by LaFontaine, Londeree and Spath (1981). They examined the relationship between the treadmill velocity at 2.2 $mmol.l^{-1}$ and the paces for various running events ranging from 13.7m to 20km. Running paces for 402m, 3.22km, 8.05km, 16.09km, and 20km distances were all correlated significantly with the treadmill pace at 2.2 $mmol.l^{-1}$ lactate ($r=0.84$ to $r=0.99$). LaFontaine and coworkers concluded that the pace for essentially aerobic events (3.22km to 20km) could be closely approximated for a given subject through knowledge of the treadmill pace eliciting a blood lactate concentration of 2.2 $mmol.l^{-1}$.

In an effort to further clarify the relationship between exercise performance and muscle metabolic features Sjödin and Jacobs (1981) examined the inter-relationships between marathon running, the exercise intensity at which OBLA occurred, training volume and muscle fibre characteristics. The main finding of their study was the strong relationship between running performance and treadmill velocity corresponding to OBLA ($r=0.96$), indicating the high predictability of marathon running performance with knowledge of OBLA.

These findings were similar to other studies reported by Sjödin and coworkers. In 1982 Sjödin, Linnarsson, Wallensten, Schéle and Karlsson correlated both $\dot{V}O_2max$ and treadmill velocity corresponding to OBLA with 5000m running velocity. They reported a correlation of $r=0.59$ ($p<0.05$) between $\dot{V}O_2max$ and race pace velocity but a higher correlation, in the order of $r=0.90$, was obtained when treadmill velocity corresponding to OBLA and performance capacity in the races was correlated. Sjödin and Schéle (1982) also reported a stronger correlation between treadmill velocity at OBLA and 5000m race pace ($r=0.94$) than that found between 5000m and $\dot{V}O_2max$ ($r=0.59$).

The results of these latter two studies have been supported by several other studies. Kumagai and coworkers examined the relationship between the anaerobic threshold (AT) and 5km, 10km and 10 mile races for 17, 16-18 year olds. The correlations between $\dot{V}O_2max$ and performance in the 3 races were lower ($r=-0.65$, $r=-0.64$, $r=-0.57$) than those between $\dot{V}O_2$ at AT ($r=-0.95$, $r=-0.84$ and $r=-0.84$ respectively),

indicating that individual variance in the races was better accounted for by variance in $\dot{V}O_2$ at AT than $\dot{V}O_2max$ (Kumagai, Tanaka, Matsuura, Matsuzaka, Hirakoba and Asano, 1982).

Rhodes and McKenzie (1984) examined the relationship between actual performance times and predicted marathon times calculated from running velocity at the AT (determined through gas exchange variables). They found a highly significant correlation between the predicted and actual marathon times ($r=0.94$, $p<0.01$), suggesting running velocity at the AT may be critical in determining efficient running speed during marathons.

The potential of selected variables to predict endurance performance in a closely matched group of elite distance runners was examined by Kenny and Hodgson (1985). Using eight, 5000m runners and five, 3000m steeplechasers all with similar $\dot{V}O_2max$ values they found that age and AT (determined by expired air analysis) accounted for 77% of the variance in peak performance of the 5000m runners, while body weight and AT accounted for 98% of the variance in the performance of the 3000m steeplechasers. They recommended that with such a group of athletes, possessing equally high aerobic capacities, age, low body weight and high AT were important attributes for successful performance.

The studies reviewed thus far have clearly identified the predictive potential of both direct measurements of blood lactate and the identification of a threshold inferred from expired air analysis. In recent years, however, the noninvasive determination of the anaerobic-threshold (AT) has come under criticism from a number of researchers. In a review of the AT and the directions for future research, Brooks (1985) identified 7 teams of researchers who had subjected the AT concept to rigorous testing and failed to confirm the assumptions and predictions proposed for its noninvasive detection. In addition, Brooks highlighted the fact that such a method of detection had been dismissed by several researchers on the grounds that it was an "inappropriate and oversimplistic explanation of indirectly related phenomenon".

In general, those studies that have examined the relationship

between endurance performance and blood lactate thresholds, other than the indirectly determined AT, have taken one of two different approaches. They have either selected a fixed blood lactate concentration as a reference standard, i.e. 4 mmol.l^{-1} or OBLA, or they have attempted to identify an exercise intensity at which a sudden increase in blood lactate concentration occurred. In recent years, however, a number of studies have been conducted to examine the relationship of both variables to endurance performance.

Stegmann and Kindermann (1982) examined the physiological changes that occurred as a result of exercising for 50 minutes at work rates that corresponded to the individual's AT and the fixed reference concentration of 4 mmol.l^{-1} blood lactate. Their results revealed that exercise at the AT did not result in a gradual lactate accumulation or exhaustion within 50 minutes exercise, whereas exercise at 4 mmol.l^{-1} led to a gradual increase in blood lactate concentration associated with exhaustion at a mean time of 14.4 $\pm$ 6.3 minutes. They concluded that the AT was a better indicator of the work load that could be maintained for prolonged periods of steady state exercise than OBLA.

Tanaka and coworkers compared the contribution of both the AT and OBLA with endurance performance in 11 non-endurance trained males. Their results revealed that OBLA related variables were significantly higher than AT related variables, and that the relationship between OBLA $\dot{V}O_2$ and 1500m run performance (r=-0.61) was lower than that between AT-$\dot{V}O_2$ and 1500m run performance (r=-0.82). They concluded that the AT variables could explain endurance performance in a shorter distance event to a greater extent than variables related to a rigid threshold of 4 mmol.l^{-1}, but that both AT and OBLA related variables could have a significant influence on success in endurance performance (Tanaka, Matsuura, Kumagai, Matsuzaka, Hirakoba and Asona, 1983).

In a later study Tanaka and Matsuura (1984) used marathon performance to examine the association of AT and OBLA to endurance performance. They hypothesised that the running velocity corresponding to the AT would more accurately approximate the actual measured marathon race velocity than would the running velocity corresponding to OBLA. They based this assumption on 2 factors, firstly, marathon runners had been reported to utilise approximately 75% of their $\dot{V}O_2max$

while performing their best marathons and this was almost identical to AT values determined during their own studies, and secondly, treadmill velocity corresponding to OBLA had previously been reported to occur at 81-94% of $\dot{V}O_2max$, a more representative average running velocity for the 10 mile or shorter race. Their results revealed statistically significant differences between treadmill velocity at OBLA and marathon running velocity, whilst there was no significant difference between treadmill velocity at AT and marathon running velocity. In addition, treadmill velocity at AT correlated with marathon velocity to a greater extent than treadmill velocity corresponding to OBLA ($r=0.78$ and $r=0.68$ resectively).

More recently Yoshida and coworkers conducted a study to determine the "practical usefulness of blood lactate parameters proposed as measures of fitness" by comparing 4 measures of blood lactate with $\dot{V}O_2max$ and 12-minute run time (Yoshida, Chida, Ichioka and Suda, 1987). The measures they selected for comparison with performance were, the first initial rise in blood lactate above resting level (lactate threshold, LT), and blood lactate concentrations of 1, 2, and 4 $mmol.l^{-1}$. Of the 4 measures selected, LT correlated best with both $\dot{V}O_2max$ and running performance and Yoshida and coworkers concluded, therefore, that the LT was the best indicator of aerobic capacity and endurance running performance.

Despite the evidence that the directly determined LT or AT appears to be a better predictor of performance in distances ranging from 1500m to the marathon than OBLA, the ease with which OBLA can be determined has several advantages. Firstly, the detection of OBLA requires a limited amount of blood sampling. This factor, therefore, means that there is minimal discomfort for the subject. In addition, it also reduces the time required for analytical procedures. Secondly, the selection of a specific reference lactate concentration illiminates the problems associated with determining a "break point".

To summarise, experimental evidence has indicated that up to a given exercise intensity little or no accumulation of lactate will take place in the blood. A slight increase in intensity above a critical limit may then lead to a rapid increase in blood lactate accumulation. Although the work load corresponding to this level may

vary largely between individuals what seems apparent is that the absolute or relative work rate at which an individual exercises, over a given period of time, may to a large extent be influenced by the exercise intensity at which this increase in lactate occurs. Determination of the work rate corresponding to metabolic thresholds, however, is varied and due to the uncertainty regarding appropriate procedures many studies have adopted a given lactate concentration (eg 4 $mmol.l^{-1}$) as a reference point. Although the adopted concentration does not necessarily correspond to each individual's threshold level it can provide valuable descriptive information concerning an individual's ability to perform endurance work. Since the whole body's capacity to take up oxygen does not, under normal circumstances, appear to be a limiting factor for exercise below $\dot{V}O_2max$ a better description of endurance and improvement in endurance must, therefore, come from metabolic characteristics of the muscle, and the change in these characteristics as a result of training. For this reason factors such as the individual's ability to exercise at a relative exercise intensiy, or the relative exercise intensity at which blood lactate concentration begins to accumulate exponentially are seen to be important indicators of endurance capacity.

2.6 THE EFFECT OF ENDURANCE TRAINING ON SUBMAXIMAL BLOOD LACTATE CONCENTRATION

The effect of training on blood lactate concentration at both absolute and relative work intensities has generally been examined in two ways, firstly, through cross-sectional studies that identify the differences between trained and untrained individuals, and secondly, through longitudinal studies that examine subjects before and after a given period of training.

Many of the cross-sectional studies that have compared differences in blood lactate concentration between trained and untrained subjects have reported the common finding that lactate concentration is lower in the trained subjects than the untrained ones when working at the same absolute work rate (Williams, Wyndham, Kok and von Rahden 1967; Ekblom, 1969). In addition, reference thresholds

such as OBLA, OPLA and the AT also appear to occur at a higher work rate for trained subjects than for untrained subjects. These findings are not suprising since blood lactate accumulation is a function of the $\%\dot{V}O_2max$ at which the subject is exercising (Hermansen and Saltin, 1967), and since the trained subjects cited in these studies are often characterised by high $\dot{V}O_2max$ values, exercise at a given absolute work rate represents a lower $\%\dot{V}O_2max$ for them compared with an untrained subject.

In addition to accumulating less lactate at a given absolute work rate, however, many other studies have reported that trained subjects also accumulate less lactate at a given $\%\dot{V}O_2max$ (Ekblom, 1969; Hermansen, 1971; Astrand and Rodahl, 1977; Hurley, Hagberg, Allen, Seals, Young, Cuddihee and Holloszy, 1984) and as a result of this can exercise at a higher $\%\dot{V}O_2max$ before OBLA, OPLA, and the AT occur (McDougall, 1977; Kumagai, Tanaka, Matsuura, Matsuzaka, Hirakoba and Asano, 1982).

Closer examinations of the effects of training on blood lactate concentration have been made by researchers who have undertaken longitudinal studies where repeated measures are made on the same subject before and after a controlled period of training. The initial focus of attention of many of these studies was on the decrease in lactate at submaximal work rates, expressed both in absolute terms (W, $m.s^{-1}$ or $\dot{V}O_2$) and relative terms ($\%\dot{V}O_2max$). The reported findings from many of these studies have been similar to those reported from the cross-sectional studies.

Ekblom (1969) studied 8 subjects before and after 16 weeks of physical training and found that blood lactate was lower post-training during exercise at a given $\dot{V}O_2$. After the study was fininshed 1 subject continued to train for a time period totalling 51 months during which time repeated performance measures were made. Results revealed that the blood lactate concentrations at a given absolute work rate ($\dot{V}O_2$) and a given $\%\dot{V}O_2max$ were lower after 51 months of training than they had been before training commenced.

Saltin and Karlsson (1971) studied 15 male conscripts at induction and after 12 and 28 weeks' endurance training. They found

that blood lactate concentration was markedly reduced at the same work rate after the first part of the training and further reduced during the latter part. When work rate was expressed as $\%\dot{V}O_2max$ a highly significant reduction in blood lactate concentration at the same $\%\dot{V}O_2max$ was observed.

In a study examining the time course of the adaptive responses of aerobic power to training Hickson and coworkers determined the rapidity in the decrease in blood lactate during a standardised exercise test in response to a constant training stimulus (Hickson et al., 1981). Nine subjects trained at constant work rates for 4 weeks after which the work rates were increased and kept constant for a further 5 weeks. Blood lactate concentration 5 minutes following an exercise test, which initially required 95% $\dot{V}O_2max$, was significantly lower after 2 weeks of training (6 days per week) but there was no further decrease in the lactate in the last 2 weeks of the initial training period. Another significant decrease in the lactate concentration occurred during the first 3 weeks of the second training period, but there was no further change after that. Their results revealed that unless the training stimulus was increased high intensity exercise did not result in further decreases in the blood lactate response to submaximal exercise after 3 weeks.

While these studies have tended to make generalised statements about the decrease in blood lactate concentration with training during exercise at submaximal work rates, other studies have focused more specifically on the changes in concentration at a given reference point, i.e. one of the thresholds previously identified.

Williams, Wyndham, Kok and von Rahden (1967) were one of the first research groups to measure changes in blood lactate concentration at a given reference point. They examined the changes in the level of oxygen intake at which anaerobic metabolism started, measured as "excess lactate", before and after a 4 to 16-week training regimen. When excess lactate concentrations were plotted against $\dot{V}O_2$ they were higher in the untrained than the trained state. As a result of this the turning point of the excess lactate/oxygen intake curve occurred at a lower level of oxygen intake in the untrained state than the trained state.

Aware that training reduced blood lactate concentration at submaximal work rates, Davis and coworkers set up a study to examine the extent to which the gas analysis determined anaerobic threshold in middle aged sedentary men was altered after 9 weeks of endurance training (Davis et al., 1979). The major finding of their study was that the AT increased by 44% when expressed as $\dot{V}O_2$ ($l.min^{-1}$), and 15% expressed relative to $\dot{V}O_2$ max. Significant increases in $\dot{V}O_2$ max (25%) were also observed.

In an 8-week training study of 8 healthy college students Yoshida, Suda and Takeuchi (1982) examined the effect of endurance training at an intensity corresponding to 4 $mmol.l^{-1}$ arterial blood lactate concentration. Post-training exercise tests revealed a significant increase of 37% in $\dot{V}O_2$ corresponding to the AT (the point at which arterial lactic acid rose above the resting level) while $\dot{V}O_2max$ increased by 14%.

Sjödin, Jacobs and Svedenhag (1982a) also prescribed training intensity at a work rate corresponding to 4 $mmol.l^{-1}$ blood lactate (OBLA). Once a week for 14 weeks 8 well-trained male runners added a 20-minute treadmill run at a velocity corresponding to 4 $mmol.l^{-1}$ lactate to their regular training programme. They also found that training at this intensity increased the running speed at which OBLA occurred (range 0-7%) while $\dot{V}O_2$ max did not significantly alter (maximum change of 3%).

Many of the studies cited above have reported differences in the training induced changes in $\dot{V}O_2max$ and threshold values. Hurley and coworkers hypothesised that the differences in the changes in these 2 variables was due to the fact that the metabolic responses to submaximal exercise and $\dot{V}O_2max$ were to some degree dependent upon different physiological processes. Their study was undertaken to determine whether endurance exercise training resulted in a decrease in blood lactate concentration at the same relative exercise intensity. After a 12-week exercise programme $\dot{V}O_2max$ increased by 26%, $\dot{V}O_2$ at the work rate required to elicit a blood lactate concentration of 2.5 $mmol.l^{-1}$ was 39% higher, while the $\%\dot{V}O_2max$ at which 2.5 $mmol.l^{-1}$ lactate was achieved increased from $68\pm4\%$ $\dot{V}O_2max$ to $75\pm3\%$

$\dot{V}O_2max$. They concluded that their results indicated that changes in $\dot{V}O_2max$ and submaximal blood lactate were to some extent independent of each other (Hurley, Hagberg, Allen, Young, Cuddihee and Holloszy, 1984).

In a study examining the effects of training on the lactate threshold and $\dot{V}O_2max$ Henritze, Weltman, Schurrer and Barlow (1985) obtained results that supported the ideas of Hurley and coworkers. Thirty-three college women either trained for 12 weeks at, or above, their lactate threshold (LT) or acted as control subjects. Post-training, none of the groups significantly changed their $\dot{V}O_2max$ as a result of the training, only the "above LT" group showed a significant increase in $\dot{V}O_2$ at AT (48%), while both the training groups showed an increase in the $\%\dot{V}O_2max$ at which LT occurred (=LT 16%, >LT 42%). They concluded that training above the lactate threshold resulted in an improvement in $\dot{V}O_2$ at LT and that large improvements in $\dot{V}O_2max$ may not be required for large improvements in $\dot{V}O_2$ at LT.

Not all the studies reported in the literature concerning changes in blood lactate concentration have reported decreases in concentration at a given relative exercise intensity post-training. Saltin et al. (1969) found that blood lactate concentration at a given relative exercise intensity was unchanged for 42 men who took part in an 8 to 10-week training programme that induced an 18% increase in $\dot{V}O_2max$ (range 8-44%). Davis and coworkers concluded that these findings may have been due to the fact that a) Saltin's subjects trained by running but were tested on a cycle ergometer, b) the training frequency was low and c) only a few blood samples were used to discern AT (Davis et al., 1979). They are assuming, however, that there should be a decrease in blood lactate concentration at a given relative exercise intensity. As previously reviewed, Ekblom (1969) reported lower blood lactate concentrations at a given relative exercise intensity for 1 subject who trained for 51 months, however, he failed to indicate that there was no change in the blood lactate concentration at a given relative exercise intensity after the first 16 weeks of the study. In addition, the results of his study revealed that 50% of the change in the $\dot{V}O_2max$ of his subject occurred during the first 4 months of the 51 month study. It would appear, therefore,

that only after the major central cardivascular changes had occurred did the more peripheral metabolic changes become evident. Their data would suggests, therefore, that a training-induced change in blood lactate concentration at a given relative exercise intensity may not always be evident.

In summary, one of the most consistent findings in the literature is the decrease in submaximal blood lactate concentration at a given absolute work rate as a result of endurance training. Reports of the changes in blood lactate concentration at a given $\%\dot{V}O_2max$, however, are less well documented, often inconsistent, and largely dependent upon the duration of the training study itself and the relative change in $\dot{V}O_2max$.

3. GENERAL METHODS

3.1 EQUIPMENT

3.1.1 Cycle ergometer

A Monark cycle ergometer (Model 864) was used for all the tests in this study. It was a mechanically braked, free-wheeled type with a basket weight loading mechanism and adjustable handlebars, saddle height and toe straps. The load setting was manually administered by adding free weights to the basket - the weights ranging from 0.1 - 3.0kg in size (calibration of these weights was performed by the manufacturer, Monark). The basket itself weighed 0.5kg and, therefore, represented the lowest frictional load available during testing (a range of 0.5 - 5.5kg was used in this study). Before each test the cycle ergometer was checked to ensure that at the heaviest work load the basket was hanging free of the restraining straps.

The deflection on the speedometer attached to the handle bars was proportional to the subject's pedal frequency (r.p.m.). Subjects were required to exercise at a pedal frequency of 60rpm (as indicated by the speedometer) during all performance tests with the exception of T30min.

3.1.2 Pedal frequency counter

An electro-mechanical counter attached to the flywheel of the cycle ergometer recorded the number of flywheel revolutions in a given period of time. To obtain a pedal frequency value the flywheel revolution count was divided by a conversion factor of 3.7 (the ratio of flywheel revolutions to pedal revolutions) and thus, a flywheel count of 222 in 1 minute would represent a pedal rate of 60 rpm.

Work rate was calculated using the equation:

$$\text{WORK RATE} = \frac{\text{FORCE} \times \text{DISTANCE}}{\text{TIME}}$$

where force is the frictional load (eg. 1kg) multiplied by gravitational acceleration (9.81m.$s^{-1}s^{-1}$), and distance is the flywheel revolutions (eg. 222) multiplied by the flywheel circumference (1.62m). Thus the work rate of a subject cycling against a resistance of 1kg would be:

$$\frac{0.981\ (N) \times (222 \times 1.62\ m)}{60\ (s)} = 58.9\ Nm.s^{-1}\ or\ W$$

This method of calculating work rate was used during all the $\dot{V}O_2max$ and submaximal incremental tests, and also during the 30-minute endurance tests in Chapter 5.

3.1.3 Computer system

For the purpose of continually monitoring the pedal frequency during the endurance tests a computerised data logging system was constructed. A small D.C. generator (R.S. Components Ltd.) driven by the flywheel of the cycle ergometer produced a voltage proportional to the speed of the flywheel. This voltage output was fed either into a Commodore Pet microcomputer (Model 4032) or a BBC (Model B) microcomputer via an external (Commodore) or internal (BBC) analogue-to-digital converter. Both systems sampled at approximately 10Hz. Once converted into S.I. units the output voltage values, together with information concerning the applied frictional load, were used to calculate work rate. During the test the computer screen displayed the following information:

time elapsed (minutes and seconds),
pedal revolutions (rpm) - updated every 2 seconds,
average pedal revolutions over a sampling period of 15 seconds (rpm/time) - updated every 15 seconds,
average work rate (AWR) over a sampling period of 15 seconds (work rate/time) - updated every 15 seconds,
and cumulative average work rate (CAWR) (total work done / total exercise time) updated every 15 seconds.

Every 15 seconds a hard copy of all the above information was generated on an Epsom FX-80 printer.

3.1.4 Heart rate

Heart rates were monitored during each test on a Rigel oscilloscope (Model 302) from 3 chest electrodes. The first of these electrodes was placed to the top of the sternum, the remaining two on the fifth rib 10cm either side of the mid-line. Before applying the electrodes the skin surface was thoroughly cleaned and slightly abraided to lower skin resistance. During the $\dot{V}O_2max$ and sub-maximal incremental tests heart rates were recorded manually every 30 seconds. During the endurance tests the cardiometer was interfaced with the microcomputer and a hard copy of the heart rates was generated and printed out automatically every 15 seconds.

3.1.5 Height

Subject height was recorded using a Holtain Stadiometer. All subjects were measured in bare feet. Measurements were taken to the nearest 0.1cm.

3.1.6 Weight

Subject weight was recorded using a beam balance (Avery Ltd., Model 3306 ABV). All subjects were weighed in bare feet wearing only shorts (males) or shorts and a t-shirt (females). Measurements were to the nearest 0.05kg.

3.1.7 Body composition

A Harpenden skinfold caliper (Holtain Ltd.) was used for the measurement of skinfold thickness from which percentage body fat and lean body mass values were estimated. Measurements were taken from four sites on the body (biceps, triceps, subscapular and suprailiac) in accordance with the specifications of Durnin and Wormersley (1974). Three measurements were taken at each site and an average value obtained. The estimates of body composition were calculated from the sum of the four skinfolds using the equations reported by Siri (1956).

3.1.8 Expired air collection

During expired air collections the subjects were required to wear a small noseclip (Harvard Equipment), and breathe into a rubber mouthpiece (Harvard Equipment). The mouthpiece was connected to a light-weight two-way valve (Jakeman and Davies, 1979). Wide bore (30mm) low resistance light-weight tubing (Falconia) connected the valve to a two-way tap which opened or closed a 150 litre capacity Douglas Bag (Harvard Equipment).

3.1.9 Expired air analysis

i. Oxygen analyser The oxygen (O_2) content in expired air was analysed using a paramagnetic oxygen analyser (Sybron; Taylor Servomex, Model 570A), with a digital read out accurate to 0.1%. The calibration procedure for this analyser together with the gas analysis procedure can be found in Appendices 1 and 2.

ii. Carbon dioxide analyser The carbon dioxide (CO_2) content in expired air was analysed using an infrared carbon dioxide analyser (Mines Safety Appliances Ltd.; Lira Model 303). The meter reading displayed by the analyser was in an analogue form and was converted to a percentage of carbon dioxide through use of a calibration curve supplied by the manufacturer and unique to that analyser. The calibration of this analyser together with the gas analysis procedure can be found in Appendices 1 and 2.

iii. Gas meter Gas volumes were determined using a Parkinson Cowan meter (one revolution = 50 litres). Calibration of this instrument was through use of a 6001 Tissot Spirometer (Collins Ltd.). A thermistor was fitted inside the air inlet pipe, and linked to a thermometer (Edale type 2984, Model C), for measurement of the temperature of the expired air.

3.1.10 Blood sampling

i. Blood lactate and glucose Duplicate 25 µl arterialised capillary blood samples were taken from the thumb using a sterile

blood lancet (Lance Blades) and calibrated micro pipettes (Dade, Diagnostics Inc.). The samples were deproteinised in 0.25 ml. perchloric acid, spun in a centrifuge (Eppendorf, Model 5412) for 2-3 minutes and placed in a freezer at -20°C before analysis at a later date.

ii. Haemoglobin Duplicate 20 µl samples of arterialised capillary blood were collected from the thumb, as described above, and mixed with 5 ml Drabkins Solution for the determination of haemoglobin concentration (Boehringer kit).

3.1.11 Blood analysis

The blood lactate and glucose assays, together with the procedures used for determination of haemoglobin concentrations are described in Appendix 3. However, the main equipment used is summarised below:-

i. Centrifuge: Blood samples were spun in an Eppendorf centrifuge (Model 5412) at a rate of 12000 rpm for 4 minutes in order to separate the supernatant from the precipitant.

ii. Whirlimixer: During various stages of blood analysis mixing of the samples was carried out using an electric Whirlimixer (Fisons Ltd, Model 250).

iii. Pipettes: Precision air displacement pipettes (Gibson Medical Electronics) and disposable tips were used for biochemical analysis of the capillary blood (the size of the pipettes used in this study ranged fom 20µl to 5000µl).

iv. Photometer: An Eppendorf Photometer (Model 1101M) was used to measure absorbance during determination of blood glucose and haemoglobin concentrations.

v. Fluorimeter: A Perkin-Elmer fluorimeter (1000m) was used for the fluorometric determination of nicotinamide-adenine dineucleotide in its reduced form (NADH).

3.1.12 Perceived rate of exertion

During each expired air collection subjects were required to indicate their perceived rate of exertion. This was achieved using a 6-20 rating scale devised by Borg (1973).

3.2 FAMILIARISATION

Prior to testing, all subjects were given a detailed account of the tests to be undertaken in the study and informed that, if necessary, they were free to cease exercise at any stage during a test. The subjects then underwent a familiarisation session in the laboratory. During this session age, height and weight were recorded and four skinfold measurements were taken.

Familiarisation with the cycle ergometer required the subject to exercise for three-minute periods of increasing work rates at a constant pedal rate of 60rpm. The work rate was individually set so that the intensity increased steadily from an initially low work rate to a final, near maximal, work rate. During the third minute of each work rate an expired air collection was taken, and the perceived rate of exertion indicated. When the exercise intensity was rated at about 17 or 18 the test was stopped. The purpose of this session was to fully familiarise the subject with exercise on the cycle ergometer, the prescribed pedal frequency for the forthcoming tests (60rpm), and the use of the expired air collection apparatus (the expired air was not analysed).

3.3 SUBJECT PREPARATION

Specific details of the subjects used in each study will be given in the relevant chapters. Prior to each test the subjects arrived at the laboratory after a fast of at least 2 hours. Weight was recorded and chest-electrodes placed in position. Where blood sampling was undertaken the subject's hand was immersed in warm water to cause skin vasodilation. On completion of the blood sampling the subject was seated on the cycle ergometer and connected to the heart-rate oscilloscope. The subject was then ready to perform the test. On all occasions drinking water and an electric fan were available.

3.4 DETERMINATION OF MAXIMUM OXYGEN UPTAKE ($\dot{V}O_2MAX$)

A 3-minute incremental test was used to determine $\dot{V}O_2max$. Subjects were required to warm up for 5 minutes at a work rate 59W

less than their initial test work rate. On completion of the warm up the friction load was increased and the test started. Subjects exercised at a constant pedal frequency of 60rpm throughout the test with increments in work rate being the result of an increase in frictional load. During each 3-minute exercise period expired air was collected for 60 seconds between minutes 1:45-2:45. In addition, a final 60-second collection was made when the subject signalled that he/she could only exercise at the prescribed rate for one more minute. During each expired air collection a pedal rate count was taken and perceived rate of exertion measured. The criteria used for $\dot{V}O_2max$ were based on subjective exhaustion, an R value in excess of 1.15 (Issekutz, Birkhead and Rodahl, 1962), a plateau in $\dot{V}O_2$ with an increase in work rate (Taylor, Buskirk and Henschel, 1955) and a heart rate close to the expected peak mean for the age of the subjects (Astrand, 1952).

3.5 SUBMAXIMAL INCREMENTAL TEST

A 16-minute test, where work rate was increased every 4 minutes by 29W, was used to determine the relationships between submaximal $\dot{V}O_2$ and work rate, and submaximal blood lactate concentration and work rate. Unlike other studies, i.e running studies, where common speeds can be administered to all subjects, it proved impractical in this study to administer common work rates for all the subjects. To have done so would have required some of the subjects to exercise through a range of 29W-206W for the females and 118W-265W for the males before eliciting 80% of their $\dot{V}O_2max$. Since this would represent a test in excess of 20 minutes the work rates were individually set to suit each individual. The starting work rate for each individual was determined by two factors, firstly that the 4th work rate should elicit in excess of 80% of the subject's $\dot{V}O_2max$, and secondly that work rate increments should be no greater than 29W for any subject.

Prior to the test a resting sample of arterialised capillary blood was taken from a pre-warmed hand for the determination of blood lactate concentration. During the fourth minute of each of the 4 work rates an expired collection was taken, the subject's pedal rate recorded, and perceived rate of exertion indicated. On completion of the expired air collection a sample of arterialised capillary blood was taken from the thumb prior to the work rate being increased.

3.5.1 Determination of the onset of blood lactate accumulation (OBLA)

From the data collected during the submaximal incremental test the relationship between work rate and blood lactate concentration was plotted for each individual, where work rate was expressed either in absolute terms (W) or relative to the subject's $\dot{V}O_2max$ (%$\dot{V}O_2max$). The work rate equivalent to a blood lactate concentration of 4 $mmol.l^{-1}$ (OBLA) was then interpolated from the graph and expressed as $OBLA_w$ or OBLA% (Figure 3.1).

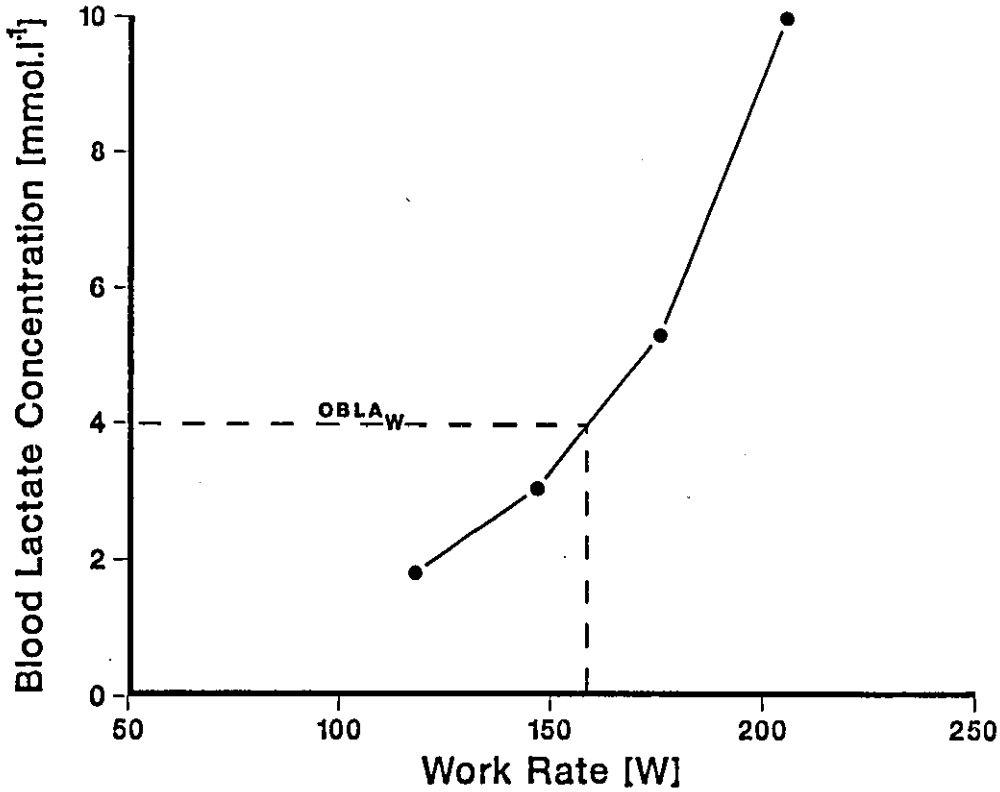
3.5.2 Determination of the endurance test work rate

A linear regression equation describing the relationship between submaximal oxygen uptake ($l.min^{-1}$) and work rate (W) was calculated for each individual using the gas analysis results from the submaximal incremental test. From this equation the work rate required to elicit 80% of the subject's $\dot{V}O_2max$ was estimated by interpolation.

3.6 30-MINUTE ENDURANCE TEST (T30min)

Subjects reported to the laboratory in a rested state, and where blood sampling was required (Chapters 5, 6 and 7) after an overnight fast. Weight was recorded, electrodes attached, and a resting sample of arterialised capillary blood taken from a pre-warmed hand. Subjects were then required to warm up on the cycle ergometer at a work rate equivalent to 50% of their $\dot{V}O_2max$. During this warm up period the interface between the cycle ergometer and the computer system was calibrated to ensure that the pedal frequency values displayed by the microcomputer were a true reflection of those shown by the speedometer. A full description of the calibration procedures can be found in Appendix 1. On completion of the warm up the subject was informed of the format of the test, with emphasis placed on performing "as much work as possible in the time available".

For the first 5 minutes of T30min the subject was required to exercise at a work rate equivalent to approximately 80% of their $\dot{V}O_2max$. For the remaining 25 minutes they were free to exercise at a work rate of their choice, this was achieved by altering the pedal



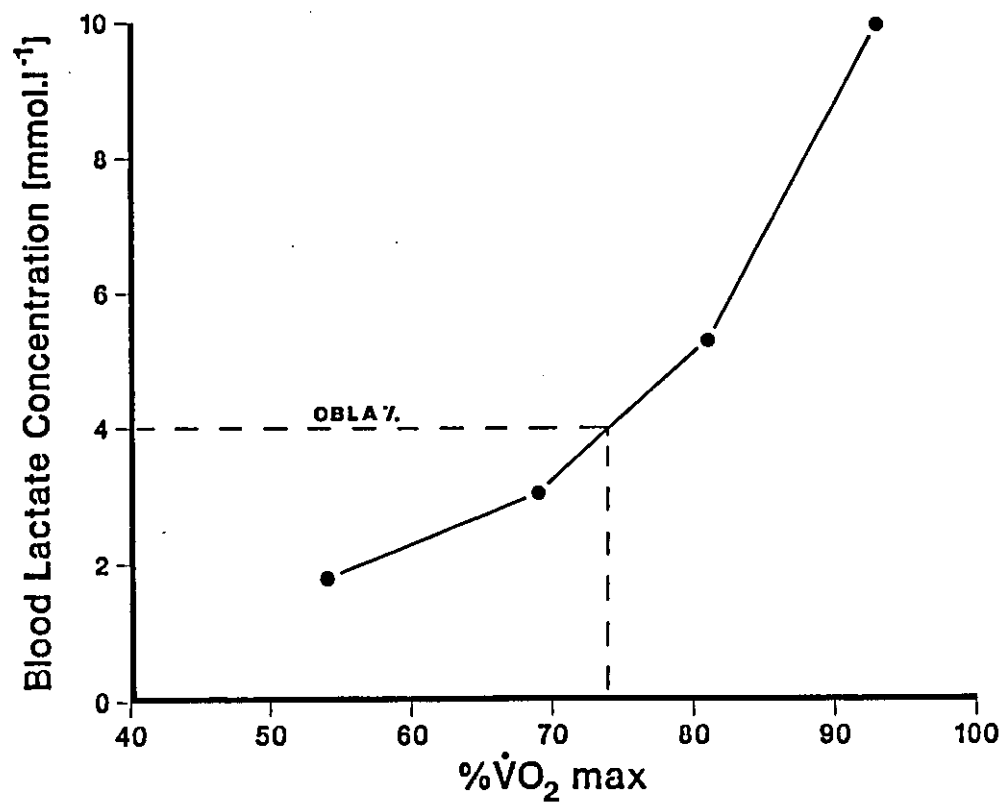


Figure 3.1 Determination of the work rate (watts and $\%\dot{V}O_{2}max$) equivalent to OBLA.

frequency whilst the frictional load remained constant. Constant feedback on performance was available to the subject throughout the test from a microcomputer screen positioned infront of the cycle ergometer. The screen displayed the subject's pedal revolutions, average pedal revolutions, average work rate and cumulative average work rate throughout the 30-minute test. In addition, performance was also displayed graphically on the screen. The abscissa of the graph was divided into 30, one-minute time periods which represented the test time elapsed. The ordinate represented the pedal revolutions (rpm). At intervals of 0.5s a vertical line, proportional to the pedal revolutions, was blocked in giving an ongoing display of the work rate of the subject throughout the test. A line representing 60 rpm was drawn across the graph to act as a guideline for the required pedal rate during the first five minutes, and an indication of the subject's performance during the remainder of the test.

During the test four, 60-second expired air collections were made, namely between minutes 3:45-4:45, 8:45-9:45, 18:45-19:45 and 28:45-29:45. Perceived rate of exertion was also recorded during these collection times. At the end of each expired air collection a sample of arterialised capillary blood was taken from the thumb for the determination of blood lactate concentration. Heart rate, pedal frequency and work rate values were all monitored continuously by the microcomputer and printed out every 15 seconds. A schematic representation of the 30-minute test protocol can be seen in Figure 3.2.

3.7 80% $\dot{V}O_2$MAX ENDURANCE TEST (T80%)

This test refers to the training study chapter only. Subjects reported to the laboratory after an overnight fast and in a rested state. Weight was recorded, electrodes attatched and a resting sample of arterialised capillary blood was taken from a pre-warmed hand for the determination of blood lactate, blood glucose and haemoglobin concentrations. Subjects were then required to warm up on the cycle ergometer for four minutes at a work rate equivalent to 50% of their $\dot{V}O_2max$. The subject was then informed of the format of the test and that the aim was to exercise to exhaustion at a work rate equivalent

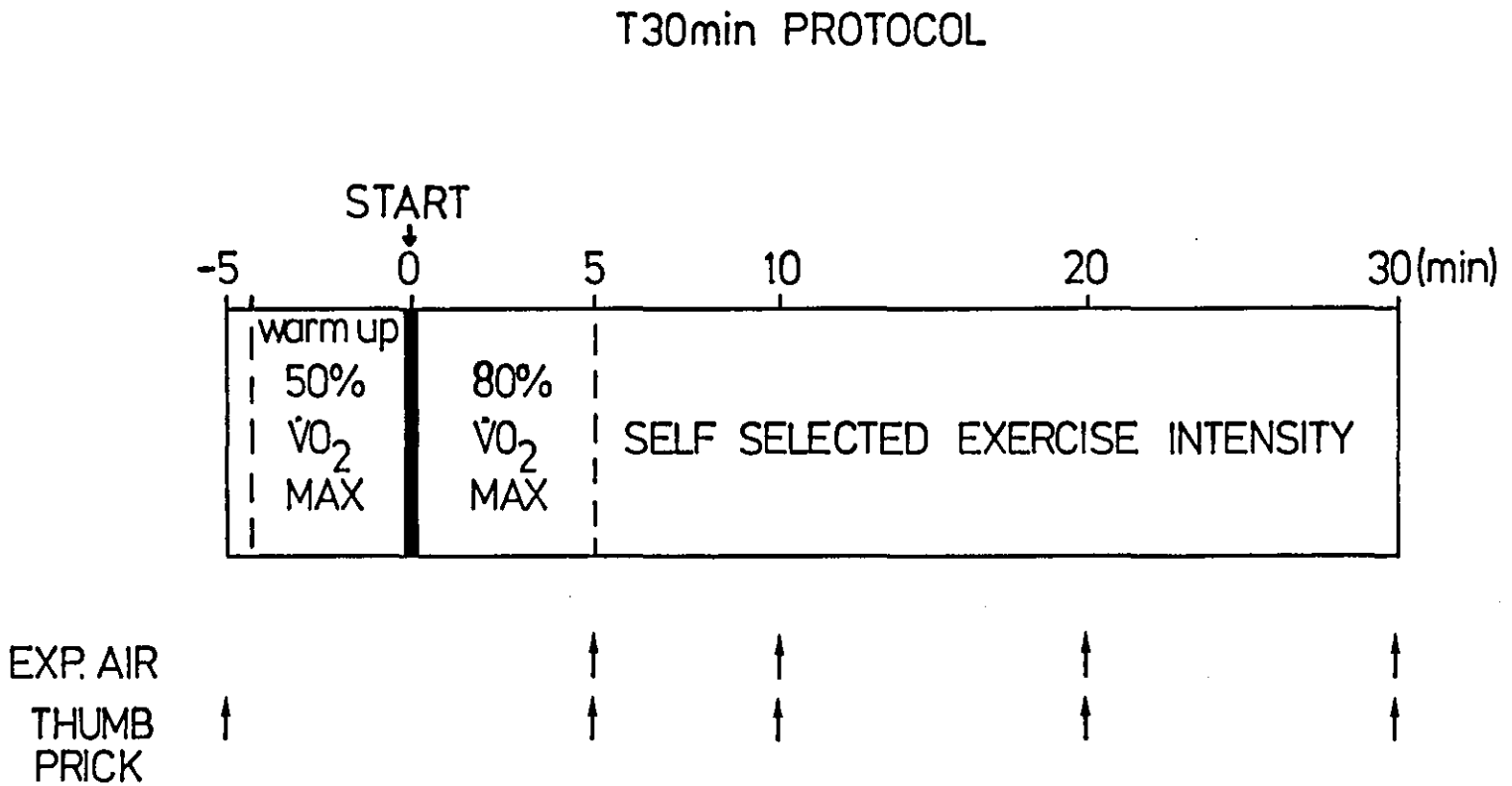


Figure 3.2 A schematic representation of the 30-minute endurance test protocol.

to 80% $\dot{V}O_2$max. This work rate was comprised of the same frictional load and pedal frequency as used during the first 5 minutes of T30min.

Routine collections of expired air were taken at 5 and 10 minutes and every 10 minutes thereafter during the first hour. If the subject continued beyond the hour (post-training only) expired air collections were reduced to every 20 minutes. Routine blood sampling took place at 5, 10, 20 and 30 minutes and on the hour. If the subject continued exercise beyond the hour blood sampling was reduced to every 60 minutes. A final one minute expired air collection was taken when the subject indicated that she could continue to maintain the prescribed work rate for only one more minute. At the end of this one minute collection the test was stopped and a final blood sample collected. A schematic representation of the test protocol can be seen in Figure 3.3.

Throughout the test a microcomputer screen display was clearly visible to the subject informing them of the time elapsed, pedal revolutions and average pedal revolutions over the last 15 seconds. For the exercise intensity to be equivalent to 80% of the subject's $\dot{V}O_2$max it was important for the subject to keep the pedal revolutions as close to 60rpm as possible. If the average pedal revolutions dropped below 58rpm on two consecutive sampling periods (i.e. 30 seconds) the experimenter gave the subject a warning. After two warnings the experimenter would impose a final minute on the subject and stop the test if the rate again fell below that prescribed.

3.8 STATISTICAL METHODS

Standard parametric statistical techniques were used throughout (Cohen and Holliday, 1979). Unless stated otherwise, all values reported in the text and the tables refer to group means ($\bar{x}$) and standard deviations (S.D.). Where subjects were required to perform two 30-minute endurance tests results from the more successful of the two tests (based on CAWR) were used for data analysis. Relationships between two or more variables were evaluated using the Pearson Product Moment correlation coefficient. Student's t-test was used for testing the significance of the difference between two means, using the appropriate test for correlated or independent means. Differences and relationships were considered significant at the 0.05 level.

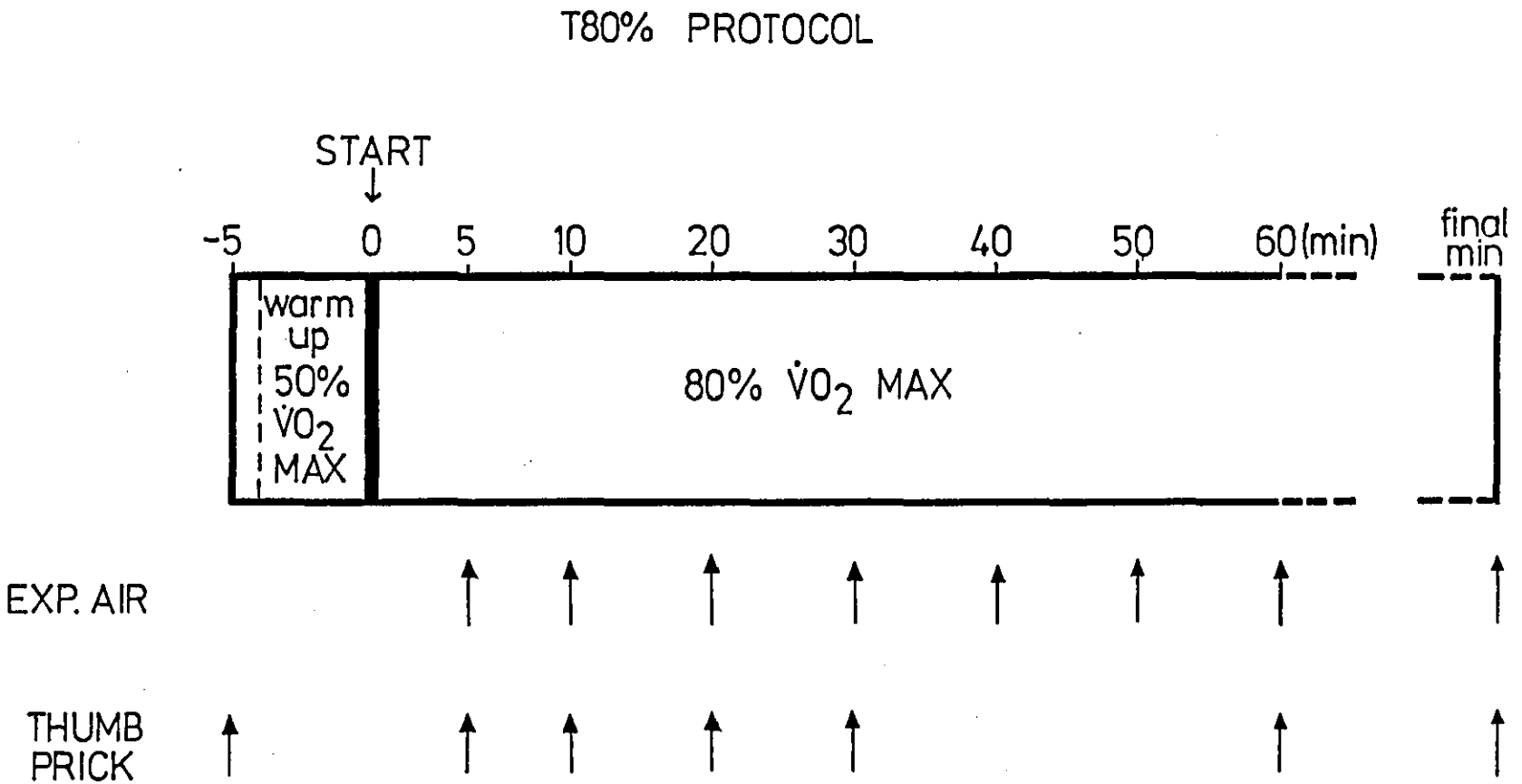


Figure 3.3 A schematic representation of the 80% $\dot{V}O_{2max}$ endurance test protocol.

4. DEVELOPENT OF A 30-MINUTE CYCLE ERGOMETER TEST OF ENDURANCE PERFORMANCE

4.1 INTRODUCTION

The measurement of endurance performance and the assessment of a subject's state of conditioning or fitness has been the interest of exercise physiologists for many years. However, although numerous researchers have advocated methods of measuring endurance no standard method has emerged. In the past a number of researchers have adopted performance tests where the subjects are required to perform as much work as possible in a given period of time (Katch and Katch, 1972; Boulay et al., 1984), or exercise for as long as possible at a given absolute work rate (Wilmore, 1969; Hickson et al., 1977). Because of the linear relationship between oxygen uptake and energy expenditure and because metabolic and cardiovascular responses occur in relation to the relative exercise intensity at which the subject is exercising (Hermansen and Saltin, 1967; Rowell, 1974) performance on these tests is influenced largely by $\dot{V}O_2max$ rather than the subject's training status.

As a result of this some studies have employed tests where the relative exercise intensity ($\%\dot{V}O_2max$) is the same for all individuals. Tests such as exercise time to exhaustion at a given $\%\dot{V}O_2max$ (Williams and Nute, 1983, 1986) or measurements of the $\%\dot{V}O_2max$ tolerable over a given distance (Davies and Thompson, 1979; Maughan and Leiper, 1983) have permitted direct comparisons of endurance performance between individuals with largely different $\dot{V}O_2max$ values. There are, however, no studies to the authors knowledge that use a cycle ergometer to measure a subject's ability to tolerate as high a $\%\dot{V}O_2max$ as possible during a standardised time period.

The purpose of this study was to develop a laboratory test on a cycle ergometer designed to measure the highest $\%\dot{V}O_2max$ tolerable during a 30-minute time period and to report on its reproducibility. In addition, the relationship between $\dot{V}O_2max$ and performance variables measured by the test was also examined.

4.2 METHODS

In establishing the protocol for the 30-minute endurance test the following factors were taken into consideration:

a) The test should be long enough to ensure that a large energy demand be placed on the aerobic energy system, but since subjects were required to exercise at a maximal rate that the test be limited in length for motivational reasons.
b) That there be a standardised period of time (5 minutes) where all subjects were required to exercise at the same $\%\dot{V}O_2max$. This period would help prevent subjects misjudging the work rate at the start of the test and provide them with an indication of the pace they could tolerate for the remainder of the test.
c) The $\%\dot{V}O_2max$ selected for the start of the test should be one which all subjects were capable of tolerating for 5 minutes but provocative enough to ensure that the subjects' responses would vary during the remaining 25 minutes of the test, i.e. that some subjects would have to decrease their work rate due to fatigue while others would be able to increase theirs.

In order to determine the optimal $\%\dot{V}O_2max$ for the first 5 minutes of the test it was necessary to undertake some preliminary experiments. These experiments are described in Appendix 4. On the basis of these preliminary experiments, together with information from a previous study employing the same test format (Evans, 1984), it was concluded that 80% $\dot{V}O_2max$ should be the starting work rate for the test.

The selection of the relationship between the pedal frequency and work load at which the subjects exercised during the first 5 minutes of the test was based on empirical evidence. Cycle ergometer exercise tests performed in the University laboratories have routinely used 60rpm as the standard pedal frequency. To enable the direct comparison of subject data with existing data on subjects of comparable age and activity patterns all preliminary tests in this study were also carried out at 60rpm. Since the T30min work rate (80% $\dot{V}O_2max$) was interpolated from the submaximal test data, to ensure that the work

rate elicited approximately 80% $\dot{V}O_2max$, it was important that the pedal frequency during the first 5 minutes of T30min was the same as that used during the submaximal test, i.e. 60rpm.

4.2.1 Subjects

Five male physical education students, 1 male physical education lecturer and 6 female physical education students acted as subjects for the study. All subjects participated in regular physical activtiy but none were engaged in serious endurance training. Prior to testing all subjects were fully familiarised with exercise on a cycle ergometer as described in Chapter 3 (3.2).

4.2.2 Preliminary tests

Maximum oxygen uptake was determined during a 3-minute incremental test as described in Chapter 3 (3.4). Maximal work rate ranged from 186.8W to 255.2W for the females, and 253.3W to 300.8W for the males. Where subjects did not achieve any of the criteria for attaining $\dot{V}O_2max$ they were required to perform the test again on a different day.

The relationship between $\dot{V}O_2$ and work rate was determined during 4 minutes of steady-rate exercise at 4 increasing submaximal work rates. The work rates ranged from 54.4W to 182.8W for the females and 112.9W to 279.3W for the males, no work rate was common to all 12 subjects. The work rate required to elicit 80% of each individual's $\dot{V}O_2max$ was derived using individual regression equations for the relationship between $\dot{V}O_2$ and work rate, as described in Chapter 3 (3.5.2). No blood sampling was undertaken during this test.

4.2.3 30-minute endurance test (T30min)

Each subject performed T30min on two occasions, at least 48 hours apart, and at the same time of the day where possible. On both occasions a standardised 4-minute warm up, at a work rate 59W lower than the T30min work rate, was administered. Immediately following the warm up the subject started the test, exercising for 5 minutes at a work rate equivalent to 80% $\dot{V}O_2max$ and 25 minutes at a work rate of

their choice. Expired air collections were made during minutes 3:45-4:45, 8:45-9:45, 18:45-19:45 and 28:45-29:45, and heart rates were recorded manually every minute. A schematic representation of the T30min protocol can be seen in Figure 3.2, in this study, however, no blood sampling was undertaken.

4.2.4 Computer system

A Commodore Pet microcomputer (model 4032) and an external anologue-to-digital converter were used to monitor pedal frequency throughout the test (see Chapter 3). On completion of the test the computer screen displayed the subject's average work rate (AWR) (W) and cumulative average work rate (CAWR) (W) values for each of the 30 minutes of the test. These values were then used, in conjunction with individual regression equations describing the relationship between $\dot{V}O_2$ and work rate, to calculate the estimated $\%\dot{V}O_2max$ that the subject had been exercising at during each of the 30 minutes (AWR $\%\dot{V}O_2max$), and the estimated average $\%\dot{V}O_2max$ that the subject had been exercising throughout the test ($\%\dot{V}O_2max_E$).

4.3 RESULTS

4.3.1 Preliminary tests

The physical and physiological characteristics of the male (n=6) and female (n=6) subjects, and the group as a whole (n=12) are presented in Tables 4.1. and 4.2. Statistical analysis of the differences between the males and the females is included in Chapter 6 and will not be presented in this chapter, any subsequent reference to group means, therefore, will refer to the group as a whole (n=12).

The mean $\dot{V}O_2max$ for the group was 3.3 $\pm$ 0.6 $l.min^{-1}$, ranging from 2.42 to 4.34 $l.min^{-1}$. Six of the subjects achieved a plateau in the $\dot{V}O_2$ despite an increase in work rate (Taylor et al., 1955), whilst a final R value in excess of 1.15 was recorded by all subjects (Issekutz et al., 1962).

Table 4.1 Physical characteristics of the subjects (mean ± S.D.).

		MALES (N=6)	FEMALES (N=6)	GROUP (N=12)
Age	$\bar{x}$	25.9	21.1	23.5
(yrs)	S.D.	14.6	1.6	10.4
Height	$\bar{x}$	179.0	166.5	172.8
(cm)	S.D.	5.6	3.9	8.0
Weight	$\bar{x}$	76.0	64.9	70.4
(kg)	S.D.	6.7	5.7	8.3
Body Fat	$\bar{x}$	12.9	25.1	19.0
(%)	S.D.	4.4	3.4	7.4

Table 4.2 Physiological characteristics of the subjects (mean ± S.D.).

		MALES (N=6)	FEMALES (N=6)	GROUP (N=12)
$\dot{V}O_2max$	$\bar{x}$	3.85	2.80	3.33
($l.min^{-1}$)	S.D.	0.36	0.22	0.66
$\dot{V}O_2max$	$\bar{x}$	50.91	43.41	47.29
($ml.kg^{-1}min^{-1}$)	S.D.	5.76	1.89	5.80
$\dot{V}E$ max	$\bar{x}$	130.1	104.0	171.1
($l.min^{-1}$)	S.D.	21.6	10.2	21.2
HR max	$\bar{x}$	188	195	191
($b.min^{-1}$)	S.D.	14	9	12
Max Work Rate	$\bar{x}$	274.4	228.8	251.6
(W)	S.D.	19.8	23.1	31.4

The highest values for age, height, weight, maximum ventilation ($\dot{V}E$ max) and work rate at $\dot{V}O_2max$ were all recorded by male subjects, whilst the lowest values for each of these variables were recorded by females. The lowest percentage body fat and maximum heart rate (HR max) were recorded by males, whilst the highest values were recorded by females.

The oxygen cost of exercise at increasing submaximal work rates is presented in Tables 4.3. and 4.4 and Figures 4.1 and 4.2. A linear relationship was found between these two variables both individually and for the group as a whole. The changes in heart rate during submaximal exercise are presented in Table 4.3. and 4.4 and Figures 4.3 and 4.4. The curvilinear relationship found between heart rate and work rate for the group as a whole may be the result of the differences in the gradients of the regression lines describing the relationship between heart rate and work rate for the male and female subjects.

4.3.2 T30min Test-retest reliability

Cumulative average work rate and $\%\dot{V}O_2max_E$ values for Test 1 (T1) and Test 2 (T2) are presented in Table 4.5. Although differences in mean CAWR and $\%\dot{V}O_2max_E$ for T1 and T2 were statistically significant at 10 and 20 minutes there was no significant difference in these two variables at 30 minutes. These results suggest that the total work done and the relative work rate at which the subjects performed T30min were both reproducible. The results did reveal, however, a tendency for subjects to exercise at a slightly higher absolute and relative work rate during the second T30min (Figure 4.5 and 4.6).

Oxygen uptake values during T1 and T2 are presented in Tables 4.5 and Figures 4.7. None of the observed mean differences approached the level of significance, and strong relationships were seen between T1 and T2 measurements ($r=0.81$ to $r=0.95$). Similar test-retest reliability was found for heart rate and $\%\dot{V}O_2max$ (Table 4.6 and Figures 4.8 and 4.9), whilst $\dot{V}E$ ($l.min^{-1}$) was significantly higher during T2 at 10 minutes ($p<0.01$) but at no other collection time (Table 4.6 and Figure 4.10).

Table 4.3 Work rate (W), oxygen uptake ($l.min^{-1}$) and heart rate ($b.min^{-1}$) during the submaximal incremental test for the males (n=6) and females (n=6). Mean ± S.D.

MALES

n	WORK RATE (W)	$\dot{V}O_2$ ($l.min^{-1}$)	HR ($b.min^{-1}$)
3	118.0 ± 4.6	1.99 ± 0.25	140 ± 31
4	146.7 ± 3.6	2.24 ± 0.24	149 ± 21
6	175.0 ± 2.2	2.59 ± 0.25	158 ± 19*
6	205.9 ± 5.2	3.05 ± 0.22	172 ± 15*
3	235.6 ± 3.8	3.42 ± 0.25	174 ± 9*
2	273.7 ± 7.6	3.95 ± 0.56	178*

* n-1

FEMALES

n	WORK RATE (W)	$\dot{V}O_2$ ($l.min^{-1}$)	HR ($b.min^{-1}$)
1	54.5	0.96	106
6	89.7 ± 2.7	1.31 ± 0.15	132 ± 11
6	119.5 ± 2.0	1.58 ± 0.28	151 ± 14
6	148.3 ± 3.1	2.07 ± 0.13	165 ± 16
5	178.6 ± 2.4	2.42 ± 0.08	177 ± 17

Table 4.4 Work rate (W), oxygen uptake ($l.min^{-1}$) and heart rate ($b.min^{-1}$) during the submaximal incremental test for the group (n=12). Mean ± S.D.

GROUP

n	WORK RATE (W)	$\dot{V}O_2$ ($l.min^{-1}$)	HR ($b.min^{-1}$)
1	54.5	0.96	106
2	89.7 ± 2.7	1.31 ± 0.15	132 ± 11
9	119.0 ± 2.9	1.77 ± 0.26	147 ± 20
10	147.7 ± 3.2	2.13 ± 0.19	159 ± 19
11	176.6 ± 2.9	2.51 ± 0.20	167 ± 20
6	205.9 ± 5.2	3.05 ± 0.22	172 ± 15*
3	235.6 ± 3.8	3.42 ± 0.25	174 ± 9*
2	273.7 ± 7.6	3.95 ± 0.56	178*

* n-1

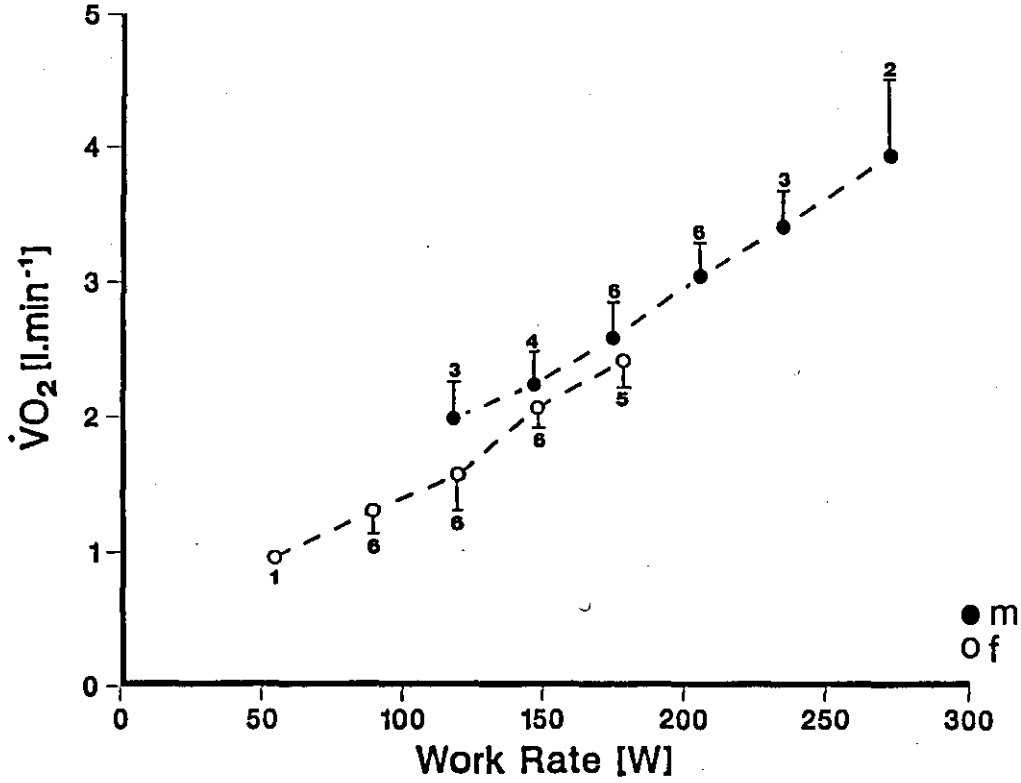


Figure 4.1 Oxygen uptake during the incremental test for the males (n=6) and the females (n=6). Numbers represent sample size

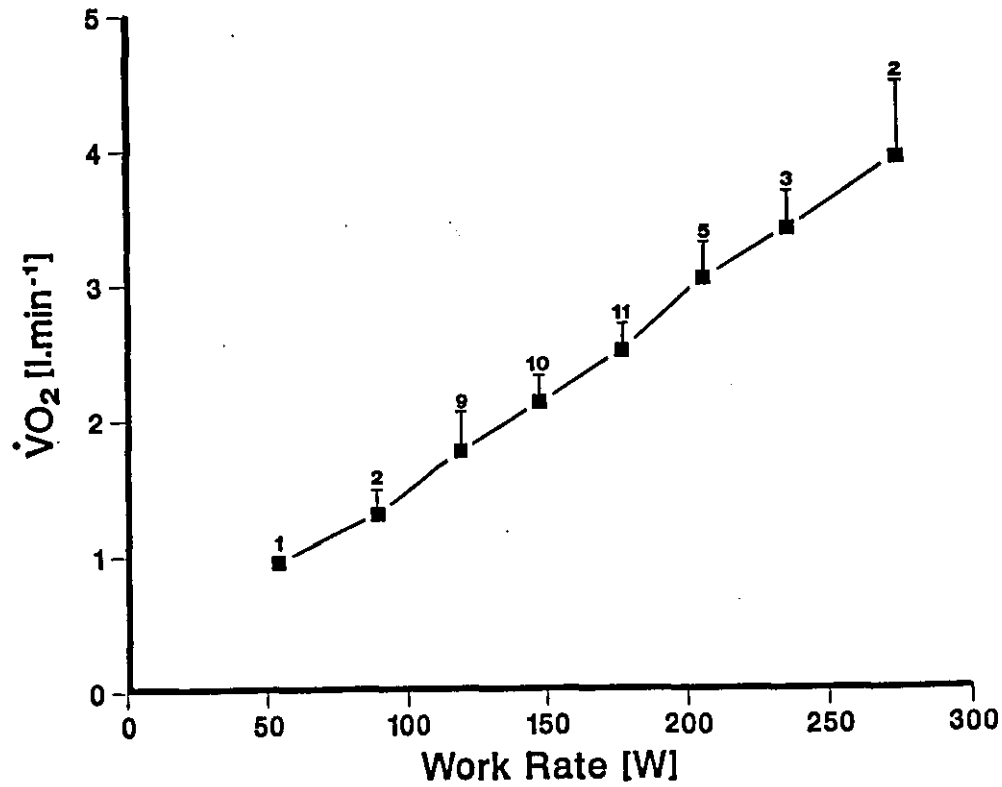


Figure 4.2 Oxygen upake during the incremental test for the group (n=12). Numbers represent sample size

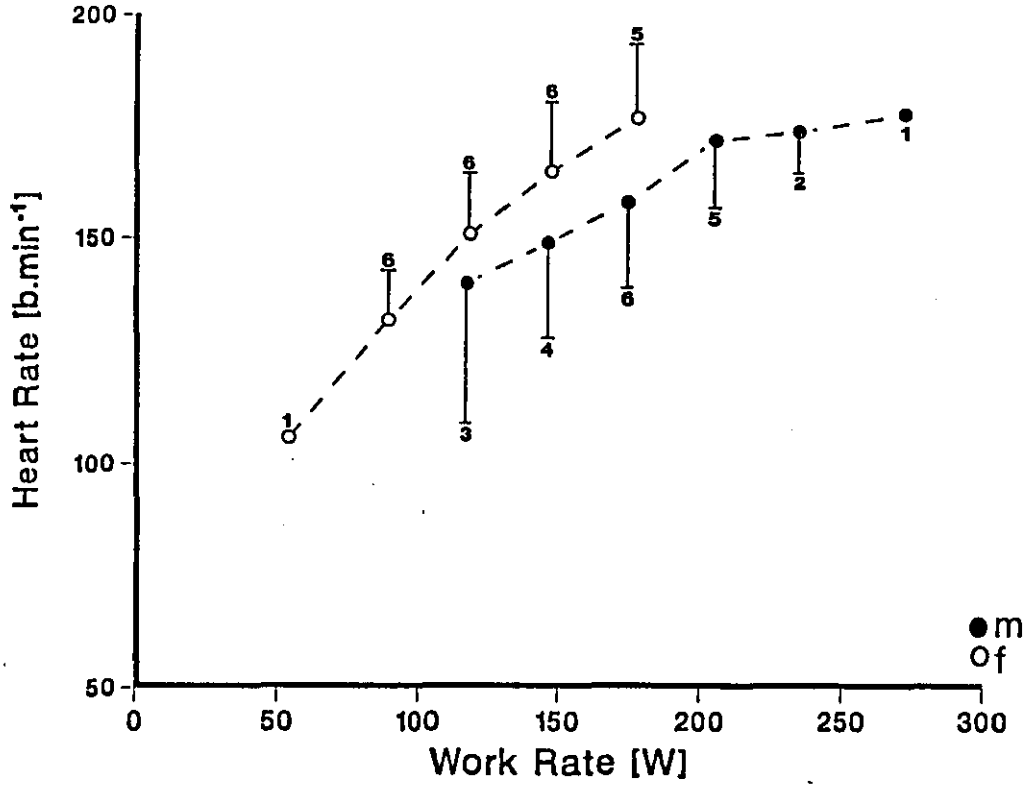


Figure 4.3 Heart rate during the incremental test for the males (n=6) and the females (n=6). Numbers represent sample size.

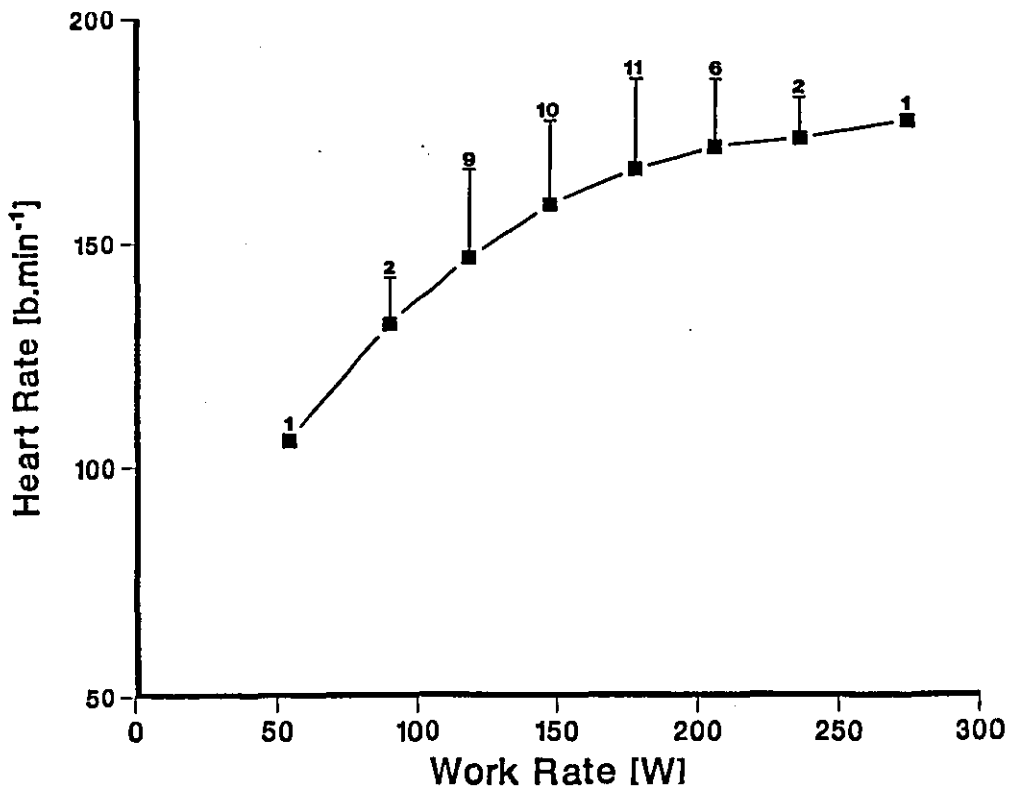


Figure 4.4 Heart rate during the incremental test for the group (n=12). Numbers represent sample size.

Table 4.5 Reproducibility and correlation coefficients for cumulative average work rate (W), $\%\dot{V}O_{2}max_{E}$ and oxygen uptake ($l.min^{-1}$) during T30min (n=12). Mean ± S.D.

CAWR (W)

TIME (min)	TEST 1	TEST 2	X DIFF	r
5	185.3 ± 26.5	186.9 ± 23.1	1.6	0.93
10	188.1 ± 27.1	192.5 ± 26.5**	4.4	0.99
20	189.6 ± 28.3	195.3 ± 24.8*	5.7	0.98
30	191.9 ± 28.6	198.4 ± 26.0	6.5	0.93

$\%\dot{V}O_{2}max_{E}$

TIME (min)	TEST 1	TEST 2	X DIFF	r
5	80.0 ± 1.3	79.4 ± 1.1	-0.6	0.42
10	81.0 ± 2.7	82.9 ± 2.9**	1.9	0.79
20	81.8 ± 5.7	84.1 ± 4.6*	2.3	0.88
30	82.9 ± 6.9	85.3 ± 4.6	2.4	0.82

$\dot{V}O_{2}$ ($l.min^{-1}$)

TIME (min)	TEST 1	TEST 2	X DIFF	r
5	2.61 ± 0.47	2.54 ± 0.41	-0.07	0.95
10	2.75 ± 0.51	2.83 ± 0.54	0.08	0.93
20	2.85 ± 0.50	2.81 ± 0.42	-0.04	0.81
30	3.09 ± 0.55	3.08 ± 0.51	-0.01	0.87

Significantly different from T1 ** $p<0.01$ * $p<0.05$

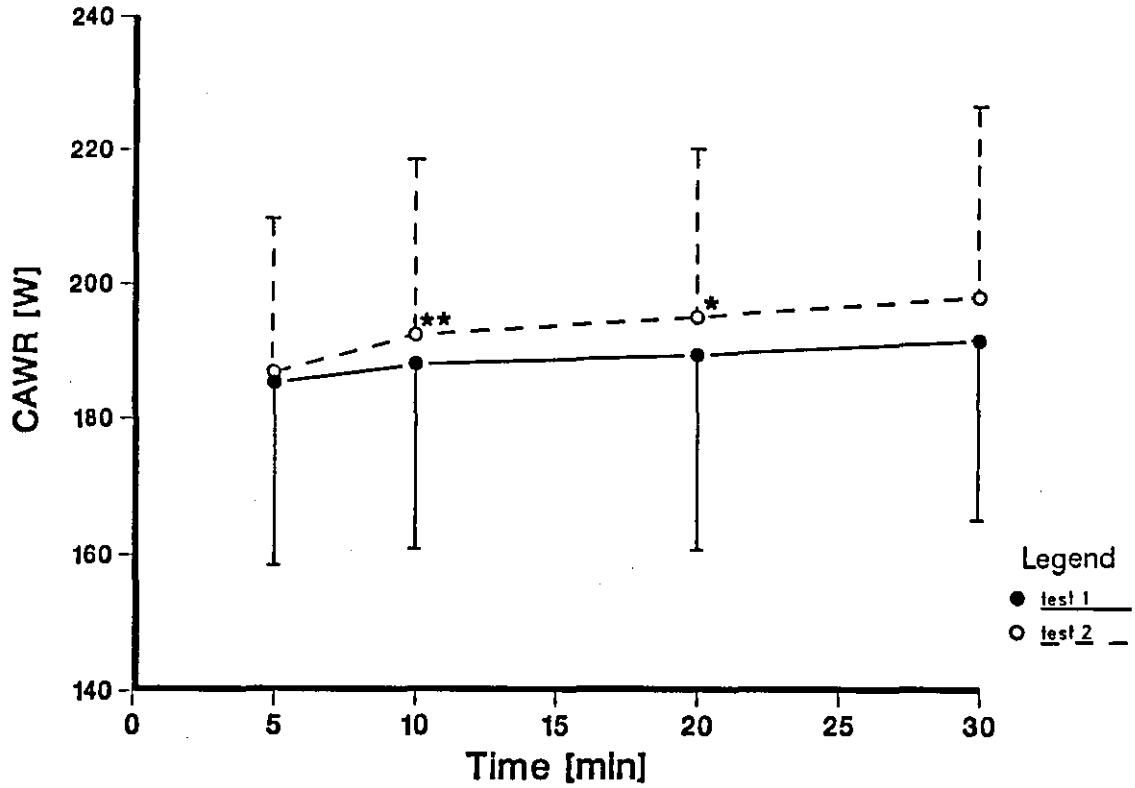


Figure 4.5 Cumulative average work rate during Test 1 and Test 2. Significantly different from Test 1 * p<0.05 ** p<0.01.

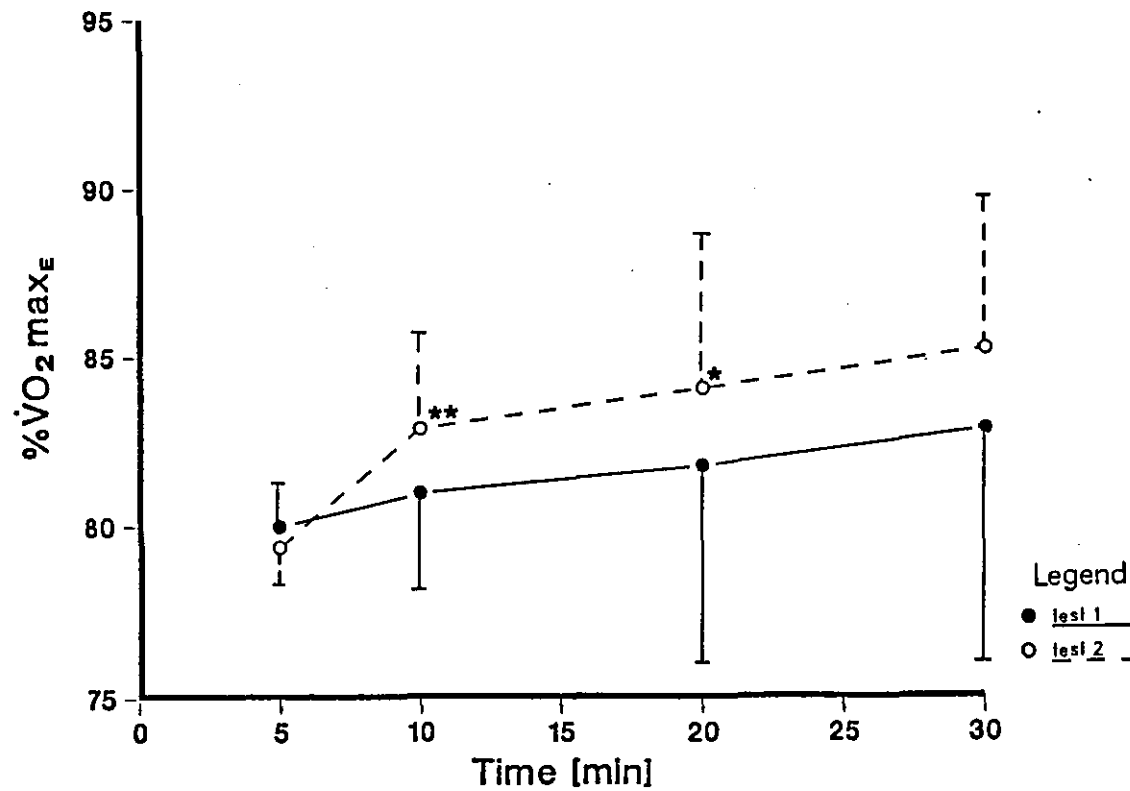


Figure 4.6 Estimated relative exercise intensity during Test 1 and Test 2. Significantly different from Test 1 * p<0.05 ** p<0.01

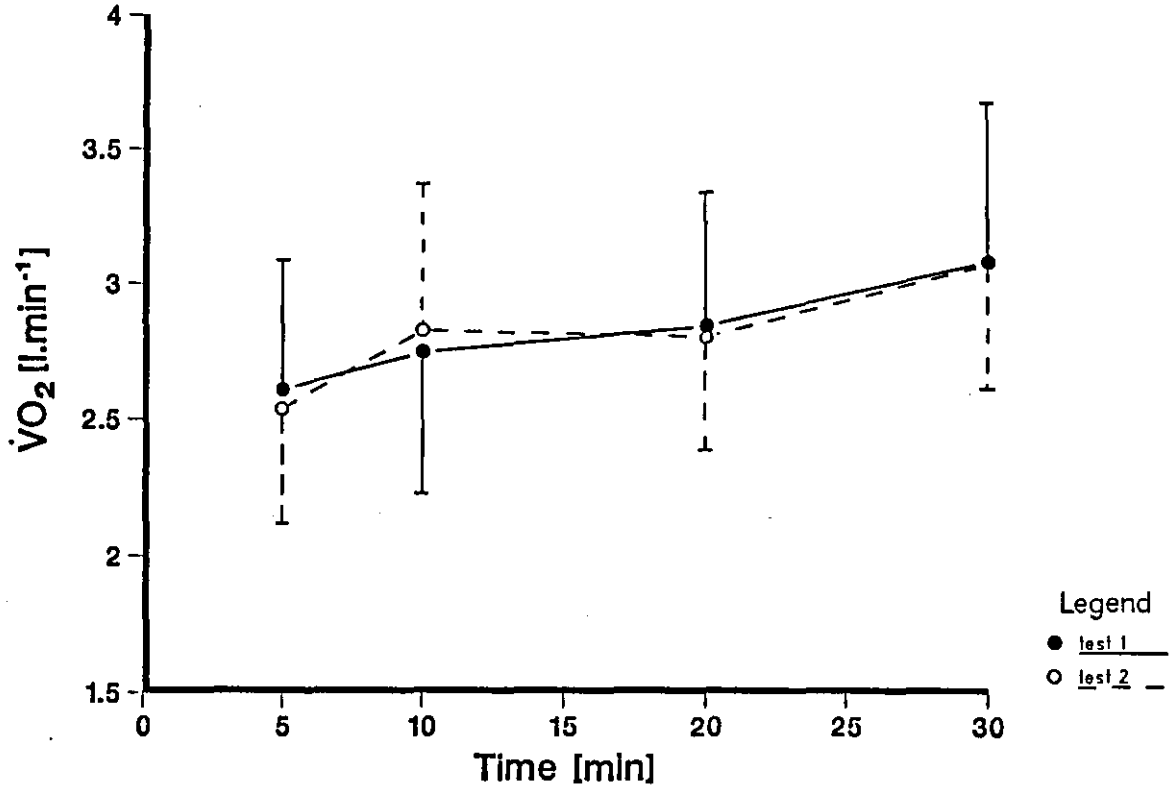


Figure 4.7 Oxygen uptake during Test 1 and Test 2.

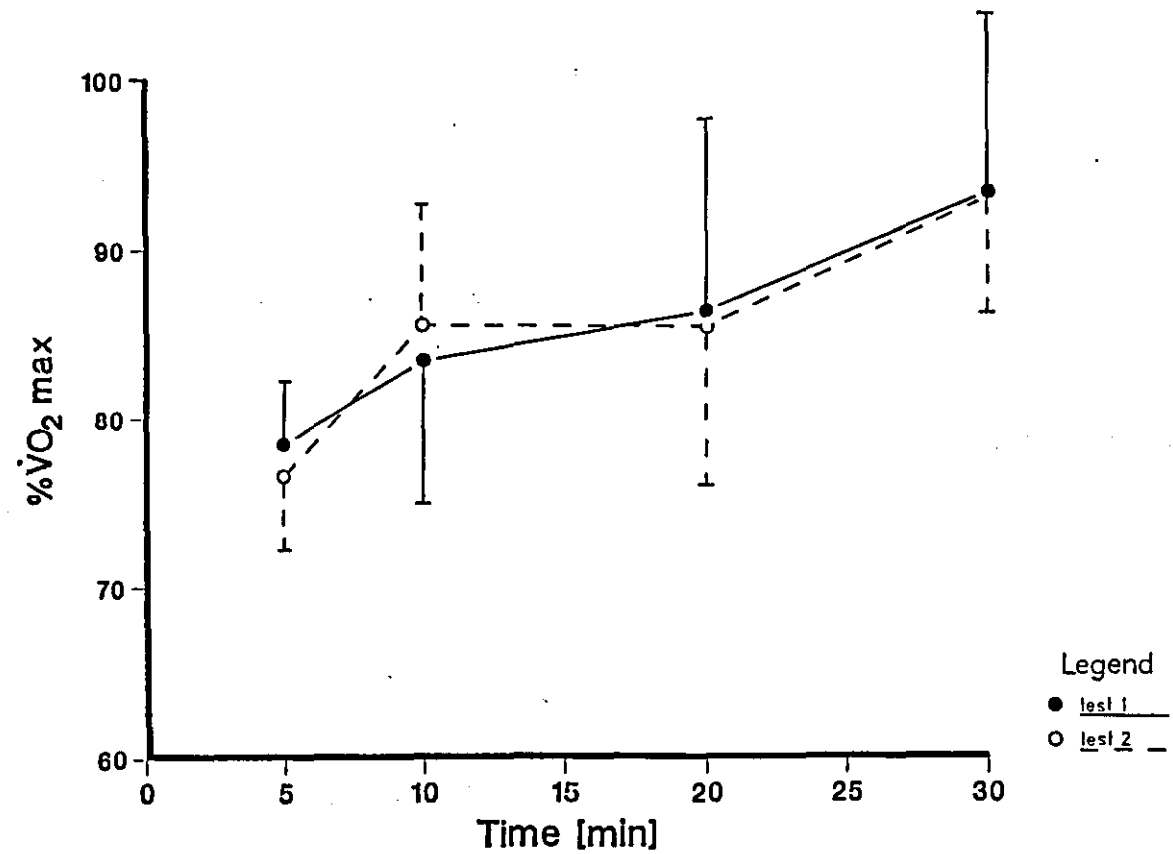


Figure 4.8 Relative exercise intensity during Test1 and Test 2.

Table 4.6 Reproducibility and correlation coefficients for relative exercise intensity (%$\dot{V}O_2max$), heart rate ($b.min^{-1}$) and ventilation ($l.min^{-1}$) during T30min (n=12). Mean ± S.D.

%$\dot{V}O_2max$

TIME (min)	TEST 1	TEST 2	X DIFF	r
5	78.5 ± 3.8	76.6 ± 4.1	-1.9	0.34
10	83.5 ± 8.4	85.6 ± 7.1	2.1	0.76
20	86.4 ± 11.7	85.5 ± 9.6	-0.9	0.66
30	93.5 ± 10.4	93.2 ± 7.1	-0.3	0.45

Heart Rate ($b.min^{-1}$)

TIME (min)	TEST 1	TEST 2	X DIFF	r
5	166 ± 13	162 ± 16	-4	0.87
10	172 ± 14	170 ± 15	-2	0.79
20	178 ± 14	177 ± 14	-1	0.91
30	187 ± 17	186 ± 15	-1	0.45

$\dot{V}E$ ($l.min^{-1}$)

TIME (min)	TEST 1	TEST 2	X DIFF	r
5	62.4 ± 8.2	62.6 ± 8.4	0.2	0.92
10	69.6 ± 10.5	75.8 ± 6.2**	6.2	0.78
20	76.7 ± 13.2	82.5 ± 13.5	5.8	0.64
30	98.5 ± 24.7	102.9 ± 18.9	4.4	0.91

Significantly different from T1 ** $p<0.01$

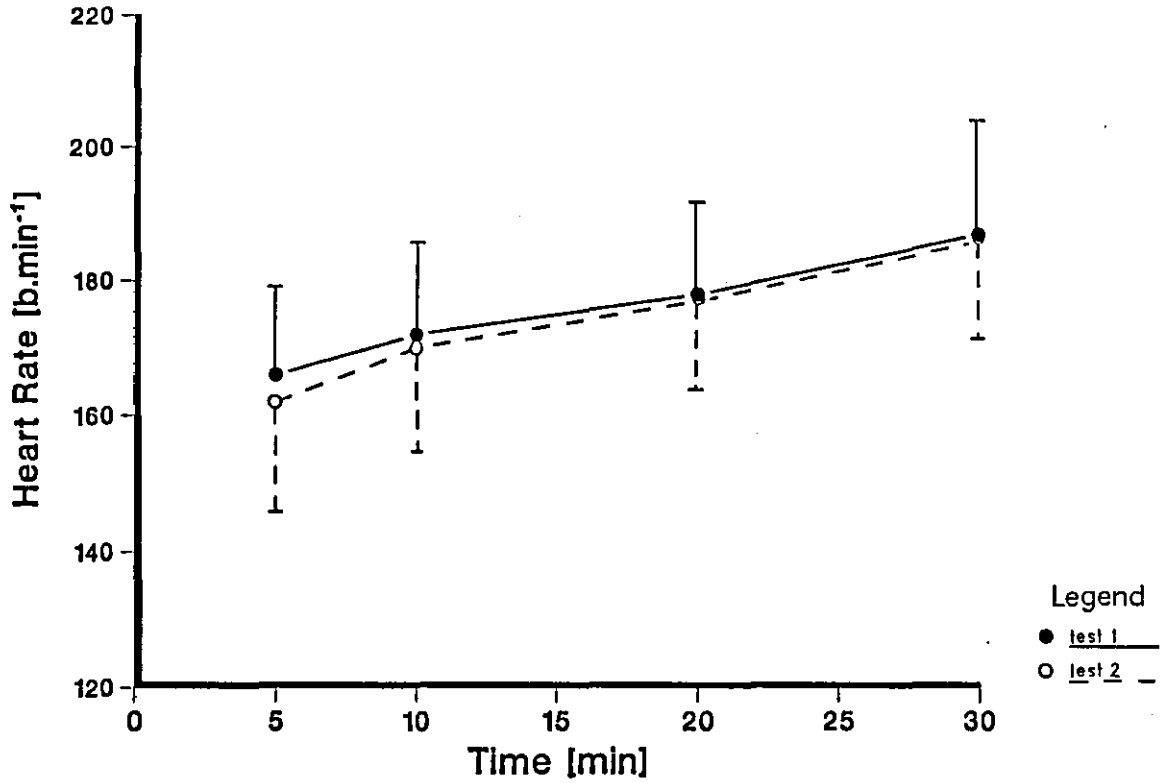


Figure 4.9 Heart rate during Test 1 and Test 2.

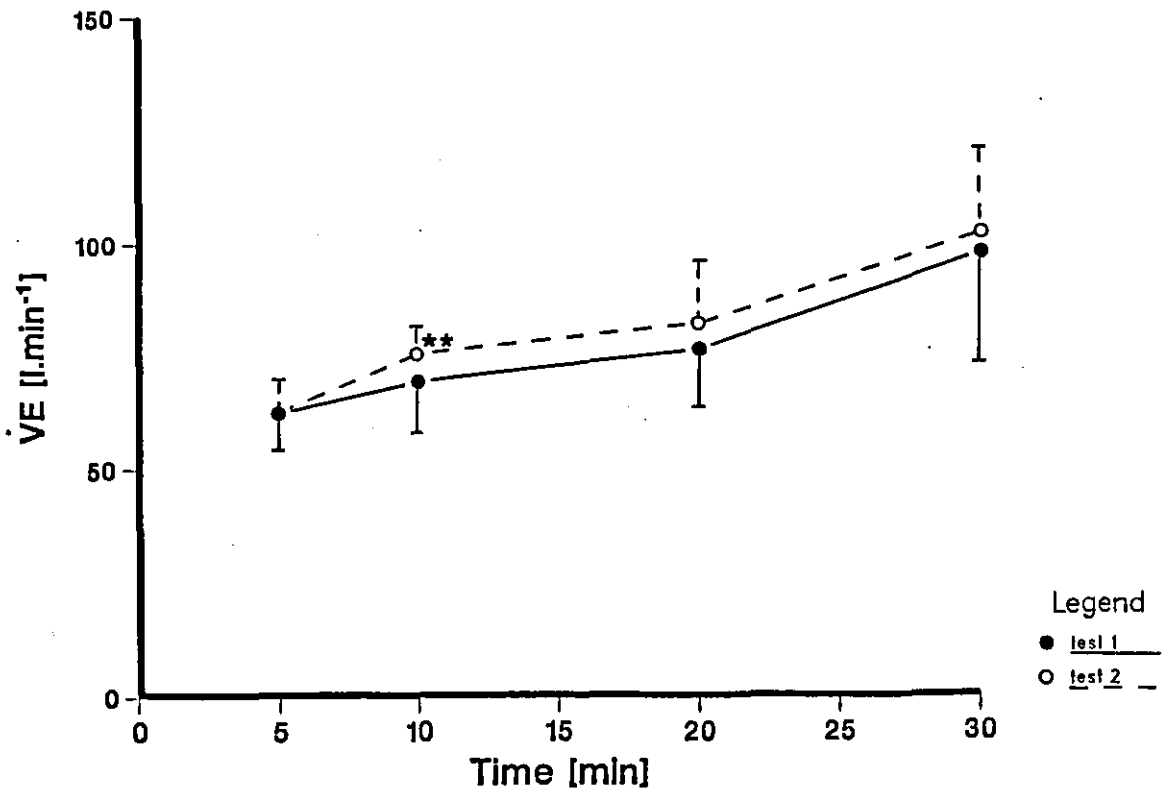


Figure 4.10 Ventilation during Test 1 and Test 2.
Significantly different from Test 1 ** $p<0.01$.

4.3.3 T30min performance and physiological characteristics

A summary of some of the physiological changes and changes in performance during T30min can be seen in Table 4.7. Mean CAWR for the group increased gradually throughout T30min, and was paralleled by a similar trend in $\dot{V}O_2$ and heart rate. During the final expired air collection of T30min four of the subjects attained $\dot{V}O_2$ values equal to their $\dot{V}O_2max$, whilst one other subject achieved HR max.

The relationship between performance variables and $\dot{V}O_2max$ can be seen in Figures 4.11 and 4.12. The rank order of the subjects according to their $\dot{V}O_2max$, CAWR and $\%\dot{V}O_2max_E$ can be seen in Table 4.8. Statistical analysis revealed a strong correlation between $\dot{V}O_2max$ and CAWR ($r=0.88$; $p<0.01$), but only poor correlations between $\dot{V}O_2max$ and $\%\dot{V}O_2max_E$ ($r=-0.38$; NS) and CAWR and $\%\dot{V}O_2max_E$ ($r=0.14$; NS), suggesting that for this group of subjects $\%\dot{V}O_2max_E$ was independent of $\dot{V}O_2max$ (Table 4.9).

Table 4.7 Summary of the T30min results (mean ± S.D.).

		5 (min)	10 (min)	20 (min)	30 (min)
CAWR	$\bar{x}$	185.4	191.4	196.0	200.1
(W)	S.D.	26.5	25.1	26.0	27.1
$\%\dot{V}O_2max_E$	$\bar{x}$	79.8	83.4	84.3	86.2
	S.D.	0.7	2.3	4.4	4.7
$\dot{V}O_2$	$\bar{x}$	2.55	2.83	2.88	3.14
($l.min^{-1}$)	S.D.	0.39	0.45	0.41	0.46
$\%\dot{V}O_2max$	$\bar{x}$	76.9	86.0	87.8	95.5
	S.D.	4.4	7.3	10.1	8.2
Heart rate	$\bar{x}$	162	170	178	187
($b.min^{-1}$)	S.D.	17	15	14	15

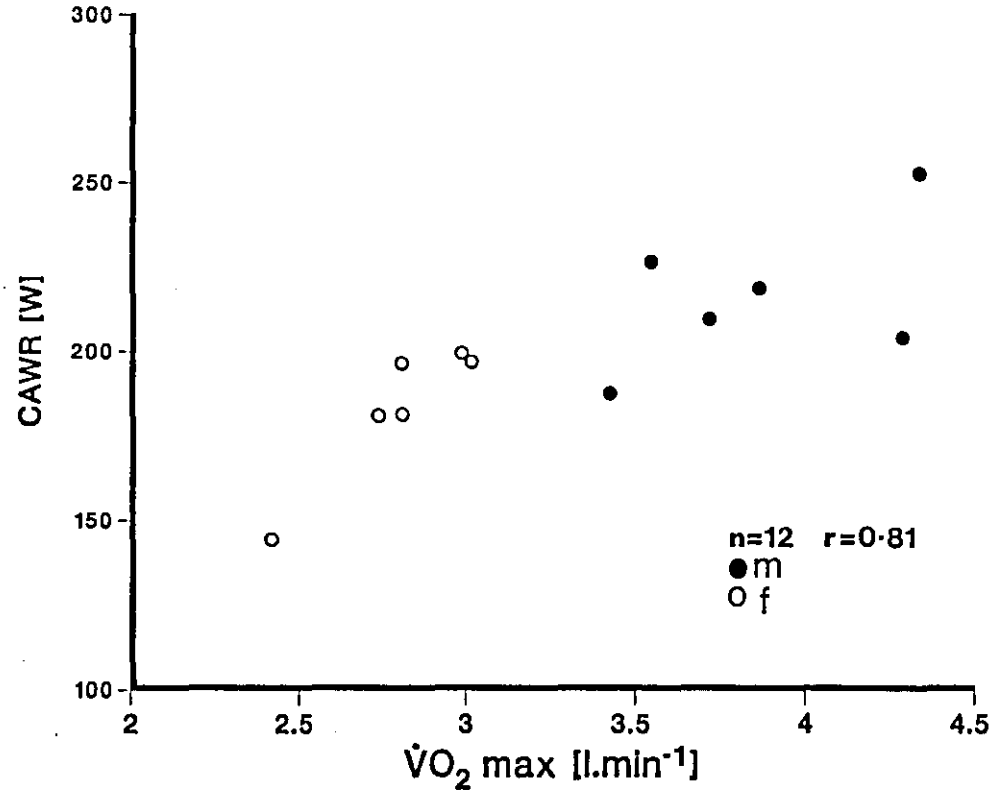


Figure 4.11 Relationship between maximum oxygen uptake and cumulative average work rate.

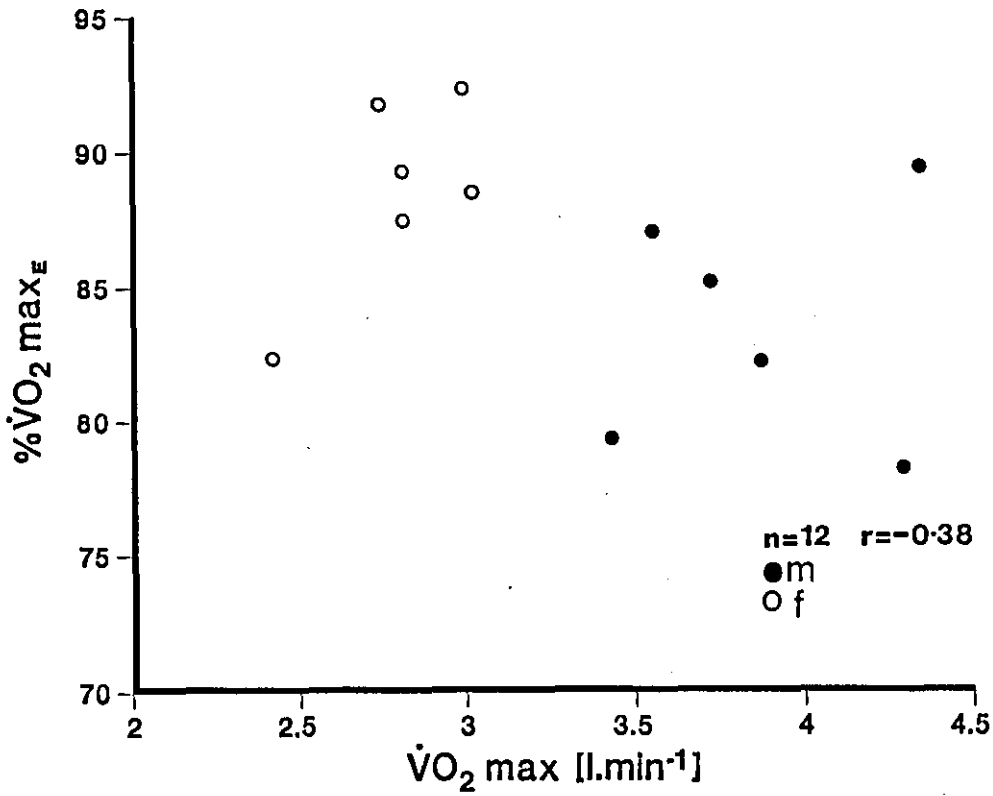


Figure 4.12 Relationship between maximum oxygen uptake and estimated relative exercise intensity.

Table 4.8 Subject Rank Order for maximum oxygen uptake, cumulative average work rate and $\%\dot{V}O_2max_E$.

Subject	$\dot{V}O_2max$ ($l.min^{-1}$)	CAWR (W)	$\%\dot{V}O_2max_E$
1*	4	4	8
2*	1	5	12
3*	2	1	3
4*	6	9	11
5*	3	3	10
6*	5	2	7
7	11	11	2
8	8	6	1
9	9	8	6
10	9	10	4
11	7	7	5
12	12	12	9

* denotes male subject

Table 4.9 Pearson Product Moment correlations coefficients for maximum oxygen uptake, cumulative average work rate and $\dot{V}O_2max_E$ (n=12).

	$\dot{V}O_2max$	CAWR	$\%\dot{V}O_2max_E$
$\dot{V}O_2max$	-	0.81	-0.38
CAWR	0.81	-	0.14
$\%\dot{V}O_2max_E$	-0.38	0.14	-

4.4 DISCUSSION

The mean $\dot{V}O_2max$ values for the male and female physical education students and for the group as a whole were 3.85 ± 0.36 $l.min^{-1}$, 2.80 ± 0.22 $l.min^{-1}$ and 3.33 ± 0.66 $l.min^{-1}$ respectively. These values compare favourably with cycle ergometry results reported by Hardman (1984), for a group of 18 male physical education students (3.51 ± 0.38 $l.min^{-1}$), Evans (1984), for a group of 8 female physical education students (2.70 ± 0.27 $l.min^{-1}$) and Bland (1982), for a group of 6 male and 2 female untrained students (3.18 ± 0.67 $l.min^{-1}$), all from similar populations of undergraduate students. During the $\dot{V}O_2max$ test all subjects attained at least one of the required criteria to demonstrate that $\dot{V}O_2max$ had been achieved (see Chapter 3).

The oxygen cost of exercise at increasing work rates is presented in Tables 4.3 and 4.4. All the subjects demonstrated a linear response in $\dot{V}O_2$ with an increase in work rate, indicating that the work rates were all submaximal. Comparison of the data with submaximal $\dot{V}O_2$ values reported for both males and females by Hardman (1984) revealed that the $\dot{V}O_2$ values for the males in this study were higher at each work rate than those reported by Hardman, whilst the values reported for the females were of a similar magnitude. It would appear, therefore, that the males in this study were less economical in terms of $\dot{V}O_2$ at a given work rate when compared with both the males reported by Hardman and the females in the same study.

The T30min work rate, i.e. the work rate required to elicit 80% $\dot{V}O_2max$, was calculated using individual regression equations describing the relationship between $\dot{V}O_2$ and work rate. Results from T1 revealed that, during the first 5 minutes of the test the group were exercising on average, at a work rate equivalent to 78.5% of their $\dot{V}O_2max$ (males 81.6%, females 78.3%). Based on these results it was accepted that the method for determining the test work rate was adequate and the same work rates should be administered for T2. Results of T2 revealed, however, that the same work rate elicited on average only 76.6% of each subject's $\dot{V}O_2max$. This change in the mean $\%\dot{V}O_2max$ of the test was largley influenced by the results of the male

group. Whereas the mean $\%\dot{V}O_2max$ for the female group was 78.3 ± 4.8% and 79.1 ± 4.1% in T1 and T2 respectively, the mean $\%\dot{V}O_2max$ for the males decreased from 81.6 ± 3.3% in T1 to 74.0 ± 2.3% in T2. Since both groups underwent the same preliminary test procedures and the same method of work rate selection one of the reasons for the increased economy of the male subjects at a given work rate may have been due to their initial level of familiarity with the exercise mode. Four out of the six female subjects had previously been involved in exercise testing on a cycle ergometer whereas only one of the male subjects had had any previous testing experience. Despite a thorough familiaristion, the relative unfamiliarity of the laboratory procedures may have thus influenced the $\dot{V}O_2$ at a given work rate causing it to be slightly elevated due to anxiety and an inefficient style on T1 (this could also account for the higher values reported for the males in comparison to those reported by Hardman, 1984). The T30min work rate for the males may, therefore, have been underestimated, a factor not evident until T2 when subjects were a) well familiarised with the exercise mode and b) well familiarised with the test itself.

The difference in the mean $\%\dot{V}O_2max$ at 5 minutes between T1 and T2, although not significant for the group as a whole, did highlight the importance of the following factors in any subsequent testing:

a) The need for a thorough familiarisation of all the subjects.
b) The need to perform the $\dot{V}O_2max$ test before the submaximal test so that any elevated $\dot{V}O_2$ due to initial anxiety and inefficient style would not lead to overestimation of the oxygen demand of a given work rate.
c) The comparison of submaximal $\dot{V}O_2$ values with $\dot{V}O_2max$ test $\dot{V}O_2$ values at the same work rate and submaximal $\dot{V}O_2$ values from other subjects (any large discrepancies between $\dot{V}O_2$ values at a given work rate would result in the subject being required to repeat the test).

The heart rate response to submaximal exercise for the males, females and group as a whole can be seen in Tables 4.3 and 4.4 and Figures 4.3 and 4.4. While the mean values at a given work rate for the males was in agreement with data for the same work rates reported by Hardman (1984), the mean values for the females were on average 10

$b.min^{-1}$ lower. Although both the males and the females demonstrated a linear relationship between heart rate and work rate, there was a curvilinear relationship between the two variables for the group as a whole (Figure 4.4). This curvilinear relationship may be accounted for by the disparity in the gradients of the male and female regression lines. Becaues heart rate increases in relation to the relative stress of the activity (Astrand and Ryhming, 1954), the gradient of the female regression line was steeper because each increment in work rate represented a greater increase in relative exercise intensity.

The 30-minute performance test showed good test-retest reliability on all the variables measured. The strong correlation found between T1 and T2 for CAWR (r=0.93), was higher than that reported by Wilmore (1969), for test-retest exercise time to exhaustion (r=0.89) and total work output (r=0.83) during a constant load test; Katch and Katch (1972), for test-retest "cumulated work performed" in a 10 minute "drop-off" test; and Weltman and Regan (1982), for test-retest of performance time and pedal revolutions in a constant load cycle ergometer test (r=0.92). It was lower, however, than that reported by Boulay et al. (1984), for test-retest of the total work output during a 90-minute "Maximal Aerobic Capacity" test (r=0.99).

The significant difference between T1 and T2 in CAWR and $\%\dot{V}O_2max_E$ at 10 and 20 minutes but not at 30 minutes (Tables 4.5) would indicate a difference in the performance trends during the two tests. During T1 the subjects may have been unfamiliar with the task and, therefore, unsure of the pacing until nearer the end of the test. During T2 the subjects exercised at a significantly higher work rate during the middle stages of the test despite no difference in either CAWR or $\%\dot{V}O_2max_E$ by the end of the test.

The changing trends from T1 to T2, and the higher CAWR and $\%\dot{V}O_2max_E$ values in T2 for 9 out of the 12 subjects would emphasise the need for the test to be performed on two occasions. This would ensure that the performance scores were not influenced by the naivety of the subjects on the task. The high reproducibility of the test, however, would indicate that in extreme circumstances, if the subject was unable to perform the test on two occasions, the results from their

first test would be an adequate and acceptable measure of their endurance performance on T30min.

The good reproducibility of the physiological and performance variables measured during T30min is in agreement with the results reported by Evans (1984). In her study six physical education students performed T30min on three occasions. Analysis of variance revealed no significant difference in CAWR, heart rate and $\dot{V}O_2$ between the three tests. This present study also found no significant difference in heart rate, $\dot{V}O_2$ and $\%\dot{V}O_2max$ between either of the two tests. The only physiological variable to show a significant difference between trials was $\dot{V}E$ ($l.min^{-1}$). The $\dot{V}E$ value recorded at 10 minutes in T2 was signicantly higher than that recorded in T1 despite no difference at 5, 20 or 30 minutes. One explanation for this increase may be due to a combination of the higher CAWR, $\%\dot{V}O_2max_E$ ($p<0.01$) and $\dot{V}O_2$ (NS) at 10 minutes in T2.

The physiological and performance characteristics during T30min can be seen in Table 4.7. As might be expected, due to the linear relationship between $\dot{V}O_2$ and work rate, those subjects with high $\dot{V}O_2max$ values were able to exercise at a higher absolute work rate during T30min than those with low $\dot{V}O_2max$ values. This is confirmed by the strong correlation of $r=0.81$ ($p<0.01$) between CAWR and $\dot{V}O_2max$. This correlation is in keeping with reports in the literature where statisticlly significant relationships have been found between $\dot{V}O_2max$ and work output on a cycle ergometer test to exhaustion ($r=0.84$; Wilmore, 1969), and total work done during a 12-minute cycle ergometer performance test ($r=0.78$; Katch, 1973).

The results of this study would appear to confirm that performance on T30min, like many other tests where an absolute work rate is recorded, is strongly related to $\dot{V}O_2max$. Although CAWR provides a measure of the subject's ability to perform endurance exercise this measure does not necessarily reflect their training status. When CAWR was expressed relative to $\dot{V}O_2max$ ($\%\dot{V}O_2max_E$) a more informative description of performance was obtained. When $\%\dot{V}O_2max_E$ was correlated with CAWR, only a poor correlation of $r=0.14$ (NS) was found, implying that those subjects who were exercising at the highest CAWR were not necessarily exercising at the highest $\%\dot{V}O_2max_E$. In

addition, only a poor relationship was found between $\dot{V}O_2max$ and $\%\dot{V}O_2max_E$ (r=-0.38, NS), implying that those individuals with the highest $\dot{V}O_2max$ values were not able to exercise at the highest $\%\dot{V}O_2max_E$ (Figure 4.12). These findings are confirmed in Table 4.8 which shows the rank order of the subjects according to $\dot{V}O_2max$, CAWR and $\%\dot{V}O_2max_E$. The table highlights the fact that all six male subjects recorded higher $\dot{V}O_2max$ values than the females, with five of the males also recording higher CAWR values. However, when performance was expressed as $\%\dot{V}O_2max_E$ five out of the six females were found to have been exercising at a higher $\%\dot{V}O_2max_E$ than the males. These results therefore suggest, that the ability to exercise at a high $\%\dot{V}O_2max$ is not dependent on $\dot{V}O_2max$ *per se*. In addition, if the $\%\dot{V}O_2max$ an individual can exercise at is an appropriate method of describing endurance fitness or training status, $\dot{V}O_2max$ alone does not adequately reflect this factor.

This study also highlighted the advantage of T30min over other performance tests in that it provides two different measures of endurance performance. Cumulative average work rate indicates the subject's ability to exercise at a given absolute work rate, a performance characteristic which most individuals seek to improve. Whilst $\%\dot{V}O_2max_E$ provides a measurement that can be used to a) make direct comparisons of endurance performance between individuals with varying $\dot{V}O_2max$ values, and b) provide an indication of an individual's training status.

In summary, the results of this study revealed the high reproducibility of both physiological and performance variables during T30min. The tendency to exercise at a higher work rate during the second of the 2 endurance tests, however, indicated the need for the test to be performed on 2 occasions. The necessity of a high $\dot{V}O_2max$ in order to exercise at a high absolute work rate was confirmed by the strong relationship between $\dot{V}O_2max$ and CAWR (r=0.81), whilst the ability to exercise at a high relative exercise intensity was found to be independent of $\dot{V}O_2max$ (r=-0.38), and confirms the findings previously reported in the literature that $\dot{V}O_2max$ does not adequately reflect an individual's capacity for submaximal endurance.

5. ENDURANCE PERFORMANCE AND ONSET OF BLOOD LACTATE ACCUMULATION IN ENDURANCE-TRAINED AND SPRINT-TRAINED ATHLETES

5.1 INTRODUCTION

The results reported in Chapter 4 highlight the reproducibility and reliability of T30min as a method of measuring endurance performance. The results also support the proposition that the quality of endurance, defined as the ability to tolerate a high $\%\dot{V}O_2max$ over a given period of time, is independent of $\dot{V}O_2max$. The study, however, provided little information concerning the characteristics of those individuals who could tolerate a high $\%\dot{V}O_2max_E$ during T30min.

It has been well documented in the literature that endurance-trained athletes are characterised by the ability to tolerate a high $\%\dot{V}O_2max$ over a given period of time (Costill and Fox, 1969; Davies and Thompson, 1979), and it has been suggested that this is due to the the greater oxidative potential of the skeletal muscle and the lower levels of blood lactate concentration at a given absolute and relative work rate that occur as a result of training (Gollnick et al., 1973). The training-induced improvement in the quality of endurance, however, appears to be the result of endurance training rather than training *per se*, since reports from animal studies have revealed no improvement in endurance performance following sprint training despite an increase in $\dot{V}O_2max$ (Davies et al., 1982).

The direct comparison of the performance characterisics of sprint-trained and endurance-trained athletes has, in recent years, been almost exclusively concerned with short-term high intensity performance (Thomson and Garvie, 1981; Sejested, Medbo and Hermansen, 1982; Cheetham, Williams and Lakomy, 1985) and consequently few studies have examined the differences in the endurance characteristics of these two groups of athletes.

The aim of this study, therefore, was to examine the differences in the physiological responses during a 30-minute endurance test of endurance-trained and sprint-trained athletes. The hypothesis was

established that, if free to self-select an exercise intensity of their choice, endurance-trained athletes would exercise at a higher %$\dot{V}O_2max$ than sprint-trained athletes. In addition, the relationship between a reference blood lactate concentration of 4mmol.l-1 (OBLA) and endurance performance on T30min was examined, since OBLA has been reported to be a good predictor of endurance performance (Sjödin and Jacobs, 1981; Williams and Nute, 1983).

5.2 METHODS

5.2.1 Subjects

Sixteen physical education students volunteered for this study. All of the subjects had a history of at least 3 years training and were categorised according to their training as either endurance-trained (4 males, 4 females) or sprint-trained (4 males, 4 females). The endurance-trained (ET) group comprised of 5 subjects who had recently completed the London marathon (2 male, 3 female), a Scottish 1500m International (male), a Welsh Cross-Country International (female), a good club-standard 1500m athlete (male), and an orienteerer (male). The sprint-trained (ST) group comprised of an English 400m hurdles International (female), a Scottish Junior 100m International (male), an English Junior 400m International (male), a long jumper (12th in the female UK rankings), 3 club-standard sprinters (1 male, 2 females) and a club standard decathlete (male - specialist areas long jump and 110m hurdles). Prior to testing all subjects were fully familiarised with exercise on the cycle ergometer as described in Chapter 3 (3.2).

5.2.2 Preliminary tests

Maximum oxygen uptake was determined during a 3-minute incremental test as described in Chapter 3 (3.4). Maximal work rate ranged from 178.1W to 276.6W for the ST group and from 228.9W to 351.2W for the ET group. Two subjects did not achieve any of the criteria indicating that $\dot{V}O_2max$ had been achieved and were required to repeat the test on a separate day. On this occasion the criteria were

achieved.

The relationship between $\dot{V}O_2$ and work rate was determined during 4 minutes' steady-rate exercise at each of 4 increasing work rates. Expired air collections were obtained during the final minute of each work rate. The work rates ranged from 58.3W to 251.2W for the ST group and from 91.4W to 271.9W for the ET group. No work rate was common to all 16 subjects, and only 1 work rate was common to all 8 subjects within the ST group and within the ET group. The work rate for the endurance performance test (80% $\dot{V}O_2max$) was determined using individual regression equations for the relationship between $\dot{V}O_2$ and work rate, as described in Chapter 3 (3.5.2).

Immediately following each expired air collection a sample of arterialised capillary blood was taken from the hand for the determination of blood lactate concentration (see Appendix 3). The work rate equivalent to a blood lactate concentration of 4mmol.l^{-1} (OBLA) was determined, by interpolation, from individual graphs of the relationship between blood lactate concentration and work rate (Figure 3.2).

5.2.3 30-Minute endurance test (T30min)

Each subject performed T30min on two occasions, at least 48 hours apart, and at the same time of the day where possible. Each test was preceded by the collection of a sample of arterialised capillary blood from a pre-warmed hand, and a standardised warm up at a work rate equivalent to 50% of the subject's $\dot{V}O_2max$. The 30-minute test was conducted in the manner descibed in Chapter 3 (3.6). A schematic representation of the test protocol can be seen in Figure 3.2. Unlike the previous study, blood samples were obtained during both performance tests, immediately following each of the four expired air collections.

5.2.4 Computer system

A BBC (Model B) microcomputer and an internal analogue-to-digital converter were used to provide a graphical display of the subject's performance during the test. Due to calibration difficulties this

system was used only for display purposes and not, as described in Chapter 3, as a means of monitoring the subjects pedal frequencies. Pedal frequency was monitored manually using two pedal rate counters, as described in Chapter 3 (3.1.2). The counters were used in conjunction with each other so that one recorded the flywheel revolutions of the cycle ergometer during the first minute of exercise while the second recorded the flywheel revolutions during the second minute, and so on. In this way, while one counter was in use, the values recorded by the other counter could be manually recorded and the dial reset in preparation for the subsequent minute. Using this system, the flyheel revolutions for each minute of the test were recorded, translated into pedal revolutions, and used in conjunction with the subject's frictional load to calculate their average work rate (AWR) for each of the 30 minutes. From these AWR values the subject's CAWR for T30min was then calculated (sum of the 30 AWR values/30). The estimated relative exercise intensity at which the subjects were exercising ($\%\dot{V}O_2max_E$) was calculated from individual regression equations describing the relationship between work rate and $\dot{V}O_2$ as described in Chapter 4 (4.2.4).

5.3 RESULTS

5.3.1 Preliminary tests

The physical characteristics of the sprint-trained (ST) group and the endurance-trained (ET) group are shown in Table 5.1. The ET group were signifiantly older than the ST group, ranging in age from 18.8 years to 30.0 years compared with 19.3 years to 24.8 years. There was no significant difference in the mean height, weight or percent body fat of the two groups.

The mean $\dot{V}O_2max$ ($l.min^{-1}$) of the ET group and the ST group were 3.47 ± 0.64 $l.min^{-1}$ and 3.06 ± 0.64 $l.min^{-1}$ respectively (NS), with the ET group recording a greater range in $\dot{V}O_2max$ values than the ST group (2.78 - 4.59 $l.min^{-1}$ vs 2.27 - 3.76 $l.min^{-1}$). When $\dot{V}O_2max$ was expressed in $ml.kg^{-1}min^{-1}$ a significant difference was found between the two groups. The lower body weight of the ET group and their higher

Table 5.1 Physical characteristics of the sprint-trained group and the endurance trained group (mean ± S.D.).

		SPRINT (N=8)	ENDURANCE (N=8)
Age	$\bar{x}$	20.8	23.7*
(yrs)	S.D.	1.7	3.2
	range	19.3-24.8	18.9-30.0
Height	$\bar{x}$	171.8	169.2
(cm)	S.D.	8.2	9.4
	range	157.0-180.7	153.5-183.2
Weight	$\bar{x}$	63.1	61.3
(kg)	S.D.	7.9	7.9
	range	53.5-75.4	49.8-72.5
Body Fat	$\bar{x}$	14.32	15.11
(%)	S.D.	5.51	6.25
	range	7.56-22.46	5.54-24.67

Significantly different from ST * $p<0.05$

$\dot{V}O_2max$ in $l.min^{-1}$ resulting in a significantly higher $\dot{V}O_2max$ value compared with the ST group (56.83 ± 5.41 and 48.36 ± 6.59 $ml.kg^{-1}min^{-1}$ respectively). All subjects achieved at least one of the required criteria to indicate that $\dot{V}O_2max$ was achieved. No significant difference was found between the two groups for $\dot{V}E$ max ($l.min^{-1}$), maximum heart rate, or the work rate at $\dot{V}O_2max$ (Table 5.2).

The oxygen cost of exercise at increasing submaximal work rates for the ET group and the ST group is shown in Table 5.3. A linear relationship was found between these two variables for both groups, and there was no significant difference in $\dot{V}O_2$ at a given work rate for either group.

The heart rate response of the ET group and the ST group to submaximal exercise of increasing intensity is shown in Table 5.3. A linear relationship was also found between these two variables for both groups. The gradient of the regression line describing the relationship between heart rate and work rate was slightly steeper for the ST group than the ET group, however, there was no significant difference in heart rate at a given work rate between groups.

The relationship between blood lactate concentration and submaximal work rate for the ET group and the ST group is shown in Figure 5.1 and 5.2. At a given absolute work rate (W) and relative work rate (%$\dot{V}O_2max$) blood lactate concentration was lower for the ET group than the ST group. As a result of this there was a significant difference in the work rate at which OBLA occurred for the ET group compared to the ST group both in absolute terms (195 ± 28W vs 154 ± 32W, $p<0.05$) and relative terms (73 ± 7% vs 64 ± 9%, $p<0.05$) (Table 5.4).

5.3.2 30-minute endurance test (T30min)

A summary of some of the performance changes during T30min can be seen in Table 5.5 and Figures 5.3 and 5.4. Throughout T30min the ET group exercised at a higher CAWR than the ST group (220.5 ± 33.6W vs 181.5 ± 39.3W; NS). When work rate was expressed relative to each subject's $\dot{V}O_2max$ the results revealed that the ET group self-selected a significantly higher $\%\dot{V}O_2max_E$ (82.5 ± 2.9%) than the ST group (76.5 ± 6.2%) ($p<0.05$). Figure 5.4 shows the trend in performance of the

Table 5.2 Physiological characteristics of the sprint-trained group and the endurance-trained group (mean ± S.D.).

		SPRINT (N=8)	ENDURANCE (N=8)
$\dot{V}O_2max$	$\bar{x}$	3.06	3.47
($l.min^{-1}$)	S.D.	0.64	0.64
	range	2.27-3.76	2.78-4.59
$\dot{V}O_2max$	$\bar{x}$	48.36	56.83*
($ml.kg^{-1}min^{-1}$)	S.D.	6.59	5.41
	range	39.25-60.00	48.74-64.10
$\dot{V}E$ max	$\bar{x}$	111.4	118.2
($l.min^{-1}$)	S.D.	29.6	17.6
	range	62.6-163.1	94.9-148.4
HR max	$\bar{x}$	190	188
($b.min^{-1}$)	S.D.	7	6
	range	178-202	180-198
Max Work Rate	$\bar{x}$	241.4	270.7
(W)	S.D.	40.0	37.2
	range	178.1-276.6	228.9-351.2

Significant difference between means * $p<0.05$

Table 5.3 Summary of the submaximal incremental test results for the sprint-trained group (n=8) and the endurance-trained group (n=8). Mean ± S.D.

SPRINT TRAINED

	Work rate 1	Work rate 2	Work rate 3	Work rate 4
Work Rate (W)	101±40	132±40	162±41	192±42
$\dot{V}O_2$ ($l.min^{-1}$)	1.39±0.52	1.73±0.60	2.11±0.64	2.53±0.68
$\%\dot{V}O_2max$	44±9	55±9	68±8	82±8
$\dot{V}E.\dot{V}O_2^{-1}$	23.5±2.5	24.8±2.4	25.7±5.2	28.6±5.2
HR ($b.min^{-1}$)	126±14	143±14	160±12	174±11
Blood Lactate ($mmol.l^{-1}$)	2.22±1.29	2.94±1.28	4.33±1.57	6.91±2.18

ENDURANCE TRAINED

	Work rate 1	Work rate 2	Work rate 3	Work rate 4
Work Rate (W)	135±33	166±34	195±34	225±33
$\dot{V}O_2$ ($l.min^{-1}$)	1.69±0.40	2.08±0.47	2.53±0.46	2.93±0.53
$\%\dot{V}O_2max$	49±4	60±5	73±4	85±5
$\dot{V}E.\dot{V}O_2^{-1}$	22.9±3.1	24.1±2.8	25.2±3.1	27.2±4.6
HR ($b.min^{-1}$)	129±7	145±8	159±6	171±4
Blood Lactate ($mmol.l^{-1}$)	1.82±0.63	2.47±0.76	4.10±1.10	7.02±1.68

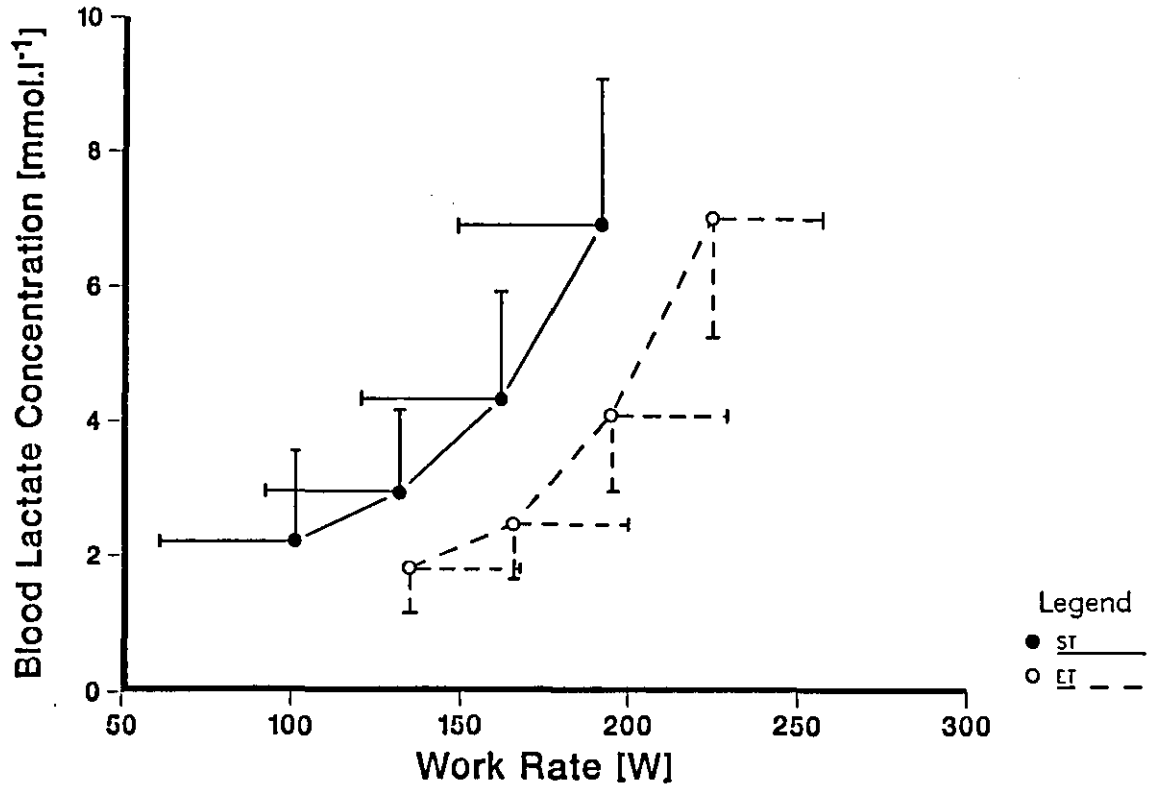


Figure 5.1 Blood lactate concentration during the incremental test for the sprint-trained group (n=8) and the endurance-trained group (n=8).

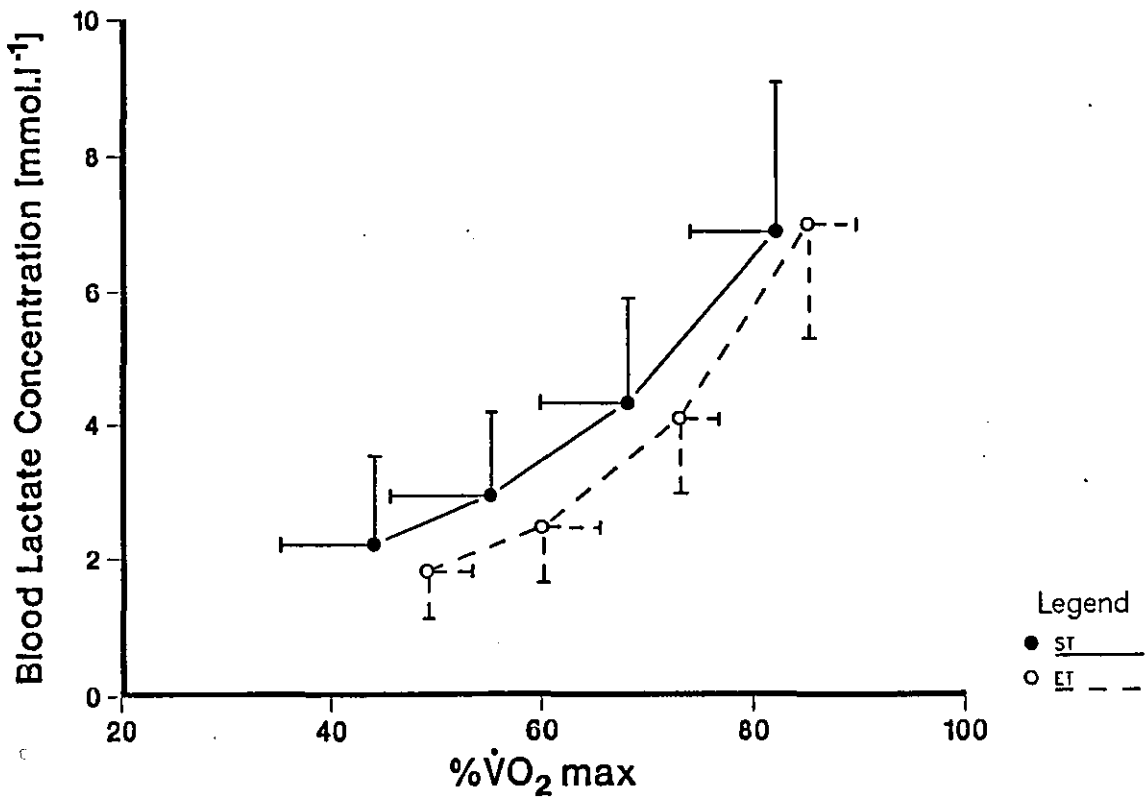


Figure 5.2 Blood lactate concentration in relation to relative exercise intensity during the incremental test for the sprint-trained group (n=8) and the endurance-trained group (n=8).

Table 5.4 Onset of Blood Lactate Accumulation (OBLA) for the sprint-trained group (ST) and the endurance-trained-group (ET). Individual values.

Subject		OBLA	
		W	%$\dot{V}O_2max$
ST	1*	199	77
	2*	181	61
	3*	150	56
	4*	178	67
	5	103	54
	6	152	64
	7	145	76
	8	123	58
	MEAN	154	64
	S.D.	32	9
ET	9*	238	67
	10*	191	81
	11*	181	60
	12*	232	75
	13	182	74
	14	198	78
	15	187	74
	16	151	72
	MEAN	195*	73*
	S.D.	28	7

* denotes male subject

Significantly different from ST * $p<0.05$

Table 5.5 Summary of the T30min results for the sprint-trained group (ST) and the endurance-trained group (ET). Mean ± S.D.

		5 (min)	10 (min)	20 (min)	30 (min)
CAWR	ST	190.0±31.9	186.2±36.6	181.8±37.8	220.5±33.6
(W)	ET	216.3±34.9	219.3±34.1	219.8±34.0	220.5±33.6
$\%\dot{V}O_{2max_E}$	ST	80.2±1.5	78.5±4.4	76.6±5.6	76.5±6.2
	ET	80.8±1.6	82.0±2.3	81.0±4.7	82.5±2.9*
$\dot{V}O_2$	ST	2.63±0.36	2.46±0.44	2.48±0.61	2.63±0.65
($l.min^{-1}$)	ET	2.71±0.60	2.95±0.66	3.06±0.70	3.28±0.61*
$\%\dot{V}O_{2max}$	ST	77.8±6.4	80.6±5.5	80.5±6.7	85.6±6.8
	ET	78.2±7.8	85.0±9.7	88.3±9.9	94.7±6.7
R	ST	1.01±0.03	0.95±0.06	0.91±0.05	0.92±0.06
	ET	1.02±0.05	0.99±0.06	0.95±0.05	0.96±0.05
Blood	ST	5.93±1.64	7.23±1.30	7.73±2.13	8.65±2.12
Lactate	ET	5.94±1.39	8.77±2.32	10.15±3.01	11.88±3.51*
($mmol.l^{-1}$)					

Significantly different from ST * $p<0.05$

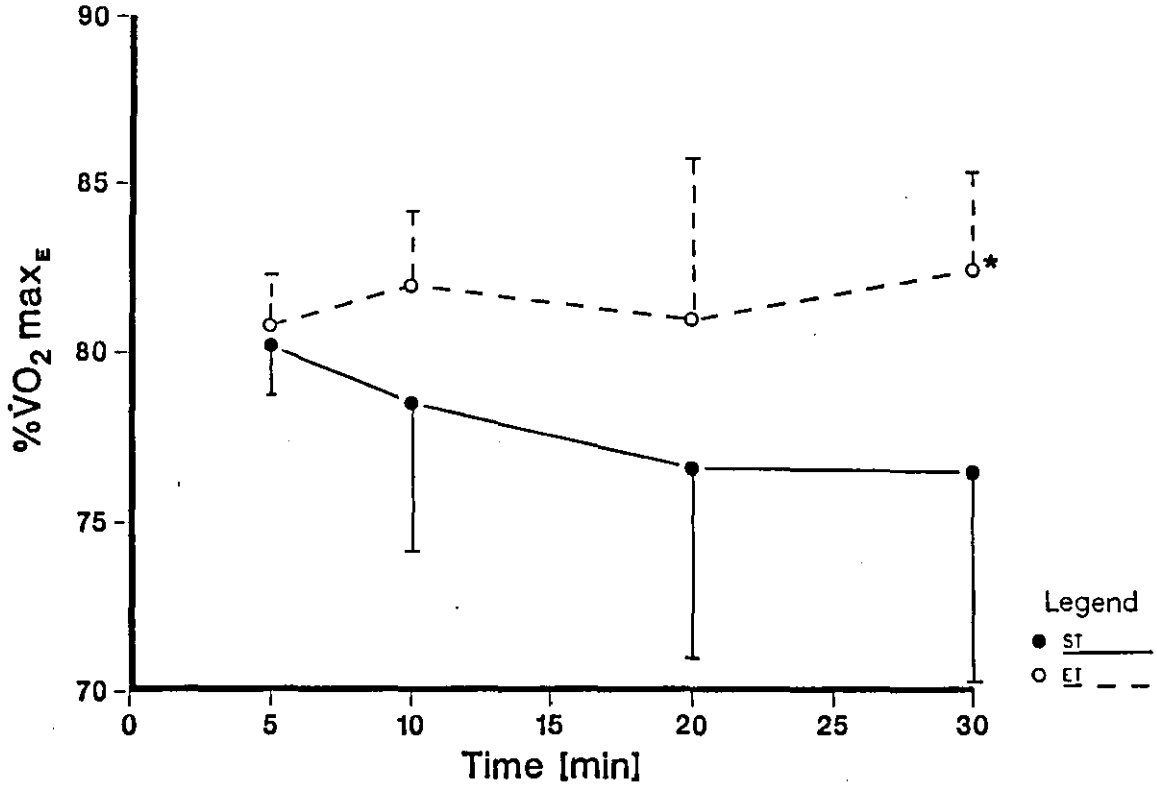


Figure 5.3 Estimated relative exercise intensity during T30min for the sprint-trained group (n=8) and the endurance-trained group (n=8).

Significantly different from ST * $p<0.05$

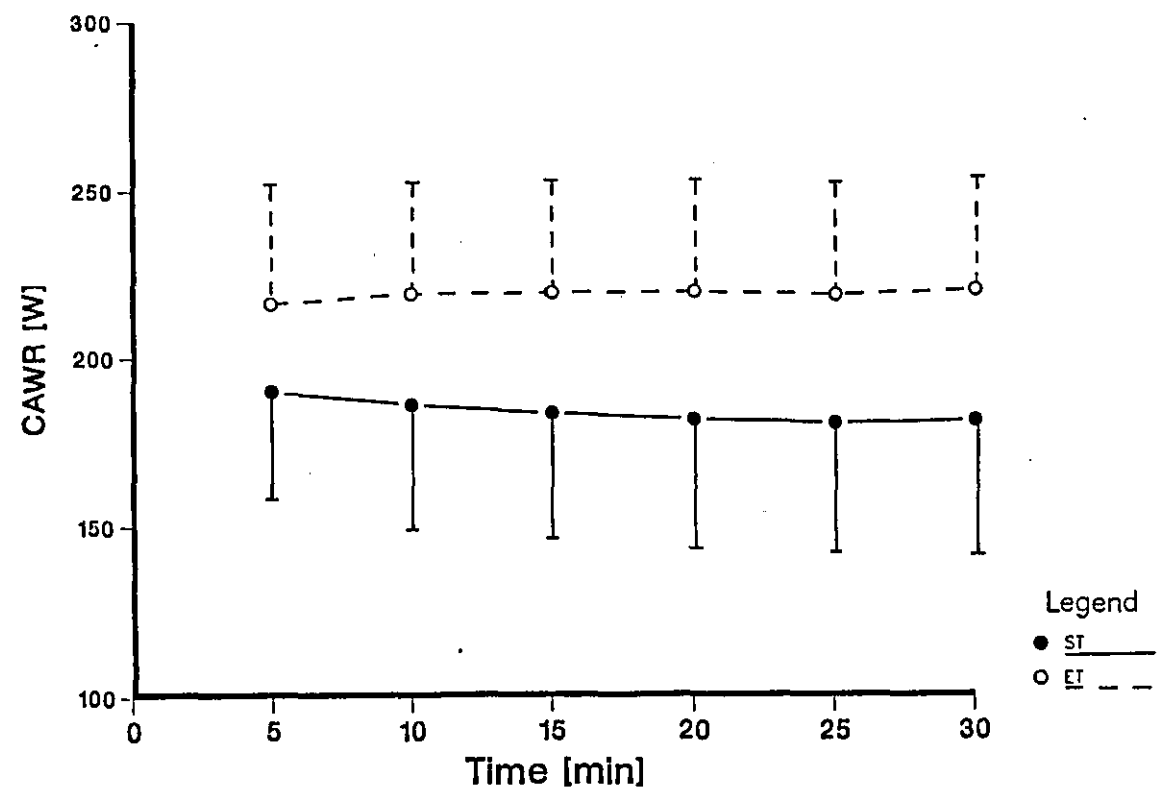


Figure 5.4 Cumulative average work rate during T30min for the sprint-trained group (n=8) and the endurance-trained group (n=8).

two groups during T30min. While the ET group were able to increase their work rate following the initial 5-minute standardised period, the work rate of the ST group decreased during the remaining 25 minutes.

Table 5.5 and Figures 5.5 and 5.6 show a summary of the physiological changes during T30min for the ET group and the ST group. The oxygen uptake values for the ET group were higher than those of the ST group throughout T30min (NS). When $\dot{V}O_2$ was expressed relative to each subject's $\dot{V}O_2max$ the ET group were also exercising at a higher $\%\dot{V}O_2max$ from 10 minutes to 30 minutes, with the difference being significant at 30 minutes (94.7 $\pm$ 6.7% vs 85.6 $\pm$ 6.8%; $p<0.01$). No significant difference was found between the two groups for heart rate, ventilatory equivalent ($\dot{V}E.\dot{V}O_2^{-1}$) or respiratory exchange ratio (R) during T30min, although the ET group recorded slightly higher values for both heart rate and R, and slightly lower values for $\dot{V}E.\dot{V}O_2^{-1}$

Analysis of the blood lactate concentrations during T30min revealed similar blood lactate concentrations for the two groups following the first 5 minutes of standardised exercise (ST group: 5.93 $\pm$ 1.64 $mmol.l^{-1}$; ET group: 5.94 $\pm$ 1.39 $mmol.l^{-1}$). During the remaining 25 minutes of the test there was a steady rise in blood lactate concentrations for both groups, with the ET group recording a significantly higher value than the ST group by the end of the test (11.88 $\pm$ 3.51 $mmol.l^{-1}$ vs 8.56 $\pm$ 2.12 $mmol.l^{-1}$) (Figure 5.5).

The relationship between $\dot{V}O_2max$, CAWR and $\%\dot{V}O_2max_E$ for the ST and ET groups can be seen in Figures 5.8 and 5.10. A strong correlation was found between $\dot{V}O_2max$ and CAWR for both the ET group ($r=0.93$) and for the ST group ($r=0.95$) (Figure 5.8). Only a poor relationship was found between $\dot{V}O_2max$ and $\%\dot{V}O_2max_E$ for the ET group ($r=0.23$), while these two variables showed a stronger relationship for the ST group ($r=0.74$) (Figure 5.10). Similarly, when CAWR was correlated with $\%\dot{V}O_2max_E$ only a poor relationship was in evidence for the ET group ($r=-0.10$) while a strong relationship was found for the ST group ($r=0.89$). It would appear, therefore, that within the ET group, those subjects who exercised at a high $\%\dot{V}O_2max_E$ did not necessarily possess a high $\dot{V}O_2max$, whereas within the ST group, it was those subjects who

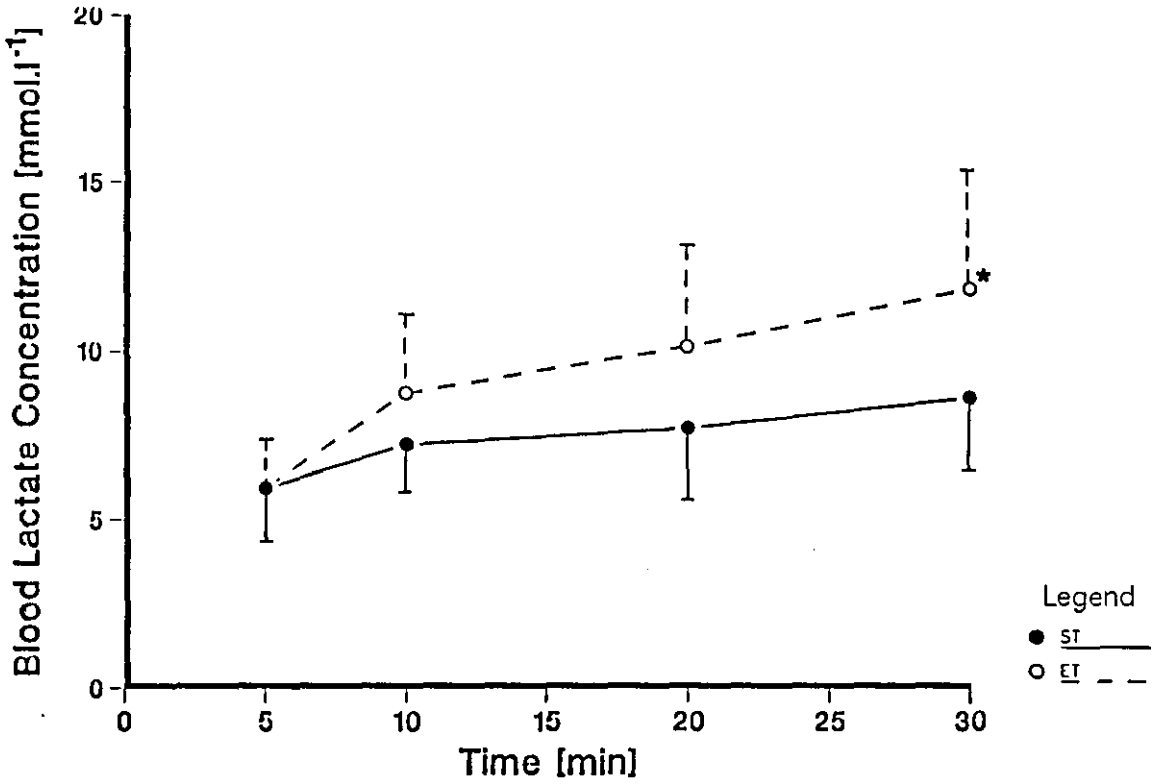


Figure 5.5 Blood lactate concentration during T30min for the sprint-trained group (n=8) and the endurance-trained group (n=8).

Significantly different from ST * $p<0.05$

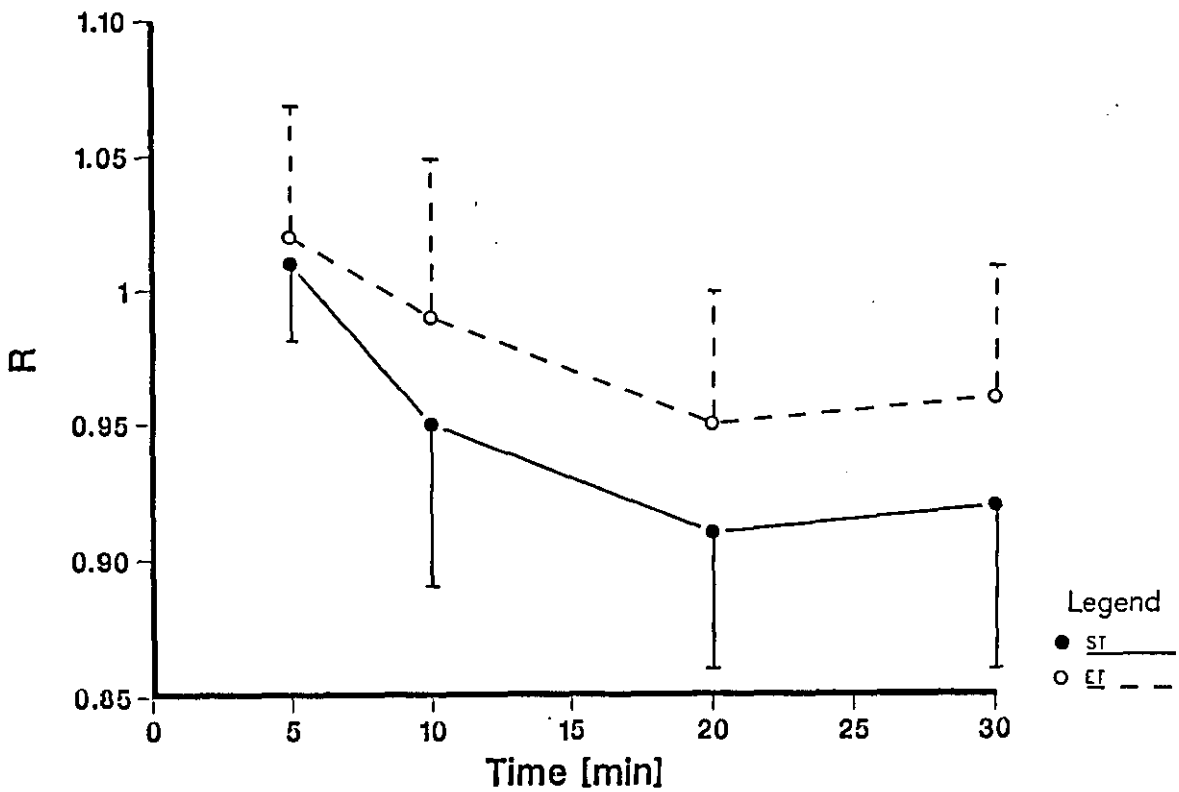


Figure 5.6 Respiratory exchange ratio during T30min for the sprint-trained group (n=8) and the endurance-trained group (n=8).

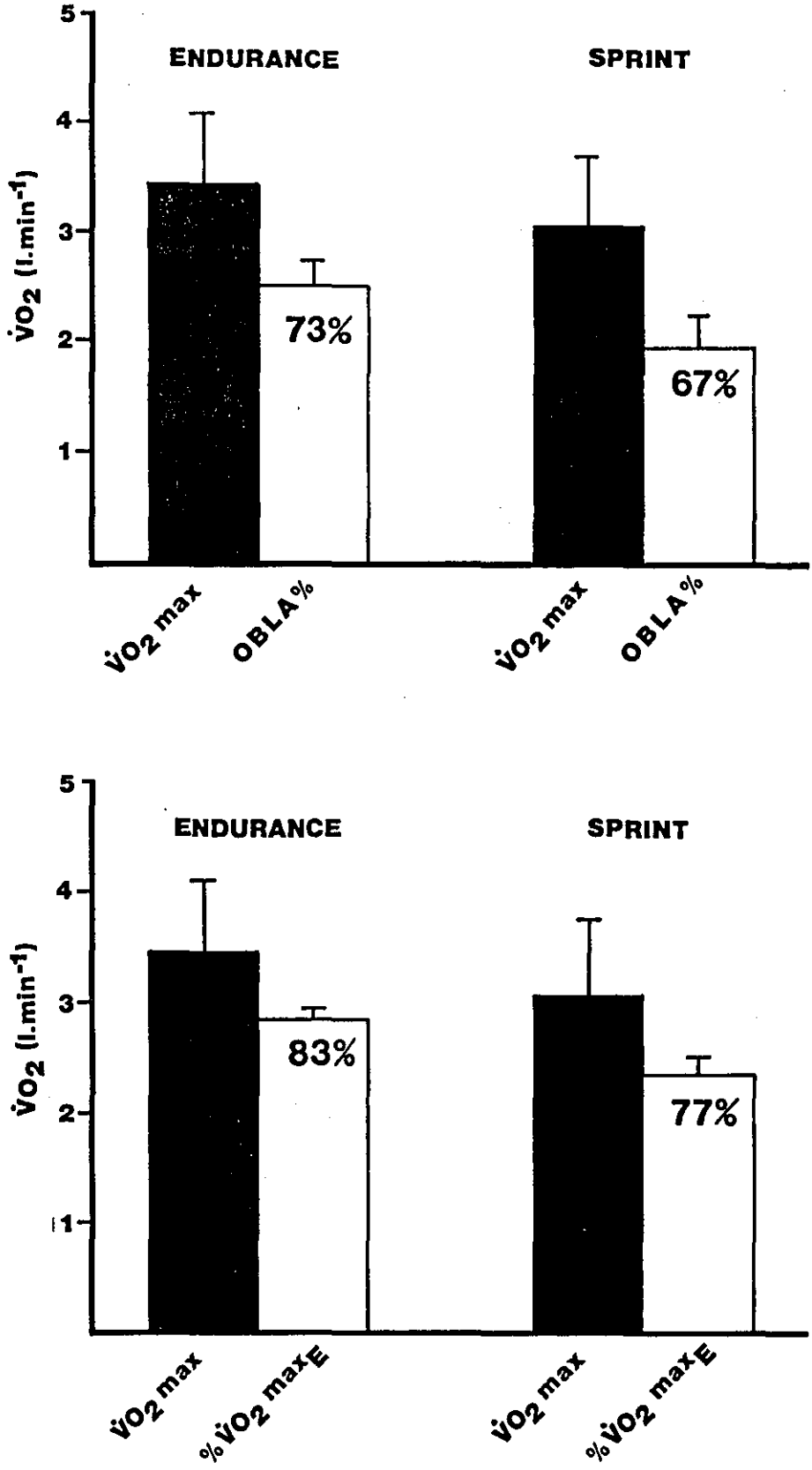


Figure 5.7 OBLA (%) and estimated relative exercise intensity during T30min in relation to maximum oxygen uptake for the sprint-trained group and the endurance-trained group.

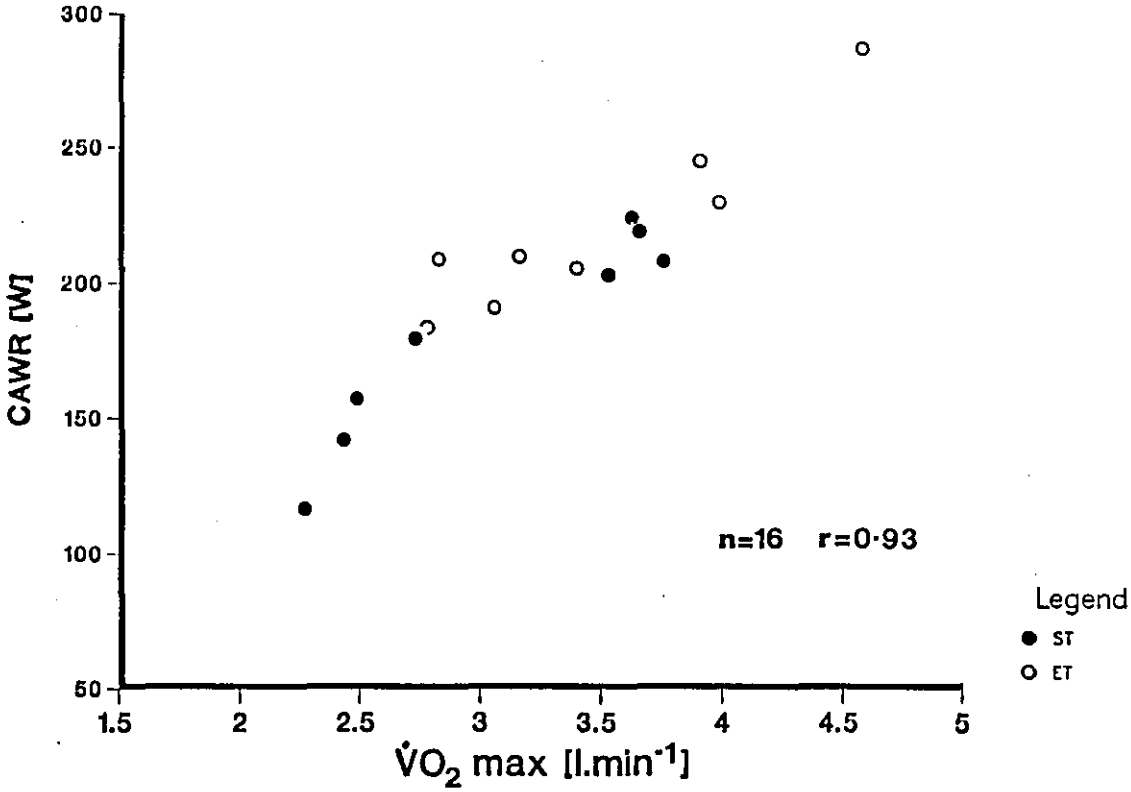


Figure 5.8 Relationship between maximum oxygen uptake and cumulative average work rate.

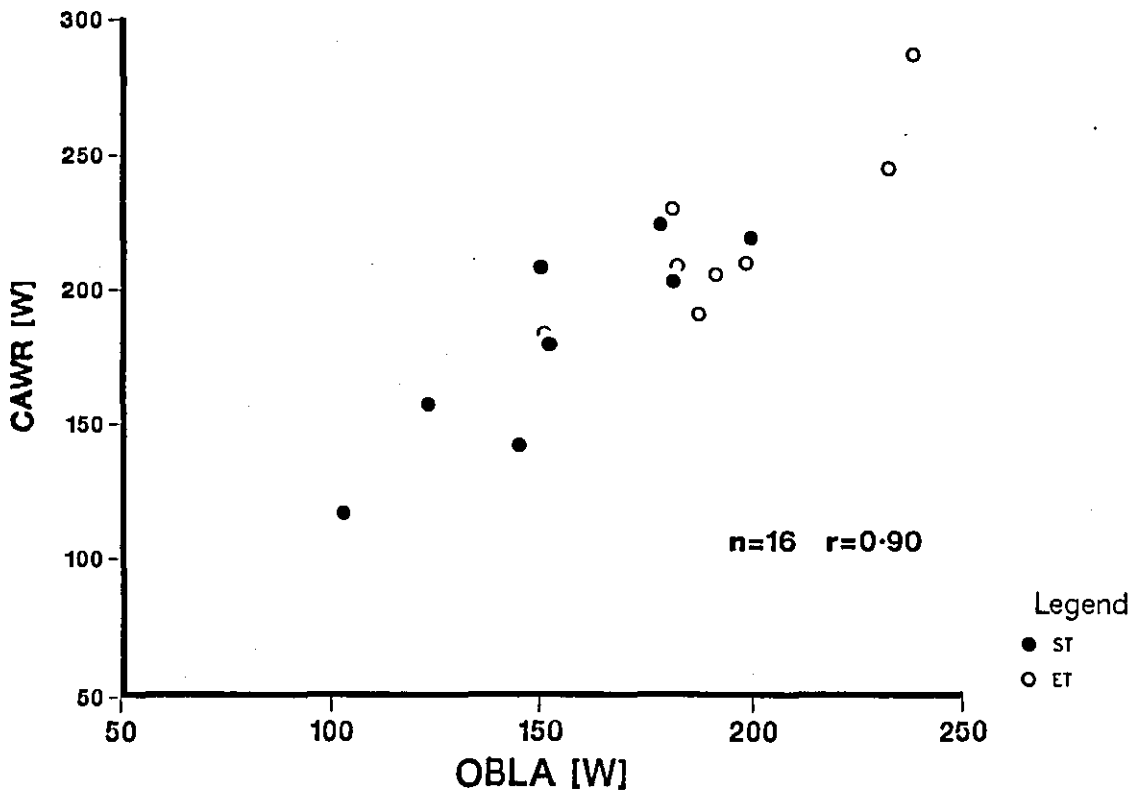


Figure 5.9 Relationship between OBLA (W) and cumulative average work rate.

possessed a high $\dot{V}O_2max$ who were able to sustain a high $\%\dot{V}O_2max_E$ during T30min.

The relationship between $OBLA_w$ and CAWR, and OBLA% and $\%\dot{V}O_2max_E$ can be seen in Figures 5.9 and 5.11. A strong correlation was found between $OBLA_w$ and CAWR for both the ET group (r=0.86) and for the ST group (r=0.88) (Figure 5.9). These correlations, however, were not as strong as those found beteen $\dot{V}O_2max$ and CAWR, suggesting that $\dot{V}O_2max$ was a better predictor of CAWR in T30min for these subjects than $\dot{V}O_2max$. Modest correlations were found between OBLA% and $\%\dot{V}O_2max_E$ for the ET group (r=0.64), the ST group (r=0.51) and the group as a whole (r=0.66) (Figures 5.11). The relationship of these two variables for the whole group was stronger than the relationship found between $\dot{V}O_2max$ and $\%\dot{V}O_2max_E$ (r=0.49) indicating that OBLA% was a better predictor of $\%\dot{V}O_2max_E$ than $\dot{V}O_2max$ for the group as a whole.

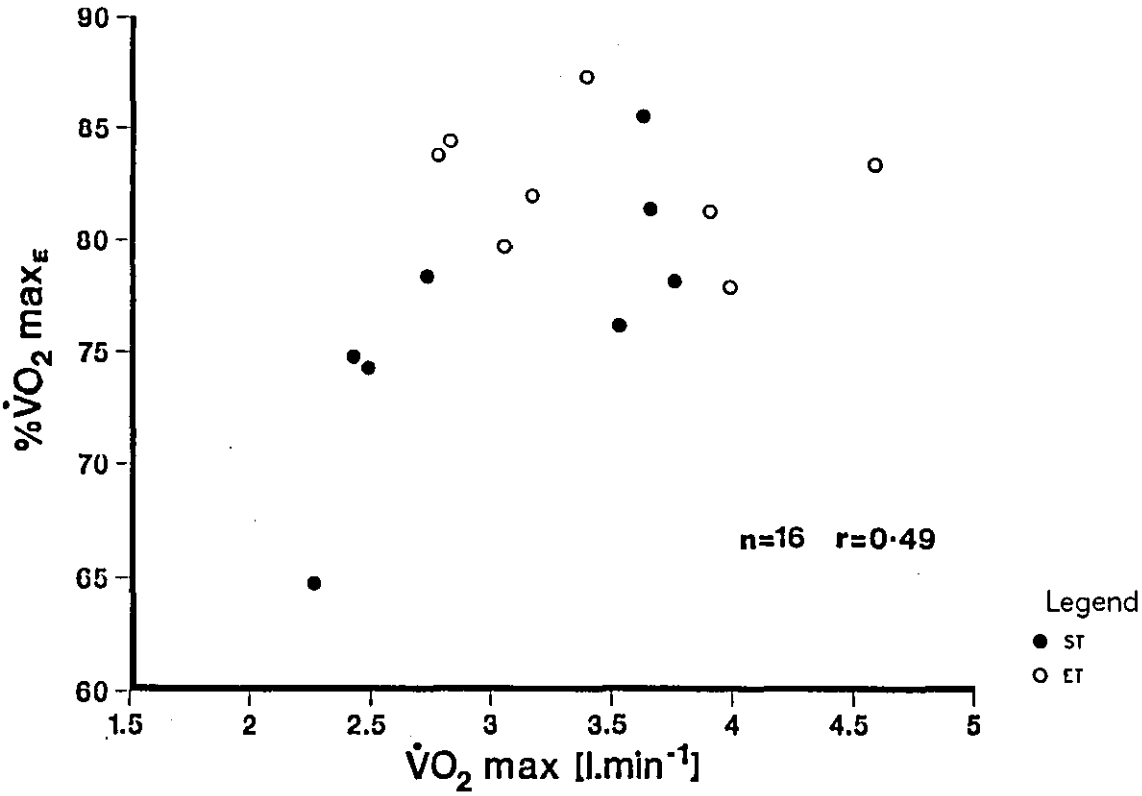


Figure 5.10 Relationship between maximum oxygen uptake and estimated relative exercise intensity.

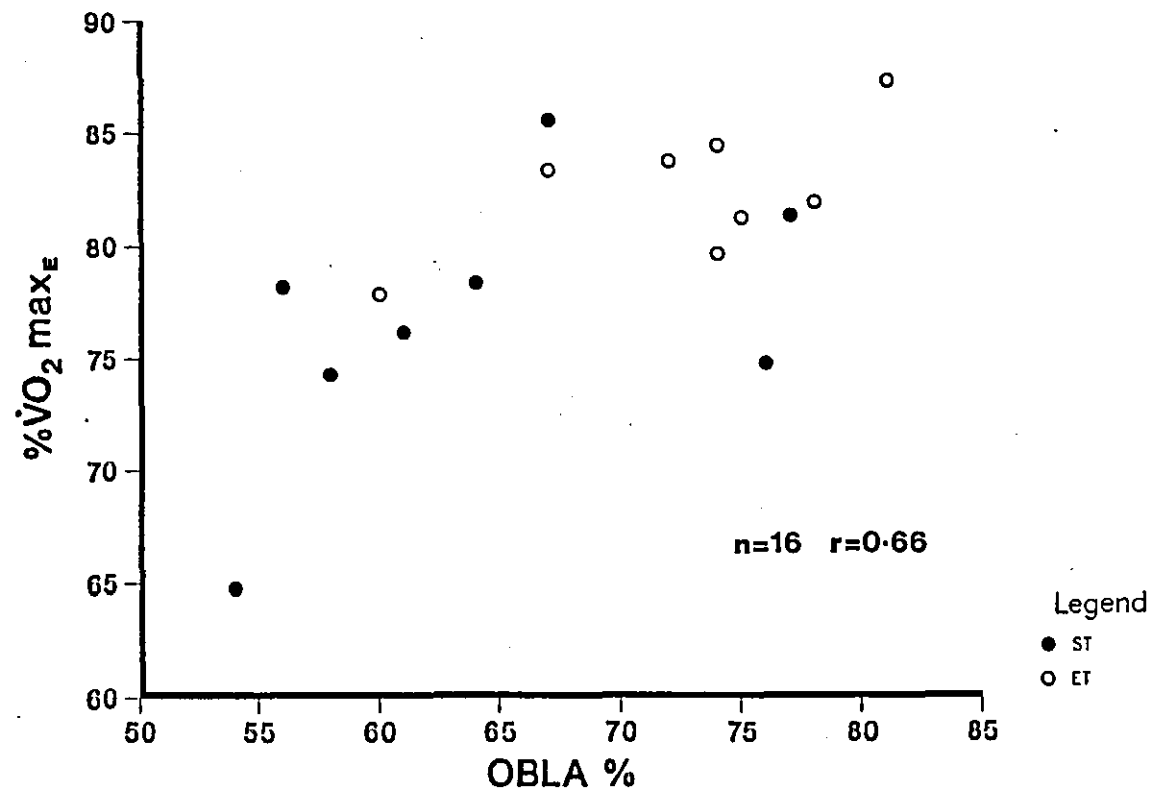


Figure 5.11 Relationship between OBLA (%) and estimated relative exercise intensity.

5.4 DISCUSSION

The ET group were significantly older than the ST group (23.7 ± 3.2 yrs vs 20.8 ± 1.7 yrs, $p<0.01$). Differences between the two groups for height, weight and percentage body fat, however, did not reach the level of statistical significance.

The difference in the mean weight of the two groups (3%) was smaller than that reported in the literature by Ohkuwa et al. (1984), Cheetham et al. (1985), Thomson and Garvie (1981), Kellett, Mahon and Willan (1983) and Niemela, Palatsi and Takkunen (1980) who all reported studies where the mean weight of sprint-trained athletes was 10-20% heavier than that of endurance-trained athletes. Suprisingly there was no difference in the percentage body fat of the two groups (ET 15.11 ± 6.25%; ST 14.32 ± 5.21%), with the ST group recording the slightly lower values. Since it is more disadvantageous for the ET athlete to have to carry 'dead weight', i.e. body fat, over the longer distances these findings are contrary to the findings of Rusko et al. (1978), and Kellett et al. (1983), who found lower percentage body fat in endurance-trained athletes when comparisons were made with sprint-trained athletes.

The mean $\dot{V}O_2max$ of the ST group and the ET group was 3.06 ± 0.64 $l.min^{-1}$ and 3.47 ± 0.64 $l.min^{-1}$ respectively (NS). The 13% difference between the mean $\dot{V}O_2max$ values of the two groups is similar to the differences reported between sprint-trained and endurance-trained athletes by Crielaard and Pirnay (1981), Kellett et al. (1983), Niemela et al. (1980) and Rusko et al. (1978). The importance of a high $\dot{V}O_2max$ for high speed running and cycling, and success in endurance competition has been previously highlighted, during sprinting, however, the rate of demand for energy cannot be met by aerobic metabolism alone and the sprinter must rely on anaerobic metabolism. For this group of athletes, therefore, a high $\dot{V}O_2max$ has been found to be of minimal advantage for short-term high intensity exercise. Thomson and Garvie (1981), and Cheetham (personal communication) both report that aerobic metabolism only contributes to about 20-28% of the energy demands during maximal sprinting. This may, therefore, account for the observed differences in $\dot{V}O_2max$ between sprint- and

endurance-trained athletes in the studies reported in the literature.

Despite the fact that a high $\dot{V}O_2max$ is not a prerequisite for success in sprint events, and sprint-trained athletes do not train specifically to enhance their aerobic capacity, the difference between the mean $\dot{V}O_2max$ values for the ST group and ET group in this study was not significant. This lack of difference might be due to either the genetic predisposition of the athletes or to the fact that, just as endurance training will have increased the $\dot{V}O_2max$ of the ET group, sprint training may have increased the $\dot{V}O_2max$ of the ST group equally as much. This notion would tend to support the findings of Davies et al. (1982) and Fournier et al. (1982) who reported an increase in $\dot{V}O_2max$ following sprint training. The lack of difference in $\dot{V}O_2max$ of the ET and ST groups highlights the fact that the adoption of $\dot{V}O_2max$ as an indicator of endurance capacity or training status has its shortcomings since it fails to differentiate between two groups who, by the nature of their training, should demonstrate differing capacities for endurance performance. In addition, such a finding confirms the necessity of a performance test other than $\dot{V}O_2max$, to assess submaximal endurance.

Exercise at a submaximal work rate revealed no significant difference between either group in $\dot{V}O_2$ or heart rate at a given absolute exercise intensity. There was, however, a difference between the two groups in blood lactate concentration. At each work rate common to both groups blood lactate concentration was lower for the ET group than the ST group. A significant difference was, therefore, found between the groups in the work rate (W) at which OBLA occurred ($OBLA_w$) (ST 154 $\pm$ 32W; ET 195 $\pm$ 28W; $p<0.05$). The difference in $OBLA_w$ could in part be due to the higher $\dot{V}O_2max$ of the ET group, since it has been shown that metabolic changes (as reflected by blood lactate concentrations) occur in relation to the $\%\dot{V}O_2max$ at which the individual is exercising (Hermansen and Saltin, 1967). Therefore, at a given absolute work rate the relative physiological stress of the activity would be lower for the ET group and thus account for their lower blood lactate concentration.

There was also, however, a difference between the two groups in blood lactate concentration when work rate was expressed as $\%\dot{V}O_2max$.

At a given $\%\dot{V}O_2max$ blood lactate concentrations were higher for the ST group, and as a result the $\%\dot{V}O_2max$ at which OBLA% occurred was significantly higher for the ET group (73 ± 7%) than the ST group (64 ± 9%; $p<0.05$). These results would suggest that the differences between the ST group and ET group in blood lactate concentration at a given absolute work rate were due to factors other than the $\%\dot{V}O_2max$ that that work rate represented.

A further explanation for the differences in submaximal blood lactate concentrations may be due to the differences in the metabolic profiles of the muscles which characterises these two distinct subject groups.

It has been well documented that endurance training can lead to an increase in skeletal muscle oxidative enzyme activity (Gollnick et al., 1973; Henriksson and Reitman, 1977; and Fournier et al., 1982;), and mitochondria concentration (Gollnick and King, 1969). This increased oxidative potential of the muscle enables the endurance athlete to cover more of the energy demands by aerobic metabolism, thus reducing the anaerobic contribution and consequent lactate production. This factor may have been reflected by the lower $\dot{V}E.\dot{V}O_2^{-1}$ values of the ET group at the same absolute work rate. In addition, it has been well documented that endurance-trained athletes are characterised by a high proportion of Type I or slow twitch muscle fibres, whereas sprinters have been shown to have a high proportion of Type II or fast twitch fibres (Gollnick et al., 1972). Characteristically fast twitch fibres have a well developed glycolytic enzyme system, fatigue quickly, and consequently produce more lactate than slow twitch fibres which are characterised by a high potential for oxidative enzyme activity. It has been proposed, therefore, that subjects who are characterised by a high proportion of fast twitch fibres (eg. sprint-trained athletes) may accumulate more lactate at the same absolute or relative exercise intensity than those subjects with a lower proportion (Karlsson et al., 1982). As no histochemical analysis was undertaken in this study these suggestions cannot be confirmed, but together with the reported improved oxidative capacity of the endurance-trained muscle they may partially account for the lower blood lactate concentrations of the ET group.

The exercise intensity self-selected by the ET group during T30min was higher than that of the ST group throughout the test (CAWR, 220.5 ± 33.6W vs 181.5 ± 39.3W). Since there exists a linear relationship between work rate and $\dot{V}O_2$ it is not suprising that the $\dot{V}O_2$ values were higher for the ET group than the ST group throughout the test. The prerequisite of a high $\dot{V}O_2max$ in order to exercise at a high work rate was also confirmed since the average work rate of the ET group during the final minute of exercise required an oxygen uptake 7% greater than the mean $\dot{V}O_2max$ of the ST group.

Although the subjects' $\dot{V}O_2max$ may largely dictate the absolute work rate at which they can exercise, the $\%\dot{V}O_2max$ an individual can tolerate over a given period of time has been found to be independent of $\dot{V}O_2max$ (Brewer, 1986). In this study, however, not only did the ET group exercise at a higher absolute work rate than the ST group during T30min, when CAWR was expressed as $\%\dot{V}O_2max_E$ it was revealed that the ET group had also been exercising at a significantly higher $\%\dot{V}O_2max_E$ than the ST group (82.5 ± 2.9% and 76.5 ± 6.2% respectively, $p<0.01$)).

The measurement of the accumulation of blood lactate concentration during T30min may to some extent help explain the differences in the self-selected exercise intensities of the two groups. After the first 5 minutes of standardised exercise the blood lactate concentrations of the ET and ST groups were of a similar magnitude (5.94 ± 1.39 $mmol.l^{-1}$ and 5.93 ± 1.64 $mmol.l^{-1}$ respectively). During the remaining 25 minutes of the test the blood lactate concentrations continued to rise for both groups despite a decrease in the work rate of the ST group. This might, therefore, suggest that during the initial standardised period the rate of lactate production was not matched by the rate of lactate clearance, resulting in lactate accumulation. This accumulation may subsequently have forced the ST group to reduce their work rate due to fatigue, whilst the nature of the test prevented them from reducing it to a point where equilibrium in lactate production and clearance could eventually be restored. The ET group, however, were able to increase their work rate after 5 minutes despite a blood lactate concentration similar to that of the ST group. Their work rate continued to increase throughout the test, paralleled by an increase in blood lactate

concentration. It would appear, therefore, that the ET group were able to sustain exercise of a greater intensity than that of the ST group because they were better able to tolerate the consequence of that exercise, i.e. lactate accumulation.

The significantly higher blood lactate concentrations of the ET group at the end of the test is in contrast to studies in the literature where higher lactate concentrations have been reported for sprint-trained as opposed to endurance-trained subjects following maximal exercise. These studies, however, have tended to focus upon brief high intensity exercise. The generation of high levels of lactate in these cases are beneficial rather than detrimental to the athletes since they reflect the greater rate of anaerobic glycolysis of the muscles and the resultant superior performance characteristics of the sprint-trained subjects (Thomson and Garvie, 1981). During T30min, however, the accumulation of blood lactate is detrimental to performance and, therefore, the ability to delay the accumulation of blood lactate is beneficial, and it is the endurance-trained athletes rather than the sprint-trained athletes who possess this characteristic.

It would, therefore, appear that the combination of a higher $\dot{V}O_2max$ and the lower blood lactate concentration at a given absolute work rate enabled the ET group to exercise at a higher CAWR during T30min, whilst their ability to increase the $\%\dot{V}O_2max$ at which blood lactate accumulation occurred enhanced their ability to exercise at a high $\%\dot{V}O_2max_E$.

The fact that the ET group could tolerate a higher blood lactate concentration during T30min cannot be readily explained by the available data from this study. The suggestion that the ET group were able to buffer the hydrogen ions produced from the reduction of lactic acid better than the ST group and thus prevent a drop in muscle and blood pH group would be in contrast to the work of Parkhouse and coworkers who found that the buffering capacity of sprint-trained athletes was better than that of endurance-trained athletes (Parkhouse, McKenzie, Hochahka and Ovalle, 1985). A second suggestion of the differences in the ability to exercise at high blood lactate concentrations may be that the efflux of the lactate from the muscles

into the blood was quicker for the ET group than the ST group due to greater capillarisation of the muscles and smaller fibre size. Blood lactate concentrations may not, therefore, have represented muscle lactate concentrations to the same extent for the two groups. Futhermore, the blood lactate concentration values at the end of T30min are consistent with those previously recorded by endurance athletes following a 3,000m race (12 $mmol.l^{-1}$; Ohkuwa et al., 1984). It is possible that the ET athletes also train at blood lactate concentrations as high as these, enhancing their physiological as well as psychological tolerance of such high levels.

Due to the skeletal muscle adaptations that occur as a result of training, endurance-trained athletes are characterised by their ability to place greater reliance on fat metabolism during submaximal exercise (Henriksson, 1977). This was reflected during the submaximal incremental test by the lower R values at a given work rate for the ET group compared to the ST group. There was, however, no evidence from the R values during T30min to suggest that the ET group were able to utilise more fat than the ST group during this test. In fact, the ET group R values were slightly higher than those of the ST group throughout the test. These higher values may, however, be a function of the higher $\%\dot{V}O_2max$ at which the ET group were exercising, as it has been shown that the proportion of energy derived from fat falls as the exercise intensity increases (Pruett, 1970).

The R values would also indicate that the test was largely aerobic in nature as they were below unity for the majority of the test, and that carbohydrate was the more dominant fuel source. The high blood lactate concentrations would indicate, however, that aerobic metabolism was being complemented by anerobic metabolism. The reliance on anaerobic metabolism to supplement aerobic metabolism suggests that the rate of energy production through aerobic metabolism was inadequate to match the rate of demand. This rate of energy demand could account for why the ET group were unable to rely on their ability to utilise fat as a major fuel source.

The heart rate response of the ET and ST groups were similar during T30min, with both groups showing a gradual increase throughout the test. The rise in heart rate in the absence of an increased work

rate (eg. ST group) has been reported in a number of studies where heart rate increases during steady-state exercise (Brewer, 1986). This upward drift has been referred to as 'cardiovascular drift' and is often regarded as a consequence of the decrease in stroke volume secondary to a peripheral displacement of central blood volume due to thermoregulatory demand (Rowell, 1974).

Although there was no difference in the heart rate of the two groups at any given time during the test the work rate of the two groups was largely different. This therefore meant, that while the ET group were exercising at a higher absolute and relative work rate than the ST group the cardiovascular stress was very similar for both groups.

The strong correlations found between $\dot{V}O_2max$ and CAWR for both the ET group ($r=0.93$) and the ST group ($r=0.95$) is in agreement with reports in the literature for the relationship between $\dot{V}O_2max$ and work output during a work capacity test on a cycle ergometer ($r=0.84$; Wilmore, 1969), $\dot{V}O_2max$ and cumulated work done during a 12 minute test on a cycle ergometer ($r=0.78$; Katch, 1973) and $\dot{V}O_2max$ and CAWR during T30min reported in the previous study ($r=0.81$). These strong correlations for the ET group, the ST group and the group as a whole ($n=16$, $r=0.93$) indicates the strong predictability of endurance performance during T30min (CAWR) from $\dot{V}O_2max$.

When the relationship between $\dot{V}O_2max$ and $\%\dot{V}O_2max_E$ was examined for the two independent groups distinct differences were found. While only a poor correlation was found between these two variables for the ET group ($r=0.23$), a strong relationship was found for the ST group ($r=0.74$). This would suggest that the $\%\dot{V}O_2max_E$ that the ET group exercised at during T30min was independent of their $\dot{V}O_2max$, whilst the opposite was found for the ST group, i.e. those subjects with a high $\dot{V}O_2max$ exercised at a high $\%\dot{V}O_2max_E$. This variation may in part be accounted for by the homogeneity of the subjects within each group, in terms of their training requirements. Within the ST group the females had a history of training for short-duration events such as 100 meters or long jump, whilst the males trained for longer duration events such as 400 meters. It could be hypothesised, therefore, that the males should possess a better endurance capacity, since their training would

involve a degree of speed-endurance, and thus they should be able to tolerate a higher $\%\dot{V}O_2max_E$ than the females. Since the males also possess genetically higher $\dot{V}O_2max$ values than the females, this would account for the strong correlation between $\dot{V}O_2max$ and $\%\dot{V}O_2max_E$.

The ET group, however, were more alike in terms of the endurance events for which they trained. As a result, the males and the females were more homogeneous in terms of their training status and therefore, the $\%\dot{V}O_2max$ that they could tolerate was independent of their $\dot{V}O_2max$.

This difference in the homogeneity of the ET and ST groups may also account for the differences in the relationship between CAWR and $\%\dot{V}O_2max_E$ exhibited by the two groups. The strong correlation between these two variables for the ST group ($r=0.89$) showed that those subjects who were exercising at a high CAWR were also exercising at a high $\%\dot{V}O_2max_E$. This is not a suprising finding in the light of the fact that a strong correlation was found for this group between $\dot{V}O_2max$ and both CAWR and $\%\dot{V}O_2max_E$.

The poor relationship between CAWR and $\%\dot{V}O_2max_E$ for the ET group ($r=-0.10$) revealed that, unlike the ST group, those individuals who exercised at the highest absolute work rate were not necessarily exercising at the highest $\%\dot{V}O_2max_E$. This suggests that some of the females had a better training status than their male counterparts, despite possessing a lower $\dot{V}O_2max$.

Several studies reported in the literature have claimed that metabolic parameters measured during submaximal exercise are better predictors of endurance performance than $\dot{V}O_2max$ (Kindermann et al., 1979; Sjödin and Svedenhag, 1985). The results of this study revealed, however, that when endurance performance was expressed as CAWR, slightly weaker relationships were found between endurance performance and $OBLA_W$ for the ET ($r=0.86$) and for the ST group ($r=0.88$) than between endurance performance and $\dot{V}O_2max$ ($r=0.93$ and $r=0.95$ respectively). When performance was expressed as $\%\dot{V}O_2max_E$, however, the relationship between OBLA% and $\%\dot{V}O_2max_E$ ($r=0.66$, $n=16$) was stronger than that found between $\dot{V}O_2max$ and $\%\dot{V}O_2max_E$ ($r=0.49$). It would appear, therefore, that for this group of subjects, the ability to delay the accumulation of blood lactate at a given $\%\dot{V}O_2max$ was a

more important factor in determining the $\%\dot{V}O_{2max_E}$ the individual could tolerate during T30min than $\dot{V}O_{2max}$ *per se*.

In conclusion, the results of this study confirm the findings reported previously in the literature, that endurance-trained subjects are characterised by the capacity to exercise at a high absolute and relative work rate over a given period of time. The results of this study suggest that the enhanced capacity of the ET group to exercise at a higher absolute work rate during T30min in comparison to the ST group was a function of their slightly higher $\dot{V}O_{2max}$ values and the ability to delay the accumulation of blood lactate during submaximal exercise. Their ability to exercise at a higher $\%\dot{V}O_{2max_E}$ than the ST group was found to be independent of $\dot{V}O_{2max}$ but to a large extent dependent on their ability to delay the accumulation of blood lactate at a given relative exercise intensity.

6. A COMPARATIVE STUDY OF ENDURANCE PERFORMANCE IN MALES AND FEMALES

6.1 INTRODUCTION

Studies reported in the literature investigating the differences between males and females in physiological parameters such as $\dot{V}O_2max$ and physiological adjustments during periods of physical training, have repeatedly demonstrated that, whilst the males are superior to females in $\dot{V}O_2max$ (MacNab et al., 1969) women respond to endurance training in a manner quantitatively similar to men (Pedersen and Jorgensen, 1978).

Although the possession of a high $\dot{V}O_2max$ gives the males a clear advantage over their female counterparts during physiological activities such as running and cycling, the ability to sustain a high relative exercise intensity during running does not appear to be influenced by sex, providing the subjects are of a similar training status (Davies and Thompson, 1979; Maughan and Leiper, 1983; Brewer, 1986). These findings would support the results reported in Chapters 4 and 5 indicating that the ability to tolerate a high $\%\dot{V}O_2max$ is independent of $\dot{V}O_2max$, since the higher $\dot{V}O_2max$ values of the males do not manifest themselves in the ability to exercise at a higher $\%VO_2max$.

The purpose of this present study was to re-examine the data presented in Chapters 4 and 5 with regard to sex. A cross-sectional approach was taken to determine whether the individual differences in physiological and performance characteristics during T30min, reviewed in the previous chapters, could be attributed to sex differences.

6.2 METHODS

A full description of the subjects can be found in Chapter 4 (4.2.1) and Chapter 5 (5.2.1). The experimental protocols followed are also described in Chapter 4 (4.2.2 - 4.2.4) and Chapter 5 (5.2.2 - 5.2.4).

6.2.1 Blood sampling

Because no blood sampling was undertaken during the submaximal incremental test in the first study, the analysis of the relationship between OBLA and performance variables was restricted to 16 out of the 28 subjects (8 male, 8 female). The collection of blood samples during T30min was, however, performed on 4 out of the 12 subjects during the first experimental study (not previously reported). Analysis of blood lactate concentrations during T30min was, therefore, extended to 20 out of the 28 subjects (10 male, 10 female).

6.3 RESULTS

6.3.1 Preliminary tests

A summary of the physical and physiological characterisics of the male subjects (n=14) and female subjects (n=14) can be seen in Tables 6.1 and 6.2. The males were taller and heavier than the females and had less body fat (all $p<0.01$). The males had significantly higher $\dot{V}O_2max$ values than the females (3.83 $\pm$ 0.36 $l.min^{-1}$ vs 2.75 $\pm$ 0.27 $l.min^{-1}$; $p<0.01$) and required a significantly higher work rate to elicit $\dot{V}O_2max$ (279.5 $\pm$ 24.3W vs 228.8 $\pm$ 27.3W; $p<0.01$). There was no significant difference in the maximum heart rate of the two groups (males, 188 $\pm$ 10 $b.min^{-1}$; females, 192 $\pm$ 7 $b.min^{-1}$).

The oxygen cost of submaximal exercise for the males and females can be seen in Table 6.3. The males recorded slightly higher $\dot{V}O_2$ values for a given work rate than the females, but the difference was not statistically significant at 100W or 150W.

The heart rate response of the males and females to submaximal

Table 6.1 Physical characteristics of the male and female subjects (mean ± S.D.).

		MALES (N=14)	FEMALES (N=14)
Age	$\bar{x}$	24.0	21.6
(yrs)	S.D.	9.6	2.2
	range	19.2-55.8	18.9-25.8
Height	$\bar{x}$	177.4	165.5**
(cm)	S.D.	6.3	5.3
	range	163.1-186.3	153.5-172.0
Weight	$\bar{x}$	71.1	60.3**
(kg)	S.D.	7.8	6.3
	range	55.9-85.1	49.8-75.1
Body Fat	$\bar{x}$	11.2	21.9**
(%)	S.D.	3.8	4.1
	range	5.5-19.4	17.3-29.7

Significantly different from the males ** $p<0.01$

Table 6.2 Physiological characteristics of the the male and female subjects (mean ± S.D.).

		MALES (N=14)	FEMALES (N=14)
$\dot{V}O_2max$	$\bar{x}$	3.83	2.75**
($l.min^{-1}$)	S.D.	0.36	0.27
	range	3.40-4.59	2.27-3.17
$\dot{V}O_2max$	$\bar{x}$	54.55	46.08**
($ml.kg^{-1}min^{-1}$)	S.D.	6.12	5.35
	range	41.70-64.10	39.25-56.50
$\dot{V}E$ max	$\bar{x}$	131.2	100.3**
($l.min^{-1}$)	S.D.	17.7	14.4
	range	107.0-148.4	62.6-116.6
HR max	$\bar{x}$	188	192
($b.min^{-1}$)	S.D.	10	7
	range	167-202	183-208
Max Work Rate	$\bar{x}$	279.5	228.8**
(W)	S.D.	24.3	27.3
	range	253.3-351.2	178.1-271.9

Significantly different from the males ** $p<0.01$

Table 6.3 Summary of the submaximal incremental test results for the male (n=14) and female subjects (n=14) (mean ±S.D.).

MALES

	Work rate 1	Work rate 2	Work rate 3	Work rate 4
Work Rate (W)	145±27	175±27	204±28	235±28
$\dot{V}O_2$ ($l.min^{-1}$)	1.93±0.35	2.42±0.30	2.87±0.32	3.34+_0.38
$\%\dot{V}O_2max$	52.1±5.8	63.1±6.4	75.0±6.2	87.2±7.1
HR ($b.min^{-1}$)	133±15	148±13	162±12	174±11
Blood Lactate ($mmol.l^{-1}$)	2.30±0.79	3.18±1.19	4.76±1.50	7.41±2.23

FEMALES

	Work rate 1	Work rate 2	Work rate 3	Work rate 4
Work Rate (W)	88±22	118±22	147±22	177±22
$\dot{V}O_2$ ($l.min^{-1}$)	1.21±0.25	1.52±0.30	1.91±0.30	2.27±0.30
$\%\dot{V}O_2max$	43.4±5.7	54.6±6.9	69.1±5.5	82.4±5.6
HR ($b.min^{-1}$)	126±13	144±13	161±12	173±11
Blood Lactate ($mmol.l^{-1}$)	1.49±0.44	2.22±0.65	3.67±0.86	6.52±1.47

exercise can be seen in Table 6.3. The males recorded a significantly lower mean heart rate at each of the work rates common to both groups, and the gradient of the regression line describing the relationship of heart rate to work rate was less steep for the males in comparison to the females.

The relationship between blood lactate concentration and submaximal work rate can be seen in Table 6.3 and Figures 6.1 and 6.2. At a given absolute work rate blood lactate concentration was lower for the males than the females, resulting in a significantly higher $OBLA_w$ for the males (194 ± 29W vs 155 ± 33W; $p<0.05$). When work rate was expressed relative to each subject's $\dot{V}O_2max$ there was no difference between the groups in the $\%\dot{V}O_2max$ at which blood lactate accumulation occurred and, therefore, no difference in the $\%\dot{V}O_2max$ at which OBLA occurred (males, 68 ± 9%; females, 69 ± 9%) (Table 6.4).

6.3.2 30-minute endurance test (T30min)

A summary of some of the performance characteristics and physiological changes during T30min can be seen in Table 6.5 and Figures 6.3 - 6.6. The males were exercising at a significantly higher CAWR throughout the test in comparison to the females (223 ± 25W vs 178 ± 28W). When CAWR was expressed as $\%\dot{V}O_2max_E$ no significant difference was found in the relative work rate of the two groups during T30min (males, 82.4 ± 4.1%; females, 82.3 ± 7.8%) (Figure 6.4).

Oxygen uptake was significantly higher for the males at each of the 4 expired air collections during the test ($p<0.01$), but when expressed as $\%\dot{V}O_2max$, a significant difference was found only at 5 minutes (males, 74.7 ± 4.2%; females, 80.4 ± 6.1%; $p<0.01$). For the remainder of the test there was no difference in the actual $\%\dot{V}O_2max$ that the two groups were exercising at.

No difference was found between the two groups for heart rate, R or blood lactate concentration throughout the test (Figures 6.5 and 6.6).

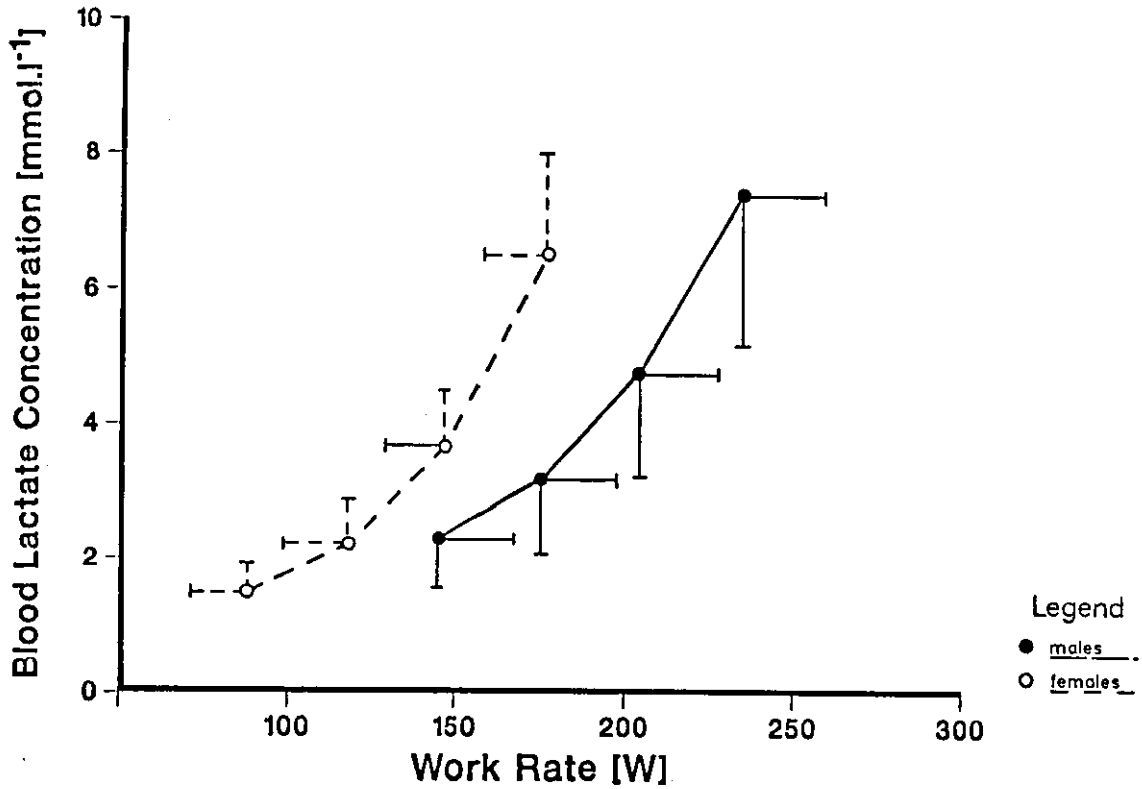


Figure 6.1 Blood lactate concentration during the incremental test for the males (n=14) and the females (n=14).

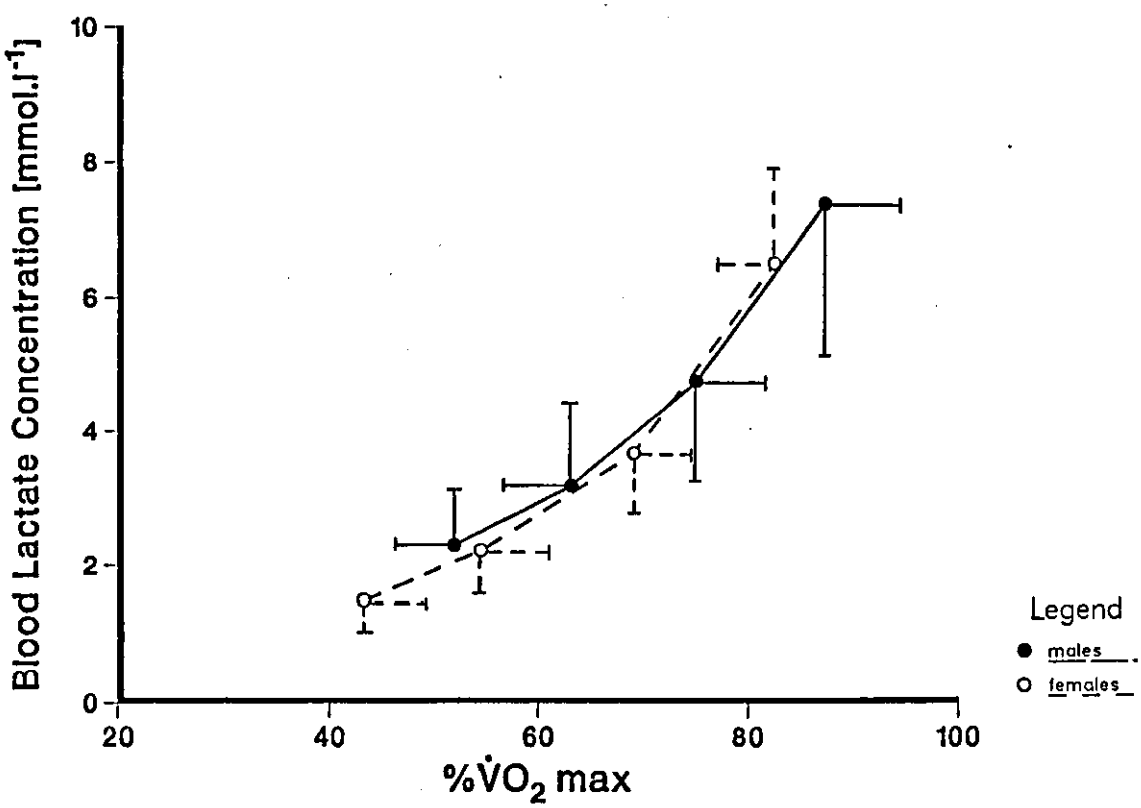


Figure 6.2 Blood lactate concentration in relation to relative exercise intensity during the incremental test for the males (n=14) and the females (n=14).

Figure 6.4 Onset of Blood Lactate Accumulation (OBLA) for the male (M) and female (F) subjects. Individual values

Subject		OBLA	
		W	%$\dot{V}O_{2}max$
M	1	199	77
	2	181	61
	3	238	67
	4	191	81
	5	150	56
	6	181	60
	7	232	75
	8	178	67
	MEAN	194	68
	S.D.	29	9
F	9	103	54
	10	152	64
	11	145	76
	12	182	74
	13	198	78
	14	151	72
	15	123	58
	16	187	74
	MEAN	155*	69
	S.D.	33	9

Significantly different from the males * $p<0.05$

Table 6.5 Summary of the T30min results for the male (M) and female (F) subjects. Mean ± S.D.

		5 (min)	10 (min)	20 (min)	30 (min)
CAWR	M	218.9±24.1	220.8±24.2	220.9±25.5	223.4±25.3
(W)	F	171.9±20.4**	175.0±23.9**	176.4±26.6**	177.9±27.7**
$\%\dot{V}O_2Max_E$	M	80.6±1.3	81.3±1.8	81.4±3.6	82.4±4.1
	F	79.8±1.1	81.0±4.5	81.6±6.9	82.3±7.8
$\dot{V}O_2$	M	2.89±0.41	3.13±0.45	3.19±0.15	3.45±0.47
($l.min^{-1}$)	F	2.21±0.21**	2.38±0.29**	2.45±0.40**	2.62±0.40**
$\%\dot{V}O_2max$	M	74.7±4.2	81.8±6.8	83.2±8.8	90.1±6.7
	F	80.4±6.1	86.7±8.0	88.5±9.7	94.8±9.5
HR	M	164±16	171±13	177±12	184±11
	F	171± 9	177± 9	182±10	189±10
R	M	1.04±0.05	1.00±0.07	0.99±0.08	1.01±0.09
	F	1.03±0.06	1.02±0.08	0.98±0.08	1.00±0.09
Blood	M	5.73±1.51	7.57±1.27	9.26±2.23	11.16±2.79
Lactate	F	6.24±1.09	7.99±1.99	9.02±3.22	10.22±3.93
($mmol.l^{-1}$)					

Significantly different from males ** $p<0.01$

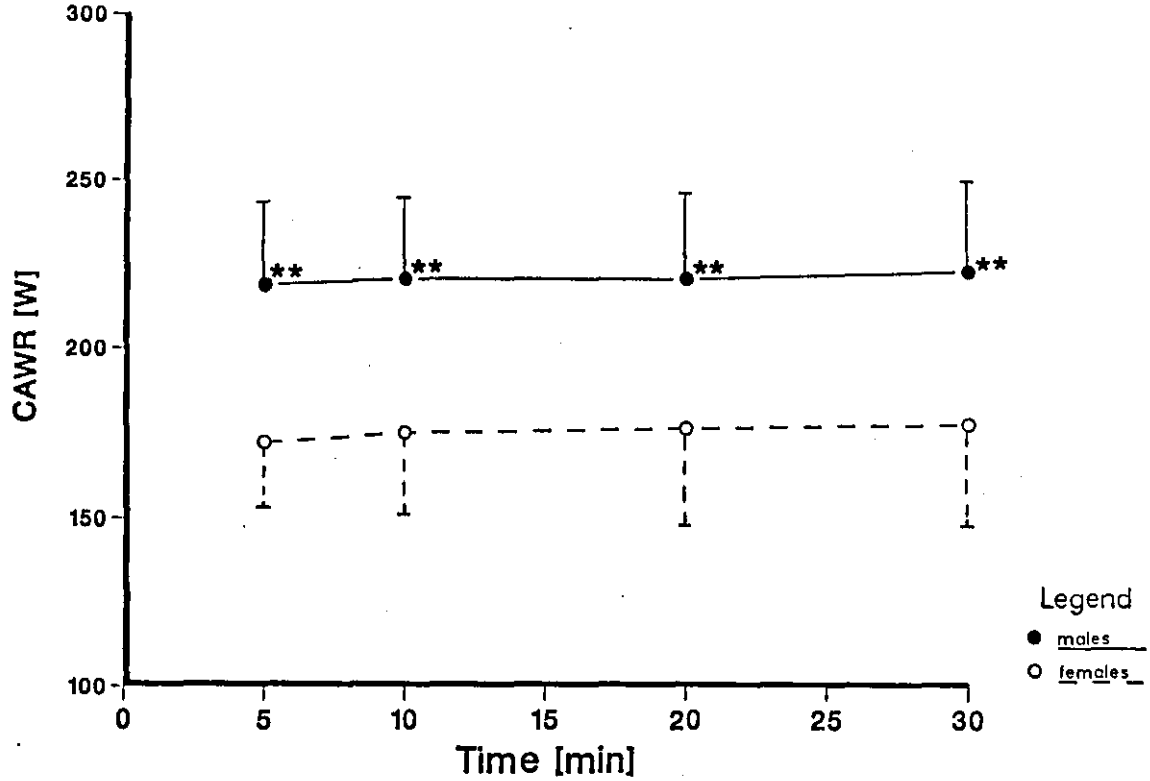


Figure 6.3 Cumulative average work rate during T30min for the males (n=14) and the females (n=14).

Significantly different from females ** $p<0.01$

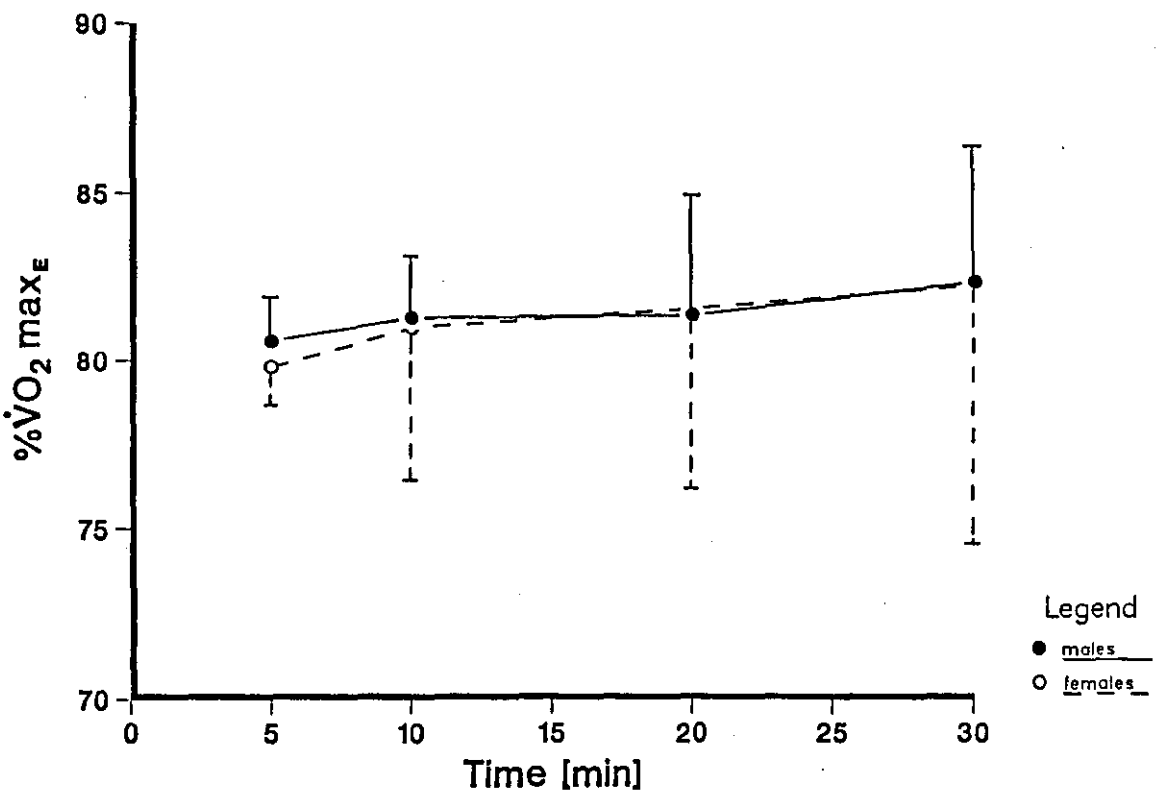


Figure 6.4 Estimated relative exercise intensity during T30min for the males (n=14) and the females (n=14).

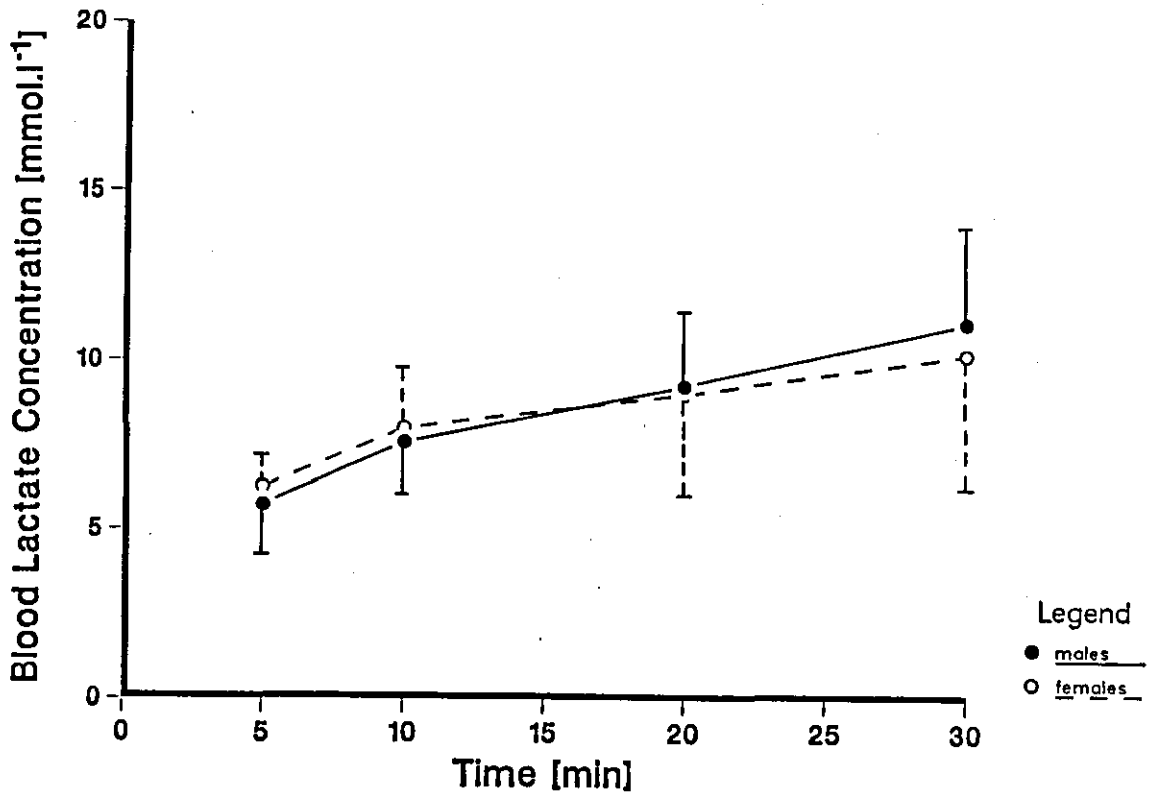


Figure 6.5 Blood lactate concentration during T30min for the males (n=14) and the females (n=14).

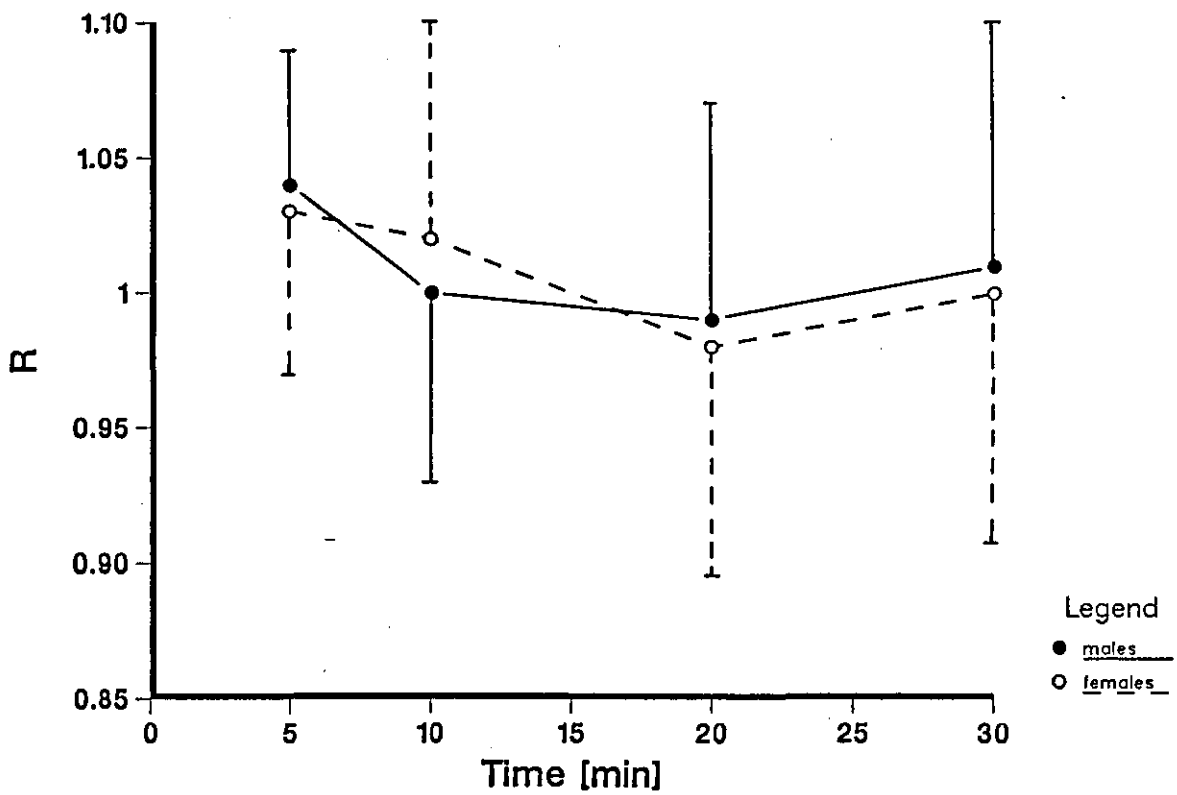


Figure 6.6 Respiratory exchange ratio during T30min for the males (n=14) and the females (n=14).

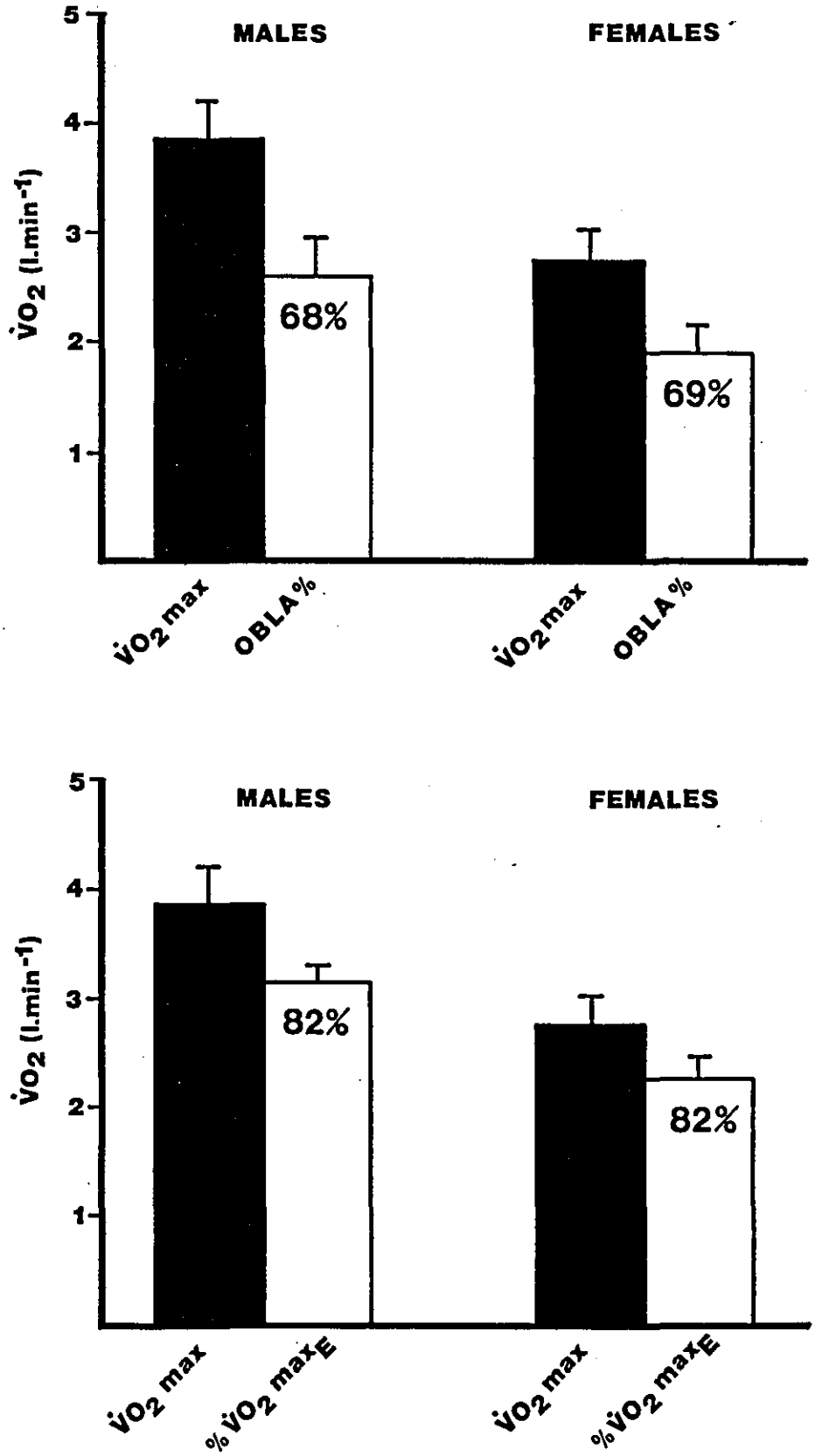


Figure 6.7 OBLA (%) and estimated relative exercise intensity during T30min in relation to maximum oxygen uptake for the males (n=14) and the females (n=14).

The relationship between $\dot{V}O_2max$ and CAWR is shown in Figure 6.8. A strong correlation was found between these two variables for the males ($r=0.74$, $p<0.01$), the females ($r=0.93$, $p<0.01$) and for the group as a whole ($p<0.88$, $p<0.01$). Correlation coefficients of a similar magnitude were also found for the relationship between $OBLA_w$ and CAWR for the males ($r=0.79$, $p<0.01$), females ($r=0.91$, $p<0.01$) and the group as a whole ($r=0.90$, $p<0.01$) (Figure 6.9) revealing that, for this group of subjects $OBLA_w$, was a better predictor of CAWR than $\dot{V}O_2max$.

The relationships between $\%\dot{V}O_2max_E$ and $\dot{V}O_2max$, and $\%\dot{V}O_2max_E$ and CAWR were poor for the females, with correlation coefficients of $r=0.05$ and $r=0.37$ respectively. These relationships were stronger, however, for the males ($r=0.63$, $p<0.05$; and $r=0.72$, $p<0.01$ respectively). Statistically significant correlations were also found between $\%\dot{V}O_2max_E$ and OBLA% for both the males ($r=0.71$, $p<0.01$) and the females ($r=0.76$, $p<0.01$). In addition, the relationship between $\%\dot{V}O_2max_E$ and OBLA% for the group as a whole ($r=0.66$, $p<0.01$) was stronger than that found for the same group between $\dot{V}O_2max$ and $\%\dot{V}O_2max_E$ ($r=0.16$) (Figures 6.10 and 6.11). These results imply that, for the group as a whole, the ability to tolerate a high $\%\dot{V}O_2max$ was strongly influenced by the ability to delay the onset of blood lactate accumulation at work rates relative to $\dot{V}O_2max$.

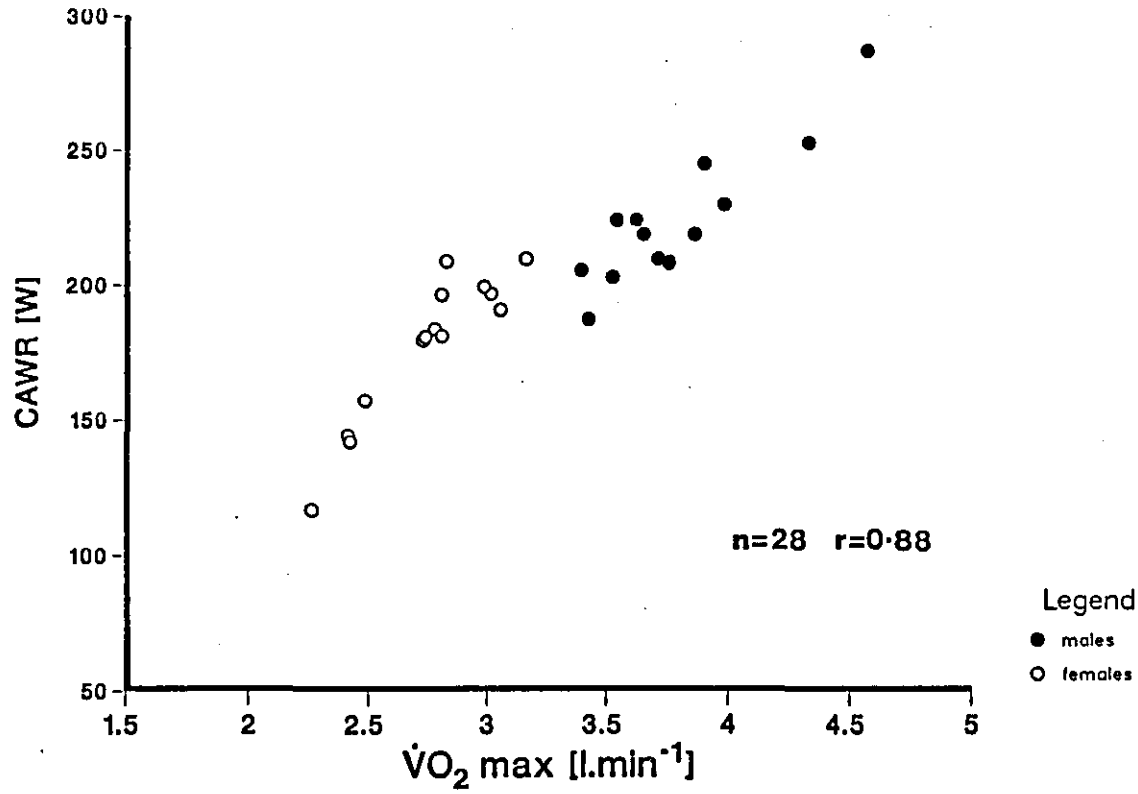


Figure 6.8 Relationship between maximum oxygen uptake and cumulative average work rate.

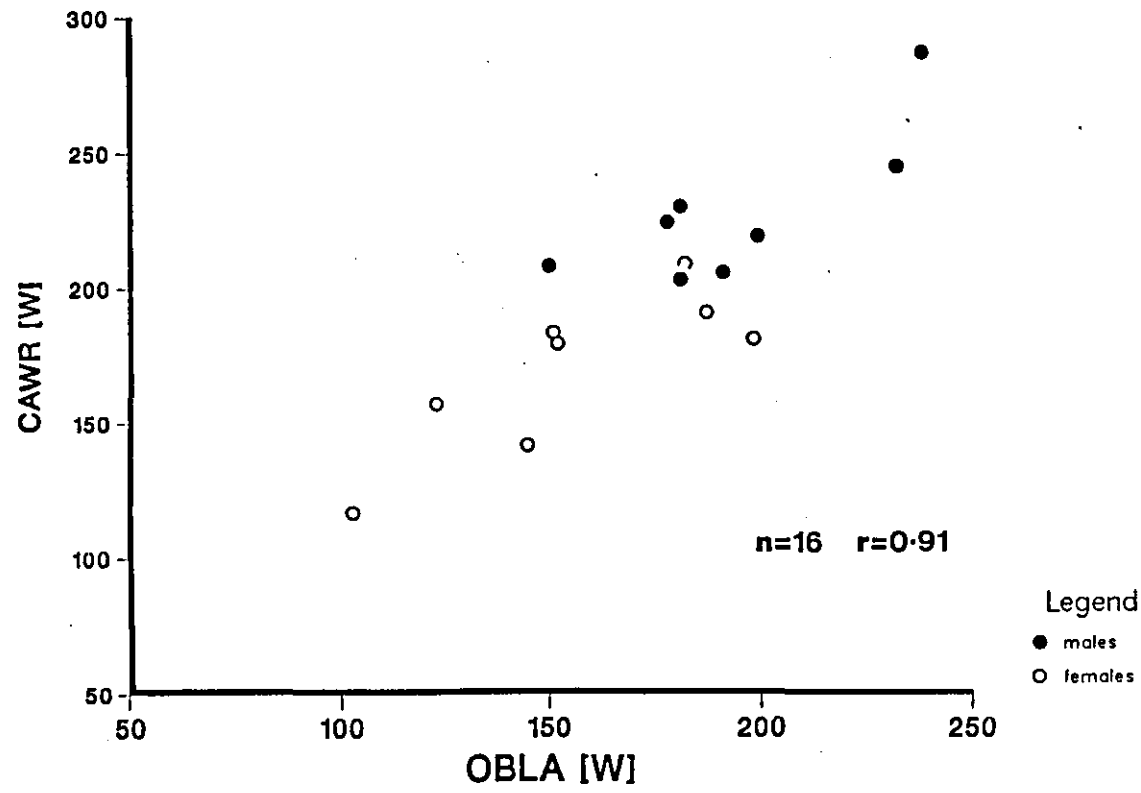


Figure 6.9 Relationship between OBLA (W) and cumulative average work rate.

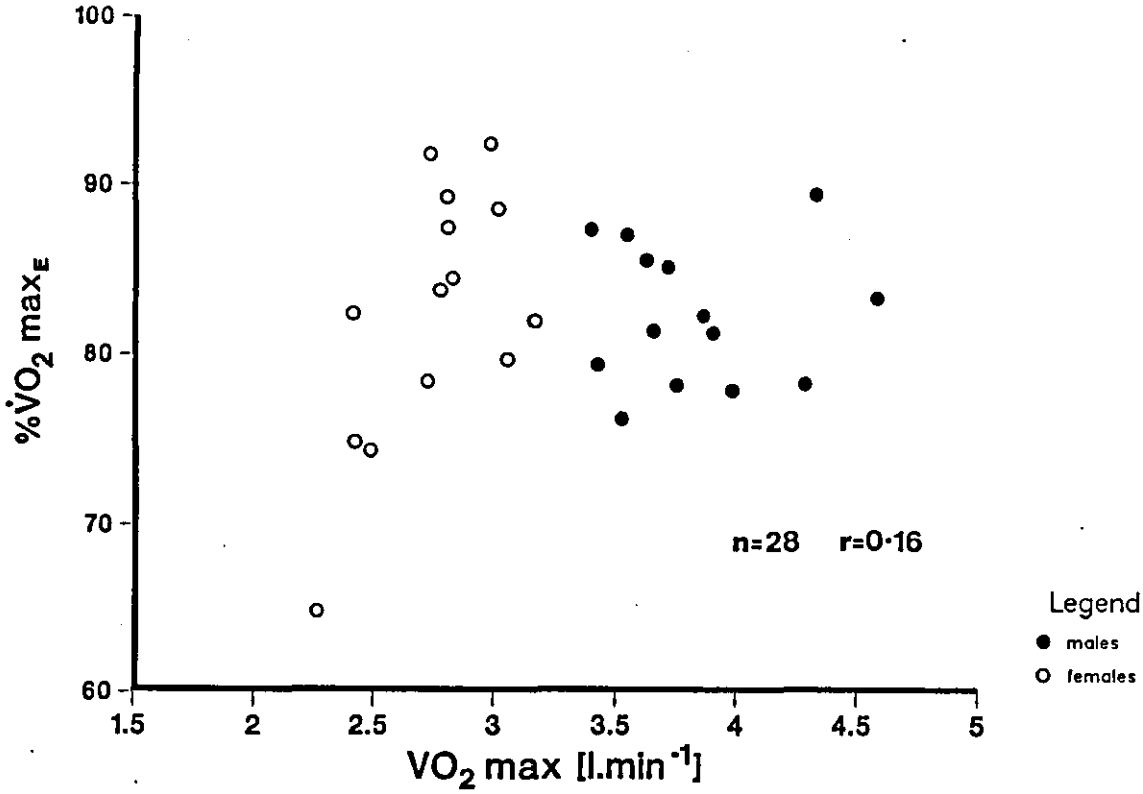


Figure 6.10 Relationship between maximum oxygen uptake and estimated relative exercise intensity.

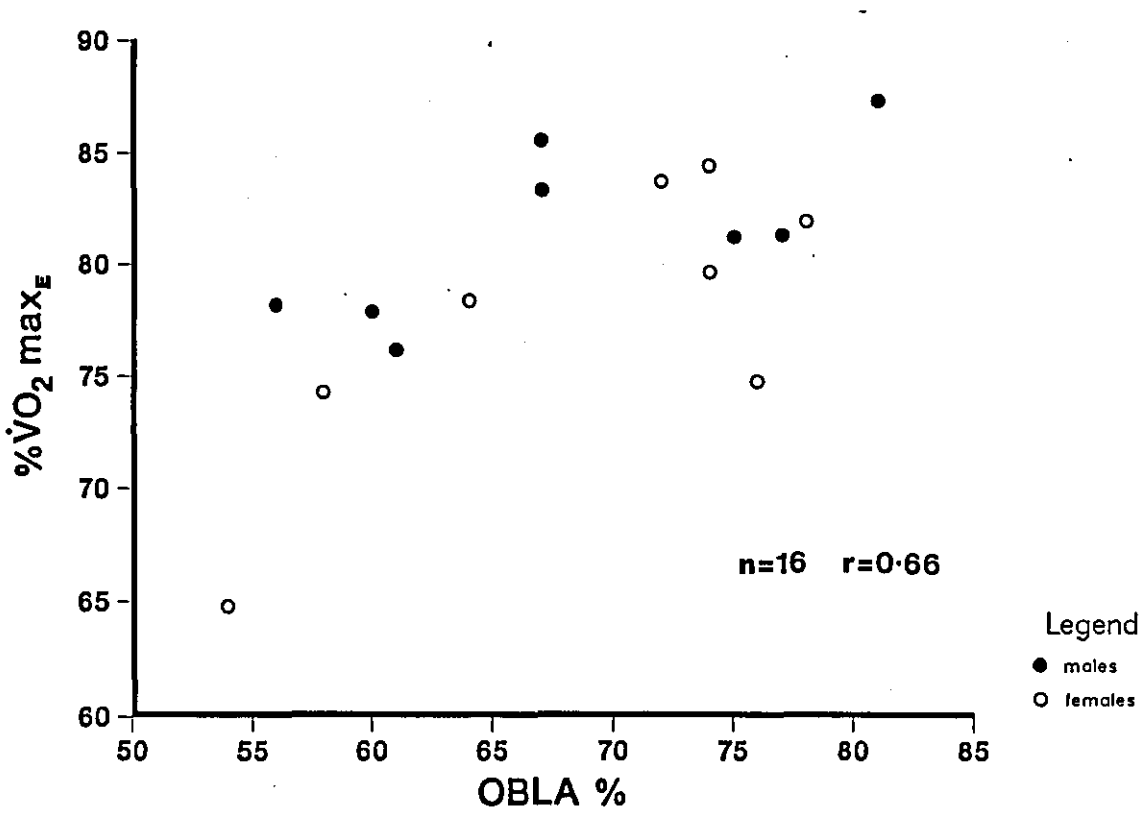


Figure 6.11 Relationship between OBLA (%) and estimated relative exercise intensity.

6.4 DISCUSSION

The well documented differences in $\dot{V}O_2max$ between males and females was supported by the results of this study. The mean $\dot{V}O_2max$ for the males of 3.83 $l.min^{-1}$ was similar to values reported by Williams (1981), Bland (1982) and Hardman (1984) for male PE students from the same establishment (4.30, 4.78 and 3.51 $l.min^{-1}$ respectively); higher than group mean values reported for sedentary males (Ekblom, 1969; Lortie et al., 1984) or active but untrained individuals (Wilmore, et al., 1980; Tanaka et al., 1983; Denis et al., 1984;); similar to student groups from other establishments (Rusko et al., 1978; Crielaard and Pirnay, 1983); but lower than values reported for well-trained male endurance athletes (Saltin and Astrand, 1967; Costill et al., 1973; Daniels et al., 1978b).

A similar trend was also seen for the females. The mean $\dot{V}O_2max$ of 2.75 $l.min^{-1}$ for the females in this study was similar to values reported by Williams (1981), Bland (1982) and Williams and Nute (1983) for females PE students from the same establishment (2.50, 2.73 and 2.80 $l.min^{-1}$ respectively); higher than values reported in the literature for sedentary females (Pedersen and Jorgensen, 1978; Lortie et al., 1984) and active females (Smith and Stransky, 1976; Henritze et al., 1985; Yoshida et al., 1987); but lower than values reported for well-trained female endurance athletes (Saltin and Astrand, 1967; Rusko et al., 1978; Jakeman, 1986).

The higher values reported in this study for both males and females compared to the sedentary individuals reported in the literature may be explained not only by the active nature of the subject groups (PE students) but also the inclusion of endurance-trained athletesin the sample population. The inclusion of only 4 endurance-trained athletes in each group, however, did not increase the group means to the magnitude reported in the literature for the well-trained or elite endurance athletes.

The differences between the mean $\dot{V}O_2max$ values for the males and females in this study (28% $l.min^{-1}$, 18% $ml.kg^{-1}min^{-1}$) are consistent with differences reported in the literature by MacNab et al. (1969),

Massicotte and Corriveau (1979), and Haymes and Dickinson (1980). It has been reported from running studies that the large differences found between the sexes in $\dot{V}O_2max$ $ml.kg^{-1}min^{-1}$ is due in part to the higher relative body fat of the females (Flint et al., 1974; Astrand and Rodahl, 1977). When $\dot{V}O_2max$ is expressed relative to lean body weight a smaller percentage difference (Flint et al., 1974) or no difference at all between the sexes (Astrand and Rodahl, 1977) has been reported. A similar finding was in evidence from the results in this study. Maximum oxygen uptake, expressed as $ml.kg^{-1}min^{-1}$, was only 3% higher for the males compared to the females. In studies using cycle ergometry, however, the influence of body fat on performance is minimised because weight is fully supported during the exercise. Differences between males and females in $\dot{V}O_2max$, therefore, are mainly a function of the larger muscle mass utilised during the exercise by the significantly taller and heavier males. This factor was emphasised by the strong correlation found between $\dot{V}O_2max$ $(l.min^{-1})$ and estimated lean body mass for the group as a whole (r=0.88).

The oxygen cost of exercise during the submaximal incremental test was slightly higher for the males compared to the females, but this difference was not statistically significant at 100W or 150W. In addition, the results revealed that $\dot{V}O_2$ increased in a linear fashion during cycling regardless of the sex of the subject. Direct comparison of $\dot{V}O_2$ between the two groups was difficult due to the fact that the same standardised work rates were not administered to all of the subjects. To have done so would have required that the male subjects start the test at a very low $\%\dot{V}O_2max$ (i.e. similar to the lowest absolute work rate for the females), and would have resulted in the test exceeding 20-24 minutes for some of the more capable subjects. Comparison of $\dot{V}O_2$ values between the males and females, therefore, was made at work rates that were common to the majority of the subjects in the two groups (100W and 150W).

The lack of a significant difference in $\dot{V}O_2$ between the two groups further supports the reports in the literature where the oxygen cost of exercise has been compared between males and females. Davies and Thompson (1979), Mayhew et al. (1979) and Maughan and Leiper (1983) all reported that the oxygen cost of treadmill running (when corrected for body weight) did not differ between males and females.

These findings are contrary to the findings of Bransford and Howley (1977) who reported significant differences between trained and untrained male and female subjects during treadmill running; and Bland (1982) who found significant differences between the $\dot{V}O_2$ of the sexes at slower speeds during treadmill running. Bland explained that these differences were the result of the difficulty of the males to run at the slower speeds. Many of these comparative studies, however, have examined the differences between $\dot{V}O_2$ during treadmill running rather than cycling. One of the few comparisons made for $\dot{V}O_2$ between males and females during cycling was by Hardman (1984), who found no significant difference in $\dot{V}O_2$ between the sexes at a given absolute work rate (W). Hardman's findings, together with the results from this study, would tend to suggest that the similarity in the O_2 cost of exercise for males and females during treadmill running also holds true for cycling.

At a given absolute work rate blood lactate concentration was higher for the females than the males during the submaximal incremental test. The work rate corresponding to OBLA was consequently higher for the males than the females (193.8 $\pm$ 29.1W vs 155.1 $\pm$ 32.6W; $p<0.05$). The $OBLA_w$ value recorded for the males is similar to values reported by Denis et al. (1984) for middle aged men (172 $\pm$ 42W) and male students (173 $\pm$ 24W); and by Tanaka et al. (1983) for a group of "very active" males (217 $\pm$ 34W). The higher values reported by Tanaka and coworkers may be attributed to the active nature of their subjects. Equivalent data for the females, concerning the work rate at which OBLA occurs, appears to be confined to treadmill running tests. Similarly the determination of OBLA for men has been more extensively studied during running compared with cycling.

The difference between the males and females in the blood lactate concentrations at a given absolute work rate during the submaximal incremental test may be accounted for by the difference in the $\%\dot{V}O_2max$ at which the males and females were exercising, since metabolic responses to exercise occur in relation to $\dot{V}O_2max$ (Hermansen and Saltin, 1967). This was confirmed further when work rate was expressed relative to each subject's $\dot{V}O_2max$. In so doing, it was found that there was no difference between the males and the females in the blood lactate concentration at a given $\%\dot{V}O_2max$ (Figure 6.2). Consequently

there was also no difference in the %$\dot{V}O_2$max at which OBLA occurred for the males (68.0 ± 8.9%; range 56% - 81%), or the females (68.8 ± 8.9%; range 54% - 78%). These values for OBLA% are consistent with the results reported for cycle ergometry by Hoppeler, Claasen and Howald (1983), who found a range in OBLA% from 60% - 82% for 10 untrained subjects (no sex specified); and Shephard et al. (1968), who studied 24 young Canadian men, and found that the work rate equivalent to 4mmol.l^{-1} occurred just below 65% $\dot{V}O_2$max. Tanaka et al. (1983), and Jacobs and Sjödin (1985), however, report much higher values for OBLA% during cycling studies. Tanaka and coworkers reported a mean OBLA% of 84% for 11 non-endurance trained active male subjects, whilst Jacobs abd Sjödin reported OBLA% to occur at 79% $\dot{V}O_2$max for 12 male subjects (no details of training status were given). The difference between these values and those presented in this study cannot be readily explained, but it may be proposed that the subjects in both of the studies cited above were in a better trained state, i.e. fitter, than those used in this study.

The direct comparison of the female data with other female data is limited to studies where OBLA% has been determined during treadmill running (Williams and Nute, 1983; Jakeman, 1986). Such comparisons are misleading however, since the exercise intensity (both absolute $\dot{V}O_2$ and %$\dot{V}O_2$max) which corresponds to a given blood lactate concentration differs significantly according to the exercise mode used. This point was highlighted by Shephard and coworkers who presented data on blood lactate concentrations at different relative exercise intensities for bench stepping, treadmill running and cycling (Shephard et al., 1968). Their study revealed that at a given %$\dot{V}O_2$max blood lactate concentration was lowest during stepping and highest during cycling. In addition, there was a 10% $\dot{V}O_2$max difference in the work rate equivalent to a blood lactate concentration of 4 mmol.l^{-1} between running and cycling, and over 20% $\dot{V}O_2$max difference between cycling and stepping. These findings were later confirmed by Jacobs and Sjödin (1985) who demonstrated that OBLA occurred at a higher steady state VO_2 during treadmill running compared with cycling (16% difference in OBLA $\dot{V}O_2$ and 7% difference in OBLA%). Direct comparison of the female data in this study with reports from the literature is therefore difficult. The comparison of OBLA% values reported in the literature for females during treadmill running with similar data for men,

however, has found values of a similar magnitude for both sexes (Williams and Nute, 1983; Jakeman, 1986). These reports would tend to support the findings of this study that there is no sex difference in the $\%\dot{V}O_2max$ at which blood lactate begins to accumulate during submaximal exercise.

The higher mean $\dot{V}O_2max$ value of the male subjects gave them a clear advantage over the females in terms of endurance potential for T30min. This was confirmed by the significantly higher CAWR of the males (233.4 $\pm$ 25.3W) compared to the females (177.9 $\pm$ 27.7W). As a consequence of the higher CAWR, $\dot{V}O_2$ was also significantly higher for the males throughout the test ($p<0.01$). The necessity of a high $\dot{V}O_2max$ for exercise at a high work rate was confirmed by the fact that throughout the test, the mean $\dot{V}O_2$ of the male group was in excess of the mean $\dot{V}O_2max$ for the female group. This factor confirms the already existing belief that, if individuals with varying $\dot{V}O_2max$ values are to be compared in terms of their endurance capabilities, the measurement of performance must be presented in some form other than absolute work rate so that the influence of genetically predetermined factors such as the sex differences in $\dot{V}O_2max$ may be eliminated.

The importance of a high $\dot{V}O_2max$ for successful performance on T30min, in terms of absolute work rate, was also confirmed by the strong correlation between $\dot{V}O_2max$ and CAWR for the males ($r=0.74$), the females ($r=0.93$) and the group as a whole ($r=0.88$, Figure 6.8).

The belief that metabolic parameters (such as blood lactate concentration) measured during submaximal exercise may be better indicators of endurance capacity than the measurement of $\dot{V}O_2max$ (Sjödin and Svedenhag, 1985) was substantiated by the results from this study. The relationship between $OBLA_w$ and CAWR was similar to that foung between $\dot{V}O_2max$ and CAWR for the females ($r=0.91$) but stronger than that found for the males ($r=0.79$) and the group as a whole ($r=0.91$, Figure 6.9).

The ability of the males to exercise at a higher CAWR during T30min than the females was a logical consequence of their higher $\dot{V}O_2max$. When CAWR was expressed relative to each subject's $\dot{V}O_2max$ ($\%\dot{V}O_2max_E$), however, no significant difference was found between the

males and the females in terms of the $\%\dot{V}O_2max_E$ tolerated during T30min (males, 82.4 $\pm$ 4.1W; females, 82.3 $\pm$ 7.8W). Therefore, despite the males possessing higher $\dot{V}O_2max$ values than the females, they were unable to tolerate a higher percentage of $\dot{V}O_2max$ during T30min. The poor relationship between $\dot{V}O_2max$ and $\%\dot{V}O_2max_E$ for the group as a whole (r=0.16) further emphasises the fact that the ability to tolerate a high percent of $\dot{V}O_2max$ is not dependent on $\dot{V}O_2max$ *per se*. A strong correlation was found, however, between $\%\dot{V}O_2max_E$ and OBLA% for the males (r=0.71), the females (r=0.76) and the group as a whole (r=0.66) indicating that the ability to exercise at a high proportion of $\dot{V}O_2max$ was influenced by the ability of the subject to delay the accumulation of blood lactate during submaximal exercise.

Analysis of blood lactate concentrations during T30min revealed that, despite the males exercising at a significantly higher absolute work rate, there was no difference between the males and the females in blood lactate concentration during the test. Since both groups were exercising at the same relative work rate these findings not only confirm those of Hermansen and Saltin (1967), that blood lactate accumulation occurs relative to $\dot{V}O_2max$, but also reinforces the findings from the submaximal incremental test where there was no significant difference between the sexes in the blood lactate concentration at a given $\%\dot{V}O_2max$.

The lack of a sex difference in the $\%\dot{V}O_2max$ at which the two groups performed T30min is consistent with other findings in the literature where the ability to exercise at a $\%\dot{V}O_2max$ has been observed. Bland (1982) reported no sex difference in the $\%\dot{V}O_2max$ tolerated during a 2 mile time trial (both 89% $\dot{V}O_2max$), whilst Ramsbottom (1986) reported that during a 5km run male and female subjects exercised at an average of 87% and 89% $\dot{V}O_2max$ respectively (NS). In a study examining the race pace of subjects during marathon running Davies and Thompson (1979) revealed that the average $\%\dot{V}O_2max$ tolerated by the subjects during the race ranged from 76% - 87% $\dot{V}O_2max$ for the males and 68% - 86% for the females. Maughan and Leiper (1983) also reported no difference between males and females in the $\%\dot{V}O_2max$ tolerated during marathon running (74% and 76% respectively). In addition, Brewer (1986) established that there was no sex difference in exercise time to exhaustion at 70% $\dot{V}O_2max$. Mean run time for the

males was 113.45 minutes compared to 112.9 minutes for the females.

In conclusion, the results from this study revealed that, whilst the larger dimensions and functional capabilities of the male oxygen transport system enabled them to exercise at a higher average work rate than the females during T30min, the capacity to sustain a high $\%\dot{V}O_2max$ over 30 minutes was not influenced by the subject's sex. Since both the males and the females exercised at the same $\%\dot{V}O_2max_E$ during T30min, and had similar blood lactate concentrations, the results from T30min support the findings of the submaximal incremental test that revealed no sex difference in the $\%\dot{V}O_2max$ at which OBLA% occurred. The results from this study were similar to those reported in the previous section implying that regardless of sex, the possession of a high $\dot{V}O_2max$, and the ability to delay the accumulation of blood lactate at an absolute work rate were important determinants of the ability to exercise at a high absolute work rate, whilst the ability to exercise at a high $\%\dot{V}O_2max$ was independent of $\dot{V}O_2max$ but influenced by the subject's ability to delay the accumulation of blood lactate at a given $\%\dot{V}O_2max$. Futhermore, the results from this study confirm the findings of Davies and Thompson (1979), Leiper and Maughan (1983) and Brewer (1986) which state that the ability to sustain a high $\%\dot{V}O_2max$ during exercise does not appear to be influenced by the subject's sex.

7. THE INFLUENCE OF SHORT-TERM TRAINING ON MAXIMUM OXYGEN UPTAKE, SUBMAXIMAL BLOOD LACTATE CONCENTRATION AND ENDURANCE PERFORMANCE

7.1 INTRODUCTION

The evidence presented in Chapter 6 supported the suggestion that the ability to sustain a high relative exercise intensity is conferred by the peripheral adaptions of the skeletal muscle to endurance training. In addition, the results highlighted that this ability appears to be the result of endurance training rather than training *per se*. The adoption of a cross-sectional approach, i.e. comparing already well-trained endurance athletes with sprint-trained athletes, or more commonly, with untrained subjects does not, however, rule out the possibility that performance differences between two groups of subjects may be due to genetically-determined differences which may favour one group or the other. In addition, no insight into the time course of the changes that occur as a result of training can be gleaned from such a study.

The purpose of this present study, therefore, was to adopt a longitudinal approach to examine the effect of short-term training on two different measures of endurance performance. The ability to tolerate a high $\%\dot{V}O_2max$ over a prescribed period of time was assessed by T30min, whilst the ability to exercise at a constant work rate was assessed by the exercise time to exhaustion at a work rate equivalent to 80% of the subject's $\dot{V}O_2max$ (T80%). The relationship between performance on these two tests and the onset of blood lactate accumulation (OBLA) was also examined, as was the relationship between the training-induced changes in performance and changes in cardiovascular and metabolic parameters.

7.2 METHODS

7.2.1 Subjects

The female volunteer subjects participating in this study were 13 physical education students and 2 physical education teachers. Seven subjects were assigned to the training group (TG), whilst 8 acted as controls (CG). Two of the subjects within the TG were inactive prior to the study due to injury, the remaining subjects were all active. Prior to testing all subjects were familiarised fully with exercise on a cycle ergometer, as described in Chapter 3 (3.2).

7.2.2 Preliminary tests

Maximum oxygen uptake was determined by an incremental test where the work rate was increased every 3 minutes to exhaustion. Two subjects were required to repeat the test after failing to fulfil the criteria adopted to indicate that $\dot{V}O_2max$ was attained. These criteria were achieved during the second test.

The relationship between $\dot{V}O_2$ and work rate was determined for each individual during 4 minutes' exercise at each of 4 increasing work rates. Expired air collections were taken during the final minute of each work rate, as described in Chapter 3 (3.4). The work rate for the endurance tests (i.e. that required to elicit 80% $\dot{V}O_2max$) was determined from individual regression equations describing the relationship between $\dot{V}O_2$ and work rate.

Duplicate samples of arterialised capillary blood were obtained at rest from a pre-warmed hand, and immediately following each expired air collection during the submaximal incremental test. The relationship between blood lactate concentration and work rate (expressed as both watts and $\%\dot{V}O_2max$) was plotted for each individual and used to determine the work rate equivalent to a blood lactate concentration of 4 $mmol.l^{-1}$ (OBLA) as in Chapter 5 (5.2.2).

7.2.3 30-minute endurance test (T30min)

Each subject performed T30min on 2 occasions in the manner described in Chapter 3 (3.6). Based on the results obtained from the initial studies reported in this thesis, which revealed the tendency for individuals to perform better on the second test when compared to the first test, the first test was used for familiarisational purposes only. During this first test, therefore, only one expired air collection was taken, namely at 5 minutes, solely for the purpose of confirming that the relative exercise intensity was 80% $\dot{V}O_2max$. Analysis of the 5-minute expired air collection revealed that for 2 subjects the 80% $\dot{V}O_2max$ work rate had been underestimated. In both cases the subjects were required to repeat their submaximal incremental test and from this the work rate equivalent to 80% $\dot{V}O_2max$ was recalculated.

All subjects performed the second T30min following an overnight fast, at least 48 hours after the first test. Prior to performing the test, a resting sample of arterialised capillary blood was collected and a 4-minute standardised warm-up at 50% $\dot{V}O_2max$ was performed. During this test 4 expired air collections and 4 blood samples were taken at the standard times indicated in Figure 3.2.

Computer system

Work rate was continually monitored throughout T30min using a BBC microcomputer and an internal analogue-to-digital converter as described in Chapter 3 (3.1.3). Through use of the individual regression equations describing the relationship between $\dot{V}O_2$ and work rate the estimated oxygen cost of the test and estimated $\%\dot{V}O_2max$ the subject was capable of tolerating were calculated.

7.2.4 80% VO_2max Endurance test (T80%)

All subjects performed T80% following an overnight fast, and where possible at the same time of the day as T30min. Performance of T80% was preceded by the collection of a resting sample of arterialised capillary blood from a pre-warmed hand, and a standardised 4-minute warm up on the cycle ergometer at a work rate

equivalent to 50% $\dot{V}O_2max$. The subjects were then required to exercise to exhaustion at a work rate equivalent to 80% of their $\dot{V}O_2max$. The times of expired air collections and blood sampling are shown in Figure 3.3. Where subjects continued exercise beyond the hour (post-training only) expired air collections were reduced to three times an hour and blood sampling to once an hour.

Computer system

Pedal frequency and work rate were continually monitored throughout T80% using the same computer system as that used for T30min.

All subjects performed the familiarisation T30min before either of the two performance tests. A cross-over design was then used so that half of the TG and CG performed T30min first, whilst the other half performed T80% first.

7.2.5 Training

Each subject trained on the cycle ergometer 3 times a week, for 6 weeks. The training work rate was initially that used for T80%, i.e. 80% $\dot{V}O_2max$, and the subjects were required to train for a maximum of 30 minutes per session. When the subjects could exercise at this prescribed work rate for 30 minutes, on three different occasions, the work rate was increased by either 15W or 29W according to body weight. During the training period both the TG and the CG maintained their normal physical activity patterns.

7.2.6 Post-training tests

Following the six-week training period the subjects performed the $\dot{V}O_2max$ test, the submaximal incremental test and T80% at the same work rates as pre-training. In order to ensure that a blood lactate concentration of at least 4 $mmol.l^{-1}$ was achieved during the submaximal incremental test all of the TG and 2 of the CG were required to exercise for an additional 4 or 8 minutes, at increasing work rates, until reaching a work rate equivalent to approximately 80% of their post-training $\dot{V}O_2max$. Performance of T30min post-training

required that the subjects exercise for the first 5 minutes of the test at the same work rate as pre-training, following which they were free to exercise at a work rate of their choice.

7.3 RESULTS

7.3.1 Preliminary tests

A summary of the physical characteristics of the TG and the CG pre- and post-training can be seen in Table 7.1. No significant difference was found between the two groups for age, height, weight or percent body fat either pre- or post-training.

Table 7.2 shows a summary of the results from the $\dot{V}O_2max$ test for the TG and the CG pre- and post-training. No significant difference was found between the two groups for $\dot{V}O_2max$ ($l.min^{-1}$) pre-training. In the post-training test both the TG and the CG significantly increased their $\dot{V}O_2max$ values (24% and 7% respectively), however, the increase for the TG was significantly greater than that for the CG in both absolute ($p<0.05$) and relative (%) ($p<0.01$) terms. Post-training $\dot{V}E$ max was significantly higher than pre-training for the TG ($p<0.05$) (CG, NS) whilst there was no significant change in maximum heart rate for either the TG or the CG.

The work rate required to elicit $\dot{V}O_2max$ was significantly higher pre-training for the CG than for the TG ($p<0.01$). However, post-training work rate at $\dot{V}O_2max$ increased significantly for the TG ($p<0.01$) whilst remaining unchanged for the CG. Consequently there was no significant difference in $\dot{V}O_2max$ work rate between the two groups post-training. Exercise time to exhaustion during the $\dot{V}O_2max$ test increased significantly for both the TG ($p<0.01$) and the CG ($p<0.05$) in the post-training test. The increase for the TG, however, was significantly greater than that for the CG in both absolute ($p<0.05$) and relative terms ($p<0.01$).

A summary of the results from the submaximal incremental test for the TG pre- and post-training can be seen in Tables 7.3 and 7.4. The oxygen cost of exercise at increasing submaximal work rates remained

Table 7.1 Physical characteristics of the training group (TG) and the control group (CG) pre- and post-training. Mean ± S.D.

		PRE-TRAINING	POST-TRAINING
Age	TG	20.9 ± 2.2	21.0 ± 2.2
(yrs)	CG	22.3 ± 1.8	22.4 ± 1.8
Height	TG	168.5 ± 4.6	168.5 ± 4.6
(cm)	CG	164.8 ± 7.1	164.8 ± 7.1
Weight	TG	64.4 ± 8.3	64.7 ± 8.9
(kg)	CG	62.5 ± 8.1	62.5 ± 8.7
Body fat	TG	26.2 ± 4.5	25.7 ± 3.9
(%)	CG	24.5 ± 4.9	23.9 ± 4.0

Table 7.2 Physiological characteristics of the training group (TG) and the control group (CG) pre- and post-training. Mean ± S.D.

		PRE-TRAINING	POST-TRAINING	% CHANGE
$\dot{V}O_2max$	TG	2.42±0.50	2.93±0.36^{b}	23.5±16.1
($l.min^{-1}$)	CG	2.66±0.45	2.87±0.56^{b}	7.0±4.4*
$\dot{V}O_2max$	TG	37.36±5.29	45.19±1.94^{b}	23.0±18.4
($ml.kg^{-1}min^{-1}$)	CG	43.15±6.42	46.86±6.47^{b}	8.8±5.6
$\dot{V}E$ max	TG	79.3±24.0	90.1±21.0^{a}	16.7±18.1
($l.min^{-1}$)	CG	93.9±16.1	96.1±18.3	-2.2±7.7*
HR max	TG	193±12	192±9	-0.4±3.6
($b.min^{-1}$)	CG	196±5	195±6	-0.3±1.5
Max Work Rate	TG	197±37	233±27^{b}	20.0±15.0
(W)	CG	221±27**	224±38	2.1±6.0**
Ride time	TG	8.9±1.2	12.7±2.1^{b}	44.1±16.5
(min)	CG	9.5±1.2	10.0±1.1^{a*}	4.8±4.8**

Significantly different from pre-training ^{b} $p<0.01$ ^{a} $p<0.05$

Significantly different from TG ** $p<0.01$ * $p<0.05$

Table 7.3 Work rate (W), heart rate ($b.min^{-1}$) and blood lactate concentration ($mmol.l^{-1}$) for the training group during the submaximal incremental test pre- and post-training. Mean ± S.D.

		Work rate 1	Work rate 2	Work rate 3	Work rate 4	Work rate 5
Work rate	pre	68.1±33.2	98.1±33.5	127.9±33.1	154.9±35.5	-
(W)	post	68.3±33.3	98.0±33.0	127.1±33.2	153.7±36.1	181.6±32.3
Heart rate	pre	126±25	145±24	165±18	178±14	-
($b.min^{-1}$)	post	114±15	127±17[b]	146±14[b]	161±13[b]	175±9
Blood lactate	pre	1.62±0.74	2.54±0.96	4.50±1.34	7.60±1.92	-
($mmol.l^{-1}$)	post	1.17±0.35	1.45±0.51[b]	2.42±0.93[b]	4.13±1.55[b]	7.19±2.19

Significantly different from pre-training [b] $p<0.01$

Table 7.4 Summary of the submaximal incremental test results for the training group pre- and post-training. Mean ± S.D.

		Work rate 1	Work rate 2	Work rate 3	Work rate 4	Work rate 5
$\dot{V}O_2$	pre	0.97±0.36	1.32±0.41	1.67±0.44	2.02±0.45	-
($l.min^{-1}$)	post	0.99±0.36	1.33±0.34	1.66±0.43	1.98±0.47	2.36±0.39
R	pre	0.83±0.11	0.91+0.09	0.97±0.06	1.02±0.06	-
	post	0.82±0.08	0.88±0.04	0.90±0.03[a]	0.96±0.03[a]	1.00±0.03
$\dot{V}E$	pre	23.2±8.7	32.1±11.3	43.7±13.9	57.5±15.9	-
($l.min^{-1}$)	post	21.0±6.6	27.7±6.8	35.0±10.2[b]	45.4±13.2[b]	56.4±11.7
$\dot{V}E.\dot{V}O_2^{-1}$	pre	23.8±2.4	24.4±2.2	26.4±2.8	29.2±4.9	-
	post	20.9±2.3	20.4±1.8[b]	20.7±2.1[b]	21.9±3.1[a]	22.8±3.1
F_EO_2	pre	16.8±0.5	16.9±0.5	17.0±0.5	17.2±0.5	-
	post	16.3±0.5	16.1±0.5[b]	16.1±0.5[b]	16.3±0.6[b]	16.5±0.6
$\%\dot{V}O_2max$	pre	39.3±8.4	53.6±8.3	68.6±6.8	83.6±6.7	-
	post	33.3±8.4[b]	44.7±6.7[b]	56.0±7.8[b]	66.9±8.1[b]	80.3±5.7

Significantly different from pre-training [a] $p<0.05$ [b] $p<0.01$

unchanged as a result of 6 weeks' training (Table 7.3). However, due to the increase in $\dot{V}O_2max$ the relative exercise intensity that each work rate represented was significantly lower post-training ($p<0.01$).

Despite submaximal $\dot{V}O_2$ remaining unchanged for a given work rate significantly lower values were recorded for $\dot{V}E$ ($l.min^{-1}$) at work rates 3 and 4 ($p<0.01$), the ventilatory equivalent ($\dot{V}E.\dot{V}O_2^{-1}$) and the fractional concentration of oxygen in the expired air ($F_EO_2\%$) at work rates 2, 3 and 4 ($p<0.01$) and $\dot{V}CO_2$ and respiratory exchange ratio (R) at work rates 3 and 4 ($p<0.05$). In addition, heart rate was significantly lower at work rates 2, 3 and 4 ($p<0.01$) despite an unchanged maximum heart rate.

The blood lactate concentrations for the TG during the submaximal incremental test pre- and post-training can be seen in Table 7.3 and Figures 7.1 and 7.2. Post-training blood lactate concentration was significantly lower at work rates 2, 3 and 4 than the pre-training values ($p<0.01$) (Figure 7.1). However, when work rate was expressed as $\%\dot{V}O_2max$ there was no change in the blood lactate concentration at a given $\%\dot{V}O_2max$ (Figure 7.2).

A summary of the submaximal incremental test results for the CG can be seen in Tables 7.5 and 7.6. When compared with pre-training values, the oxygen cost of exercise during the post-training test was unchanged at work rates 1, 3 and 4 but significantly higher ($p<0.05$) at work rate 2. No significant difference was found pre- and post-training in $\%\dot{V}O_2max$, $\dot{V}E$, $F_ECO_2\%$, heart rate and blood lactate concentration, whilst $\dot{V}E.\dot{V}O_2$ and $F_EO_2\%$ were significantly lower at work rate 3 ($p<0.05$) and R was significantly lower at work rates 3 ($p<0.05$) and 4 ($p<0.01$).

The absolute work rate at which OBLA occurred increased significantly for both the TG ($p<0.01$) and the CG ($p<0.05$) in the post-training test (Table 7.7). The 26% increase for the TG, however, was significantly greater ($p<0.01$) than that for the CG (5%). Whilst there was no change in the $\%\dot{V}O_2max$ at which OBLA occurred for either the TG or the CG, post-training OBLA% was significantly higher for the CG than the TG ($72.6 \pm 5.7\%$ vs $65.9 \pm 6.4\%$; $p<0.05$) (Figure 7.10).

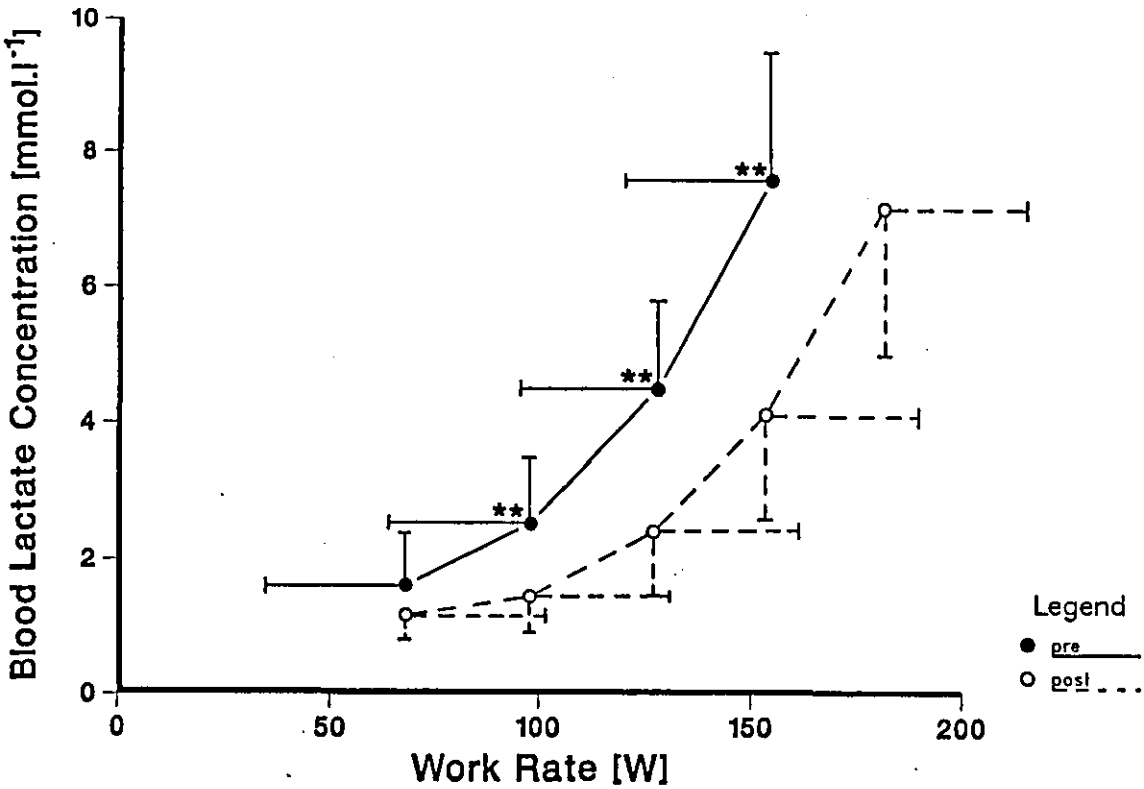


Figure 7.1 Blood lactate concentration during the incremental test for the training group pre- and post training. Significantly different from post-training ** $p<0.01$

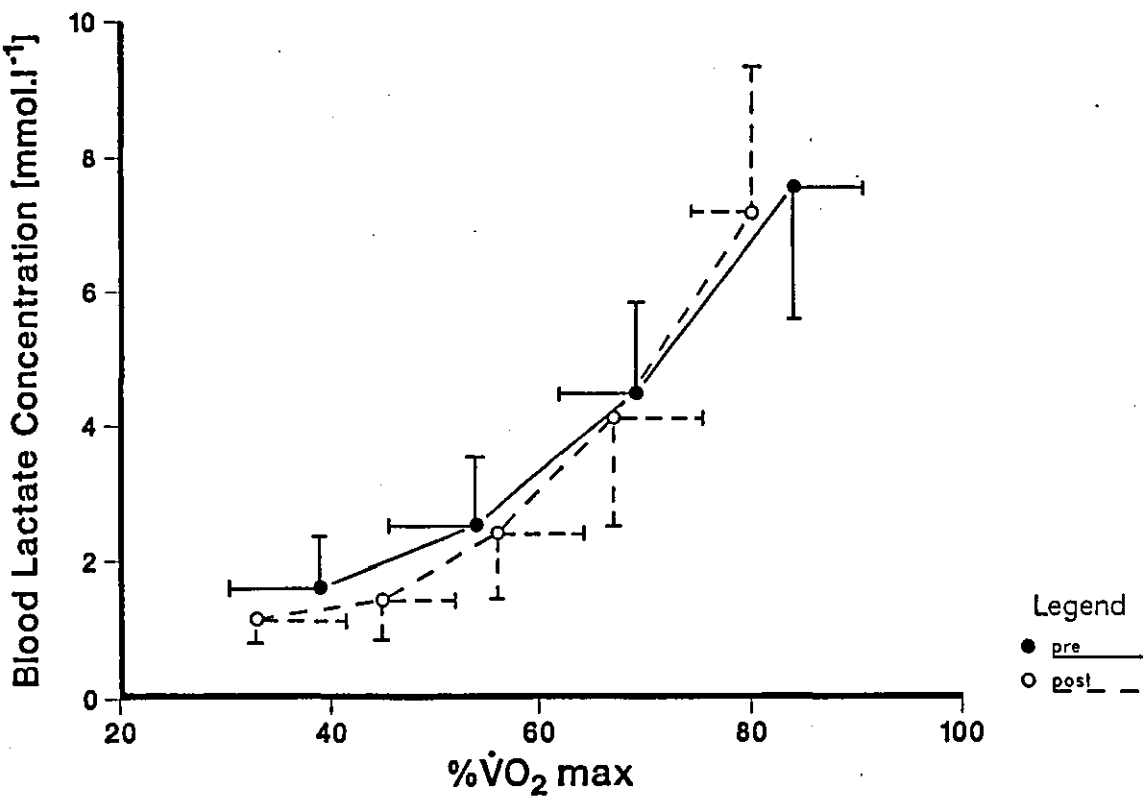


Figure 7.2 Blood lactate concentration in relation to relative exercise intensity during the incremental test for the training group pre- and post-training.

Table 7.5 Work rate (W), heart rate ($b.min^{-1}$) and blood lactate concentration ($mmol.l^{-1}$) for the control group during the submaximal incremental test pre- and post-training. Mean ± S.D.

		Work rate 1	Work rate 2	Work rate 3	Work rate 4
Work rate	pre	85.5±41.0	115.8±41.3	146.1±41.4	171.8±38.6
(W)	post	86.1±41.0	117.3±42.0	146.3±41.6	172.8±38.6
Heart rate	pre	124±12	140±13	159±12	174±8
($b.min^{-1}$)	post	125±16	140±18	157±15	172±9
Blood lactate	pre	1.82±0.76	2.53±0.99	4.06±1.41	6.86±1.81
($mmol.l^{-1}$)	post	1.49±0.55	2.10±0.71	3.63±1.35	5.98±1.78

Table 7.6 Summary of the submaximal incremental test results for the control group pre- and post-training. Mean ± S.D.

		Work rate 1	Work rate 2	Work rate 3	Work rate 4
$\dot{V}O_2$	pre	1.19±0.49	1.48±0.55	1.85±0.57	2.19±0.53
($l.min^{-1}$)	post	1.25±0.39	1.61±0.48^a	1.96±0.53	2.29±0.47
R	pre	0.89±0.06	0.94+0.05	0.98±0.03	1.01±0.06
	post	0.85±0.05	0.91±0.05	0.96±0.03^a	0.98±0.04^b
$\dot{V}E$	pre	27.3±9.5	36.5±11.4	48.2±13.2	59.4±12.7
($l.min^{-1}$)	post	27.6±7.4	37.1±10.6	47.7±12.3	59.3±13.0
$\dot{V}E.\dot{V}O_2^{-1}$	pre	23.8±3.8	25.3±3.1	26.2±2.2	27.4±3.4
	post	22.5±1.4	23.2±0.9	24.5±1.7^a	26.2±2.3
F_EO_2	pre	16.8±0.6	17.0±0.2	17.1±0.3	17.2±0.5
	post	16.6±0.3	16.7±0.2	16.9±0.3^a	17.1±0.3
$\%VO_2max$	pre	43.1±12.3	54.1±12.8	68.0±11.5	81.6±7.3
	post	42.5±6.3	55.1±7.2	67.6±7.6	80.0±7.3

Significantly different from pre-training ^{a} $p<0.05$ ^{b} $p<0.01$

Table 7.7 Onset of Blood Lactate Accumulation (OBLA) for the training group (TG) and the control group (CG) pre- and post-training. Mean ± S.D.

		$OBLA_w$	OBLA %
TG	pre	118 ± 26	66.0 ± 8.1
	post	146 ± 26[b]	65.9 ± 6.4
	% change	25.7 ± 18.8	0.3 ± 14.6
CG	pre	141 ± 32	67.3 ± 7.2
	post	151 ± 31[a]	72.6 ± 5.7[a]
	% change	5.4 ± 10.1[a*]	12.7 ± 17.3[a]

Significantly different from pre-training [a] $p<0.05$ [b] $p<0.01$

Significantly different from TG [*] $p<0.05$ [b] $p<0.01$

7.3.2 30-minute endurance test (T30min)

The physiological changes and performance characteristics of the TG and the CG during T30min, pre- and post-training, can be seen in Tables 7.8 - 7.17, and Figures 7.3 - 7.5. Post-training the TG exercised at a significantly higher CAWR than pre-training ($p<0.01$), whilst there was no change in CAWR for the CG (Table 7.8). The changes in work rate with time of the two groups during T30min can be seen in Figure 7.3. Pre-training the TG showed a gradual decrease in CAWR throughout the test, whilst post-training there was a marked increase in CAWR following the standardised 5 minute period. There was no change in the performance trends of the CG pre- and post-training, who maintained a fairly constant work rate throughout the test.

When CAWR was expressed as $\%\dot{V}O_2max_E$, there was no significant difference pre- and post-training in the $\%\dot{V}O_2max_E$ at which the TG and the CG performed T30min, i.e. neither the TG nor the CG could exercise at a higher percentage of their post-training $\dot{V}O_2max$ during T30min when compared with their pre-training performance (Table 7.9). Due to the increased $\dot{V}O_2max$ of the TG and the requirement to exercise at a standardised rate during the initial stages of the test, the $\%\dot{V}O_2max_E$ was significantly lower in the post-training test at 5 minutes ($p<0.01$). It was also significantly lower during the post-training test at 10 minutes ($p<0.01$) and 20 minutes ($p<0.05$) (Figure 7.4).

The oxygen cost of exercise during the first 5 minutes of the test remained the same for the TG post-training, but increased significantly for the CG ($p<0.05$) (Table 7.10). No obvious explanation can be advanced for this finding for the CG. Throughout the remainder of the post-training test, however, $\dot{V}O_2$ was significantly higher than pre-training for the TG (10 and 30 minutes $p<0.01$, 20 minutes $p<0.05$), whilst there was no difference pre- and post-training for the CG.

When $\dot{V}O_2$ was expressed as $\%\dot{V}O_2max$, the directly measured values confirmed those estimated from CAWR ($\%\dot{V}O_2max_E$). Relative exercise intensity for the TG was significantly lower post-training than pre-training at 5 minutes ($p<0.01$) and 10 minutes ($p<0.05$) but there was no difference at 20 and 30 minutes. No significant difference was found pre- and post-training in the $\%\dot{V}O_2max$ utilised by the CG at any

Table 7.8 Cumulative average work rate (W) during T30min for the training group (TG) and the control group (CG) pre- and post-training. Mean ± S.D.

		5 min	10 min	20 min	30 min
TG	pre	150.4±28.2	148.9±26.7	145.8±22.2	147.0±20.6
	post	150.9±28.9	156.7±30.8^{a}	161.5±31.6^{b}	165.3±31.0^{b}
CG	pre	165.5±33.6	166.7±36.2	165.9±37.0	166.1±36.7
	post	165.1±33.6	165.9±36.7	164.8±38.3	165.8±38.6

Significantly different from pre-training ^{a} $p<0.05$ ^{b} $p<0.01$

Table 7.9 Estimated relative exercise intensity (%$\dot{V}O_{2}max_{E}$) during T30min for the training grpuo (TG) and the control group (CG). Mean ± S.D.

		5 min	10 min	20 min	30 min
TG	pre	81.0±2.8	80.4±4.1	79.1±6.0	79.8±6.7
	post	65.6±5.1^{b}	68.6±5.4^{b}	70.5±5.4^{a}	72.1±5.1
CG	pre	79.5±5.1	80.0±5.0	79.5±5.0	79.6±5.0
	post	76.5±8.2	76.9±8.0	76.3±8.0	76.7±7.0

Significantly different from pre-training ^{a} $p<0.05$ ^{b} $p<0.01$

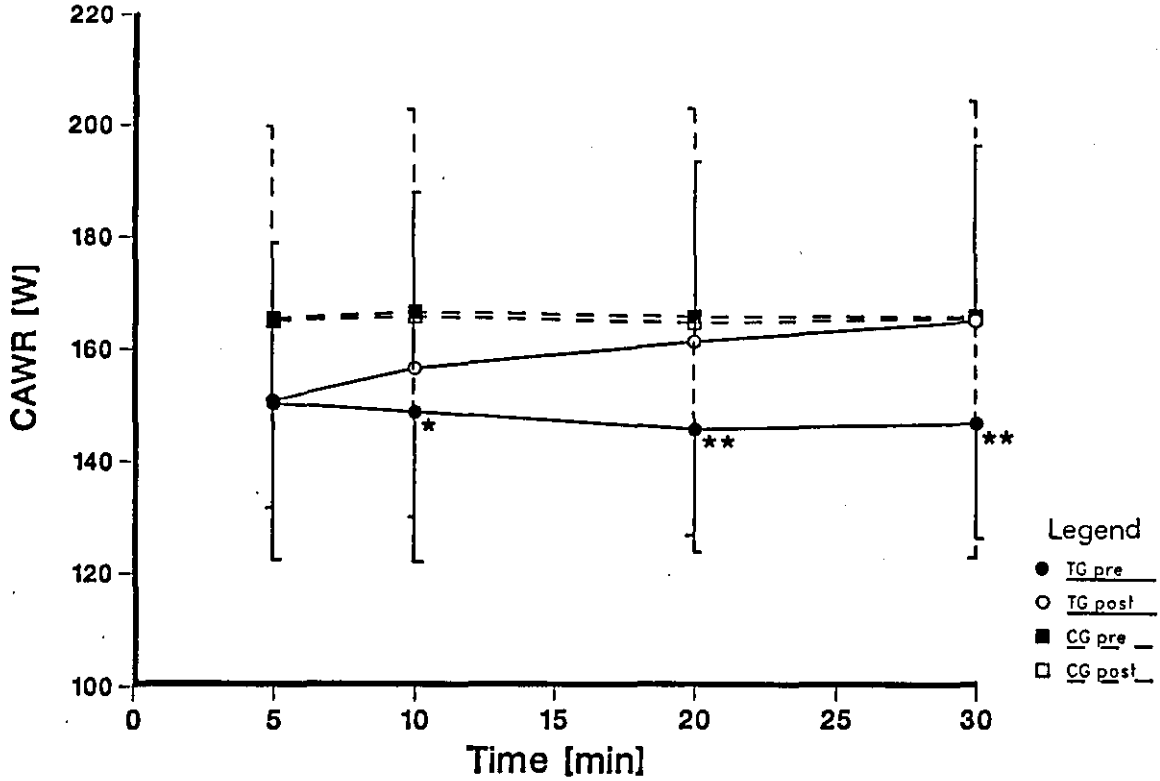


Figure 7.3 Cumulative average work rate during T30min for the training group and the control group pre- and post-training. Significantly different from post-training * p<0.05 ** p<0.01

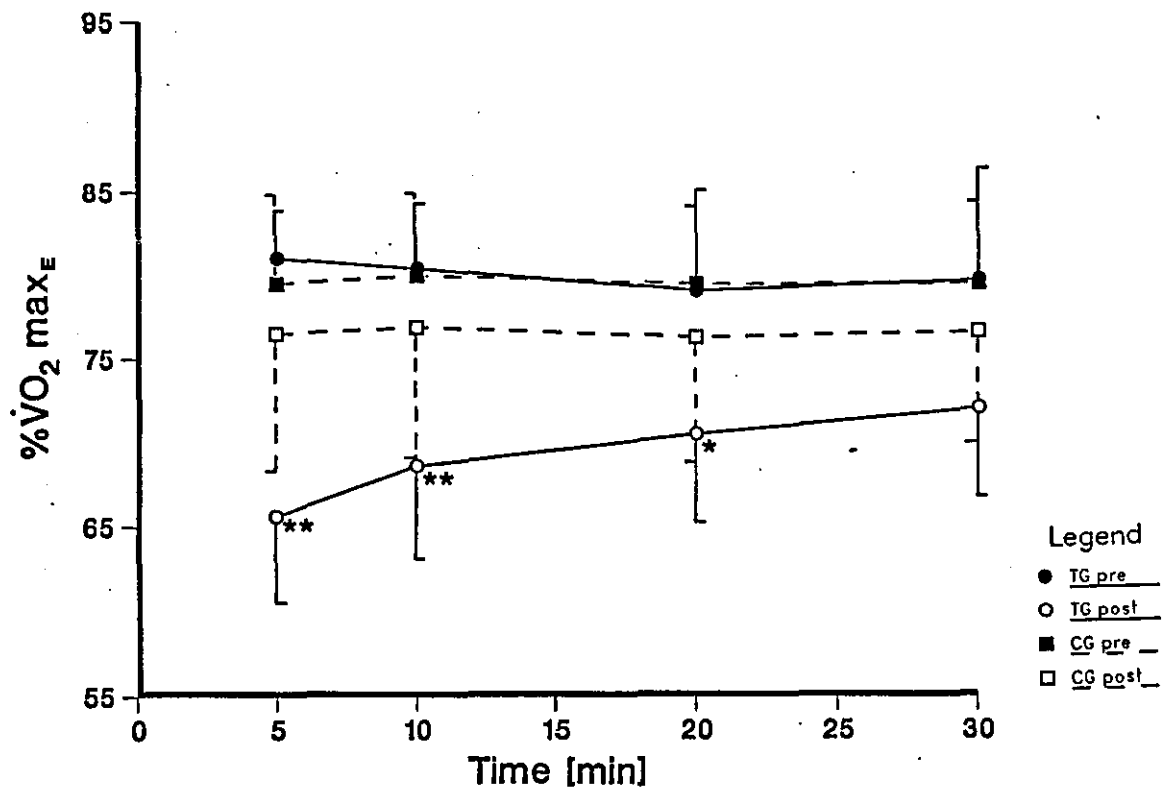


Figure 7.4 Estimated relative exercise intensity during T30min for the training group and the control group pre- and post-training. Significantly different from post-training * p<0.05 ** p<0.01

Table 7.10 Oxygen uptake ($l.min^{-1}$) during T30min for the training group (TG) and the control group (CG) pre- and post-training. Mean ± S.D.

		5 min	10 min	20 min	30 min
TG	pre	2.02±0.42	2.08±0.40	2.14±0.30	2.39±0.30
	post	2.05±0.29	2.25±0.36^{b}	2.42±0.43^{a}	2.62±0.34^{b}
CG	pre	2.08±0.37	2.22±0.45	2.25±0.49	2.57±0.41
	post	2.21±0.36^{a}	2.33±0.53	2.34±0.54	2.49±0.49

Significantly different from pre-training ^{a} $p<0.05$ ^{b} $p<0.01$

Table 7.11 Relative exercise intensity (%$\dot{V}O_{2}max$) during T30min for the training group (TG) and the control group (CG) pre- and post-training. Mean ± S.D.

		5 min	10 min	20 min	30 min
TG	pre	83.5±6.0	86.5±7.8	90.0±10.1	100.7±11.0
	post	69.8±6.4^{b}	76.7±8.4^{a}	82.0±7.5	89.3±7.1
CG	pre	78.2±7.2	83.4±8.3	84.2±7.5	91.9±6.8
	post	78.0±9.8	81.1±9.4	81.2±8.1	90.5±7.6

Significantly different from pre-training ^{a} $p<0.05$ ^{b} $p<0.01$

stage during the test (Table 7.11).

Athough $\dot{V}E$ was slightly higher for the TG during the post-training test, and F_EO_2% was slightly lower, the differences were not statistically significant. A significant difference was found pre- and post-training, however, in $\dot{V}E.\dot{V}O_2^{-1}$, which was lower throughout the test (5 and 20 minutes, $p<0.05$). No significant change was found in either heart rate or R values for the TG (Tables 7.12 and 7.13).

The results for blood lactate concentrations during T30min for the TG and the CG can be seen in Table 7.14 and Figure 7.5. Post-training blood lactate concentration was significantly lower than pre-training for the TG following the initial 5-minute standardised exercise period ($p<0.01$; CG, NS), whilst there was no significant difference pre- and post-training in blood lactate concentration after 30 minutes for either the TG or the CG.

7.3.3 80% $\dot{V}O_2$max endurance test (T80%)

Exercise time to exhaustion on T80% increased significantly by 347% for the TG post-training ($p<0.01$), but there was no significant change in exercise time for the CG (Table 7.18). Post-training $\dot{V}O_2$ for the TG was not significantly different from pre-training at any stage during the test, supporting the results of T30min and the submaximal incremental test where the oxygen cost of exercise at a given work rate remained unchanged post-training (Table 7.19). When $\dot{V}O_2$ was expressed as %$\dot{V}O_2$max, however, the relative exercise intensity of T80% was significantly lower post-training than pre-training for the TG (Table 7.20).

Post-training heart rate, R, $\dot{V}E$, $\dot{V}E.\dot{V}O_2^{-1}$, F_EO_2%, blood lactate concentrations and blood glucose concentrations for the TG were all significantly lower than pre-training values at a) the start of T80% (5 and 10 minute collections), b) when the final minute of the pre-training test was compared with the equivalent time in the post-training test, and c) when the final minutes of the pre-training and post-training tests were compared directly (Tables 7.21 - 7.27; Figures 7.6 - 7.9).

Table 7.12 Heart rate ($b.min^{-1}$) during T30min pre- and post-training for the training group (TG) and the control group (CG). Mean ± S.D.

		5 min	10 min	20 min	30 min
TG	pre	174±12	180±13	186±12	192±8
	post	165±13	175±12	182±10	189±8
CG	pre	170±9	178±9	181±8	189±9
	post	170±9	179±6	184±5	192±6

Table 7.13 Respiratory exchange ratio (R) during T30min for the training group (TG) and the control group (CG) pre- and post-training. Mean ± S.D.

		5 min	10 min	20 min	30 min
TG	pre	1.03±0.07	0.97±0.05	0.95±0.04	0.97±0.06
	post	0.96±0.05	0.95±0.05	0.94±0.04	0.94±0.04
CG	pre	1.01±0.06	0.97±0.07	0.94±0.04	0.94±0.06
	post	0.98±0.05	0.95±0.06	0.91±0.04*	0.93±0.06

Significantly different from pre-training * $p<0.05$ ᵇ $p<0.01$

Table 7.14 Blood lactate concentration (mmol.l^{-1}) during T30min for the training group (TG) and the control group (CG) pre- and post-training. Mean ± S.D.

		5 min	10 min	20 min	30 min
TG	pre	6.68±2.09	8.53±2.84	9.90±2.66	11.98±2.38
	post	4.57±1.88^{b}	6.10±2.85^{a}	8.24±3.40	11.79±3.36
CG	pre	5.33±1.05	7.56±2.50	8.20±3.60	9.21±3.97
	post	5.67±1.65	7.13±2.78	7.74±3.22	9.63±3.00

Significantly different from pre-training ^{a} $p<0.05$ ^{b} $p<0.01$

Table 7.15 Fractional concentration of oxygen in the expired air (%) during T30min for the training group (TG) and the control group (CG) pre- and post-training. Mean ± S.D.

		5 min	10 min	20 min	30 min
TG	pre	16.8±0.7	17.0±0.7	17.2±0.9	17.5±0.7
	post	16.4±0.6	16.8±0.8	17.0±0.7	17.3±0.6
CG	pre	17.4±0.4	17.6±0.5	17.7±0.5	17.8±0.5
	post	17.1±0.4^{b}	17.3±0.4^{b}	17.4±0.4^{b}	17.6±0.4

Significantly different from pre-training ^{b} $p<0.01$

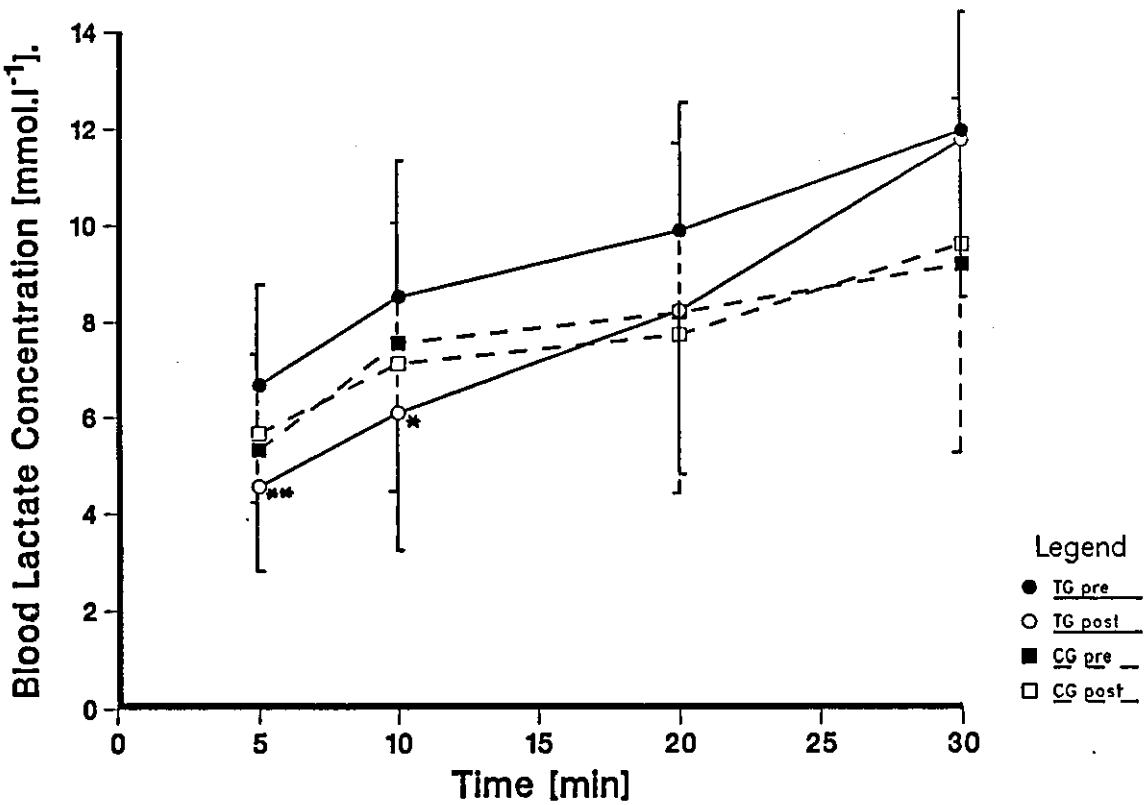


Figure 7.5 Blood lactate concentration during T30min for the training group and the control group pre- and post-training. Significantly different from pre-training * $p<0.05$ ** $p<0.01$.

Table 7.16 Ventilatory equivalent ($\dot{V}E.\dot{V}O_2^{-1}$) during T30min for the training group (TG) and the control group (CG) pre- and post-training. Mean ± S.D.

		5 min	10 min	20 min	30 min
TG	pre	24.7±3.8	25.8±4.5	28.5±4.9	31.5±5.1
	post	22.3±3.0[b]	24.7±5.5[b]	25.9±5.1[b]	28.2±5.2
CG	pre	28.5±3.7	30.0±4.5	31.0±4.8	31.8±5.4
	post	26.2±2.9	27.5±3.2	27.9±3.1	29.8±3.1

Significantly different from pre-training [b] $p<0.01$

Table 7.17 Ventilation ($l.min^{-1}$) during T30min for the training group (TG) and the control group (CG) pre- and post-training. Mean ± S.D.

		5 min	10 min	20 min	30 min
TG	pre	49.7±12.9	55.3±14.6	58.3±15.3	69.1±11.8
	post	46.7±10.8	57.4±19.0	65.0±23.1	75.3±22.0
CG	pre	58.6±9.6	66.7±16.8	69.8±19.0	82.5±21.6
	post	55.0±12.6	63.7±15.7	65.7±17.4	78.1±21.8

Table 7.18 Exercise time to exhaustion (mins) at 80% of pre-training maximum oxygen uptake for the training group and the control group pre- and post-training. Individual data.

SUBJECT		PRE-TRAINING	POST-TRAINING	% DIFFERENCE
TG	1	18.4	60.0	226.7
	2	27.4	64.8	136.4
	3	9.8	65.0	572.2
	4	36.8	135.1	267.6
	5	15.8	132.7	742.3
	6	39.8	90.0	126.4
	7	29.8	136.1	357.1
MEAN		25.4	97.7[b]	346.9
SD		11.2	35.9	231.0
CG	8	49.8	30.1	-39.8
	9	22.6	19.5	-13.6
	10	36.9	55.0	49.0
	11	36.3	47.1	29.0
	12	41.8	61.3	46.7
	13	19.8	29.8	50.6
	14	25.0	19.8	-21.0
	15	13.1	16.5	26.1
MEAN		30.6	34.9**	16.0**
SD		12.4	17.3	35.6

Significantly different from pre-training [b] $p<0.01$

Significantly different from TG ** $p<0.01$

Table 7.19 Oxygen uptake ($l.min^{-1}$) during T80% for the training group and the control group pre- and post-training. Mean ± S.D.

Training group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	6	1.97 ± 0.46	7	2.00 ± 0.43
10	7	2.18 ± 0.45	7	2.09 ± 0.40
20	4	1.96 ± 0.39	7	2.14 ± 0.37
30	3	1.88 ± 0.37	7	2.17 ± 0.39
60	-	-	7	2.24 ± 0.41
120	-	-	3	2.00 ± 0.88
Exh 1	7	2.32 ± 0.46	7	2.17 ± 0.37
Exh 2			7	2.29 ± 0.37

Control group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	8	2.13 ± 0.36	7	2.24 ± 0.33
10	8	2.21 ± 0.36	8	2.33 ± 0.32
20	7	2.34 ± 0.41	7	2.41 ± 0.36
30	4	2.59 ± 0.07	5	2.46 ± 0.38
Exh	8	2.45 ± 0.43	8	2.46 ± 0.38

Table 7.20 Relative exercise intensity (%$\dot{V}O_{2}max$) during T80% for the training group and the control group pre- and post-training. Mean ± S.D.

Training group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	6	83.7 ± 8.3	7	67.7 ± 7.4[b]
10	7	90.2 ± 7.1	7	70.9 ± 8.2[b]
20	4	94.0 ± 6.2	7	72.7 ± 7.2[b]
30	3	97.1 ± 8.5	7	73.8 ± 7.8[b]
60	-	-	7	76.1 ± 8.2
120	-	-	3	69.2 ± 3.0
Exh 1	7	96.1 ± 6.4	7	73.3 ± 7.4[b]
Exh 2			7	77.0 ± 7.5[b]

Control group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	8	80.2 ± 7.3	7	78.9 ± 5.9
10	8	83.2 ± 7.5	8	82.2 ± 7.2
20	7	86.9 ± 6.1	7	83.7 ± 8.5
30	4	86.4 ± 2.7	5	81.0 ± 6.0
Exh	8	92.2 ± 8.0	8	86.3 ± 8.8

Significantly different from pre-training [b] $p<0.01$

Table 7.21 Heart rate ($b.min^{-1}$) during T80% for the training group and the control group pre- and post-training. Mean ± S.D.

Training group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	6	175 ± 12	7	161 ± 15*
10	7	183 ± 11	7	167 ± 14*
20	4	186 ± 13	7	172 ± 13
30	3	184 ± 11	7	174 ± 13
60	-	-	7	175 ± 13
120	-	-	3	171 ± 4
Exh 1	7	187 ± 9	7	173 ± 13*
Exh 2			7	177 ± 12*

Control group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	8	173 ± 8	7	172 ± 8
10	8	180 ± 8	8	180 ± 9
20	7	187 ± 7	7	184 ± 8
30	4	187 ± 4	5	186 ± 3
Exh	8	190 ± 6	8	188 ± 6

Significantly different from pre-training * $p<0.05$

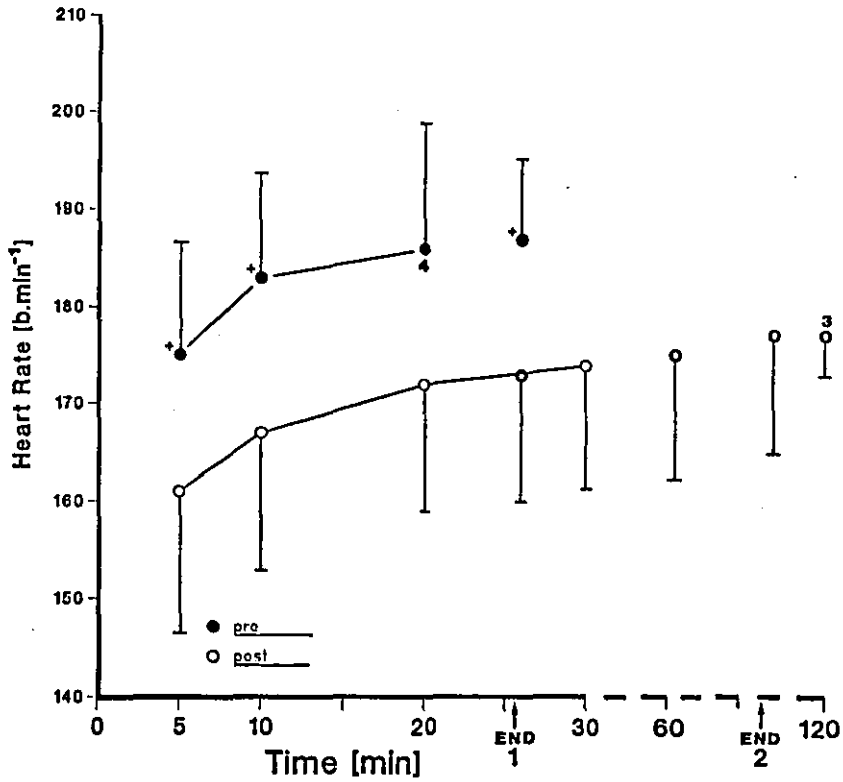


Figure 7.6 Heart rate during T80% for the training group pre- and post-training. n=7 unless otherwise stated. Significantly different from post-training * p<0.05 ** p<0.01.

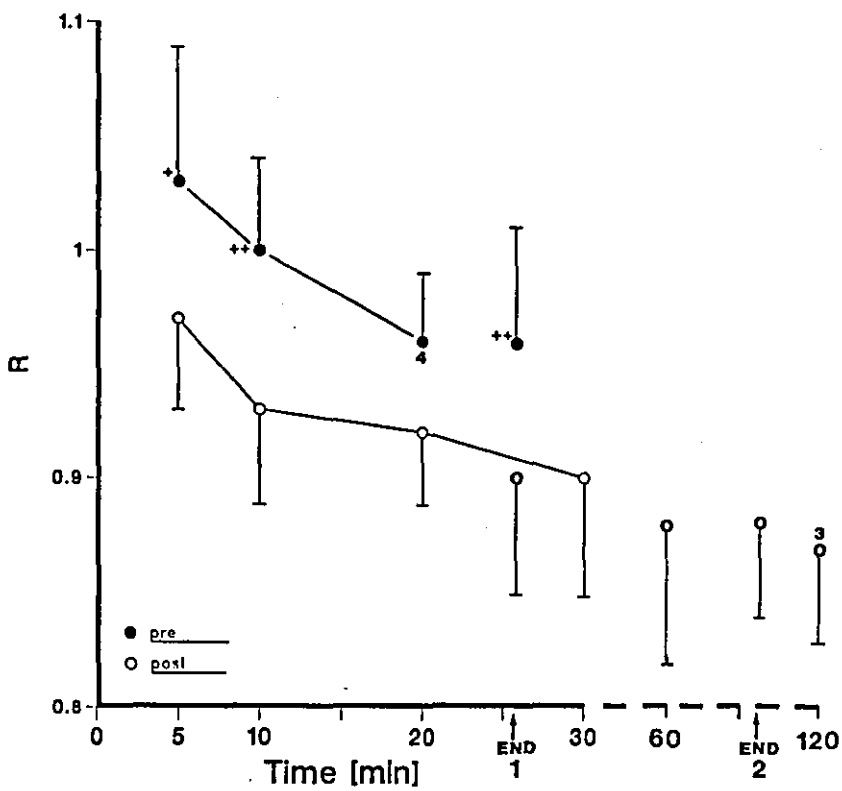


Figure 7.7 Respiratory exchange ratio during T80% for the training group pre- and post-training. n=7 unless otherwise stated. Significantly different from post-training * p<0.05 ** p<0.01.

Table 7.22 Respiratory exchange ratio (R) during T80% for the training group and the control group pre- and post-training. Mean ± S.D.

Training group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	6	1.03 ± 0.06	7	0.97 ± 0.04[a]
10	7	1.00 ± 0.04	7	0.93 ± 0.04[b]
20	4	0.96 ± 0.03	7	0.92 ± 0.03
30	3	0.95 ± 0.04	7	0.90 ± 0.05
60	-	-	7	0.88 ± 0.06
120	-	-	3	0.87 ± 0.04
Exh 1	7	0.96 ± 0.05	7	0.90 ± 0.05[b]
Exh 2			7	0.88 ± 0.04[b]

Control group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	8	1.03 ± 0.04	7	0.99 ± 0.04[a]
10	8	0.99 ± 0.03	8	0.94 ± 0.02[b]
20	7	0.97 ± 0.03	7	0.92 ± 0.01[b]
30	4	0.96 ± 0.04	5	0.91 ± 0.02
Exh	8	0.95 ± 0.05	8	0.91 ± 0.02

Significantly different from pre-training [a] $p<0.05$ [b] $p<0.01$

Table 7.23 Ventilation ($l.min^{-1}$) during T80% for the training group and the control group pre- and post-training. Mean ± S.D.

Training group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	6	51.1 ± 11.6	7	44.2 ± 11.0[b]
10	7	60.8 ± 14.6	7	49.9 ± 10.9[b]
20	4	59.1 ± 16.7	7	50.9 ± 13.6[b]
30	3	53.1 ± 3.0	7	51.9 ± 15.2
60	-	-	7	55.7 ± 19.4
120	-	-	3	44.0 ± 3.7
Exh 1	7	71.2 ± 19.4	7	50.2 ± 15.6[b]
Exh 2			7	56.7 ± 18.5[a]

Control group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	8	58.3 ± 7.5	7	58.3 ± 6.2
10	8	65.3 ± 10.3	8	62.6 ± 9.4
20	7	71.9 ± 13.5	7	66.5 ± 11.9[a]
30	4	76.2 ± 6.7	5	64.3 ± 5.1
Exh	8	78.9 ± 15.1	8	71.4 ± 11.7[a]

Significantly different from pre-training [a] $p<0.05$ [b] $p<0.01$

Table 7.24 Ventilatory equivalent ($\dot{V}E.\dot{V}O_2^{-1}$) during T80% for the training group and the control group pre- and post-training. Mean ± S.D.

Training group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	6	26.1 ± 2.3	7	22.0 ± 1.8[b]
10	7	27.5 ± 3.4	7	22.4 ± 2.2[b]
20	4	30.3 ± 5.0	7	23.6 ± 3.3[b]
30	3	28.8 ± 4.9	7	23.7 ± 3.7
60	-	-	7	24.8 ± 5.4
120	-	-	3	22.3 ± 2.3
Exh 1	7	30.1 ± 4.4	7	23.4 ± 3.7[b]
Exh 2			7	24.9 ± 5.6[b]

Control group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	8	27.7 ± 2.9	7	26.4 ± 3.3
10	8	29.8 ± 3.1	8	27.2 ± 4.2[b]
20	7	31.0 ± 4.1	7	27.8 ± 4.9[b]
30	4	29.5 ± 2.4	5	25.4 ± 1.4
Exh	8	32.3 ± 3.4	8	29.5 ± 4.3[b]

Significantly different from pre-training [b] $p<0.01$

Table 7.25 Fractional concentration of oxygen in the expired air (F_EO_2%) during T80% for the training group and the control group pre- and post-training. Mean ± S.D.

Training group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	6	17.1 ± 0.4	7	16.4 ± 0.4[b]
10	7	17.2 ± 0.5	7	16.5 ± 0.5[b]
20	4	17.6 ± 0.6	7	16.7 ± 0.6[b]
30	3	17.4 ± 0.6	7	16.7 ± 0.6
60	-	-	7	16.9 ± 0.8
120	-	-	3	16.5 ± 0.5
Exh 1	7	17.6 ± 0.5	7	16.6 ± 0.8[b]
Exh 2			7	16.9 ± 0.8[b]

Control group

Time (min)	n	PRE TRAINING	n	POST TRAINING
5	8	17.3 ± 0.3	7	17.1 ± 0.4
10	8	17.6 ± 0.4	8	17.3 ± 0.6
20	7	17.7 ± 0.4	7	17.3 ± 0.6[a]
30	4	17.6 ± 0.3	5	17.1 ± 0.2
Exh	8	17.8 ± 0.4	8	17.5 ± 0.5[a]

Significantly different from pre-training [a] $p<0.05$ [b] $p<0.01$

Table 7.26 Blood lactate concentration (mmol.l^{-1}) during T80% for the training group and the control group pre- and post-training. Mean ± S.D.

Training group

Time (min)	n	PRE TRAINING	n	POST TRAINING
REST	7	0.50 ± 0.22	6	0.66 ± 0.41
5	6	6.55 ± 0.98	7	4.26 ± 1.32^{b}
10	7	8.93 ± 1.16	7	5.00 ± 1.52^{b}
20	4	9.67 ± 1.05	7	5.39 ± 1.99^{b}
30	3	9.78 ± 0.21	7	5.32 ± 2.20^{a}
60	-	-	7	5.81 ± 3.23
120	-	-	3	6.89 ± 1.51
Exh 1	7	11.20 ± 1.99	7	5.36 ± 2.14^{b}
Exh 2			7	7.32 ± 3.03^{b}

Control group

Time (min)	n	PRE TRAINING	n	POST TRAINING
Rest	8	0.54 ± 0.24	8	0.40 ± 0.24
5	8	6.16 ± 1.37	7	5.36 ± 1.07^{a}
10	8	7.09 ± 1.97	8	6.75 ± 1.76^{b}
20	7	9.36 ± 2.33	7	7.36 ± 2.29^{a}
30	4	8.01 ± 2.38	5	6.19 ± 0.97
Exh	8	10.12 ± 2.85	8	7.83 ± 2.56^{a}

Significantly different from pre-training ^{a} $p<0.05$ ^{b} $p<0.01$

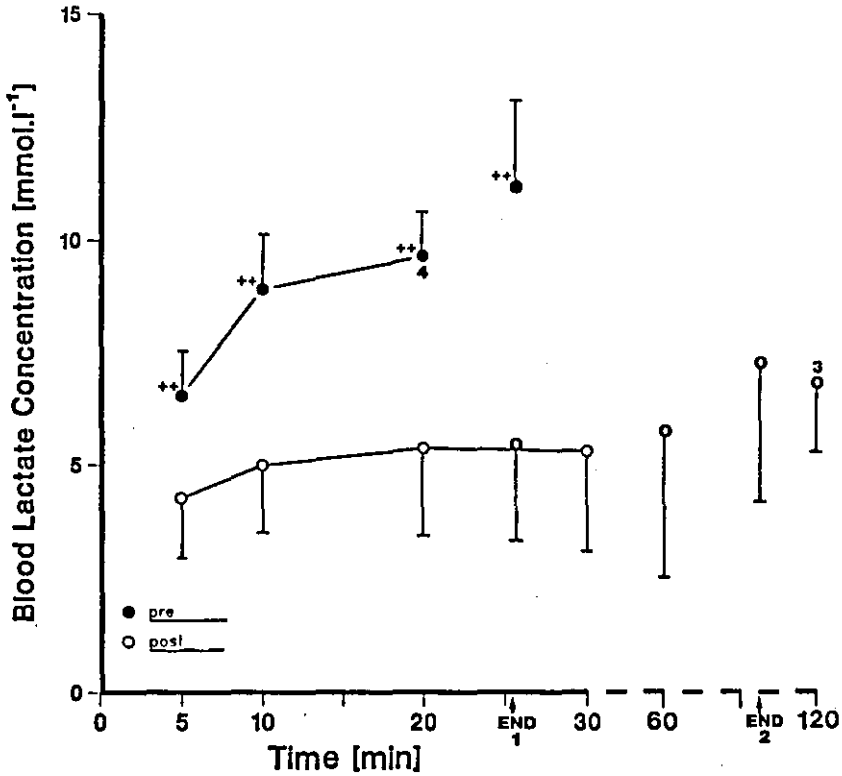


Figure 7.8 Blood lactate concentrations during T80% for the training group pre- and post-training. n=7 unless otherwise stated. Significantly different from post-training * p<0.05 ** p<0.01.

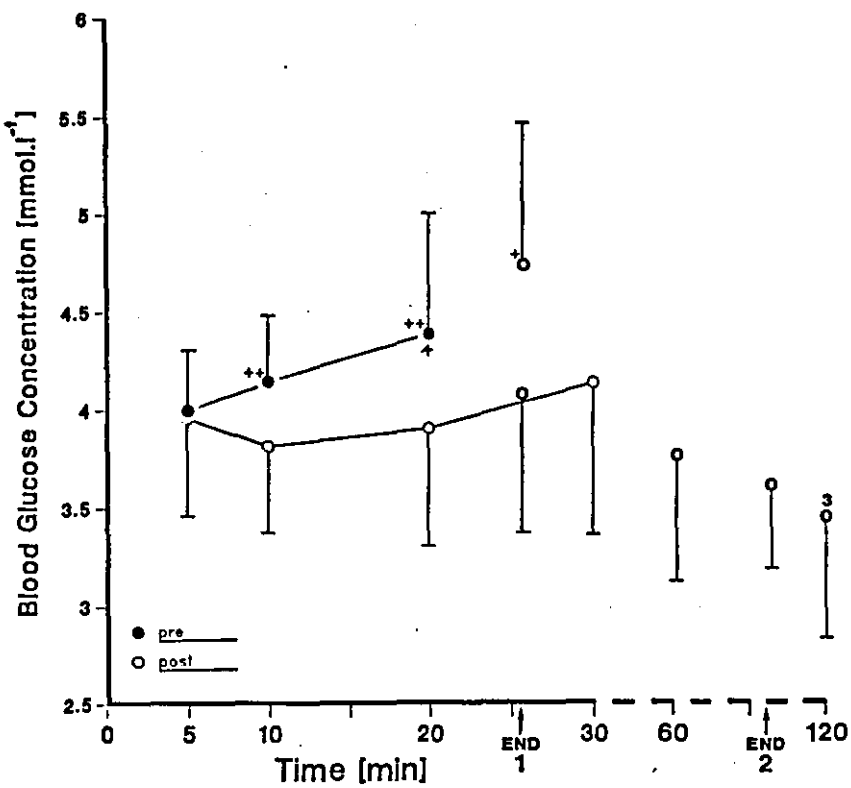


Figure 7.9 Blood glucose concentrations during T80% for the training group pre- and post-training. n=7 unless otherwise stated. Significantly different from post-training * p<0.05 ** p<0.01.

Table 7.27 Blood glucose concentration (mmol.l^{-1}) during T80% for the training group and the control group pre- and post-training. Mean ± S.D.

Training group

Time (min)	n	PRE TRAINING	n	POST TRAINING
REST	7	4.18 ± 0.28	6	4.02 ± 0.32
5	6	4.00 ± 0.31	7	3.96 ± 0.52
10	7	4.15 ± 0.33	7	3.82 ± 0.43[b]
20	4	4.39 ± 0.62	7	3.91 ± 0.59[b]
30	3	4.35 ± 0.40	7	4.14 ± 0.78[a]
60	-	-	7	3.75 ± 0.63
120	-	-	3	3.57 ± 0.59
Exh 1	7	4.75 ± 0.74	7	4.08 ± 0.74[a]
Exh 2			7	3.46 ± 0.42[b]

Control group

Time (min)	n	PRE TRAINING	n	POST TRAINING
Rest	8	4.18 ± 0.53	8	4.32 ± 0.36
5	8	4.16 ± 0.30	7	4.15 ± 0.46
10	8	4.05 ± 0.55	8	4.03 ± 0.52
20	7	4.20 ± 0.78	7	4.07 ± 0.81
30	4	4.18 ± 0.64	5	3.86 ± 0.68
Exh	8	4.45 ± 0.95	8	4.24 ± 0.94

Significantly different from pre-training [a] $p<0.05$ [b] $p<0.01$

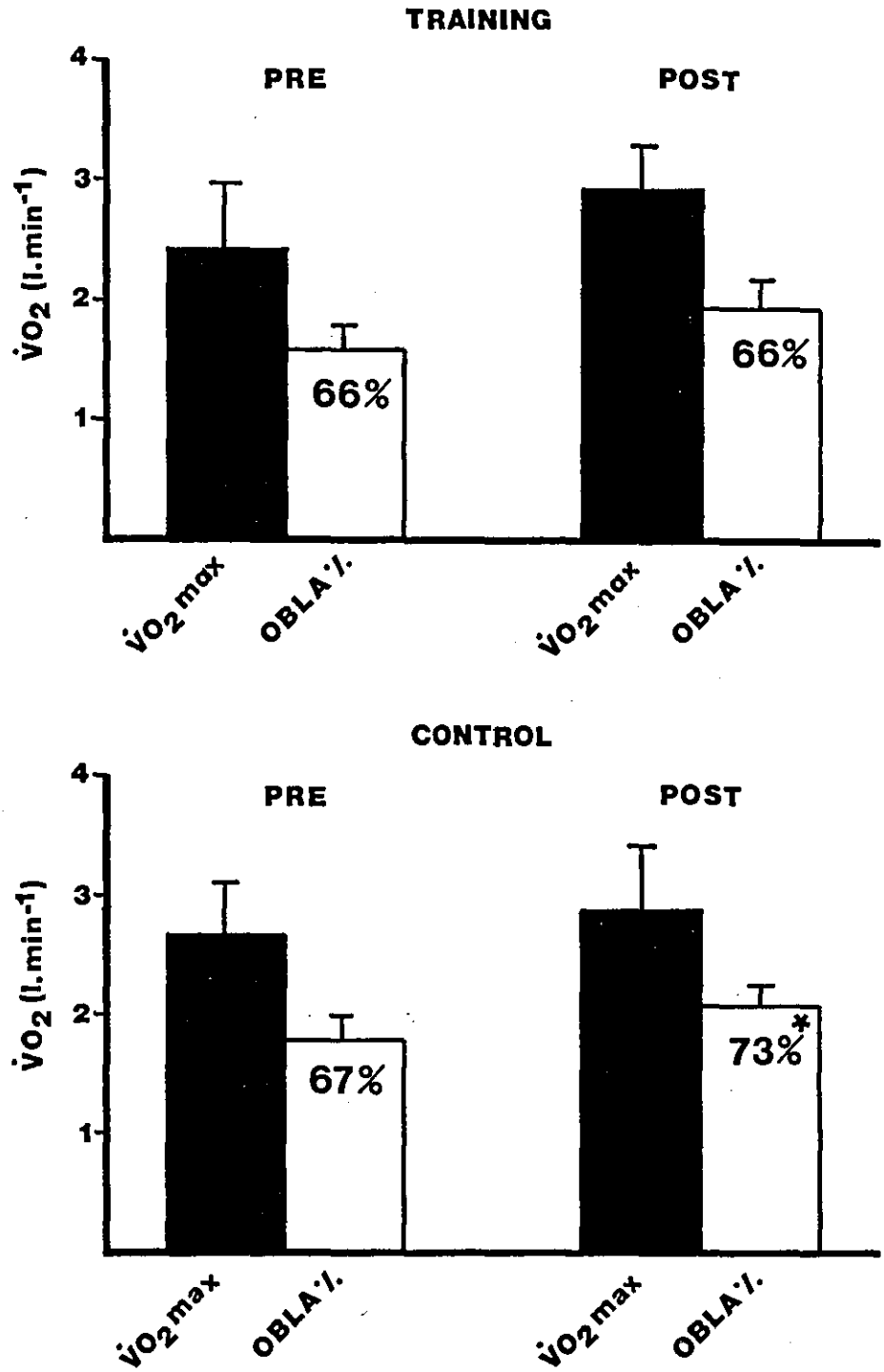


Figure 7.10 OBLA (%) in relation to maximum oxygen uptake for the training group and the control group pre- and post-training.

Significantly different from training group * $p<0.05$

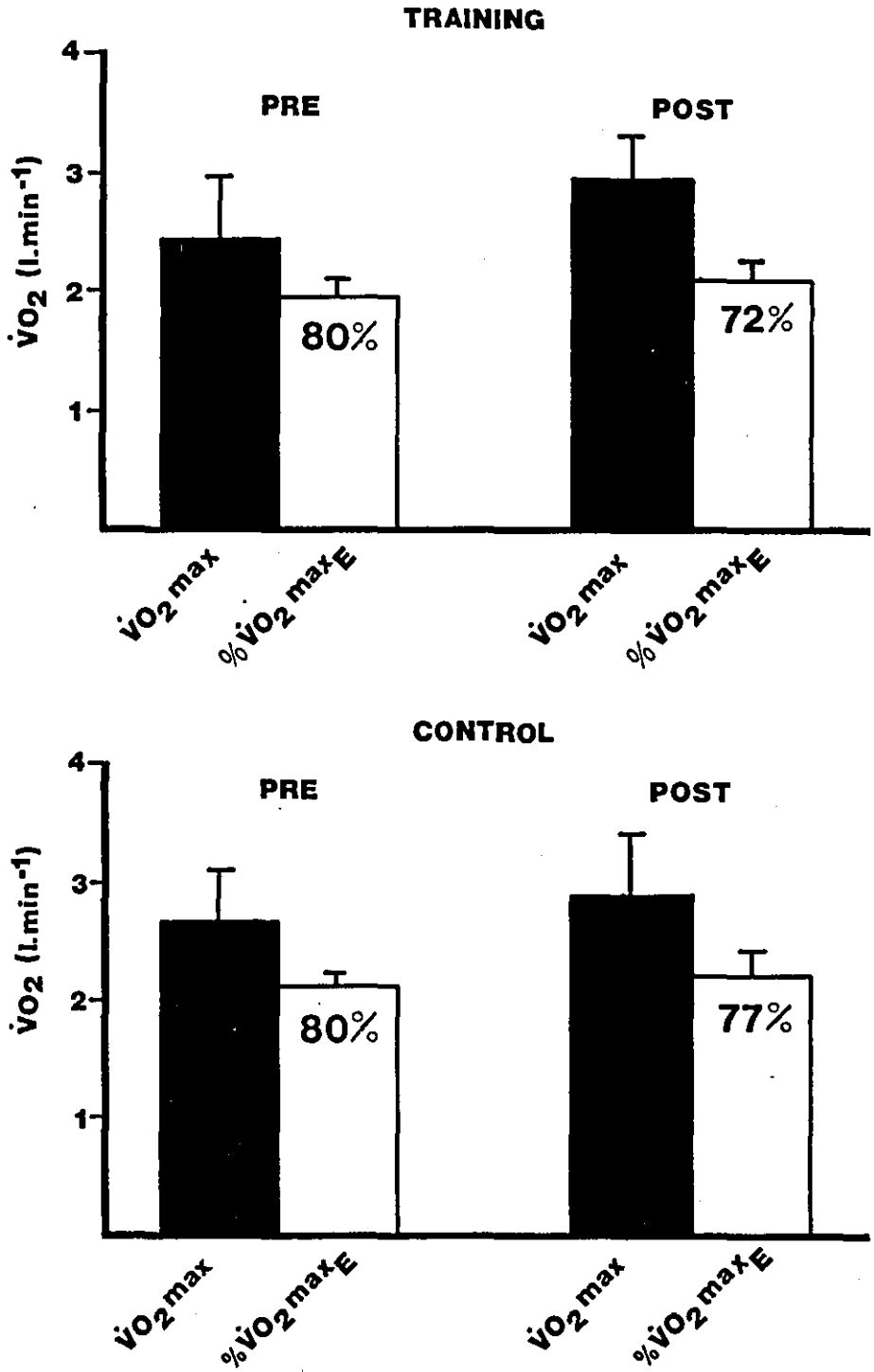


Figure 7.11 Estimated relative exercise intensity during T30min in relation to maximum oxygen uptake for the training group and the control group pre- and post-training.

The results of T80% for the CG revealed no significant difference pre- and post-training in $\dot{V}O_2$, $\%\dot{V}O_2max$, heart rate or blood glucose concentration throughout the test. Post-training $\dot{V}E$, $\dot{V}E.\dot{V}O_2^{-1}$ and $F_EO_2\%$ were all significantly lower than pre-training during both the middle stages of the test and the final minute, whilst the R values were significantly lower at comparable exercise times but not significantly different at exhaustion. The blood lactate concentrations for the CG were significantly lower throughout the test post-training compared to pre-training ($p<0.05$).

There were strong correlations for the group as a whole (n=15) between $\dot{V}O_2max$ and $OBLA_w$ (pre- r=0.79; post- r=0.77), $\dot{V}O_2max$ and CAWR (pre- r=0.84; post- r=0.83, Figure 7.12), and $OBLA_w$ and CAWR (pre- r=0.89; post- r=0.88, Figure 7.13), revealing that for this group of subjects $OBLA_w$ was a better predictor of CAWR than $\dot{V}O_2max$.

Only poor correlations were found between $\dot{V}O_2max$ and $\%\dot{V}O_2max_E$ for the group as a whole (pre- r=-0.21; post- r=0.12). Results for the TG pre-training revealed an inverse relationship of r=-0.84 between these two variables, whilst post training this relationship was positive (r=0.72).

In contrast to the results reported in the previous study only poor correlations were found between $\%\dot{V}O_2max_E$ and OBLA% for the group as a whole pre- (r=0.24) and post- (r=0.42) training. Strong correlations were found pre-training, however, between OBLA% and T80% time (r=0.68) and blood lactate concentration at 5 minutes and T80% time (r=-0.63).

The percentage change in $\dot{V}O_2max$ for the TG was inversely related to initial $\dot{V}O_2max$ values (r=-0.87) indicating that those subjects with the lowest pre-training VO_2max values showed the greatest percentage change.

Although a strong correlation was found both pre- and post-training between $OBLA_w$ and CAWR, only a poor correlation was found between percentage change in CAWR and percentage change in $OBLA_w$ (r=0.29). A stronger correlation was found for the relationship between percentage change in CAWR and percentage change in $\dot{V}O_2max$ for

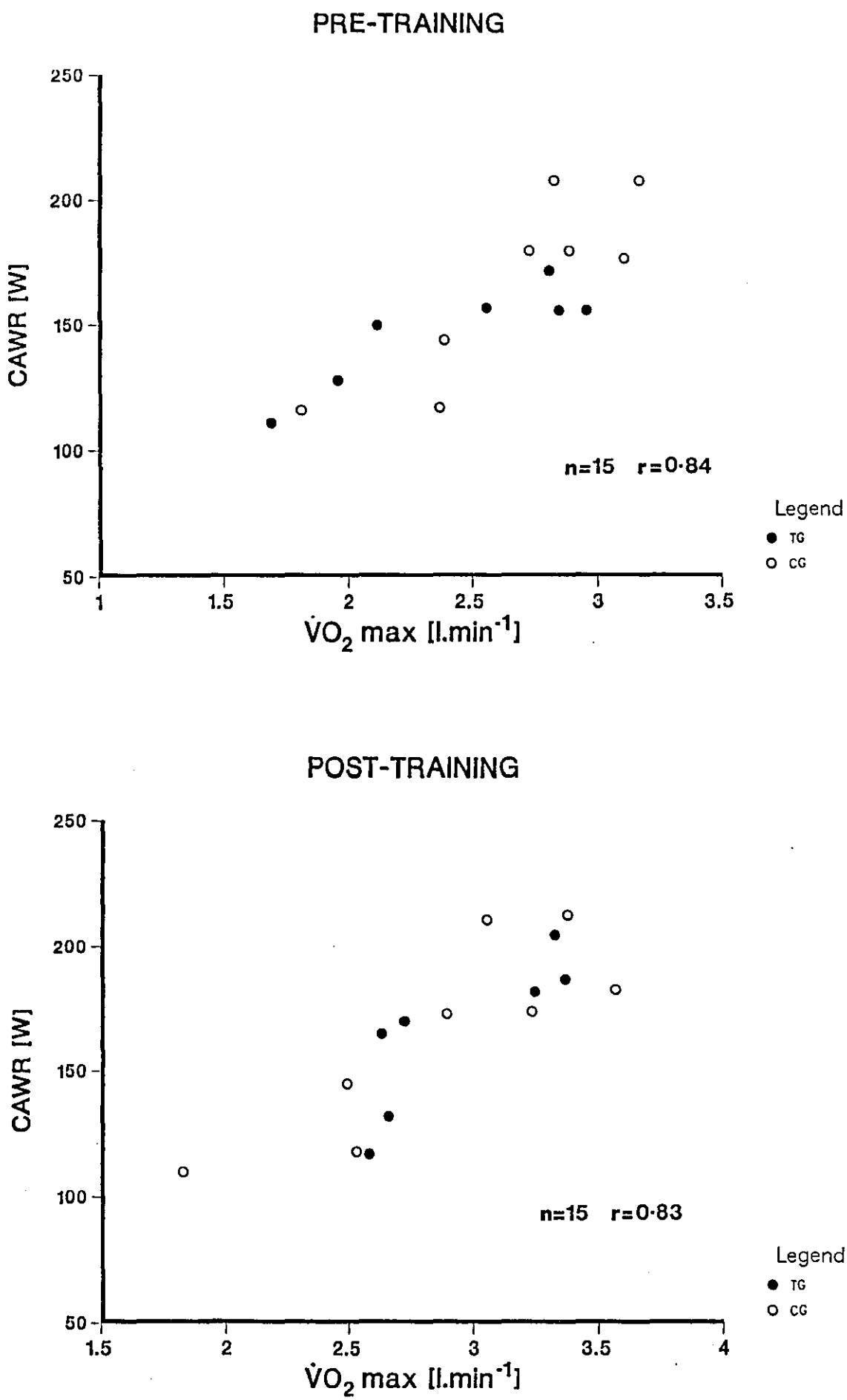


Figure 7.12 Relationship between maximum oxygen uptake and cumulative average work rate pre- and post-training.

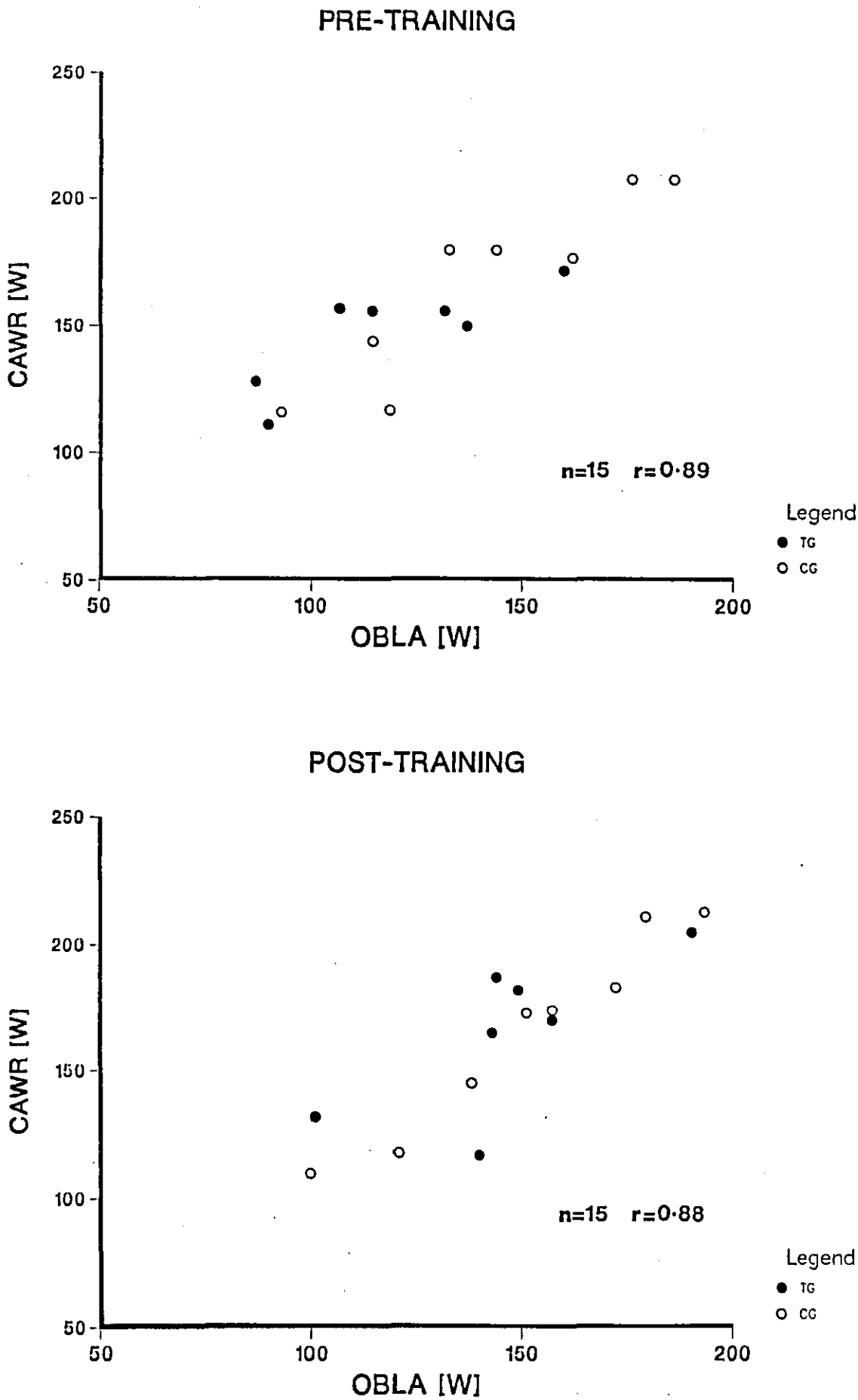


Figure 7.13 Relationship between OBLA (W) and cumulative average work rate pre- and post-training.

the CG (r=0.51), whilst a negative correlation was found between these two variables for the TG (r=-0.63).

Only a poor relationship was seen between the percentage change in $\%\dot{V}O_{2max_E}$ and percentage change in OBLA% (r=0.39). The absolute change in $\%\dot{V}O_{2max_E}$, however, was inversely related to the absolute change in $\dot{V}O_{2max}$ for both the TG (r=-0.77) and the CG (r=-0.84), implying that the greater the change in post-training $\dot{V}O_{2max}$ the lower the $\%\dot{V}O_{2max_E}$ the subject could tolerate during T30min.

The percentage change in T80% time was significantly related to the change in blood lactate concentration at 16 minutes during the submaximal incremental test (r=0.70, $p<0.01$), the change in the blood lactate concentration at 5 minutes during T80% (r=0.58, $p<0.05$), and the percentage change in $OBLA_W$ (r=0.57, $p<0.05$). In addition, a correlation coefficient of r=-0.88 ($p<0.01$) was found between post-training T80% time and T80% work rate expressed as a percentage of the post-training $\dot{V}O_{2max}$, i.e. those individuals whose work rate represented a low $\%\dot{V}O_{2max}$ were able to exercise for longer than those whose work rate represented a high $\%\dot{V}O_{2max}$ (Figure 7.14).

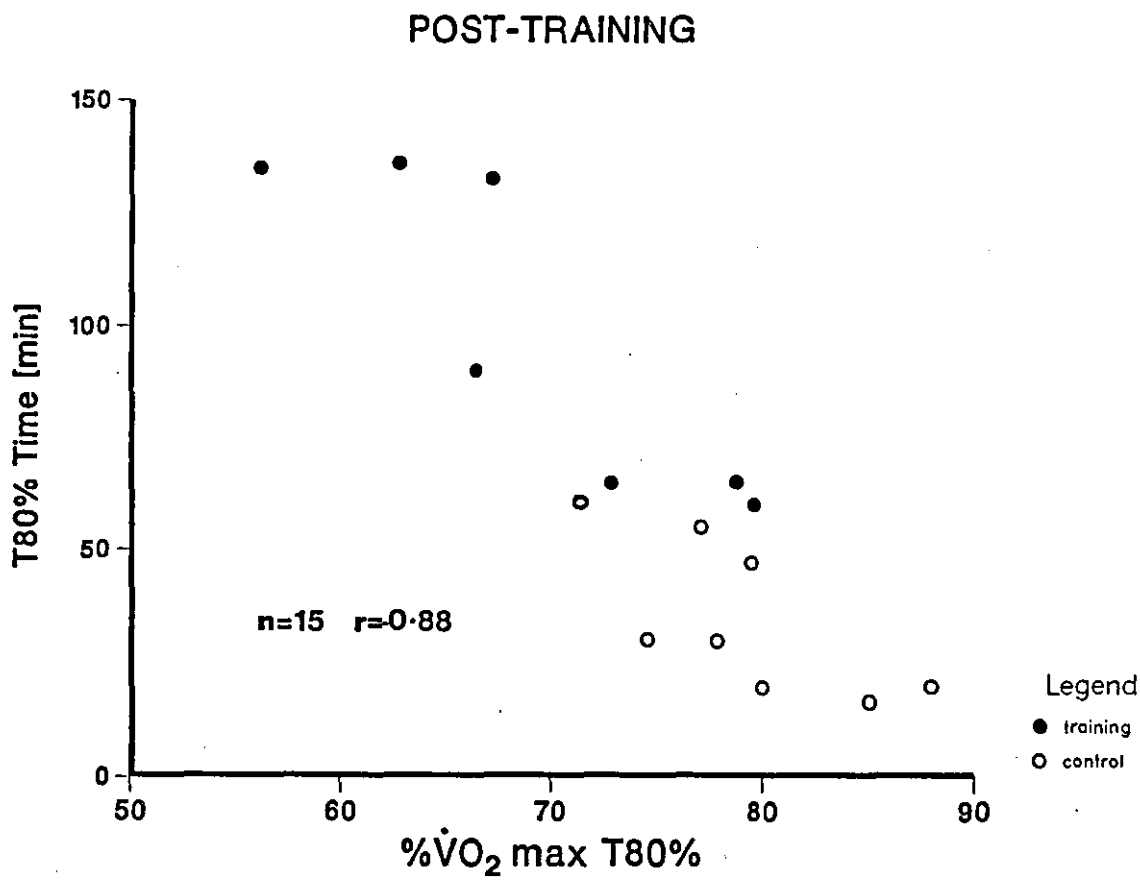


Figure 7.14 Relationship between post-training T80% endurance time and test work rate expressed relative to the post-training maximum oxygen uptake.

7.4 DISCUSSION

The results of this study revealed that after six weeks of endurance training $\dot{V}O_2max$ increased by 25%, with a range from 6%- 53%. The change in mean $\dot{V}O_2max$ was slightly higher than the results reported in the literature for studies where University and College students have been used as subjects. Pechar and coworkers, reported an 8% increase in $\dot{V}O_2max$ for 60 male PE students who trained on a cycle ergometer 3 times a week for 8 weeks at 85% of maximum heart rate (Pechar et al., 1974). Daniels and coworkers, found an increase in $\dot{V}O_2max$ of 9% for 12 previously untrained subjects who ran 20-30km a week for 8 weeks (Daniels et al., 1978b). Similar improvements in $\dot{V}O_2max$ were shown by Bland (1982) who reported an increase of 7% for 8 physically active students following 6 weeks training, 3 times a week at 70% $\dot{V}O_2max$. Whilst Williams and Nute (1986) recorded a 5% increase for 10 female games players following 6 weeks of training at 90% $\dot{V}O_2max$.

The large change in mean $\dot{V}O_2max$ for the TG compared with the studies cited above is attributable to the influence of 2 subjects within the group, who were inactive prior to the study due to medical reasons. These two subjects improved their $\dot{V}O_2max$ values post-training by 36% and 53%. The magnitude of these changes in $\dot{V}O_2max$ are in keeping with reports in the literature where previously inactive subjects (both male and female) have undergone a standardised training programme (Cunningham and Hill, 1975; Hickson et al., 1977; Lortie et al., 1984).

The change in $\dot{V}O_2max$ for the TG was also strongly influenced by the subjects' pre-training values, with a strong correlation of $r=0.87$ ($p<0.05$) between percentage change and the initial $\dot{V}O_2max$. This supports the notion that the percentage improvement in physiological parameters is related to one's initial degree of fitness (Muller, 1962), and confirms the findings of Pollock (1973) who revealed that studies that show the largest change in $\dot{V}O_2max$ commonly involved subjects with very low initial $\dot{V}O_2max$ values.

The significant change in $\dot{V}O_2max$ of the CG (7%) may be attributed

to an increase in their normal physical activity patterns during the training study period. Six out of the 8 subjects in the CG were PE students, who, on returning to University after a 5 weeks vacation, were engaged in a physically demanding course. Since the TG and the CG were from the same sample population it may be proposed, therefore, that not all of the change in $\dot{V}O_2max$ for the TG can be attributed to training on the cycle ergometer, normal physical activity patterns may also have contributed to the increase. It could be assumed, however, that the increase in $\dot{V}O_2max$ of the TG above that of the CG may be attributed to the training programme itself.

Maximum heart rate during the $\dot{V}O_2max$ test remained unchanged for both the TG and the CG. These findings are in agreement with reports by Ekblom and coworkers (1968), Smith and Stransky (1976), Pederson and Jorgensen (1978), Wilmore, (1980) and Hardman (1984), who all reported an unchanged maximum heart rate following training programmes on a cycle ergometer ranging in length from 6-20 weeks.

The significant increase in $\dot{V}O_2max$ for the TG was accompanied by a significant increase in maximum ventilation ($p<0.05$; CG, NS). Several other studies reported in the literature have published similar findings following both treadmill and cycle ergometer training (Kearney et al., 1976; Davis et al., 1979; Yoshida et al., 1982; Hardman, 1984). Since ventilation is not normally a limiting factor in maximal exercise it may be suggested that the increase shown by the TG subserved the increased $\dot{V}O_2$ and $\dot{V}CO_2$.

The 24% increase in $\dot{V}O_2max$ for the TG was also accompanied by a 20% increase in the work rate required to elicit $\dot{V}O_2max$. Changes of a similar nature (18-28%) have also been reported by other workers (Davis et al., 1979; Bland, 1982). Since there is a linear relationship between $\dot{V}O_2$ and work rate it follows that a higher work rate will be required to elicit a higher $\dot{V}O_2max$ value.

The oxygen cost of exercise at submaximal work rates remained unchanged by 6 weeks of training. This is in agreement with the findings of Davies and Knibbs (1971), Flint and coworkers (1974), and Smith and Stransky (1976), but contrary to the results reported by Ekblom and coworkers (1968) and Hardman (1984) who reported a decrease

in $\dot{V}O_2$ at a given submaximal work rate. It is generally believed, however, that the oxygen cost of exercise does not alter with training unless the training improves the efficiency of the movement tested (Cotes and Mead, 1959). Changes in the relative exercise intensity of a given work rate in these circumstances must, therefore, be due to a change in $\dot{V}O_2max$.

Despite an unchanged $\dot{V}O_2$ for the TG, $\dot{V}CO_2$ was significantly lower at the 3rd and 4th work rates so that the R values were also significantly reduced at these two work rates. This would suggest that there was an increased contribution from fat to energy metabolism, indirectly indicating an increase in the muscle oxidative capacity (Henriksson, 1977). In addition, the reduced $\dot{V}CO_2$ and R values could also result from a reduced glycolytic rate. This would be accompanied by a reduced hydrogen ion concentration and, consequently, a reduction in the evolution of CO_2 due to buffering by the bicarbonate system.

Large decreases were seen for the TG during submaximal exercise post-training in $\dot{V}E$, $\dot{V}E.\dot{V}O_2^{-1}$ and $F_EO_2\%$. Therefore, in spite of the unchanged oxygen demand, ventilation was greatly reduced. This decrease in ventilation may be a direct consequence of the decrease in blood lactate concentration. Since the ventilatory stimulus during exercise is closely tied to pCO_2 and the degree of metabolic acidosis (Girondola and Katch, 1976), the reduced blood lactate concentrations post-training and decreased $\dot{V}CO_2$ could account for the reduced ventilation. The decrease in $\dot{V}E$ may also account for the improved $F_EO_2\%$ since it permits a greater percentage extraction.

One of the most consistent findings reported in the literature is the decrease in submaximal heart rate following endurance training (Flint et al, 1974). The results of this study revealed a 10-14% decrease in the post-training heart rates during the submaximal incremental test for the TG, whilst there was no change in the CG heart rate. The magnitude of the change for the TG is consistent with some reports in the literature (Ekblom, 1970; Smith and Stransky, 1976; Davis et al., 1979; and Yoshida et al., 1982), but slightly lower than others (17% - Ekblom et al., 1968; 25% - Hickson et al., 1981). The higher percentage changes reported by these latter studies may be attributed to the relatively inactive subject groups used.

Although both studies were also longer in duration than the present study (22 weeks and 9 weeks respectively) this may not have been an important influencing factor in the magnitude of the percentage change, since several studies have reported major adaptations in heart rate after only 2-3 weeks of training (Hickson et al., 1981; Hardman, 1984). An explanation of the exact cause of the decrease in heart rate at submaximal work rates cannot be given. A decrease in the peripheral afferent nervous input and the decreased sympathetic stimulation may lead to a decrease in heart rate. In addition, it has been suggested that an improvement in venous return, an increased blood volume combined with the training-induced bradycardia may all contribute to an increased stroke volume (SV) post-training. This increased SV, in the absence of a increase in cardiac output, results in a decrease in heart rate (Astrand and Rodahl, 1977).

Blood lactate concentration was significantly reduced for the TG at work rates 2, 3 and 4 during the post-training submaximal incremental test ($p<0.01$). This is in agreement with reports in the literature where endurance training has resulted in a decrease in blood lactate concentration at a given submaximal work rate and has been attributed to an increased oxidative capacity of the skeletal muscle due to an increased concentration of mitochondria (Holloszy, 1971). This results in the ability to degrade more pyruvate oxidatively, converting less to lactate (Sjödin et al., 1982a); the ability to spare glycogen, i.e. increase the use of fat as a metabolic substrate and thus inhibit glycolysis (Karlsson et al., 1974); and the ability of other organs and tissues to take up and oxidise lactate (Hurley et al., 1984).

As a consequence of the reduced blood lactate concentration of the TG post-training, a significantly higher work rate was achieved before OBLA was attained. Findings of a similar nature have been reported by other workers who have reported significant increases in the work rate corresponding to a reference lactate or threshold following endurance training (Williams et al., 1967; Davis et al., 1979; Sjodin et al., 1982a; and Yoshida et al., 1982). Despite only a small mean increase in blood lactate concentration at a given absolute work rate post-training for the CG (NS), the work rate required to elicit $OBLA_w$ was significantly higher post-training ($p<0.05$). This is

not a surprising finding since the CG also had a significantly higher $\dot{V}O_2max$ post-training.

Despite an increase in the absolute work rate at which OBLA occurred for the TG, there was no change in the $\%\dot{V}O_2max$ at which it occurred (Figure 7.10). This is in contrast to reports in the literature which have shown a decrease in blood lactate concentration at both absolute and relative work rates following endurance training (Karlsson et al., 1972; Hurley et al., 1984; Henritze et al., 1985), but in agreement with others (Saltin et al., 1969; Yoshida et al., 1982). Both of these latter studies reported that the $\%\dot{V}O_2max$ at which the Anaerobic Threshold (AT) occurred was unchanged post-training, despite changes in other variables such as $\dot{V}O_2max$ and submaximal blood lactate concentrations at a given absolute work rate. The main reasons for the lack of change in OBLA% post-training in this study could be due to a combination of the relatively short training period, the large change in $\dot{V}O_2max$ itself, and the training status of the subjects. For relatively untrained subjects, such as those used in this study, a dominant feature of the physiological changes resulting from training is the magnitude in change of $\dot{V}O_2max$ (inversely related to the pre-training value). It could be suggested therefore that, if OBLA% reflects the peripheral aspects of exercise metabolism, and $\dot{V}O_2max$ reflects the cardivascular or central adaptations to training, changes in OBLA% may only be apparent after the major changes in the cardiovascular system have taken place.

The $\%\dot{V}O_2max$ at which OBLA occurred post-training for the CG remained unchanged. A significant difference was found, however, between the TG and the CG (65.9% and 72.6% respectively). This may be explained by the influence of individual data from two of the CG subjects. These subjects showed large changes in post-training blood lactate concentrations at a given absolute work rate despite only small increases in $\dot{V}O_2max$ (1% and 4%). As a result OBLA occurred at an increased $\%\dot{V}O_2max$ for these two subjects, causing an increase in the group mean. No obvious explanation can be advanced for these observations.

The belief that adaptions of $\dot{V}O_2max$ and skeletal muscle metabolism to training are independent were further confirmed by the

results of this study. Although the magnitude in change of $\dot{V}O_2max$ for the TG was paralleled by a similar change in $OBLA_w$, the modest correlation between the percentage change in these two variables ($r=0.41$) suggests that the changes were independent of each other and, therefore, controlled by different physiological and metabolic mechanisms.

The altered responses of the TG to submaximal exercise were also reflected in their performance in the post-training T30min. Whilst the absolute work rate at which the TG performed T30min was significantly higher post-training, the subjects were unable to exercise at a higher $\%\dot{V}O_2max$ (Figure 7.11). One of the factors influencing the $\%\dot{V}O_2max$ that the subject could tolerate may have been the magnitude of the training-induced change in $\dot{V}O_2max$. For, when percentage change in $\dot{V}O_2max$ was correlated with $\%\dot{V}O_2max_E$ during T30min a strong correlation of $r=-0.77$ ($p<0.05$) was found, implying that those individuals with a small change in $\dot{V}O_2max$ could tolerate a higher percentage of their new $\dot{V}O_2max$ than those with a large change. It could be suggested, therefore, that for these subjects the major response to training occurred at the peripheral level, i.e. improvements in the oxidative capacity of the skeletal muscle.

The inverse relationship seen between change in $\dot{V}O_2max$ and change in $\%\dot{V}O_2max_E$ for the TG would help explain why there was a strong positive correlation between $\dot{V}O_2max$ and $\%\dot{V}O_2max_E$ post-training ($r=0.72$) despite the fact there had been a strong inverse relationship pre-training ($r=-0.84$). Pre-training, those subjects with a low $\dot{V}O_2max$ could tolerate a high $\%\dot{V}O_2max_E$, these subjects also showed the greatest percentage change in $\dot{V}O_2max$ post-training, with little change in for those subjects possessing initially high $\dot{V}O_2max$ values. This factor, combined with the strong inverse relationship between the percentage in $\dot{V}O_2max$ and $\%\dot{V}O_2max_E$ meant that those subjects who had the highest pre-training $\dot{V}O_2max$ showed the smallest change in $\dot{V}O_2max$ as a consequence of training, but were able to tolerate a higher percentage of their post-training $\dot{V}O_2max$. The finding that those individuals who showed the greatest central changes (change in $\dot{V}O_2max$) showed smaller peripheral changes ($\%\dot{V}O_2max$) and vice versa suggests that peripheral changes, as reflected in the ability to exercise at a

high $\%\dot{V}O_2max$, are a later adaption to training than the central changes.

The effect of endurance training on the cardiorespiratory responses of the TG during T30min pre- and post-training were consistent with the changes demonstrated during the submaximal incremental test. Oxygen uptake was unchanged at the same absolute work rate, i.e. at 5 minutes, but was significantly increased during the remainder of the test when the work rate was also significantly higher. No significant difference was found pre- and post-training in heart rate, R, $F_EO_2\%$ or $\dot{V}E$ at any stage during the test for the TG. Since CAWR was significantly higher post-training this represented the equivalent of a decrease in these variables for a given absolute work rate.

The significantly lower heart rate and R values recorded by the TG in the post-training test may be explained by the fact that they were exercising at a significantly lower $\%\dot{V}O_2max$ between 5 and 20 minutes. Since the response of both heart rate and R are largely dependent upon the relative stress of the activity (Pruett, 1970) this could explain why the largest differences in these two measures pre- and post-training was seen at 5 minutes, when the difference in the $\%\dot{V}O_2max$ was the greatest.

The slightly higher $\dot{V}E$ of the TG post-training may be partially attributable to the higher work rate and $\dot{V}O_2$ of the group. Since the difference in $\dot{V}E$ pre- and post-training did not reach statistical significance, yet $\dot{V}O_2$ was significantly higher post-training, the $\dot{V}E.\dot{V}O_2^{-1}$ of the group was decreased post-training ($p<0.01$, 5-20 minutes). A decreased blood lactate concentration was also seen post-training between 5 and 20 minutes suggesting that the difference in $\dot{V}E.\dot{V}O_2^{-1}$ may have been linked to the decreased blood lactate concentration.

Analysis of the blood lactate concentrations during T30min revealed a significant increase in blood lactate concentration throughout the 30 minutes for the TG ($p<0.01$) and for the CG ($p<0.05$) both pre- and post-training (Figure 7.5). This increase occurred despite the fact that there was no significant increase in the work

rate over the final 25 minutes in this test for either group pre-training, or the CG post-training (Figure 7.3). This increase in lactate concentration, in the absence of an increase in work rate, may be partly accounted for by the high blood lactate concentrations already present after 5 minutes of exercise (in excess of 5mmol.l^{-1}). This value is higher than that reported by Kindermann and coworkers as the level at which blood lactate concentration begins to increase during exercise at a constant work rate (Kindermann et al., 1979). At this exercise intensity and above an imbalance between lactate production and lactate clearance results in lactate accumulation. This would then prevent the subjects increasing their work rate during the remaining 25 minutes of the test and in some instances cause them to reduce it. A slightly lower blood lactate concentration at 5 minutes (4.57mmol.l^{-1}) was found for the TG in the post-training test. This value is closer to the 4mmol.l^{-1} value at which a steady state can be maintained for as long as 45-60 minutes without a further increase in lactate concentration (Kindermann et al., 1979).

The widely reported decrease in blood lactate concentration at a given absolute work rate as a result of training (Williams et al., 1967; Ekblom, 1969) as demonstrated in the submaximal incremental test, was clearly evident for the TG after the first 5 minutes standardised exercise in the post-training T30min. This decrease could be accounted for by the fact that the %$\dot{V}O_2$max at which the subjects were exercising was significantly lower. Although blood lactate concentration was significantly lower at 5 minutes in the post-training test, during the remaining 25 minutes it increased to a value similar to that recorded at the end of the pre-training test. So, despite a higher work rate post-training than pre-training, blood lactate concentration was similar at the end of both tests. In addition, since neither the %$\dot{V}O_2$max at which the subjects performed T30min nor the blood lactate concentrations at the end of this test differed significantly pre- and post-training the results of T30min are consistent with those of the submaximal test which showed no change in the %$\dot{V}O_2$max at which blood lactate accumulation occurred. As a result, the ability to exercise at a higher %$\dot{V}O_2$max was not enhanced by training.

The studies reported previously in this thesis have consistently

shown that metabolic parameters measured during submaximal exercise (i.e. blood lactate concentration) are better predictors of endurance performance, as measured by T30min, than $\dot{V}O_2max$. These findings were confirmed by the results of this study. Whilst strong correlations were found both pre- and post-training between $\dot{V}O_2max$ and CAWR for the group as a whole (r=0.84 and r=0.84 respectively), even stronger relationships were found between $OBLA_w$ and CAWR (W) (pre- r=0.88; post- r=0.87). These correlations are similar to those reported by Sjödin and Jacobs (r=0.96, 1981) and Williams and Nute (r=-0.88, 1983) for the relationship between OBLA and marathon and half marathon performance times respectively.

One of the most dramatic changes in submaximal performance as a result of the 6 weeks' training was the 347% increase in exercise time to exhaustion during T80% demonstrated by the TG (CG, NS). The large change in the TG endurance time (range 126% - 572%) is similar to reports in the literature by Gleser and Vogel (1973, 258%), Bland (1982, 478%), Hardman (1984, 251%) and Williams and Nute (1986, 200%).

This large change in exercise time to exhaustion in the absence of a large change in $\dot{V}O_2max$ (25%), and the poor relationship found between percentage change in $\dot{V}O_2max$ and percentage change in performance time (r=-0.25), supports the notion of the independence of changes in maximal and submaximal performance. A stronger relationship was found, however, when absolute change in $\dot{V}O_2max$ was correlated with absolute change in T80% performance time (r=0.60). Although the relationship between change in $\dot{V}O_2max$ and endurance time is contrary to previous reports where changes in endurance performance have occurred irrespective of changes in $\dot{V}O_2max$ (Daniels et al., 1978b), our findings do not necessarily imply that the mechanisms responsible for the increase in the ability to exercise at a maximal rate were the same ones responsible for the change in the ability to exercise at a submaximal rate. For example, because all of the subjects increased their $\dot{V}O_2max$ post-training, and because the absolute work rate of T80% remained the same, the $\%\dot{V}O_2max$ at which the subjects were exercising varied. When the $\%\dot{V}O_2max$ during the post-training T80% was correlated with post-training endurance time, strong correlations were found for the TG (r=-0.80), the CG (r=-0.75) and the group as a whole (r=-0.88) (Figure 7.14). It may thus be concluded, that the greater the change

in $\dot{V}O_2max$ the lower the $\%\dot{V}O_2max$ represented by T80%, and hence the longer the exercise time. Change in T80% endurance time, therefore, was related to change in $\dot{V}O_2max$.

Although the TG were exercising at a significantly lower $\%\dot{V}O_2max$ throughout the post-training T80% the oxygen uptakes remained unchanged post-training, supporting the results of the submaximal incremental test. There was, however, a gradual increase in $\dot{V}O_2$ between 5 minutes and exhaustion during both the pre- and post-training tests. Various reasons may be put forward for this phenomenon. A change in form may have occurred as the subject became more fatigued, such that, different muscle groups were used to help with performance, eg. upper body muscles. The subject may also have recruited inefficient groups of muscles when close to fatigue. As ventilation increased gradually during the test, possibly due to the gradual increase in blood lactate concentration, the oxygen cost of breathing would have increased. In addition, the ability to place greater reliance on fat metabolism post-training may have increased $\dot{V}O_2$, since approximately 4.0 litres of O_2 is required to resynthesize 1 mole of ATP from the metabolism of fat compared with 3.5 litres if the metabolic substrate is carbohydrate (Fox, 1979).

Comparisons of other cardiovascular and metabolic parameters pre- and post-training revealed similar changes to those identified during the incremental test. Due to the constant work rate of the test, direct comparison of these changes was easier than during T30min, where the work rate was variable.

As might be expected from the decreased $\%\dot{V}O_2max$ of T80%, heart rate was significantly lower throughout the test post-training compared with pre-training for the TG (CG, NS) (Figure 7.6). During the test, however, a gradual drift upwards in heart rate was observed for both the TG and the CG both pre- and post-training. This may represent cardiovascular drift as a result of a decrease in stroke volume as blood is displaced to the periphery for purposes of thermoregulation (Rowell, 1974).

A decrease in R values during T80% was also seen for both the TG (Figure 7.7) and the CG both pre- and post-training. Although

post-training values were lower than pre-training values for both the TG and the CG, the TG values were slightly lower than those of the CG groups. This would, therefore, suggest that at the same absolute work rate the TG were able to place a greater reliance on fat metabolism than the CG during the post-training test.

A change in the oxidative capacity of the skeletal muscle, as suggested by a decrease in the R values for the TG, was also supported by the decreased blood lactate concentrations observed during the post-training T80% (Figure 7.8). Since the first 5 minutes of both T30min and T80% were performed at the same absolute work rate it is not suprising that the decrease in blood lactate concentration for the TG at the start of T80% was similar to that found at the start of T30min.

When the blood lactate concentration at 5 minutes was correlated with pre-training T80% endurance time an inverse relationship was found between the two variables ($r=-0.64$). This suggested that a high initial blood lactate concentration was detrimental to performance. This is in agreement with the work of Kindermann and coworkers, which stated that at a work rate equivalent to a blood lactate concentration above 4 $mmol.l^{-1}$ an imbalance between lactate production and lactate clearance occurs, and the resultant lactate accumulation is then one of the major causes of fatigue (Kindermann et al., 1979). The high initial blood lactate concentration pre-training may, therefore, explain why there was a significant increase in concentration for the TG between 5 minutes and exhaustion despite the work rate remaining constant. A similar explanation of the cause of fatigue may also be advanced for the CG.

The change in blood lactate concentration at the submaximal level as a result of training was, therefore, of fundamental importance in the changes seen in endurance time for the TG post-training. When percentage change in endurance time and the decrease in blood lactate concentration at the fourth work rate in the submaximal incremental test were correlated a strong relationship of $r=0.70$ ($p<0.01$) was found. A similar finding was reported by Williams and Nute (1986) for running at 90% $\dot{V}O_2max$. This implies that those individuals who showed the greatest metabolic adaptions within the muscles, as indicated by a

decrease in blood lactate concentration, were able to increase their endurance time the most, and supports the suggestions that muscle metabolism dictates endurance (Davies, Packer and Brooks, 1981, 1982). Although there was also a modest correlation between change in $OBLA_w$ and percentage change in endurance time ($r=0.57$; $p<0.05$; $n=15$) it would appear that the changes in blood lactate concentrations were greatest at the exercise intensity at which the subjects had been training, i.e. the highest work rate in the submaximal test (80% $\dot{V}O_2max$).

The change in blood lactate concentration during the post-training T80% was similar to that seen pre-training, i.e. a significant increase between 5 minutes and exhaustion. Post-training, however, the concentration level during the final minute of exercise was significantly lower than pre-training. This factor, together with the poor relationship between T80% time and blood lactate concentration at 5 minutes ($r=-0.15$), would suggest that factors other than accumulation of blood lactate may have been the cause of fatigue. One such factor may be the depletion of muscle or liver glycogen.

It is generally believed that when exercising at work rates that can be tolerated for 60 - 90 minutes a significant depletion of the muscle glycogen stores may be the factor limiting endurance performance. Under these conditions there is usually no fall in blood glucose concentration because the duration of the work period is too short to cause a depletion of liver glycogen (Astrand and Rodahl, 1977). The proposal that muscle glycogen depletion may have been the cause of fatigue for some of the subjects in this study cannot be confirmed, therefore, since invasive techniques were not used to measure glycogen. It has also been proposed that one the causes of fatigue during longer periods of exercise may be the depletion of the hepatic glycogen causing a drop in blood glucose concentration. This factor might, therefore, have been the cause the fatigue in those subjects whose exercise time was 90 minutes and above, and whose mean blood glucose concentrations dropped 17% between rest and exhaustion, and 25% between 5 minutes and exhaustion. However, despite the large percentage decrease in blood glucose concentration during the post-training test, the mean concentration at exhaustion for these subjects (3.3 $mmol.l^{-1}$) was still well above that advocated to

represent hypoglycemia (<2.5 mmol.l^{-1}, Felig, Cherif, Minagawa and Wahren, 1982). It seems sensible to conclude, therefore, that the major cause of fatigue during T80% for the TG was not the same for all of the subjects. High blood lactate concentrations and possibly glycogen depletion may have affected those subjects whose T80% work rate represented a high %$\dot{V}O_2$max, whilst low muscle glycogen and blood glucose (combined for some individuals with high blood lactate concentrations) may have been the cause of fatigue for those exercising at a lower %$\dot{V}O_2$max. Once again, therefore, a major determinant in the post-training improvement in endurance, as measured by T80% time, was the magnitude in change of the $\dot{V}O_2$max.

In summary, the major factor influencing the change in endurance performance as a result of training was the magnitude in change of $\dot{V}O_2$max. Those subjects who showed large changes in $\dot{V}O_2$max showed the greatest change in endurance time post-training, but were unable to sustain a high %$\dot{V}O_2$max during T30min. Whilst those subjects who showed smaller changes in $\dot{V}O_2$max were unable to increase their endurance time to the same extent as the previous group, but could exercise at a higher %$\dot{V}O_2$max during T30min. The inability of the group as a whole to exercise at a higher %$\dot{V}O_2$max post training was consistent with the results from the submaximal incremental test which revealed no change in the %$\dot{V}O_2$max at which blood lactate accumulation occurred, and would support the findings in the literature that training-induced changes in skeletal muscle metabolism occur as a result of long-term rather than short-term training.

8. GENERAL DISCUSSION

The studies described in this thesis were set up to develop a performance test which could be used to assess the ability of an individual to sustain a high proportion of their $\dot{V}O_2max$ during endurance exercise and to identify the characteristics which confer this ability.

It has been well documented in the literature that, due to the linear relationship between $\dot{V}O_2$ and energy expenditure, the ability to exercise at a high absolute work rate is largely dependent on the possession of a high $\dot{V}O_2max$. These findings were confirmed by the results from this thesis which consistently revealed a strong relationship between $\dot{V}O_2max$ and the average work rate of the subjects during T30min, i.e. those subjects who had the highest $\dot{V}O_2max$ values were able to exercise at the highest work rate during the 30-minute test. In the past, these results would have been interpreted to mean that those individuals who performed more work on T30min were fitter than those who performed less work. Since females possess lower $\dot{V}O_2max$ values than males, such an assumption would immediately categorise the female subjects included in these studies as less fit than their male counterparts, irrespective of their training status. Whilst the importance of $\dot{V}O_2max$ as a determinant of the subject's potential to exercise at an absolute work rate was, therefore, confirmed by the results from the studies, these results also demonstrated the doubtful validity of adopting $\dot{V}O_2max$ as an indicator of endurance fitness.

Reports in the literature revealing the strong hereditary influence on $\dot{V}O_2max$ combined with invasive studies carried out on both animals and humans, has moved the emphasis away from $\dot{V}O_2max$ as an indicator of endurance fitness towards other submaximal performance characteristics. In two studies performed on animals Davies and coworkers reported that $\dot{V}O_2max$ was an unreliable predictor of endurance due to the fact that a) muscle oxidative capacity was the primary determinant of endurance performance and b) $\dot{V}O_2max$ was not limited by muscle oxidative capacity (Davies, Packer and Brooks, 1981, 1982). Such findings have been important in identifying that the ability to exercise at a high relative exercise intensity could

provide a better indication of endurance fitness than $\dot{V}O_2max$ since such a measure reflects the oxidative capacity of the skeletal muscle more acurately than $\dot{V}O_2max$.

The independence of $\dot{V}O_2max$ and endurance performance, as highlighted by Davies and coworkers and others, was also confirmed by the results of this study. Despite the strong relationships between $\dot{V}O_2max$ and CAWR, when endurance performance on T30min was expressed relative to the individual's $\dot{V}O_2max$ ($\%\dot{V}O_2max_E$), the relative exercise intensity at which the subject was exercising was found to be independent of $\dot{V}O_2max$.

The adequacy of adopting the $\%\dot{V}O_2max$ an individual can tolerate over a given period of time as a measure of endurance fitness was also confirmed by the results from this study. When performance and physiological characteristics of sprint- and endurance-trained athletes were examined the results revealed that there was no significant difference between the two groups for either $\dot{V}O_2max$ or CAWR during T30min. It would appear, therefore, that the two measures which previously would have been accepted as indicators of endurance fitness ($\dot{V}O_2max$ and CAWR) were unable to differentiate between two groups of athletes who, by the nature of their training, should differ in endurance fitness. Examination of their ability to sustain a high $\%\dot{V}O_2max$ did, however, reveal a significant difference between the two groups in favour of the endurance-trained athletes.

The results of the study which examined the differences between males and females also revealed that the ability to tolerate a high $\%\dot{V}O_2max$ appeared to be a good indicator of endurance fitness. Whilst the males possessed higher $\dot{V}O_2max$ values than the females, and were able to exercise at a higher absolute work rate during T30min, there was no difference between the sexes in the ability to exercise at a high $\%\dot{V}O_2max$. This finding, for males and females who were of a similar training status, together with the results from the sprint and endurance-trained study, would tend to support the adoption of the ability to sustain a high $\%\dot{V}O_2max$ as a satisfactory indicator of endurance fitness.

The results from the study comparing males and females also

provided important information concerning the influence of the subject's sex on endurance performance. It has previously been hypothesised that, because women possess more fat relative to body weight than men, they are better suited to endurance events (van Aaken, 1976). Several studies, however, have reported that this is not the case, since there does not appear to be a sex difference in either the ability to utilise fat during exercise (Powers, Riley and Howley, 1980; Hardman and Williams, 1983), or the ability to exercise at a high $\%\dot{V}O_2max$ (Maughan and Leiper, 1983; Brewer, 1986). The results of this study are in keeping with these findings.

Because of the strong relationship between the oxidative capacity of the skeletal muscle and endurance performance it has been suggested that metabolic characteristics measured during submaximal exercise, i.e. blood lactate concentration, may be a better predictor of endurance performance than $\dot{V}O_2max$, since the ability to delay the accumulation of blood lactate concentration probably reflects the ability of the skeletal muscle to cover the energy demands aerobically. These suggestions were supported by the results reported in this thesis. Measurement of the work rate equivalent to OBLA repeatedly demonstrated a strong relationship with CAWR, which at times was stronger than the relationship found between $\dot{V}O_2max$ and CAWR. It would appear, therefore, that both the possession of a high $\dot{V}O_2max$ and the ability to delay the accumulation of blood lactate at a submaximal exercise intensity were important in determining the subject's ability to exercise at a high absolute work rate during T30min. In addition, when the work rate equivalent to OBLA was expressed relative to the subject's $\dot{V}O_2max$ (OBLA%) the relationship between this parameter and $\%\dot{V}O_2max_E$ was also found to be strong. This would suggest that, irrespective of the subject's $\dot{V}O_2max$, the ability to delay the accumulation of blood lactate at an exercise intensity relative to his or her $\dot{V}O_2max$ was of major importance in determining their ability to sustain a high $\%\dot{V}O_2max$.

The strong relationship between OBLA and endurance performance and the consistent finding that performance characteristics identified in the submaximal incremental test were also reflected in T30min have important implications for future research. The ability to predict two different measures of endurance performance from the measurement of

metabolic parameters at a submaximal level supports the notion that in studies where performance tests such as T30min are not carried out measurements obtained from a submaximal test could be used to indicate an individual's potential for endurance performance. In such cases, therefore, the administration of a maximal test would not be required. In addition, just as the absolute work rate at which a reference blood lactate concentration is achieved may reflect the subject's ability to exercise at an absolute work rate, some insight into the subject's training status may also be gleaned from data concerning the $\%\dot{V}O_2max$ at which a reference blood lactate concentration is achieved.

Whilst the ability to exercise at a high $\%\dot{V}O_2max$ can be seen as a more important criterion of endurance fitness than $\dot{V}O_2max$, information concerning the effects of training on this ability is difficult to come by. In general, improvements in this ability as a result of training have been inferred from cross-sectional studies where already well-trained endurance athletes have been compared with untrained subjects. Such studies have reported similar findings to those found in Chapter 5, i.e. endurance-trained athletes are capable of exercising at a higher $\%\dot{V}O_2max$ than untrained or sprint-trained athletes. Based on these results, it is suggested that the training induced changes in the oxidative capacity of the skeletal muscle are fundamental in explaining the differences observed in performance. As has been previously highlighted, however, such studies do not rule out the possibility of genetic differences nor do they provide insight into the time course of the changes.

The purpose of including a training study in this thesis, therefore, was to examine the effects of short-term training on the ability to sustain a high $\%\dot{V}O_2max$. In the past, however, many training studies have simply assessed the effect of training by reporting the magnitude of the change in performance variables, few studies have actually tried to identify whether change in one variable is related to change in another. The training study reported in Chapter 7, therefore, was set up not only to assess the magnitude in the change in endurance performance, i.e. CAWR, T80% time and $\%\dot{V}O_2max_E$, but also to try and identify the relationship between changes in the skeletal oxidative capacity, as reflected by changes in blood lactate concentration, with changes in endurance performance. In addition,

since an improvement in performance represents an improved ability to delay the onset of fatigue it was hoped that such a study could help identify the causes of fatigue during T30min.

As stated previously, few studies have examined the affect of training on the ability to exercise at a relative exercise intensity. One such study was by Saltin and coworkers (Saltin et al., 1968). They found no significant difference in exercise time to exhaustion at 80% $\dot{V}O_2max$ pre-bed-rest, post-bed-rest and post-training, when the work rate was recalculated according to the subject's current $\dot{V}O_2max$.

The results reported in this thesis support the findings of Saltin. Despite intensive training for six weeks, there was no change in either the relative exercise intensity at which OBLA occurred or the $\%\dot{V}O_2max_E$ tolerated during T30min. The lack of change in both of these variables could be due largely to the magnitude of the change in $\dot{V}O_2max$ since it is possible that the large changes in the cardiovascular responses to exercise (central changes) actually overshadowed the peripheral changes (changes in the oxidative capacity of the skeletal muscle). It could be hypothesised that despite the fact that changes in muscle enzyme concentrations have been found to occur very rapidly (Henriksson and Reitman, 1977), the benefits of peripheral changes during exercise at a $\%\dot{V}O_2max$ (eg. a decrease in the blood lactate concentration or the ability to tolerate a high $\%\dot{V}O_2max$), would only be experienced once the major changes in $\dot{V}O_2max$ had occurred, i.e. changes in the peripheral level would only represent an increased ability to exercise at a given $\%\dot{V}O_2max$ if $\dot{V}O_2max$ itself showed only small changes or no change at all. Thus the inability to sustain a high $\%\dot{V}O_2max$ or delay the accumulation of blood lactate at a given $\%\dot{V}O_2max$ did not necessarily imply that peripheral changes had not occurred, since the decrease in blood lactate concentration at a given absolute work rate indicated that this was not the case, but rather, that they were overshadowed by the change in $\dot{V}O_2max$.

This notion that the effect of peripheral changes on endurance performance will become relatively more important after the major central changes have occurred is supported by reports in the literature where improvements in endurance performance have been

observed after a period of training, despite an unchanged $\dot{V}O_2max$ (Daniels et al., 1978b). These findings would also support the results presented in Chapter 5 which identified endurance-trained athletes as being characterised by the ability to sustain a high $\%\dot{V}O_2max$. These subjects had a history of at least 3 years endurance training, and in some cases up to 10 years. Improvements in endurance performance during the initial stages of training were likely to be the result of changes in the magnitude of their $\dot{V}O_2max$. Assuming this parameter then stabilised, any subsequent changes in performance might then have been due to the changes in the oxidative capacity of the skeletal muscle which were reflected in T30min by the ability to sustain a high $\%\dot{V}O_2max$.

The results reported in Chapter 7 would suggest, however, that the adoption of the ability to sustain a high $\%\dot{V}O_2max$ as an indicator of endurance fitness has its drawbacks. To adopt such a criterion as the sole indicator of endurance fitness would imply that 6 weeks of training did not improve the subjects' endurance fitness. Nevertheless, there were large changes in $\dot{V}O_2max$, $OBLA_w$, CAWR and exercise time to exhaustion. In short-term studies it would appear that, despite the fact that the ability to tolerate a high $\%\dot{V}O_2max$ is independent of the magnitude of $\dot{V}O_2max$, the degree to which $\dot{V}O_2max$ increases as a result of training is an important factor. It could be suggested, therefore, that changes in $\dot{V}O_2max$ and the decrease in blood lactate concentration at the absolute level must be assessed alongside the changes in the tolerable relative exercise intensity if a more complete picture of changes in endurance fitness are to be obtained.

In short-term training studies where the magnitude of the central changes, i.e. $\dot{V}O_2max$, is large, but where changes in submaximal blood lactate concentration indicate that major peripheral changes are also occurring, it is often difficult to ascertain whether peripheral or central adaptations are responsible for the changes observed in endurance performance. An attempt was made to do so using the results obtained from T80% and applying them to the model representing the relationship between $\%\dot{V}O_2max$ and endurance performance proposed by Gleser and Vogel (1971). This model allows the estimation of the relative importance of the increase in $\dot{V}O_2max$ and peripheral adaptations in determining improvements in endurance time (T80%).

As reviewed earlier, Gleser and Vogel found empirically that the length of time an individual could exercise at a given work intensity was related to the work intensity by the equation:

$$\log t = A * Lr + B$$

where t is time, Lr is relative work load and A and B are constants.

By knowing the relative exercise intensity that the subject performed T80% post-training, and by calculating A and B from the pre-training data, which did not increase with training, it was possible to estimate the endurance time that would result if changes in performance were simply a function of changes in $\dot{V}O_2max$ *per se*. Any difference in the actual and estimated times, therefore, could be attributed to peripheral changes. The results revealed that estimated endurance time for the $\%\dot{V}O_2max$ at which the TG performed T80% post-training was 35% less than the actual time. This would suggest that not all of the change in T80% time could be attributed to the change in $\dot{V}O_2max$. In addition, individual data revealed that the subject who had the smallest change in $\dot{V}O_2max$ (6%) exercised 84% longer than was predicted by the equation, whilst the subject with the largest change in $\dot{V}O_2max$ (53%) execised 42% longer than the predicted time. These results, therefore, would imply that the increase seen in endurance performance time post-training for that individual who had the smallest change in $\dot{V}O_2max$ was almost totally due to peripheral changes, whilst the change in endurance for the subject who showed the largest change in $\dot{V}O_2max$ was due to a combination of peripheral and central changes, and not, as might have been proposed, due totally to the change in magnitude of $\dot{V}O_2max$. Such suggestions, however, are speculative since the model proposed by Gleser and Vogel requires the assumption that all subjects, irrespective of state of training, can exercise for 10 minutes at an exercise intensity which elicits $\dot{V}O_2max$.

As previously discussed, the results reported in this thesis have consistently shown that the ability to delay the accumulation of blood lactate appears to be advantageous for performance on T30min (CAWR or $\%\dot{V}O_2max_E$). These findings were also confirmed by the results of the training study which highlighted that changes in blood lactate concentration were strongly related to changes in endurance performance. Since improvements in endurance performance represent improvements in the ability to delay the onset of fatigue, it seems

logical to assume that the factors associated with the accumulation of blood lactate concentration were strongly associated with the onset of fatigue. Such an assumption was supported by the results from T30min.

Analysis of T30min results revealed that the blood lactate concentration at the end of both the pre- and post-training tests was of a similar magnitude despite the higher post-training work rate. It would appear, therefore, that the limiting factor in performance was not the amount of work performed, but rather the metabolic changes occurring within the muscle. Since the exercise intensity sustained during T30min was greater than that which can be supported totally by aerobic metabolism, it could be suggested that the major cause of fatigue during T30min was due to the production of hydrogen ions as a result of anaerobic glycolysis. This increased hydrogen ion concentration could not only have interfered with the contractile processes, but also caused muscle pH to drop reducing the activity of rate limiting enzymes of glycolysis, resulting in a reduced rate of ATP resynthesis (Hermansen, 1981).

The results obtained from T80% also suggest that the accumulation of blood lactate at the submaximal level was a major determinant of endurance performance. This assumption is based on the fact that changes in the accumulation of blood lactate concentration as a result of training were strongly related to the changes seen in endurance performance. Analysis of the results of the post-training T80% test revealed that those subjects who showed the greatest metabolic changes as a result of training (i.e. the greatest decrease in blood lactate concentration) were able to increase their exercise time the most. Since the post-training test was performed at the same absolute work rate as pre-training the improvement in performance could be attributed to an enhanced capacity of the skeletal muscle to cover the energy demands aerobically, and thus reduce the rate of conversion of pyruvate to lactate.

The possibility that the underlying causes of fatigue during T30min and T80% pre-training were similar is not unacceptable since both the exercise time and the $\%\dot{V}O_2max$ at which the subjects were exercising was similar in both tests. The significant correlation found pre-training, between T80% time and the relative exercise

intensity sustained during T30min, would also support this belief ($r=0.59$; $p<0.01$).

The notion that the drop in muscle pH may have been a major cause of fatigue in T30min and in pre-training T80% is not supported by the findings of Knudsen and Pedersen (in press). They found no change in exercise time to exhaustion at 80% $\dot{V}O_2max$ when acid-base changes were experimentally administered to a group of subjects. Although exercise time to exhaustion and the intensity at which Knudsen's subjects were exercising were similar to T30min and T80% the blood lactate concentrations recorded at the end of these two tests were consistently higher than those reported by Knudsen and Pedersen and, therefore, the degree to which the acidity of the muscle was changing may have been different.

An alternative or contributing cause of fatigue may have been glycogen depletion. This possibility could not be confirmed by the data available from this study, however, Hardman (1984) reported that exercise at 80% $\dot{V}O_2max$ did not deplete fully muscle glycogen stores, since approximately 30% of the muscle glycogen was left at exhaustion. It is still possible, however, that selected depletion of glycogen in fibres of some motor units may have contributed towards fatigue.

As discussed in Chapter 7, glycogen depletion may well have been an important cause of fatigue during the post-training T80% test, since some subjects were exercising for over two hours. In addition, the possibility that hypoglycemia may have contributed to fatigue for some of the subjects was also highlighted. The lack of a significant relationship post-training between T80% time and the relative exercise intensity tolerated during T30min ($r=-0.40$) would also infer that these tests were no longer measuring a similar aspect of endurance. This is not a surprising finding since the average $\%\dot{V}O_2max$ of T80% post-training was only 67% and the average time to exhaustion was 98 minutes.

No hard and fast conclusions can be drawn as to the limiting factors of performance on T30min and T80%. The inclusion of the training study, however, did identify that changes in blood lactate concentration at a given absolute work rate were important in

determining the absolute work rate that an individual could tolerate during T30min, and the length of time they could sustain a given absolute work rate. Similarly, the lack of change in the $\%\dot{V}O_2max$ at which blood lactate accumulated was reflected by the lack of change in the ability to sustain a high $\%\dot{V}O_2max$ during T30min. It could be suggested, therefore, that the major causes of fatigue during T30min pre- and post-training and T80% pre-training, were factors directly related to the accumulation of blood lactate concentration or selected glycogen depletion In contrast, post-training T80% time is more likely to have been determined by glycogen depletion or, for some subjects, hypoglcemia.

In summary, the studies reported in this thesis consistently revealed that the major factors determining the ability to exercise at a high absolute work rate during T30min were the magnitude of the subject's $\dot{V}O_2max$ and their ability to delay the accumulation of blood lactate. The ability to exercise at a high $\%\dot{V}O_2max$, however, was independent of the magnitude of $\dot{V}O_2max$ but dependent on the ability to delay the accumulation of blood lactate concentration at a given $\%\dot{V}O_2max$. By examining the effect of training on performance it appeared that the change in endurance performance was dependent upon the changes in the metabolic characteristics of the skeletal muscle as well as the magnitude in change in $\dot{V}O_2max$. It is important, therefore, that both of these factors are taken into consideration when assessing an individual's state of conditioning.

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APPENDICES

APPENDIX 1. CALIBRATION PROCEDURES

1.a Gas Analysers

The Taylor Servomex oxygen analyser and the Lira Infra-red carbon dioxide analyser were both calibrated with a null gas (nitrogen) and a span gas mixture of a known concentration. The instruments were calibrated immediately prior to expired air analysis and recalibrated at least once an hour.

1.b Calibration of the cycle ergometer pedal revoltions and computer display.

The pedal frequency monitoring system (see Chapter 3, 3.1.3) was calibrated prior to each endurance performance test to ensure that the pedal revolutions displayed on the computer screen corresponded to the flywheel revolutions of the cycle ergometer. The calibration procedure involved monitoring the voltage output from the generator attached to the cycle ergometer flywheel and the pedal frequency simultaneously:

1) The subject cycled at a constant speed for a given period of time (usually 2 minutes).

2) During this time period the flywheel revolutions were counted using a mechanical counter (described in Chapter 3, section 1.2), and the voltage output from the generator was monitored by the computer via an A-D converter.

3) Using a computer programmme written by a member of the laboratory staff the information recorded above was used to calculate the equivalent mean voltage output for a given pedal frequency (rpm).

4) This information was stored in memory and used during the performance tests to convert voltage output from the generator to pedal revolutions.

APPENDIX 2. GAS ANALYSIS

2.a Determination of the oxygen and carbon dioxide content, volume and temperature of the expired air

The O_2 and CO_2 content together with the volume and temperature of the expired air was determined as followed:

a) Air in the douglas bag was well mixed before analysis took place.

b) A small sample of air was extracted from the Douglas Bag via a sampling tube, by means of a Hy-flow (Metcalf Industries Ltd.) pump. The rate at which the gas was extracted was measured by a gapflow meter.

c) The expired air was pumped into the CO_2 analyser for 120 seconds during which time the flow rate was recorded for the determination of the volume of expired air used during sampling. The flow was stopped after 120 seconds and the meter reading was recorded when the instrument had stabilised. The meter reading was then coverted to $\%CO_2$ through use of a calibration chart supplied by the manufacturers.

d) A second sample of expired air was pumped into the O_2 analyser for 60 seconds. After completion of the sampling period the flow was stopped and the $\%O_2$ recorded from the digital display once the instrument had stabilised.

e) The volume of the expired air was determined by evacuating the Douglas Bags through a dry gas meter. This value, together with the volume used for sampling, combined to give the total volume of expired air.

f) The temperature of the expired air was determined by a thermistor placed in the outlet tube of the gas meter.

2.b Determination of oxygen uptake

Oxygen uptake was determined by converting the volume of expired air to standard temperature and pressure for dry gases (STPD), and through the use of the Haldane transformation. The Haldane transformation uses the concentration of nitrogen (assuming no net Nitrogen uptake or production at the lung) in the inspired and expired air to derive the volume of air inspired from direct measurement of the volume expired.

i) Standardisation of $\dot{V}E$ ($l.min^{-1}$) to $\dot{V}E_{STPD}$ ($l.min^{-1}$)

$$\dot{V}E_{STPD} = \dot{V}E_{ATPS} \times \frac{(BP-SWVP_t)}{760} \times \frac{273}{273+t}$$

Where BP = Barometric Pressure (mm Hg)

$SWVP_t$ = Saturated Water Vapour Pressure (mm Hg) at ambient temperature

t = Temperature (°C) of gas as volume is determined

ATPS = Ambient temperature and pressure, saturated with water vapour

ii) Calculation of $\dot{V}O_2$ using the Haldane transformation

$$\dot{V}_I = \frac{\%N_2 \text{ in expired air}}{\%N_2 \text{ in inspired air}} \times \dot{V}E_{STPD} \ (l.min^{-1})$$

where $\dot{V}_I$ = volume of inspired air

$$\dot{V}O_2 = \dot{V}_I \times \frac{F_IO_2}{100} - \frac{F_EO_2}{100} \times \dot{V}E \ (l.min^{-1})$$

where $\dot{V}E$ = volume of expired air (STPD)

F_IO_2 = % of O_2 in the inspired air

F_EO_2 = % of O_2 in the expired air

$\dot{V}_I$ = volume of inspired air

2.c Determination of carbon dioxide production ($\dot{V}CO_2$ $l.min^{-1}$)

$$\dot{V}CO_2 = \dot{V}E \times \frac{F_ECO_2}{100} - \dot{V}_I \times \frac{F_ICO_2}{100} \quad (l.min^{-1})$$

where F_ECO_2 = % CO_2 in expired air

F_ICO_2 = % CO_2 in inspired air

2.d Determination of the respiratory exchange ratio(R)

$$R = \frac{\dot{V}CO_2}{\dot{V}O_2}$$

2.e Determination of ventilatory equivalent ($\dot{V}E.\dot{V}O_2^{-1}$)

$$\dot{V}E.\dot{V}O_2^{-1} = \frac{\dot{V}E}{\dot{V}O_2}$$

APPENDIX 3. BLOOD ANALYSIS

3.a Lactic Acid Assay

The method used was an adaption of that described by Olsen (1971). It is dependent on the release of NADH by the following reaction, which is measured by its native fluorescence:

$$\text{Lactate} + NAD^{+} + \overset{LDH}{\rightleftharpoons} \text{Pyruvate} + NADH$$

SOLUTIONS

Perchloric acid: 2.5% w/v

Hydrazine buffer (1.1 M, pH 9.0): 1.3g hydrazine sulphate, 5.0g hydrazine hydrate and 0.2g disodium ethylenediaminotetraacetic acid (EDTA) in 100ml distilled water.

Reaction Mixture: 2mg NAD^{+} and 10 µl LDH per ml of hydrazine buffer, prepared immmediately prior to use.

STANDARDS

These were made from 1.0 M Sodium L-lactate solution.

DEPROTEINISATION

25 µl of blood was deproteinised by adding it to 250 µl of perchloric acid. It was then mixed thoroughly, centrifuged and stored at -25°C before analysis.

PROCEDURE

1. Samples were removed from the freezer and allowed to thaw at room temperature.
2. Samples were mixed thoroughly and spun in a centrifuge for 4 minutes.
3. 25 µl of either the supernatant or the standard was transferred to an acid-washed test-tube.
4. 250 µl of reaction mixture was added to each test-tube.
5. Test-tubes were mixed and allowed to incubate for 30 minutes.
6. 1 ml of diluent was added to each tube.
7. The samples were then read against the standards and the blank with a Perkin-Elmer Fluorimeter. The fluorescence of the blank was

subtracted from that for samples and standards and the lactate concentration of each sample calculated from the standard curve.

DETERMINATION OF THE COEFFICIENT OF VARIATION

Ten repeated measures were made on two standard solutions for the determination of the coefficient of variation for this assay.

	S1	S2
	n=10	n=10
x	2.78	10.72
S.D.	0.06	0.09
C of V	2.1%	0.82%

3.b Glucose Assay

A Boehringer diagnostic kit was used for determination of blood glucose. The colorimetric method was based on the following principles:

$$\text{Glucose} + O_2 + H_2O_2 \xrightarrow{\text{GOD}} \text{Gluconate} + H_2O$$

$$H_2O + \text{ABTS} \xrightarrow{\text{POD}} \text{Coloured complex} + H_2O$$

DEPROTEINISATION

Blood was deproteinised in the same manner as that used for the lactate assay.

SOLUTIONS

Phosphate buffer: 100 mmol.l^{-1}, pH 7.0

POD: > 0.8 U.ml^{-1}

GOD: > 10.0 U.ml^{-1}

ABTS: 1.0 mg^{-1}

STANDARD

A 0.505 mmol.l^{-1} standard was used.

PROCEEDURE

1. Samples, standards and reaction mixture were removed from the freezer and allowed to eqilibrate at room temperature.
2. Samples were then mixed thoroughly and centrifuged.
3. 20 µl of either standard or supernatant was placed in a test-tube with 1 ml of reaction mixture and mixed well.
4. The solution was allowed to incubate for 20 minutes at room temperature.
5. An Eppendorf photometer was used to measure the absorbance of the standards and sample at Hg 436 nm in a cuvette of 1 cm light path.
6. The glucose concentration (mmol.l^{-1}) in the sample was calculated in the following way:

$$c = 5.5 \times \frac{\text{sample}}{\text{standard}}$$

3.c Haemoglobin Assay

A Boehringer diagnostic kit was used to produce the reaction mixture for this assay. A cyanmethemoglobin method was used to assess the haemoglobin concentration. This is a colorimetric method based on the following principle:

Haemoglobin + cyanide + ferricyanide ---> cyanmethaemoglobin

SOLUTIONS

Drabkins Reagent:

1.63 mmol.l^{-1} phosphate buffer.
0.75 mmol.l^{-1} potassium cyanide.
0.60 mmol.l^{-1} potassium ferricyanide.
5% detergent.

Made up to 1000 ml with redistilled water.

PROCEDURE

1. 20 μl of blood was added to 5000 μl of Drabkins reagent and mixed well to avoid clumping of the erythrocytes.
2. The solution was allowed to incubate at room temperature.
3. The absorbance (A) of the samples at 546 nm was measured with an Eppendorf photometer in a cuvette of 1cm light path against a blank of distilled water. Samples were in all cases read in less than 24 hours.
4. Haemoglobin concentration of the samples was calculated using the following equation:

$$\text{concentration} = (36.77 \times A)\ g.dl^{-1}$$

Assuming that the haemoglobin (Hb) content in the blood, i.e. the mass, does not alter during exercise, changes in Hb concentration pre- and post-exercise can be used to indicate changes in plasma volume. This is based on the principle that:

$$\text{concentration} = \frac{\text{mass}}{\text{volume}} \qquad \text{therefore,}$$

$$\text{plasma volume post-exercise} = \frac{\text{Hb pre}}{\text{Hb post}} \times \text{plasma volume pre-exercise}$$

Haemoglobin concentrations ($g.dl^{-1}$) pre- and post- exercise for T30min and T80% (n=12)

	T30min	T80%
pre	13.0±0.6	13.4±0.6
post	14.2±0.6	14.4±0.6
ratio pre/post	0.92	0.93

These results indicate that there was a 7-8% decrease in plasma volume during T30min and T80%. The measurements of blood lactate and blood glucose were not, however, corrected for the changes in plasma volume during exercise.

APPENDIX 4. THE EFFECT OF 5 MINUTES OF EXERCISE AT 90% VO_2MAX ON ENDURANCE PERFORMANCE DURING T30MIN

During endurance events where the individual is free to self-select their own exercise intensity the rate at which the subject exercises during the inital stages may greatly influence subsequent performance. For example, an athlete who starts a race too fast may be unable to live with the consequences of the initial pace and may be forced to slow down or even stop. The purpose of imposing a 5-minute standardised period at the beginning of T30min, therefore, was to help prevent subjects misjudging the exercise intensity at the beginning of the test and thus provide them with a reference point for pacing the remainder of the test.

In a previous study examining the reproducibility of T30min, Evans (1984) administered a standardised period of 5 minutes at 80% $\dot{V}O_2$max on her subjects. Her results revealed that following this initial period some subjects were able to increase their work rate during the remaining 25 minutes of the test, whilst others were forced to reduce it slightly. The extent to which some of the subjects were able to increases their work rate suggested that a more provocative work rate could be administered during this initial standardised period.

The purpose of this present study was to examine the performance characteristics of subjects who were required to exercise for the initial 5-minute period at a work rate equivalent to 90% of their $\dot{V}O_2$max.

METHODS

Two male and two female physically active subjects volunteered for this study. The physical and physiological characteristics of the subjects can be seen in Tables A1 and A2. All had had previous experience of physiological tests on a cycle ergometer.

Each subjects performed a $\dot{V}O_2$max test and a submaximal

Table A.1 Physical characteristics of the subjects

Subject	Age (yrs)	Height (cm)	Weight (kg)	Body Fat (%)
1	25.2	170	59.0	20.0
2	20.8	177	77.6	31.8
3*	23.6	164	63.9	9.9
4*	31.8	182	81.3	18.2
$\bar{x}$	25.4	172	70.4	19.9
SD	4.7	8	10.7	9.0

* denotes male subject

Table A.2 Physiological characteristics of the subjects

Subject	$\dot{V}O_2max$ ($l.min^{-1}$)	$\dot{V}E$ max ($l.min^{-1}$)	HR max ($b.min^{-1}$)	Work Rate max (W)
1	3.17	95.0	176	255.4
2	3.08	104.4	204	271.9
3*	3.57	128.2	184	265.8
4*	3.78	156.5	178	295.4
$\bar{x}$	3.40	121.0	186	272.1
SD	0.33	27.4	13	16.9

* denotes male subject

incremental test, in the manner described in Chapter 3 (3.3.4 and 3.3.5). No blood sampling was undertaken during the incremental test. On completion of the preliminary tests each subject performed T30min, on two occassions, at an initial work rate required to elicit 90% $\dot{V}O_2max$. Times for blood sampling and expired air collections are shown in Figure 3.2. Performance data from the more successful of the two tests, i.e. based on their cumulative average work rate values, was used for data analysis.

RESULTS

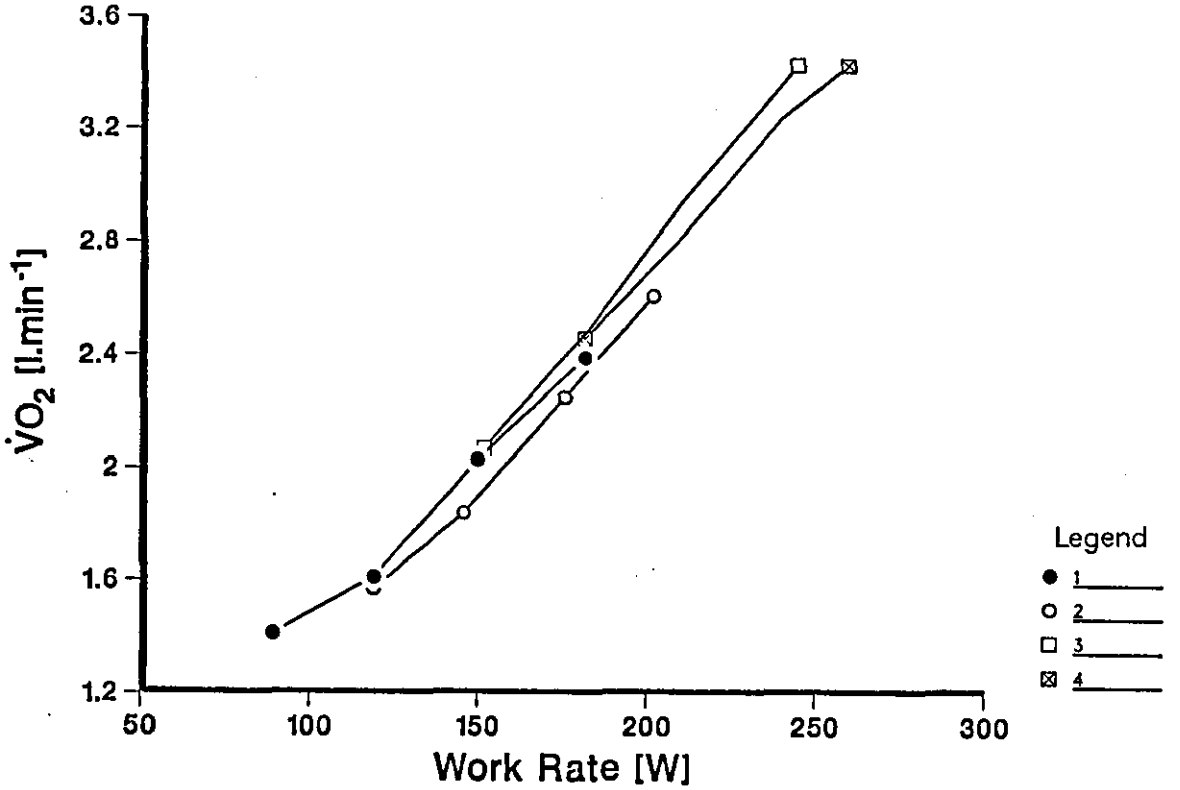
A summary of the results from the submaximal incremental test can be seen in Table A.3. A linear relationship was found between work rate and both $\dot{V}O_2$ and heart rate for all 4 subjects (Figures A.1 and A.2 respectively) indicating that the work rates were submaximal.

A summary of the changes in performance during T30min can be seen in Tables A.4 and A.5 and Figures A.3 and A.4. Three out of the 4 subjects showed a gradual decrease in CAWR following the initial 5-minute period of exercise. The fourth subject increased his work rate between minutes 5 and 10, but then showed a rapid decrease in work rate during the remaining 20 minutes (Figure A.3). The $\%\dot{V}O_2max_E$ sustained during T30min ranged from 86.0% to 80.7% and did not appear to be related to $\dot{V}O_2max$.

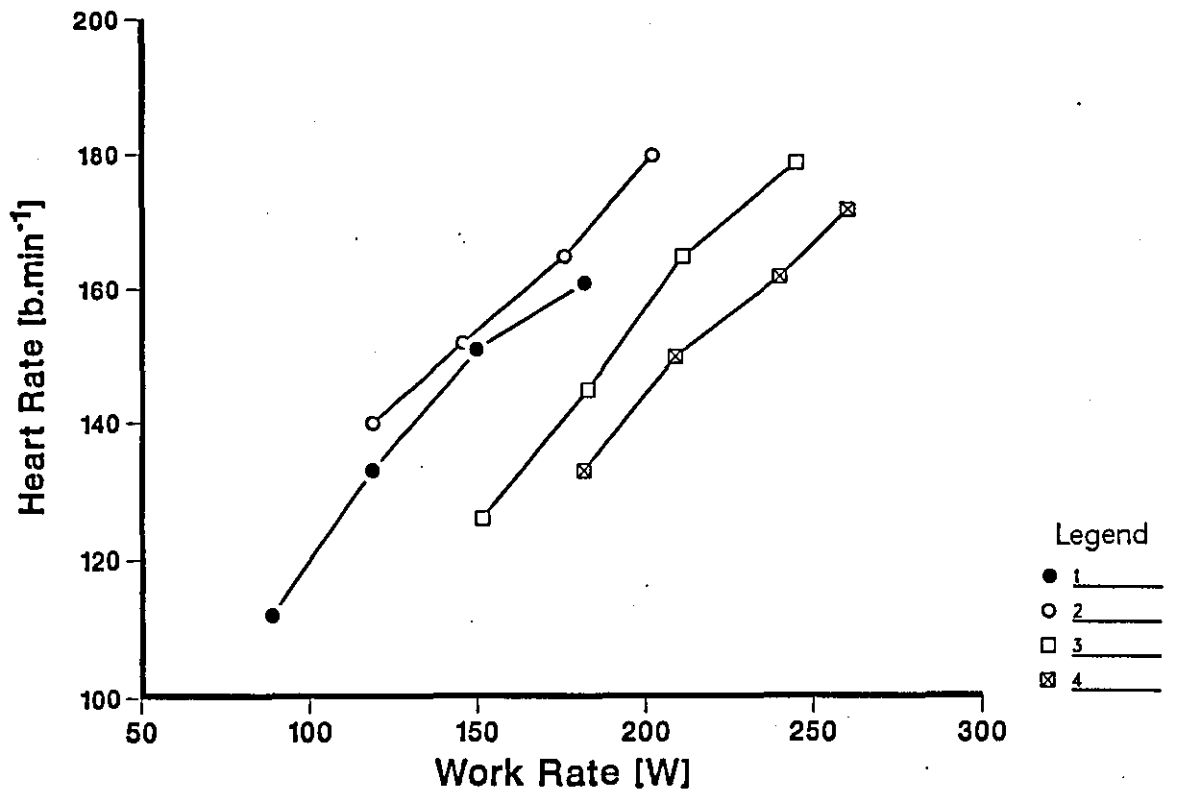
Blood lactate concentrations increased for all 4 subjects between minutes 5 and 10 (Table A.6 and Figure A.5). Between minutes 10 and 20 they continued to increase for subjects 2, 3 and 4, whilst subject 1 showed a marked decrease. During the remainder of the test blood lactate concentrations increased for subjects 1, 2 and 3, but not for subject 4.

Table A.3 Work rate (W), oxygen uptake ($l.min^{-1}$) and heart rate ($b.min^{-1}$) during the submaximal incremental test. Mean ± S.D.

n	WORK RATE (W)	$\dot{V}O_2$ ($l.min^{-1}$)	HR ($b.min^{-1}$)
1	89.1	1.41	112
2	118.6 ± 0	1.59 ± 0.03	134 ± 5
3	149.5 ± 3.0	1.98 ± 0.12	143 ± 15
4	180.6 ± 3.3	2.40 ± 0.11	151 ± 15
3	207.1 ± 4.4	2.79 ± 0.17	165 ± 15
2	242.1 ± 3.7	3.34 ± 0.13	171 ± 12
1	260.0	3.43	172



A.1 Oxygen uptake during the incremental test.



A.2 Heart rate during the incremental test.

Table A.4 Cumulative average work rate (W) during T30min.

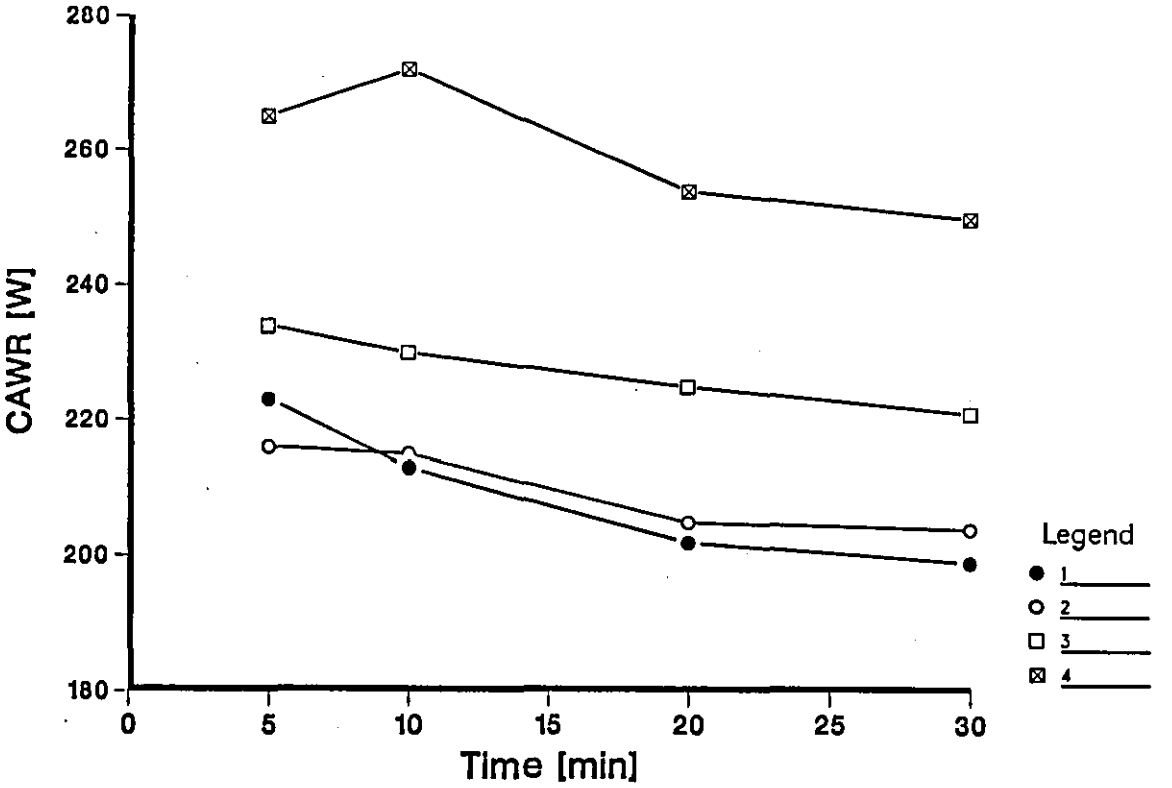
Subjects	5 min	10 min	20 min	30 min
1	223.2	213.4	201.8	199.2
2	216.3	215.4	205.2	203.8
3*	233.7	230.4	224.8	221.2
4*	265.0	272.1	254.4	249.7
$\bar{x}$	234.6	232.8	221.6	218.5
SD	21.5	27.1	24.1	22.9

* denotes male subject.

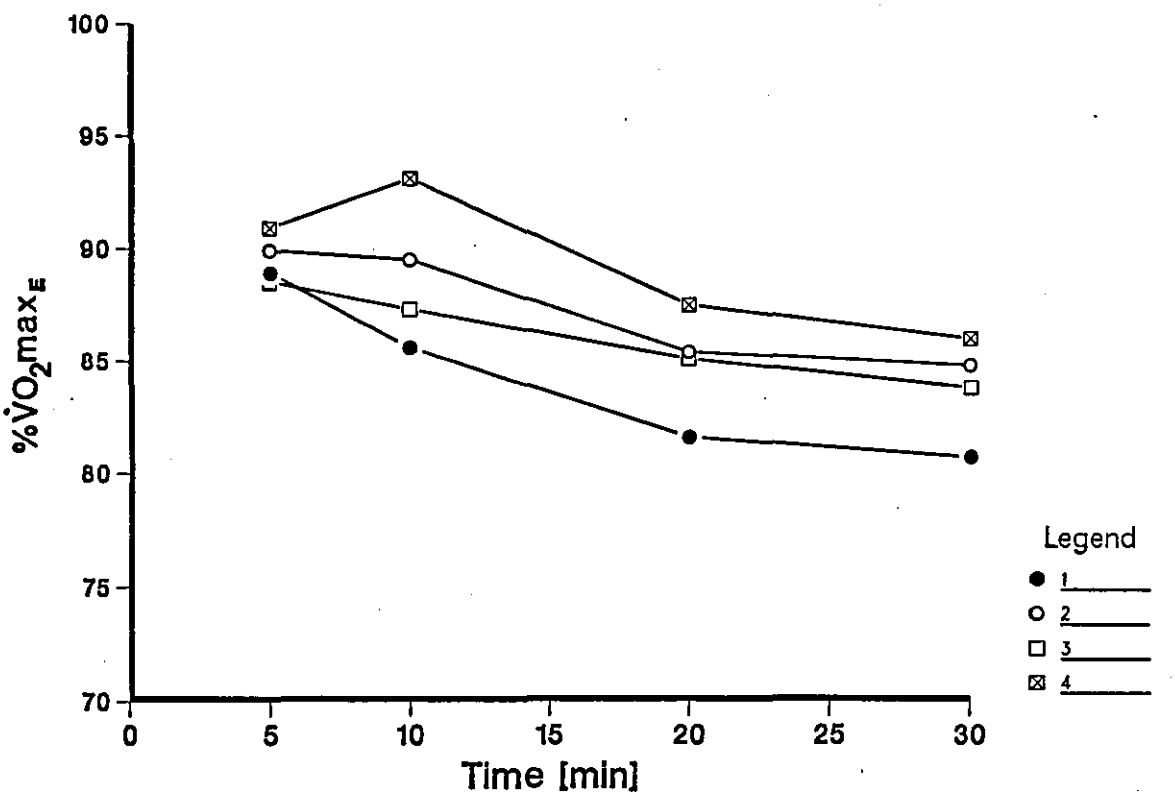
Table A.5 $\%\dot{V}O_{2max_E}$ during T30min.

Subjects	5 min	10 min	20 min	30 min
1	88.9	85.6	81.6	80.7
2	89.9	89.5	85.4	84.8
3*	88.5	87.3	85.1	83.8
4*	90.9	93.1	87.5	86.0
$\bar{x}$	89.6	88.9	84.9	83.8
SD	1.1	3.2	2.4	2.3

* denotes male subject.



A.3 Cumulative average work rate during T30min.

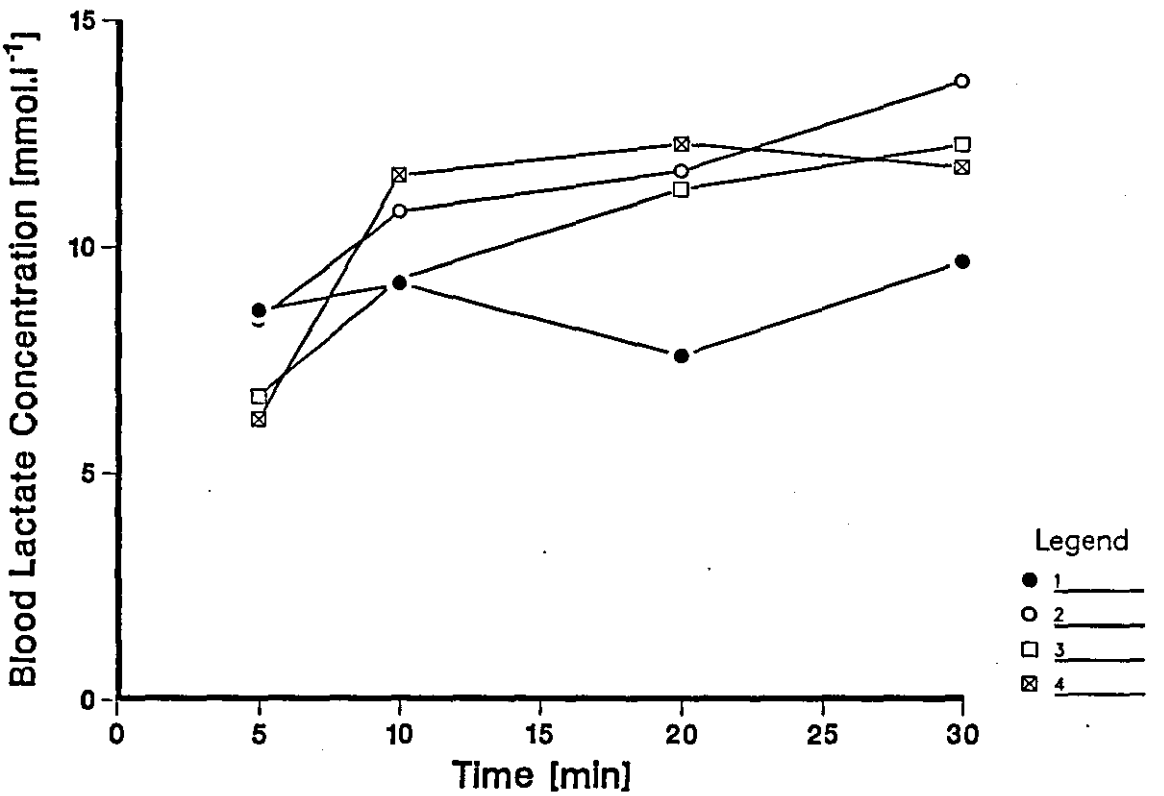


A.4 Estimated relative exercise intensity during T30min.

Table A.6 Blood lactate concentration ($mmol.l^{-1}$) during T30min.

Subjects	5 min	10 min	20 min	30 min
1	8.62	9.20	7.62	9.68
2	8.40	10.75	11.67	13.72
3*	6.73	9.25	11.30	12.34
4*	6.21	11.61	12.31	11.76
$\bar{x}$	7.49	10.21	10.73	11.88
SD	1.20	1.18	2.11	1.68

* denotes male subject.



A.5 Blood lactate concentration during T30min.

DISCUSSION

The results of this study revealed that, following an initial standardised period of 5 minutes at 90% $\dot{V}O_{2}max$, there was a gradual decrease in work rate during the remaining 25 minutes of the test. The percentage decrease in CAWR from 5 and 30 minutes ranged between 11% for subject 1 to 5% for subject 3. These values are slightly lower than the percentage decreases reported by Katch and Katch in 1972 (17.5%) and Katch in 1973 (25%) who both measured endurance as the drop off in performance over a given period of time.

As highlighted in Chapter 8, the accumulation of blood lactate concentration appears to be a major determinant of successful performance on T30min. Analysis of blood lactate concentrations during T30min may help explain some of the differences observed in performance between the 4 subjects. The subject who had the lowest blood lactate concentration at 5 minutes was the only subject able to increase his work rate following the initial 5-minute period. At 10 minutes, however, this subject had the highest concentration for the group. It is likely that a build up of hydrogen ions and the resultant drop in muscle pH may have been the cause of the rapid decrease in the work rate of this subject between 10 and 20 minutes. Despite the decrease in work rate, however, the blood lactate concentration remained high for the remainder of the test (>11.5 $mmol.l^{-1}$).

The trends in performance shown by subjects 2 and 3, were similar. Both subjects showed a decrease in their work rate between 5 and 30 minutes whilst blood lactate concentration continued to rise. It would appear, therefore, that despite the decrease in work rate the rate of lactate production could not be matched by the rate of removal, and thus lactate was accumulating.

The largest decrease in the relative exercise intensity which could be tolerated during the test was exhibited by subject 1 (this subject actually had difficulty maintaining the required work rate during the initial 5 minutes of the test). The large decrease in this subjects work rate during T30min was matched by a decrease in blood lactate concentration between 10 and 20 minutes and would suggest that

the rate of lactate clearance during this time period was better than the rate of production. This concentration rose again, however, by the end of the test, probably as a direct consequence of the sprint finish of the subject, and thus the greater reliance on anaerobic metabolism.

The results of this preliminary experiment revealed that a major determinant of the performance on T30min was the accumulation of blood lactate following the initial 5 minutes of exercise at 90% $\dot{V}O_2max$. Even highly active subjects, such as those included in this study, were unable to tolerate the consequences of the first 5 minutes of performance, and in the case of one subject, who was able to increase his work rate, this small increase had a similar fatiguing effect.

A major problem associated with maximal effort during a test such as T30min is the pacing of the effort. Originally it was believed that by imposing a high initial work rate these difficulties could be overcome, since subjects would simply try and maintain as high a work rate as possible following the initial 5-minute period, thus producing a fatigue curve similar to that reported by Katch and Katch (1972). Such was not the case, however. Subject 1 explained that after the first 5 minutes of the test she intentionally decreased her work rate, paced her efforts during the middle stages of the test, and then tried to pick up the rate again towards the end of the test.

Personal communication with the subjects also revealed that all 4 subjects found the second test very difficult to face psychologically since they were aware of the physical discomfort they were about to experience. From the results of this study, and from personal communication with the subjects, it was concluded that an initial work rate of 90% $\dot{V}O_2max$ was too high, for the following reasons:

a) Since highly active subjects found it difficult to tolerate 5 minutes at such a high work rate it was possible that, following such intense exercise, untrained subjects would be forced to stop before the end of the test.
b) Psychologically it was very difficult to face.
c) It did not overcome the problem of pacing which was overcome to a certain extent by performing the test on two occasions.