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MEASUREMENT OF EXTERNAL POWER OUTPUT
DURING HIGH INTENSITY EXERCISE

by

Henryk Krzysztof August Lakomy

A Doctoral Thesis

Submitted in partial fulfilment of the requirements
for the award of Doctor of Philosophy of the
Loughborough University of Technology.

1st June 1988.

c by H. K. A. Lakomy (1988)
Friction-loaded cycle ergometers are widely used to measure the work done in short-duration high-intensity exercise. This work is calculated conventionally from the product of flywheel speed and resistive load. This method assumes the flywheel to revolve at a constant speed and does not take into account the work required to accelerate it (uncorrected method). This study examines the possible error resulting from such an assumption, and a new method of calculation is proposed (corrected method). This new method required high frequency logging of the flywheel speed by a microcomputer. Statistical comparison of the two methods of calculation for a 30s maximal sprint showed: (1) that when no correction is made for flywheel acceleration peak power output is greatly underestimated; (2) the time taken to reach peak power is shorter when corrected values are used; (3) the instantaneous values of power throughout the test are different; (4) the total work done during the 30s is independent of the method of calculation.

The effect of load (55-115 g.kg⁻¹ bodyweight) on peak and mean power output was investigated. Optimum uncorrected peak power output was found to occur at the heaviest loads, whereas, using the corrected method greatest peak power output occurred at the lightest loads. Using both methods of calculation the heavier loads were required for maximum mean power output.

By simply measuring the instantaneous speed of the flywheel coupled with the corrected method of calculation it was shown that the profile of the torque applied to the flywheel could be obtained. This finding suggests that torque profiles can be obtained on such ergometers without the need for instrumentation of the pedals.

The assessment of power output during running has proved difficult because previous approaches have limited themselves to using motorised treadmills. In the present study the development of a non-motorised sprint treadmill ergometer is described and its characteristics examined. In order to calculate the horizontal component of the power being applied to move the treadmill belt both the horizontal component of the applied force and the treadmill belt speed were measured and their product determined. Using the treadmill to evaluate performance it was found that: (1) the peak speed attained was approximately 65-80% that achieved during running on the track; (2) peak force is attained earlier than peak power and in turn peak power occurs before peak speed; (3) the force required to propel the treadmill belt at a constant speed increased with body weight; (4) power output increases with running speed; (5) stride length and frequency could be monitored throughout the test; (6) elasticity in the tethering system acted as a low pass filter.

Bilateral asymmetry of the propulsive forces during running were found to be detected by the treadmill ergometer. It may be possible, therefore, to use the treadmill as a diagnostic tool to reduce the risk of injury in sprinting.

On both the cycle and treadmill ergometers protocols were developed to examine repeated maximum short-duration exercise. The mechanisms causing fatigue during such tests were examined and it was proposed that much of the fatigue resulted from the intrinsic force-velocity relationship of the active muscles.
ACKNOWLEDGEMENTS

This work was completed in the Department of Physical Education and Sports Science, Loughborough University of Technology and was supported by the award of a scholarship from the Sports Council.

I am indebted to my supervisor Professor Clyde Williams for his support, advice and encouragement throughout the course of this study. It is impossible to express in words how grateful I am to him for enabling me to participate fully in all the aspects of the Department, including research, lecturing and coaching.

It gives me particular pleasure to be able to thank the members of Sports Science Research Group for all the friendship and help that they have offered. It has been a real privilege to have been able to work with them and I am proud to have been one of them. In particular I should like to thank Doctor Adrianne Hardman and Doctor Mary Cheetham for their close friendship and support.

Finally I wish to thank all those subjects who volunteered to take part in the studies described in this thesis, without whom none of this would have been possible.
PREFACE

Unless otherwise indicated by acknowledgements, footnotes or references to published literature, the work contained herein is that of the author.

Parts of this study has been published as follows:

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INTRODUCTION

In the past the physiological assessment of maximal performance has been mainly aimed at measuring maximum aerobic power. A good illustration of this is seen in the review article on laboratory techniques for measuring maximal performance by Nagle (1973). Seventeen pages of the review were needed to describe tests of the "capacity of aerobic metabolic mechanisms". In contrast, only one page was dedicated to tests of "anaerobic capacity". Nagle stated that "Unlike the measurement of the anaerobic capacity, a quantification of aerobic power in human performance is quite straightforward." It appears that the limitation to measurement of short duration maximal exercise has been one of methodology. Simple tests of performance were not available and the non-invasive methods available for measuring the metabolic responses to the exercise had too slow a response a time. In the last 30 years there have been two breakthroughs which have greatly stimulated interest in short duration maximal exercise. The first, in the 1960's, was the reintroduction by Bergstrom of the Duchenne needle biopsy technique which enabled close examination of muscle metabolism in exercise (Bergstrom, 1962). The second, in the 1970's, was a simple laboratory test using a cycle ergometer (Ayalon et al., 1975; Bar-Or, 1978) which allowed the time course of the external power output of the subject to be measured during a short duration maximum test. This new test, which used friction-loaded cycle ergometers already in use in exercise physiology laboratories, allowed peak power output to be calculated and the rate of decline of power output, resulting from the fatiguing processes, to be monitored. The strength of this new test was in its simplicity. The combination of the biopsy techniques and the new test enabled metabolic changes within the muscle and the gross performance of the muscle to be correlated.

Unfortunately, in a bid to make the performance test simple to operate a major factor was overlooked. In her paper of 1923 Sylvia Dickenson pointed out that "...when the bicycle is started from rest the force P is equal to aR, plus the rate of change of momentum of the moving parts, multiplied by a suitable constant." In an accelerating system work is
done in increasing the kinetic energy of the system. The power required to increase the energy of the system was not incorporated into the calculation of the power output during the new test, thus introducing an error of unknown magnitude. The error would tend to cause peak power output to be underestimated and power output during the subsequent decline in performance to be overestimated. It was noted by researchers using the new test that the peak power output values obtained were less than those obtained using other measurement techniques. Katch and Weltman (1979) suggested that the underestimation of true power output was due to "limitations in terms of maximal possible resistance, establishment of resistance, and inability to maintain constant force on the pedals throughout a full pedal cycle." No one has, however, questioned the method of calculation used. This thesis will examine the validity of the calculation techniques used and will describe the development of improved techniques. The magnitude of the error resulting from use of the traditional method of power output calculation will also be evaluated. The adoption of the new calculation technique resulted in a dramatic increase in the versatility of the friction-loaded cycle ergometer for the examination of muscle function. Some of the studies investigating this new use will be described.

On the cycle ergometer the subjects exercise whilst their bodyweight is being supported. Questions have been raised, by researchers, as to whether measurements of performance on cycle ergometers are valid predictors of running performance. An illustration may be drawn from the measurement of maximum oxygen uptake. Comparative studies by Hermansen and Saltin (1969) and McArdle, Katch and Pechar (1973) indicated that running on a treadmill gave values of maximum oxygen uptake higher than those given by the cycle ergometer. As running is the activity most common in sport then the cycle ergometer may well be limited in its use for evaluating performance. What is required is an ergometer which is as simple in its operation as the cycle ergometer, which allows maximum performance at every instant in time,
which allows the subject to reproduce the running action as closely as possible, and on which the power output can be measured.

In the past motorised treadmills have been used to examine short duration performance, but these do not fulfil the requirements described above. Tethered sprinting has been used, as early as 1928 (Best and Partridge), to examine the dynamics of sprint running. In this thesis a unique ergometer is described. The ergometer is based on a non-motorised treadmill which allows the subjects to sprint at speeds similar to those achieved in free running. The same variability of instantaneous work rate that is available on the cycle ergometer is also permitted on the new sprint ergometer. Instrumentation of the treadmill enabled the measurement of instantaneous power output and running speed. The characteristics of the ergometer will be fully evaluated and the results of performance tests using the ergometer will be discussed. The following flow diagram describes the structure of the thesis.
Following a brief review of the literature the thesis is divided into two sections, with each section having a similar structure.

In Section A the conventional method of calculation of power output on the friction-loaded cycle ergometer is questioned and a new method of obtaining more accurate values is fully described. The magnitude of the errors resulting from the use of the conventional method of calculation are assessed. The new techniques allow measurement of inter- and intra-pedal cycle variations of power output and torque production. Results from studies which examined these variations are reported. In addition to the 30s maximal performance test the development of two new tests are described. Each of the new tests uses the friction-loaded cycle ergometer to examine performance in repeated maximal short duration sprints. In the first test the duration of each exercise bout is fixed, whereas, in the second the total work done per sprint is set. On the fixed duration test sensitivity of the system to different groups and training status is examined. The effect of different work settings on fatigue is examined in the fixed work test.

Section B fully describes the development and the characteristics of a new sprint treadmill ergometer. The variables that can be measured on the ergometer, such as force, power output, running speed, stride length and frequency, are explained. The 30 second maximum sprint test, described for the cycle ergometer, is modified for use on the treadmill ergometer. The results from this test are reported, and the sensitivity of the system evaluated. The detection of asymmetry of the propulsive forces during the course of the test are discussed. Sprinting on the treadmill ergometer is compared with sprinting on the cycle ergometer and on the track. The similarities and differences between the different modes of exercise are highlighted. Sprinting performance on the track is shown to be highly correlated with performance on the sprint treadmill. As many sports can
be described as having periods of maximum activity interspersed with periods of recovery the use of the sprint treadmill for examining repeated maximum sprints is evaluated.

Finally, the general discussion will reflect on the results obtained from the two experimental sections and will suggest ideas for future development for short-duration maximum-intensity ergometry.
CHAPTER 2

LITERATURE REVIEW

This section is a brief review of the scientific literature which relates to this study. It will examine the following areas:

1. The methods used to determine the power output produced during exercise.
2. The metabolic processes producing the energy required for exercise.
3. The effect of duration of the exercise on mean power output.
4. The force-velocity relationship of muscle.
5. The differences between overground and treadmill running.
6. The sequential relationship of force, power and speed in a system free to accelerate.

More specific references to the literature have been included in chapters 3 to 11.

2:1 MEASUREMENT OF POWER IN EXERCISE

2:1.1 DEFINITION OF POWER

In a dynamic system a mechanical engineer calculates the power produced from the product of force and velocity or from torque and angular velocity, whereas an electrical engineer defines power as the product of potential difference, current and phase angle. Although these definitions appear to be different they are precise and unambiguous, and result in power being measured in the same unit — the Watt. The common factor behind all definitions of power is that they all determine the rate at which energy is being transferred within a system. As the total
energy in a closed system is always conserved then the power generated is independent of the form in which it is manifested, whether it be mechanical, electrical or chemical. All the definitions are, therefore, compatible.

2:1.2 GENERAL PROBLEMS OF POWER MEASUREMENT IN EXERCISE

The measurement of human power in exercise requires the determination of either the rate of chemical energy production (metabolic work rate) within the body or the rate at which the energy being produced is being dissipated into the external load (mechanical power). These two rates of energy production are linked by the efficiency ratio of the system (Williams and Cavanagh, 1983) termed work efficiency by Ralston (1976), where:

\[
\text{efficiency ratio} = \frac{\text{mechanical power}}{\text{metabolic work rate}}
\]

Often in exercise neither the metabolic work rate nor the mechanical power is readily measurable. Some of the difficulties encountered are listed below:

1. Energy for muscular contraction is produced from a combination of anaerobic and aerobic metabolism. As will be shown later in this review these energy systems are interactive. They not only combine in different proportions depending on the intensity and duration of the activity, but they also have different rates of energy production.

2. The efficiency ratio of the body is not a constant. It is dependant on such variables as stride length and stride frequency in running (Gaesser and Brooks, 1975), stroke rate in rowing (Secher, 1983), pedalling rate in cycling (McCartney, 1983). Although environmental conditions such as ambient temperature, pressure (hypoxia and hyperoxia) or dehydration does not effect efficiency (Saltin, 1964. Rowell, 1974), the core temperature, or warm-up status, of
the body does appear to influence efficiency (Asmussen and Boje, 1945. Muido, 1946. Nielson, 1969). Drinkwater (1973) showed that the menstruation cycle effected the efficiency ratio, and Rodahl et al. (1976) indicated that the energy cost of swimming was influenced by the circadian rhythm.

Efficiency is also constrained by mechanical limitations such as the crank length in cycling (Inbar et al, 1983), the weight of the projectile and the shoe ground interface (Luethi and Stacoff, 1987). The efficiency ratio is dependant on the intensity and duration of the exercise, and whether the activity is continuous or intermittent (Astrand et al, 1960. Christensen et al, 1960), as well as the posture adopted and the combination of muscles used to perform the exercise task (Vokac et al, 1975). Cavagna et al (1976) and Cavagna and Kaneko (1977) showed that the mechanical efficiency of running is a function of running speed.

Although no significant differences in the ratio of oxygen uptake to power output is reported for endurance running for subjects of different training status, there appears to be a very slight trend towards increased efficiency with training (Boje, 1944. P-O Astrand, 1956. Vokac and Rodahl, 1977). Saito et al (1983) found a significant difference in this ratio between 5 trained and 3 untrained runners sprinting for 400m on a track. Although the values for oxygen uptake were found to be the same for the two groups the external mechanical work done, determined from film analysis, was found to be lower in the trained group. The trained group, therefore, has a higher efficiency ratio.

3. The effects of the external forces are often difficult to determine e.g. in contact and ball sports. In these activities the external forces are complex and their influence on the rate of energy transfer difficult to measure.
The energy required to overcome air or water resistance is dependent not only on body posture and speed (Best and Partridge, 1928; Pugh, 1970), which are constantly varying in many activities, but also on temperature, pressure, wind direction etc.

4. There is a time lag between the start of the activity and the detection of the physiological response using non-invasive techniques. Explosive activities such as jumping, throwing, hitting etc. are often over before the techniques used for measuring the physiological demands of the activity begin to detect change, by which time 'noise' is being introduced into the system e.g. the CP degraded by the exercise has already begun to be re-phosphorylated (Boobis et al., 1983).

As a consequence of the difficulties of measuring the actual power generated during exercise variables which have been shown to be correlated with power, such as running speed, stepping frequency and height and speed of swimming and cycling, are measured and are used as indicators of the power generated during the exercise.

2.1.3 MEASUREMENT OF POWER IN RUNNING

The mechanical power generated during running has been examined, by researchers, in two ways.

1. 'Internal' work: A segmental approach, which looks at the transfer of energy within the segments as well as movements of the centre of mass.
2. 'External' work: Only the work done due to the forward and vertical velocity changes of the centre of mass is examined.
'INTERNAL' WORK.

As yet there is no agreement amongst researchers as to the correct method for determining indirectly the mechanical power during running. Several methods have been proposed which examine:

1. Movements of the centre of mass in combination with movements of the limbs relative to the centre of mass;

2. Pseudowork;

3. Segmental energy levels.

The remaining techniques, characterised by the fact that they all incorporate a segmental component in their analysis, examine the 'internal' work being done during running. Techniques based on evaluating the movements of the centre of mass in conjunction with movement of the limbs relative to the centre of mass have been used to examine sprinting (Fenn, 1930) and distance running (Cavagna et al, 1977). Power outputs ranging from approximately 340W, for distance running, to 2200W, for sprinting, were obtained.

Other segmental models which examine the segmental energy levels, joint power and energy transfer have been put forward. These include the analysis procedure termed pseudowork, proposed by Norman et al (1976), in which the absolute changes in the instantaneous energy of a segment's potential, translational kinetic and rotational kinetic energies are summed. This technique has been criticized by Pierrynowski et al (1980) for not allowing for energy exchange between forms within a segment. Other segmental models attempt to account for energy transfers both within and between segments (Winter, 1978 & 1979). All the segmental techniques rely on 3-D cinematography for instantaneous segment, or centre of mass, velocity determination, and are usually used in conjunction with
force analysis using force platforms. Many assumptions have to be made in the calculations including:

1. The type of muscular contraction.

   The relationship between the mechanical power and the metabolic power depends on the type of contraction (Abbott and Bigland, 1953. Nagle et al, 1965).

2. The release of energy stored in the elastic tissues.

   Energy previously stored in the elastic components of the musculo-skeletal system can be subsequently recovered during the next phase of the activity (Asmussen and Bonde-Peterson, 1974. Cavagna et al, 1971,1977).

3. The transfer of energy between segments.

   It is not always necessary for concentric muscular contraction to occur for transfer of energy between segments to occur.

Williams and Cavagna (1983) examined several of the computational techniques described above and obtained very different results for mechanical power depending upon the particular assumptions made and the technique employed. In their discussion they stated that "Even when the values are restricted to what might be considered reasonable upper and lower bounds there are still values differing by 270%". Their findings indicate a need for greater understanding of the role played by energy transfer, negative work, and elastic storage of energy before a greater degree of confidence can be established in the measurement of mechanical power in running.
'EXTERNAL' WORK.
This technique for measuring the power generated during running examines the work done against gravity, the work due to the forward velocity changes, and the work due to the total mechanical energy changes of the centre of mass of the body only (Cavagna et al, 1971, 1976, 1977; Fukunaga et al, 1978). These changes are mainly due to the interaction between the body and the ground and are responsible for kinetic and potential changes, which represent a large fraction of the mechanical work that the muscles must do to maintain locomotion. As the present study examines the 'external' power generated during running, a more extensive review of the findings of the research in this area will be outlined.

In 1963 Cavagna and colleagues noted that during walking the potential and kinetic energy changes are in opposite phases, and as a consequence the recovery of mechanical energy, due to the pendular characteristic of walking, reached maximum values of 65% (Cavagna et al, 1976). During running, however, the potential and kinetic energy changes are in phase (Fenn, 1930; Cavagna et al, 1964) resulting in less than 4% recovery of the mechanical energy. As there is minimal recovery of mechanical energy in running the total external work must be the sum of the work done against gravity ($W_v$) and the work due to the forward velocity changes ($W_f$).

$$W_{ext} = W_f + W_v$$

The findings by Cavagna et al. (1976) and Fukunaga et al. (1980) indicate that the relationship between the work done due to forward velocity changes ($W_f$) increases exponentially with the speed of running ($V_r$).

a. Cavagna et al: $W_f = aV_r^2 / (1 + bV_r)$

(where $b$ is the ratio between time spent in the air and
the forward distance covered while on the ground during each step)

\[ b. \text{ Fukunaga et al: } W_e = 0.263V_e - 0.252 \]

Both groups reported that \( W_{ext} \) increases linearly with running speed, with \( W_e \) remaining constant.

Examination of the Cavagna equation above indicates that to reduce \( W_e \), at a given running speed, the ratio \( b \) must be increased. In order to achieve this the vertical component of the push and, therefore, the time spent in the air would have to be increased. This would result in an increase in \( W_v \). Both research groups authors reported that the work done against gravity (\( W_v \)) is independent of running speed, and, therefore, the direction of the push during running is such as to minimise \( W_{ext} \) rather than \( W_e \).

The finding that \( W_v \) is independent of running speed is of particular importance with regard to the present study.

Matsuo and Fukunaga (1983) reported that the external mechanical work, expressed per unit of body weight, was independent of age and sex.

The techniques used to measure the external power in running have been criticised by Cavagna et al. (1977) and Winter (1978) for not taking into account the work being done by the limbs and, therefore, significantly underestimating the total work done. The total mechanical work being the sum of the external and internal work:

\[ W_{tot} = W_{ext} + W_{int} \]

Although there is wide support for this statement work by Sakurai and Miyashita (1983) indicated a very high linear relationship between \( W_{tot} \) and \( W_{ext} \) (coefficient of correlation > 0.9, \( p<0.001 \)). These authors state that "at
relatively low speeds, Power\textsubscript{\text{e.s.}}, tended to be lower than Power\textsubscript{\text{tot.}}, but there was no clear difference between them at high speeds. These results did not coincide with the results from examining walking described by Winter (1979).
characteristics have been predetermined (Clarke and Greenleaf, 1971).

The friction-loaded cycle ergometers do not require such calibration. They rely on balancing of torques, where the torque being applied to the flywheel by the subject must be equal to the torque generated by the load, if the mean flywheel speed remains constant (Martin, 1914; Dickinson, 1928; von Dobeln, 1954). On such ergometers the external power is calculated from the product of the resistive load and the flywheel speed. The calculation of the work done and the power output, using this method assumes that the flywheel is revolving at a constant mean angular velocity. In most endurance tests the subjects are required to maintain a constant pedalling speed and, therefore, this condition is satisfied.

It is of interest to note that in 1928 Dickenson mentioned the problems of the work being done in accelerating the flywheel. In her description of a study examining the dynamics of pedalling on a friction loaded cycle ergometer she stated that "Now when the bicycle is started from rest, the force $P$ is equal to $aR$, plus the rate of change of momentum of the moving parts, multiplied by a suitable constant." Dickenson overcame the problem of not being able to measure the rate of change of momentum by examining the forces at maximum pedalling speed at which no acceleration was taking place and, therefore, no change of momentum. No reference to this Dickenson's paper has been made in any of the recent studies that have been reviewed in which power output has been measured and where flywheel acceleration is taking place. In these studies the problems caused by the rate of change of momentum have been ignored.

Recently tests using friction-loaded cycle ergometers have been developed to evaluate the maximal external power generated during short duration exercise (Ayalon et al, 1975; Bar-Or, 1978). These tests have become widely
accepted as useful tests of anaerobic performance capacity. Calculation of the external power generated in these tests use the method described by von Dobeln. However, for this method of calculation to be valid the flywheel must be revolving at a constant mean angular velocity. This requirement is not satisfied as acceleration of the flywheel is occurring.

There are currently several protocols adopted for applying the load in these tests. The load is applied either when the cycle is at rest or when the subjects are initially cycling against a minimal load, either at maximum speed (Bar-Or, 1978) or at a predetermined sub-maximal speed (Wootton, 1984). Thereafter, the subjects pedal at maximal intensity accelerating the flywheel.

Several studies have examined load optimisation in such tests (Evans and Quinney, 1981; Nadeau et al, 1983). In these studies peak and mean external power outputs were measured at different load settings. A more sophisticated technique for examining load optimisation was proposed by Nakamura et al (1985) in which a regression equation for maximal pedalling speed against applied load was obtained for each subject. The values of slope and intercept, obtained from the regression equation, were fed into a quadratic equation which predicted the maximum power output that the subject could generate. The load that would be required for the subject to achieve this maximum value of power output was also predicted. All the optimisation studies report that high values of applied load are required if the greatest values of peak and mean power output are to be achieved. These high loads were found to restrict the peak pedalling speeds attained by the subjects. Using constant velocity ergometers, on which the subjects are required to pedal at maximum intensity at a speed set by an electric motor connected to the pedal cranks, Sargeant et al (1981) and McCartney et al. (1983) reported a parabolic relationship between peak power output
and pedalling speed, with the maxima of the function being at around 110-120 r.p.m. This value of optimum pedalling speed is similar to those found for the friction-loaded cycle ergometers.

It must be noted, however, that the values of peak power output achieved on the constant velocity cycle ergometers were significantly greater than those generated on the friction-loaded ergometers, even when load optimisation was applied. Katch and Weltman (1979) commented on the fact that peak power output on friction-loaded cycle ergometers was always lower than those measured in other ways, such as stair running (Margaria, 1966), suggesting that it was due to "limitations in terms of maximal possible resistance, establishment of resistance, and inability to maintain constant force on the pedals throughout a full pedal cycle".

Further differences have been reported between constant velocity and friction-loaded cycle ergometers. McCartney et al. (1983) reported that the time taken to reach peak power output on the constant velocity ergometer was less than 3 seconds, with pedalling speeds of 100 to 140 r.p.m. At comparable pedalling speeds the time taken to reach peak power output on friction-loaded ergometers was substantially greater, 3 to 8 seconds (Bar-Or, 1978; Katch et al., 1977; Weltman, 1978).
2.2 THE METABOLIC PROCESSES PRODUCING ENERGY FOR SHORT DURATION MAXIMAL EXERCISE.

Short duration maximum exercise that is either continuous or intermittent requires a very high rate of energy provision. This energy for muscular contraction and movement relies exclusively on the hydrolysis of high-energy adenosine triphosphate (ATP) which is stored in the skeletal muscle. The basic equation of energy production from ATP is

\[ \text{ATP} + \text{H}_2\text{O} \rightarrow \text{ADP} + \text{Pi} + \text{ENERGY} \]

Boobis et al. (1983) measured the quantity of ATP present in resting muscle, in males, and found it to be approximately 24 m.mole.kg\(^{-1}\) dry weight. Even if the body were to allow total usage of this store muscle contraction would only be possible for a few moments. Sahlin (1986) predicted that the total ATP stores could supply energy for only 0.03 minutes at an exercise intensity of 70%\(\text{VO}_2\text{max}\). The body, however, attempts to prevent a reduction in the ATP stores by rephosphorylation or, if this is not sufficiently rapid, by decreasing the rate of energy provision and, therefore, external power.

The capacity for energy provision for rephosphorylation by oxidative metabolism is very large. Unfortunately the metabolic pathway is too slow for it to meet the energy demands of maximal exercise. Other metabolic pathways are, therefore, utilised to produce the energy required. It should be noted that although aerobic metabolism is too slow to meet the total energy demands of short duration maximal exercise it does provide some energy (Cheetham 1987). The other available pathways for energy provision for re-phosphorylation are phosphocreatine (CP) utilisation and anaerobic glycolysis.
2:2.1 PHOSPHOCREATINE UTILISATION.

Utilisation of CP is stimulated by an increase in ADP which occurs when ATP is hydrolysed. Under the control of the enzyme creatine kinase the rate of energy provision from CP being converted to creatine is so rapid that the concentration of ATP can be well maintained as long as the concentration of CP is not significantly reduced.

\[
\text{ADP} + \text{CP} \rightarrow \text{ATP} + \text{C}
\]

Boobis et al. (1983) reported resting levels of CP of 84 m.mole.kg\(^{-1}\) dry weight. As with ATP this is a relatively small store of energy and, therefore, if the utilisation rate of this and the ATP store are not immediately matched by an identical rate of restoration then exercise will not be able to continue for long. Sahlin (1986) calculated that at an exercise intensity of 70%\(\text{Vo}_{2}\text{max}\) the total CP stores could supply energy for about 0.5 minutes.

2:2.2 ANAEROBIC GLYCOLYSIS.

The increase in Ca\(^{++}\), released from the sarcoplasmic reticulum, and the increased levels of Pi stimulate glycogen degradation via the transformation of phosphorylase a to phosphorylase b, i.e. from the inactive to the active state. To maintain the flux down the metabolic pathway from G-3-P to G-1-3-P a continuous supply of NAD is required. Normally this requirement is met by re-oxidation of NAD from NADH/H\(^{-}\) by oxidative phosphorylation in the respiratory chain. However, in maximal short duration exercise the majority of the re-oxidation process is achieved by reducing pyruvate to lactate. The metabolic pathways for energy production are shown in Figure 2.1.
Figure 2.1 Metabolic pathway for energy production in skeletal muscle.
2.2.3 METABOLIC RESPONSES TO MAXIMAL SHORT DURATION EXERCISE.

Before examining the metabolic responses to maximal exercise the term 'maximal exercise' must be defined. Often exercise intensities are expressed relative to the individual's maximum oxygen uptake (\(\dot{VO}_{2\max}\)). During steady state exercise the oxygen cost of the exercise can be determined and related to the individual's \(\dot{VO}_{2\max}\), from which the relative intensity of the exercise can be calculated, and expressed as a percentage of \(\dot{VO}_{2\max}\). In activities lasting only a few seconds the maximum intensity of exercise that the subject can attain is several times that which can be met by aerobic metabolism (Wootton, 1984). These types of activities are sometimes termed 'supra-maximal' when related to \(\dot{VO}_{2\max}\). In exercise of short duration the maximum energy expenditure varies rapidly with exercise duration. Because of this rapid change in power output it is of limited value to attempt to relate the exercise intensity to \(\dot{VO}_{2\max}\).

Margaria (1964) and Margaria and Di Prampero (1969) proposed that repeated bouts of "supra-maximal" exercise lasting 10-15 seconds could be repeated indefinitely without decline in performance and increase in blood lactate, as long as the recovery period was at least 25 seconds. It was suggested that the energy supply required for this type of activity could be met by utilisation of the ATP and CP stores, and that the stores would be replenished during the recovery period. It was proposed that anaerobic glycolysis would only be initiated after significant depletion of the stores had taken place. Saltin and Essen (1971) gave further support for this view. In contrast Pernon and Wahren (1968) reported significant increases in blood lactate following 5 seconds of forearm activity. In 1983 elevations in muscle lactate following 10 seconds of maximal cycling exercise was reported by Jacobs and colleagues. Using muscle biopsy techniques, they reported that the increased level of muscle lactate concentration measured after just 10 seconds of activity averaged 59% of that measured after 30 seconds of
maximal exercise (Wingate test). In the same year Boobis and co-workers reported significantly increased levels of both muscle lactate concentration and glycolytic intermediates following just 6 seconds of maximal cycling. The conclusion drawn from the study was that glycogenolytic processes are initiated within the first six seconds of exercise and that, in conjunction with CP degradation, the processes would contribute to the provision of energy during maximal dynamic exercise. Hultman and Sjoholm (1983), using electrical muscle stimulation techniques in conjunction with muscle biopsies, provided further supporting evidence that anaerobic glycolysis is initiated during the first few moments of exercise.

Wootton and Williams (1983) suggested that the differences in the findings above reflect the magnitude of the exercise intensity which were felt to be greater in the studies by Jacobs et al. (1983) and Boobis et al. (1983) then in those by Margaria (1964) and Saltin and Essen (1971). In the study reported by Wootton and Williams, in which the exercise intensity was 'truly maximum' it was found that even when 60 seconds of recovery was permitted between the 6 second bouts of exercise, incomplete recovery of the CP stores occurred.

It would appear that in short duration maximal exercise much of the energy required is provided from anaerobic glycolysis, even in the first few seconds of the exercise. In addition the rapid replenishment of ATP occurs at the expense of CP stores within the muscle. The combination of the depletion of the CP stores and the increase in muscle acidosis will reduce the ability of the muscle fibres to maintain contractile force with increasing exercise duration. The maximum external power output will, therefore, be a function of the exercise duration.
2.3 THE EFFECT OF DURATION OF EXERCISE ON MEAN POWER OUTPUT

"It has been well recognised that power output in man increases rapidly with decreasing duration of effort..." (Davies and Rennie, 1968).

This brief review of the literature will examine some studies in which maximum external power output was measured during different durations of exercise.

Wilkie (1960) argued that the theoretical limit of power output in normal man is about 5hp (3700W). This figure assumed complete and simultaneous contraction of all antagonistic pairs of muscles within the body. This requirement cannot be met in activities such as jumping, cycling or running.

Tests with the shortest exercise duration in which maximum power output has been measured, around 0.1s, have used force platforms. Davies and Rennie (1968) and Davies (1971) reported the results of a study in which 47 male and 8 female subjects performed maximum vertical jumps off both feet from a force platform. They found that mean values achieved were 5.23 hp (3830W), for the males, and 3.15 hp (2350W), for the females. In this study Power output was calculated from the product of the force applied to the platform and the velocity of the centre of gravity, calculated from the integral of the acceleration curve.

The values of power output obtained from this study are greater than those predicted by Wilkie. Cavagna et al. (1964) has shown that energy can be stored in the elastic component of the muscle. If this energy is stored during the counter-movement and recovered during the subsequent concentric contraction phase of the movement then the power outputs in excess of 5hp, seen in this study, are easily possible.

Cavagna et al. (1965) estimated the power output generated
by sprinters at the beginning of a race over a time period
of about 0.3-0.5 seconds. He found that they were capable of
outputs of around 3hp (2200W).

Of slightly longer duration, about 3 seconds, is the stair
running test described by Margaria et al. (1966). The time
taken for the subjects to run up a set of stairs was
measured. Margaria showed that the running speed reached a
maximum after about 2 seconds and, thereafter, remained
fairly constant. It could be shown that, by allowing
sufficient run up, most of the energy expended was used in
lifting the body weight. The mechanical power output could
be calculated from the product of the vertical component of
the running speed and the weight of the subject. Maximum
mean power outputs were found to be around 1100W or about
25% of the value obtained from the force platform.

If the exercise duration is extended to 6 seconds, then mean
power output is further reduced. Wootton and Williams (1983)
reported that the maximum mean power output that could be
generated on a friction-loaded cycle ergometer over 6
seconds was approximately 800W. For 10 seconds of maximum
effort of an isokinetic cycle ergometer McCartney et al.
(1983) reported values of around 900W.

Nagle (1973) described how maximal running of 30 seconds
duration resulted in maximum power outputs of around 0.7-0.8
hp (520 to 600W). A corresponding value of around 700W was
reported by McCartney et al. (1983, 1986) for 30 seconds
maximal effort on an isokinetic cycle ergometer.

Mayes (1986) asked a group of male subjects to work as hard
as possible for 30 minutes on a friction-loaded cycle
ergometer. She found that the mean power output achieved was
around 225W.

Costill (1970) reported power outputs equivalent to 280W for
highly trained marathon runners exercising for 2.5 hours,
whilst this value dropped to around 94W for untrained males
Figure 2.2 shows the maximum power output as a function of time (Wilkie, 1960). A similar profile is shown in Figure 2.3, which is adapted from Fletcher (1964). Each of the figures suggests a different half-life for power output. Figure 2.2 indicates that power output will drop to half the initial after less than 5 seconds. The corresponding value estimated from Figure 2.3 is around 27 seconds, reflecting the lower initial value used by Fletcher.

It is clear that the maximum external power output decreases "exponentially with time...and continues to decline dramatically until aerobic synthesis of ATP begins to keep pace with the rate at which it is being utilised." (Nagle, 1973).

2.4 THE FORCE-VELOCITY RELATIONSHIP OF MUSCLE

A.V. Hill (1938) observed that the force produced by a muscle appeared to be function of its velocity of shortening. He equated mechanical and thermal measurements and developed the following equation to describe the relationship between force and velocity of shortening of muscle.

\[(P + a)(V + b) = (Po + a)b\]

where: P = force
V = velocity
Po = Maximal isometric force
a = constant with units of force
b = constant with units of velocity

This equation describes only muscle contracting concentrically. Huxley (1957) developed an equation which was based upon the kinetics of cross-bridge interaction, which would appear to be a more fundamental approach to the nature of the F-V relationship than that based on measurements of heat. Hill's equation has, however, been successfully applied to a wide variety of muscles from many
Figure 2.2 Maximum power output as a function of time of performance (After Wilkie, 1960).

Figure 2.3 Semi-log plot of energy requirement in $O_2$ equivalents and horsepower as a function of time of performance (Adapted from Fletcher, 1964).
different species (Abbott and Wilkie, 1953). The constant $a$ and the values of $P_0$ and $V_0$ (the maximum unloaded contraction velocity) varied for these different muscles. In 1984 Mashima produced a summary of the $F-V$ relationship for many different striated muscles.

In 1940 Hill made the first significant attempt to assess the applicability of his equation to human muscles. He examined data on elbow flexion from his work and that by Lupton (Hill, 1922; Hill et al., 1924; Lupton, 1922). He suggested that the equation was applicable to human muscular contraction, a finding that was supported by Dern, Levine and Blair (1947). In 1950 Wilkie reported the results from a classical study on the force-velocity relationship in human elbow flexion. Wilkie expressed his results in terms of a single equivalent muscle at the hand and found that the Hill equation did not fit the data obtained when loads of less than 30% of maximum isometric contraction was used. When the data was corrected for acceleration the data was found to be adequately described by Hill's equation. Further supporting evidence is supplied by others who measured direct readings of force (Cavagna and Grieve, 1970; Pertuzon and Bouisset, 1973). To interpret the $F-V$ relationships obtained, the muscle must be subdivided into two components. The contractile component (CC), which is the component that shortens, and the elastic component (EC), which describes a property of the muscle and connective tissues. The force produced by the CC is transmitted to the external load by the EC. The rate of stretch of the EC will depend on the rate of change of force of the CC. If there is a change of force taking place in the CC then stretching of the EC will result. As a consequence the velocity of contraction of the muscle will not equal that of the CC. In order to correctly measure the velocity of shortening of the CC the velocity of stretch of the EC must be zero. If this is done then the correct $F-V$ relationship of muscle can be determined. The analysis performed by Cavagna and Grieve (1970) was based on the above analytic process and a reasonable fit for Hill's equation was obtained for the CC. In contrast, however,
Baildon and Chapman (1983), using the same analytic technique found Hill's equation to be a poor fit to the data. In their case the F—V relationship represented the combined action of a number of muscles, during forearm rotation. They felt that the complex anatomy of these muscles may not behave like a single muscle for which Hill's equation was derived.

Several devices have been designed that keep the external angular velocity of the limb constant. Such devices have been used to examine the F—V relationship of muscles. As described above it is the force generated in the muscle, not the external angular velocity of the limb, that should be kept constant so that stretching of the EC does not occur and a true F—V relationship obtained.

Hill's equation has always been regarded as inadequate to fit the eccentric F—V relationship (Katz, 1939). Studies have shown that the maximum eccentric force can be up to 30% greater than the maximum isometric force, and that the force depends on the velocity of contraction (Cavagna et al., 1968; Grieve and Arnott, 1970).

It should be noted that the F—V relationship of muscle is modified by other factors including, the length of the muscle at which the contraction is taking place (Wilkie, 1968), its fiber composition (Wells, 1967), and the state of fatigue of the muscle.

Chapman (1985) states that "While the F—V relationship has not been verified as being universally applicable through all muscle groups within the human body, such evidence as is available does suggest that that groups of muscles exhibit some form of F—V relationship which is probably the result of a combination of several intrinsic F—V relationships within the group."

Prior to 1938 a linear relationship was thought to exist between maximum exerted force and speed of movement (Hill,
1922; Lupton 1923; Furusawa et al., 1927). Dickenson (1928) reported one of the earliest examinations of the force-velocity relationships of human muscle groups during cycling. The ergometer used was friction-loaded, on which the differences in the forces across the belt, applying friction to a flywheel, was measured. Dickenson reported that the maximum speed of pedalling was a function of the applied load. Furthermore, she found that the relationship between maximum pedalling speed and applied load was linear. She deduced that "bicycling pedalling, as other forms of movement involving the overcoming of an external resistance, will show an optimum speed at which mechanical efficiency is highest".

Following Hill's paper in 1938 many studies have described a curve for the relationship between maximum force and velocity. Sjogaard (1978) mapped out the force-velocity curve for for cycle exercise. In this study the exercise was performed on a Krogh cycle ergometer equipped with strain gauges for measuring the force applied to the pedals. Although the experimental results did not fit Hill's equation a curve was, nevertheless, obtained for the F-V relationship. The curve obtained differed from that predicted by Hill in that it tended to level off with increasing speed, in a manner similar to that reported by Cavagna et al. (1971) for sprint running.

If a limited range of pedalling speed is examined then once again a linear relationship between force and velocity has been reported. This linear relationship was described by McCartney et al. (1983) using a constant velocity cycle for a pedalling rate range of 60 to 160 r.p.m. ($r=-0.997$). Using a friction-loaded ergometer Nakamura (1985) reported a linear relationship ($r<-0.976$) for the range 110 to 225 pedal r.p.m. It would appear that we have come full circle and that for the normal range of pedalling rate used in the laboratory the relationship between maximum force and speed can be considered to be inversely and linearly related.
2:5 THE DIFFERENCES BETWEEN OVERGROUND AND TREADMILL RUNNING.

An extensive search through the literature has not revealed any papers on the analysis of the running gait on non-motorised treadmills and, therefore, this section of the review will be limited to examining the effect of running speed on gait and the differences and similarities between running on the track and on a motorised treadmill.

The velocity of running is determined from the product of stride rate and stride length (Dillman, 1975). The speed of running can, therefore, be increased by increasing one or both of these components.

2:5.1 PHASES OF THE RUNNING STRIDE.

The stride can be sub-divided into two distinct phases, namely the flight phase and the support phase. The runner is in the flight phase when neither foot is in contact with the ground, i.e. the time from the last contact of the ground at toe-off of one foot to the first touchdown by the other foot. The support phase starts at the moment a part of the foot touches the ground until that foot leaves the ground. Stride rate can, therefore, be defined as:

\[
\text{Stride rate} = \frac{60}{(\text{time of support phase} + \text{time of flight phase})}
\]

The running stride is characterised by having a flight phase whereas walking does not.

Stride length can be defined as the distance between initial foot contact of one leg to the initial foot contact of the next leg.
2:5.2 CHANGES IN THE STRIDE CYCLE WITH RUNNING SPEED.

Luhtanen and Komi (1977) filmed 6 national level track and field athletes running at speeds ranging from 3.9 to 9.3 m.s\(^{-1}\) (40 - 100% maximum speed), on an indoor track, to examine flight time (FT), contact time or support phase time (CT), stride length (SL), and stride rate (SR) during one step cycle. They found that both SL and SR increased with running speed. The increases in the two parameters were not, however, linear. At the higher speeds SL levelled off whereas the rate of increase in SR became greater. These findings of an increase in SL and SR with running speed are in agreement with the findings by other researchers for both track and treadmill running (Cavagna et al, 1965; Osterhoudt, 1968; Sinnig and Forsyth, 1970; Buchanan, 1971; Kurrakin, 1972; Nelson et al, 1972; Hoshikawa et al, 1973; Saito et al, 1974; Dillman, 1975; Ballreich, 1976). Figure 2.4 (from Dillman, 1975) illustrates the typical curvilinear relationship found between stride length and velocity of running. The dashed line of best fit at the higher speeds reflects the slight decrease in stride length at maximal running speeds reported by some investigators. Figure 2.5 illustrates the relationship between stride rate and running velocity. In order to increase running velocity it can be seen that the change in stride rate must become progressively greater.

The time for one step cycle decreased with increasing running speed, with decreases occurring in both CT and FT, but at different non-linear rates (Luhtanen and Komi, 1977). The flight time decreased more rapidly than contact time. The contact time becomes relatively longer with increasing running speed. The movement of the whole body centre of gravity (CG) was found to decrease with increasing running speed. It is this reduction of vertical movement of the body which may be practically limiting any further increases in maximum speed by increasing SL. Despite the deceleration phase of the contact time remaining a constant fraction of the total contact time (approximately one-third) it would
Figure 2.4 Relationship between stride length and horizontal running velocity (From Dillman, 1975).
Figure 2.5 Relationship between stride rate and horizontal running velocity (From Dillman, 1975).
appear that man is limited in his capacity to increase the storage and utilization of elastic energy in the leg extensor muscles, otherwise vertical oscillation of the CG of the whole body would be maintained, thereby allowing stride length to increase. This limitation of storage and utilisation of elastic energy has been demonstrated in plyometric jumping from varying drop heights by Asmussen and Bonde-Petersen (1974) and Komi and Bosco (1978).

Although stride length and stride rate were found to increase with increasing speed of running on both the track and the treadmill, researchers have shown that running on the different surfaces can result in the absolute magnitudes of these variables being different. The results from a study by Nelson et al (1972) on 16 athletes showed that runners have a longer stride length on the treadmill than on the track. These results are in contrast with those of Elliott and Blanksby (1976) and Dal Monte (1973) who found stride lengths to be shorter on the treadmill than on the track.

Nelson et al (1972) and Dal Monte (1973) both report that the vertical displacement of the centre of mass is less for treadmill running than for running on the track, for running speeds ranging from 3.55 to 6.4 m.s\(^{-1}\). This difference in running style was shown by Nelson to increase with the speed of running, whereas, Dal Monte's results showed the opposite tendency. It should be noted that the study by Dal Monte used only 3 subjects who were, however, highly habituated to treadmill running whereas in Norman's study running on the treadmill was a relatively novel experience for the 16 subjects examined. It is possible that the level of habituation will effect the results.

A further difference in treadmill and and track running was shown by Norman et al (1972) to be in the duration of the support phase. This was found to be longer on the treadmill and was as a result of the tendency for the initial contact of the foot to be made further in front of the centre of mass of the body. These differences, however, were not
2.5.3 THE EFFECTS OF AIR RESISTANCE.

One of the major differences between track and treadmill running is that on the treadmill the subject is not moving relative to the surrounding air and as a consequence is not suffering the drag due to air resistance that the track runner must endure. Hill (1927) investigated the effect of air resistance by measuring the pressure exerted on models at different wind speeds. From his results he stated that resistance to motion through the air depended on the air density, the surface area presented to the air and the square of the velocity. He concluded that air resistance accounted for about 3-5% of the total energy requirement of running. Pugh (1969) felt that the results by Hill underestimated the percentage of the total energy used in overcoming air resistance.

In his study Pugh used indirect calorimetry techniques to discover the amount of energy used to overcome air resistance in running. Expired air was collected whilst the 9 runners were running at step-wise increasing running speeds on a track (2.2 - 6 m.s⁻¹). In addition 2 runners ran on a motorised treadmill in a wind tunnel, again with collection of expired air. The results were compared with running on the treadmill in still air and showed that whereas on the treadmill in still air the the relationship between running speed and oxygen uptake was linear on the track the relationship was curvilinear. Pugh conceded that his data could, however, be adequately represented by a linear regression, however, the slope of the regression line was found to be substantially steeper than the regression line slope for treadmill running.

Pugh found that the difference between running on the treadmill and running on the track in calm air was a function of the cube of the running velocity. The magnitude of the drag being proportional to the velocity squared, which is in agreement with Hill (1927). He estimated that

reported by Dal Monte.
the energy cost of overcoming air resistance in track running to be about 8% of the total energy cost of running at 6 m.s⁻¹ rising to about 16% for sprinting 100m in 10.0 seconds. Dal Monte et al. (1973) compared the energy expenditure between treadmill and track running at given speeds. They did not find the expected reduced energy requirement of running on the treadmill.

In summary, the studies which have compared the mechanical differences between running on the treadmill and running overground have reported conflicting results. In several studies three or fewer subjects were used which may limit the reliability of the results obtained. In those studies in which significant differences have been reported between treadmill and overground running the running speeds were generally greater than 5m.s⁻¹.

2:6 THE SEQUENTIAL RELATIONSHIP BETWEEN PEAK FORCE, POWER AND SPEED IN A SYSTEM FREE TO ACCELERATE.

In section 2:4 the force-velocity relationship of human muscle was examined. It was concluded that although contraction of some muscle groups might not be fully described by Hill's equation, they do follow its general trend. Re-arranging Hill's equation for force gives

\[ P = \left( \frac{P_o + a}{b (V + b)} \right) - a \]

It can be seen that \( P \) is a maximum (\( =P_o \)) when \( V \) is a minimum (isometric contraction).

Power is the product of force and velocity. Re-arranging the equation for power gives

\[ P \cdot V = P_o \cdot b - aV - Pb \]

substituting for \( P \) in the right hand side of the equation gives
\[ P.V = P_0 \cdot b - aV - \left[ \left( \frac{(Po + a)b}{(V + b)} \right) - a \right]b \]

Because of the relative magnitudes of the constants \( a \) and \( b \) it can be shown that power is maximised when \( V \) is approximately 30% of \( V_{\text{max}} \).

To examine when velocity is maximised Hill's equation can be re-arrange to give

\[ V = \left( \frac{(Po + a)b}{(P + a)} \right) - b \]

The value of velocity is at a maximum when \( P \) is at a minimum.

Based on the above results it can be seen that, in a normal movement which starts at a low or zero velocity, peak force is generated at this low speed of contraction. Due to the acceleration resulting from the force of contraction the velocity of the limb and, therefore, the contraction velocity increases until the power output is optimised. Whilst the limb is increasing in speed the force generated by the muscle falls. The limb then continues to accelerate beyond the peak power point until maximum velocity is attained, with power output declining. The above events are characterised by the following sequence:

Peak force precedes peak power, which in turn precedes peak speed.

It is important that the limb is free to accelerate for this sequential relationship to be correct. In a restricted movement peak values may be coincident.

Further support of this sequential relationship can be obtained from experimental results. If we examine the vertical force profile, in Figure 2.6, obtained from jumping off a force platform we can see that if we superimpose the calculated power applied to the centre of gravity of the subject, and the speed at which it is moving, we can see the sequential relationship of these variables. As predicted
Figure 2.6 A typical relationship between force, power and speed during a standing jump on a force platform.
from above peak force occurred before peak power. Peak speed is attained at the moment of leaving the platform when no further force could be applied. The same result was shown by Davies and Rennie (1968).
CHAPTER 3

INTRODUCTION TO SECTION A

Friction-loaded cycle ergometers have become widely used to measure the work done both in endurance activities and in short-duration high intensity exercise. This was due to the ease and accuracy with which the work intensity can be set and monitored. Work rate can be set by applying a known load and maintaining a steady predetermined pedalling frequency, or can be monitored by simply counting the number of pedal revolutions performed in a fixed time interval against a known load, thus allowing great flexibility in the instantaneous pedalling speeds investigated, whilst still maintaining accuracy in measurement of work rate.

3.1 DEVELOPMENT OF THE FRICTION-LOADED CYCLE ERGOMETER.

In 1913 Krogh presented a paper in which he described an ergometer which could be used to measure accurately the work done during cycling. Since this early work other researchers, such as Fleisch (1950) have developed and described ergometers which have adopted different approaches to the problem of measuring the work being performed during cycling. The drawback of the ergometers being developed was not one of accuracy but one of price. In 1954 von Dobeln described a cheap but accurate cycle ergometer which used the principle of the sinus balance to "weigh" the resistive torques being applied to the flywheel of the ergometer. Von Dobeln attached a steel band to the back wheel of a stationary cycle to give a cylindrical surface. A strap brake was fitted to this surface, the pull of which could be adjusted. The frictional force acting on the strap brake to retard the flywheel is the difference between the forces at the two ends of the belt, shown in Figure 3.1. The work done by a
Figure 3.1 The frictional forces acting to retard the flywheel.

Figure 3.2 Components of the commercial ergometer based on the Sinus balance.
mechanical system is determined from the product of the applied force and distance travelled by the point of application of the force. Consequently the work done on such an ergometer is equal to the product of the frictional force, the circumference of the flywheel and the total number of flywheel revolutions. Figure 3.2 shows how the difference in the forces at the two ends of the belt was determined on the commercial ergometer using a sinus balance. If the tensions at the two ends of the belt are $F_1$ and $F_2$ then equilibrium of the sinus balance is achieved when

\[(F_1 - F_2) \times r_1 = B \times r_2 \times \sin(a)\]

where: $r_1$ is radius of sinus wheel  
$r_2$ is the length of the pendulum  
$B$ is the weight of the pendulum  

Precalibration of the sinus balance scale is achieved by removing the belt and hanging a series of known weights in place of $F_1$, with no force acting at $F_2$. If the sinus balance scale is calibrated in Newtons, then the work done on the ergometer, according to von Dobeln, is

\[W \ (J) = \text{Sinus reading (N)} \times \text{flywheel circumference (m)} \times NR\]

where: $NR$ is the number of flywheel revolutions

Based on this method of determining work done, power is calculated by dividing the work done by the time taken to do the work. If the time taken is $T$ seconds, then the power applied to the flywheel is

\[P = \frac{W}{T} \ (\text{Watts})\]
These calculations do not take into account the losses due to either the friction in the transmission system, or those caused by the cyclic acceleration and deceleration of the flywheel during the pedal revolution.

Monark-Crescent AB developed a range of friction loaded cycle ergometers based on the system developed by von Dobeln. Figure 3.3 shows a recent development in which the balance arm of the sinus balance has been replaced by a suspended weight. As with the sinus balance the system depends on the balancing of torques. As long as the sinus wheel is free to rotate the system will achieve a situation of dynamic balance where the frictional force is the same as the force due to the suspended weight. If the load applied is $L$ (kg) then the work done on the ergometer, using the von Dobeln equation above, is

$$W (J) = L(kg) \times 9.81 \times \text{flywheel circumference (m)} \times NR$$

As before the losses in the system are not accounted for.

### 3.2 THE USE OF FRICTION-LOADED CYCLE ERGOMETERS FOR THE MEASUREMENT OF ANAEROBIC PERFORMANCE

Figures 2.2 and 2.3 showed the well established relationship between the duration of an activity and the maximum value of external power output for a number of different activities which place a heavy demand on the leg extensor muscles. Clearly the maximum external power output that can be generated decreases as the duration of the activity increases, and in addition this rate of decrease is non-linear. Any system measuring anaerobic performance must, therefore, be sensitive to rapid changes in power output.
Figure 3.3 Friction system used in the Monarck basket-loaded ergometer.
The two components of anaerobic performance of most interest are peak external power output and the mean external power output or work done during the test. Peak power output is defined either as the maximum instantaneous value of external power output achieved during the activity, or the peak power averaged over a fixed time interval.

The work done during an anaerobic performance test is sometimes termed 'anaerobic capacity'. This implies that there is a finite, exhaustable store of energy that can be used for anaerobic energy metabolism and that such tests can determine the size of these stores. This author believes that neither of these statements can be supported and, therefore, other than when referring to published texts, mean power output values rather than anaerobic capacity will be discussed.

It is important to note that in tests which measure maximum anaerobic performance the external power output will be constantly varying and, therefore, steady-state will not be achieved in the systems providing the energy for muscular contraction. This constant change in power output during high intensity exercise is due to the rate of ATP (and PC) splitting being greater than the rate of resynthesis.

When deciding on the test protocol to be used to measure the maximum work rate that the anaerobic system can produce the duration of the exercise must be considered. The work by Gollnick and Hermansen (1973) showed that an exercise duration of 10 seconds was too short to fully tax the anaerobic processes. Increasing the duration of the exercise will place greater demands on the anaerobic processes, however, there will also be an increase in the proportional contribution to energy metabolism from aerobic glycolysis. Gollnick and Hermansen (1973) calculated the relative contributions of anaerobic
metabolism to the total energy output during maximal exercise. They found that for the first 10s of exercise the anaerobic contribution was approximately 83%. This value dropped to 60%, 40% and 20% for exercise durations of 1, 2 and 5 minutes, respectively. Hughson (1978, Med Sci Sports (abs) 10(1):43) reported the half-time to reach peak VO\(_2\) in exercise intensities of 110-120% VO\(_2\)\(_{max}\) to be approximately 53 seconds. As the aerobic system clearly does not achieve steady-state, in activities lasting only a few seconds, the contribution made to the total energy production by aerobic glycolysis, in this type of exercise, is difficult to measure precisely, requiring the determination of the oxygen debt which occurred during the test. Although there is general agreement that the tests of 'anaerobic capacity' must be of maximal intensity throughout, there has been no standardisation of the duration of the exercise, with test durations lasting from 20 to 240 seconds having been proposed. The work by Margaria et al (1964,1966) have greatly influenced the decisions that researchers have made regarding the duration of such tests. They estimated that the maximal lactic acid production was reached by approximately 40-60s of maximal exercise. Katch et al (1977) examined test durations of 40 and 120 seconds on a Monark cycle ergometer and found that the total cumulative work at 40s had a high (r=0.95) correlation with total cumulative work in 120 seconds. They also stated that "it can be calculated that by 40s the work rate drops to a level that is within the 'aerobic range' of oxygen requirements".

It is of further interest to note that Katch et al (1977) showed that to obtain optimal values for maximal anaerobic work on the cycle ergometer the subjects should work at an "all-out" pedal frequency from the start of the test, and that a pacing policy should not be adopted. Although Bar-Or (1978) does not refer to this paper in setting out the protocol described below, these findings certainly add support to the test protocol he proposed.
Although several different test protocols have been developed to examine anaerobic performance characteristics the most commonly adopted procedures have been based on the work by Cumming (1973) and Ayalon (1975). In 1978 Bar-Or presented a paper entitled "A new anaerobic capacity test - characteristics and applications" in which he describes a test protocol, based on the work by Cumming and Ayalon, which has become known as the "Wingate" test.

The "Wingate" or "Anaerobic Work Test (AnWT)" requires the subject to cycle at maximum speed against a pre-determined resistance for 30 seconds. The resistance setting is determined from the body weight of the subject. If a Monark ergometer is used the setting is 75g per kg body weight. On a Fleisch ergometer a resistance setting of 45g per kg body weight was recommended. For arm cranking the recommended settings were 0.5 and 0.3g.kg⁻¹, respectively.

The number of flywheel revolutions for each 5 second period is monitored. Power output could, therefore, be calculated for each 5 second period during the test as could the total work done during the test.

In the protocol described by Bar-Or the subjects start to pedal as fast as possible against a low resistance which is increased to the required level during the first 2 or 3 seconds of the test. Many researchers have replaced this stationary start with a rolling start at a pre-determined sub-maximal speed, with the maximum effort commencing once the required load has been introduced) Irrespective of the method used to start the test the subjects work as hard as possible throughout the test, with no attempt being made at "pacing" or "energy conservation". Toe clips are used to hold the feet on to the pedals. The subjects are required to remain seated throughout the test. Power output was calculated using the techniques described in the previous section.
From the test three indices of anaerobic performance are determined:

a) MAXIMAL ANAEROBIC POWER: The highest 5 second power output. This index was to reflect the peak power generated by the particular active muscle groups.

b) ANAEROBIC CAPACITY: The overall work done during the 30 second period.

c) FATIGUE INDEX: The difference between the highest and lowest 5 second power output divided by the elapsed time.

The test-retest reliability of the Wingate test was checked for various age, sex and fitness groups both on the same day and over a period of up to two weeks. For tests repeated on the same day correlation coefficients of 0.95–0.98 were obtained. Over the two week time period r values of 0.90–0.93 were obtained even when environmental conditions were modified. It was concluded that the test was highly reliable.

**TIME TO PEAK POWER**

In pilot studies using the test protocol described above it was found that peak power always occurred during the second 5 second block of exercise. This was in agreement with the test findings found by Bar-Or (1977) and other authors (Katch et al, 1977; Weltman, 1978). Although the protocol measured differences in the absolute value of peak power output it, therefore, lacked sensitivity in measuring the time taken to reach peak power. In order to achieve greater sensitivity a shorter sample time was required.

The conventional method of monitoring flywheel speed which employed a mechanical microswitch and electromagnetic
Figure 3.4 Diagram of the optoswitch system for monitoring flywheel speed.
counter was replaced by an optoswitch. A disc with 90 black and white lines was mounted on the ergometer flywheel (figure 3.4). The amplified signal from the reflective opto-switch was passed through a Schmitt-trigger and used to drive a 4x7 segment LED display which counted the total number of impulses arriving during the test (See appendix). The total number of flywheel revolutions could, therefore, be calculated. The output from the opto-switch was also fed to a frequency-to-voltage converter which gave an output voltage proportional to the input pulse frequency. This output voltage was used to drive a chart recorder. The time delay of the system was calculated to be less than 10ms.

The pulse train obtained from the optoswitch could also be used to detect the instantaneous position of the crank as there is a fixed gear ratio of 3.7:1 between flywheel and pedal speed.

The new detection system allowed much greater resolution in determining the time taken to reach peak speed. Peak speed was now found to occur between 3 and 6 seconds from the start of the exercise, i.e. earlier than would be indicated using the 5 second sample blocks.

As the instantaneous speed of the flywheel could now be measured the instantaneous value of power output could also be calculated. (Instantaneous values in this thesis refers to values obtained during very short time intervals and do not assume that $dt=0$). The six 5 second time blocks used by the Wingate protocol were replaced by thirty 1 second values thereby increasing the resolution of the system. The absolute value of peak power was found to be higher for the 1 second than the 5 second time increment ($p<0.001$). Despite these higher values for power output the values obtained were still substantially lower than corresponding values obtained from other test protocols.
such as those using isokinetic cycles. Katch and Weltman (1979) findings support this result and suggested that this underestimation of the true maximum power output of individuals was due to "limitations in terms of maximal possible resistance, establishment of resistance, and inability to maintain constant force on the pedals throughout a full pedal cycle", but did not question the accuracy of the methodology.

What became apparent from the pilot tests was that peak power and peak speed were co-incident. This was a surprising result as in mechanical systems, that are free to accelerate, peak power always occurs before peak speed. This finding stimulated the re-examination of the method used to calculate the power generated on friction-loaded cycle ergometers, which is described in the following experimental chapters.
CHAPTER 4

4:1 CALCULATION OF POWER GENERATED ON FRICITION-LOADED CYCLE ERGOMETERS.

(Using friction loaded cycle ergometers the power applied to the flywheel is conventionally calculated from the product of the resistive load and the flywheel speed (von Dobeln, 1954). The calculation of the work done and the power output in this way assumes that the flywheel is either revolving at a constant angular velocity or has no moment of inertia. As the ergometer flywheel has a very large moment of inertia and the tests of anaerobic performance require the flywheel to be accelerated then neither of these conditions are satisfied. A study was set up to measure the actual power being applied to the flywheel so that the magnitude of the errors resulting from making the conventional assumptions could be assessed.

In order to calculate correctly the power generated during the brief period of exercise, the 'effective' load on the cycle ergometer must be determined. The effective load is made up of two components:

(1) The frictional load that is applied to the flywheel.

(2) The 'acceleration balancing load' which is the frictional load that would be required at any instance to stop the subject from accelerating the flywheel.

If the flywheel is accelerating there must be a mismatch in the torques acting on the flywheel. The driving torque (Td) from the pedals must exceed that due to load (Tr):

\[ Td - Tr = I \times a \]
where: $I$ is the moment of inertia of the flywheel

$a$ is the resulting angular acceleration of the flywheel

Rearranging the equation gives

$$T_d = T_r + (I \times a)$$

The units of $(I \times a)$ are N.m, i.e. units of torque. If this excess torque, resulting from the acceleration of the flywheel, is divided by the radius of the flywheel then a value of excess load is obtained. If this load had been originally applied to the flywheel, in conjunction with the resistive load, then acceleration would have been prevented. The load required to prevent flywheel acceleration, which is constantly changing, is defined as the acceleration balancing load (ABL). The total load required to prevent acceleration is called the effective load and is, therefore, the sum of of the two load components:

$$\text{Effective load} = \text{resistive load} + \text{acceleration balancing load}$$

The corrected value of power output should, therefore, be calculated from the product of the speed of the flywheel and the effective load, rather than the conventional product of speed and resistive load. It should be noted that when the flywheel is decelerating the term ABL is negative and, therefore, this 'load' is subtracted from the resistive load to determine the effective load.

4:2 CALCULATION OF ACCELERATION BALANCING LOAD.

In order to calculate the acceleration balancing load the acceleration of the flywheel has to be constantly monitored. To achieve this a high-speed system for data collection was developed, shown in figure 4.1. It consisted of a small
electric generator which was driven by the ergometer's flywheel giving an analogue signal proportional to the angular velocity of the flywheel. The correlation coefficient between voltage output and angular velocity was checked and found to be very high \((r^2=99.8\%)\). This signal was logged by a microcomputer (initially a Commodore PET model 4032, later a BBC model B) via an analogue-to-digital converter, along with a timing signal derived from the computer's internal clock. The sampling rate was restricted to 20Hz to reduce the magnitude of the error that might have resulted from this relatively slow clock. Nevertheless, this sampling rate was still 100 times faster than that normally employed in the Wingate test. The computer was programmed to monitor the flywheel speed throughout the test and to calculate and display the test results at the conclusion of the exercise bout. The raw flywheel speed and time data were also stored on disc for later retrieval and analysis.

4.3 UNITS OF LOAD

Throughout this chapter the load applied will either be described as the amount of mass, in kilograms, applied to the loading basket or will be expressed in units of force - Newtons. The relationship between these two when only gravity is acting on the weight, as is appropriate in these tests, is:

\[
F(N) = M(kg) \times 9.81
\]

In many papers load is expressed in kiloponds (kp). A kilopond is defined as the force acting on the mass of one kilogram at normal acceleration of gravity, and is, therefore, 9.81 Newtons.

4.4 CALIBRATION OF FLYWHEEL (PEDALLING) SPEED

Prior to each test the relationship between flywheel speed and the output from the generator and analogue-to-digital
Figure 4.1 The high-speed system for data collection.
converter were carefully calibrated.

The computer was switched on at least two hours prior to the start of the calibration procedure as it was discovered that for a constant input voltage the value obtained from the computer's internal A-to-D converter drifted upward for the first two hours after switch on (see appendix).

After the warm-up period the ergometer was pedalled for about 2 minutes at approximately 65 pedal rpm. The actual speed of pedalling was not important nor was it required to be constant. Flywheel revolutions were counted using an electromechanical counter actuated by a microswitch driven by an eccentric cam mounted on the flywheel. Logging of the A-to-D reading, at approximately 10Hz was started and stopped at the same time that the electromechanical counter was switched on and off. The mean of the A-to-D readings was equated with the average speed of the flywheel and the calculated conversion factor was stored on disc for automatic retrieval by the test programs.

4:5 DETERMINATION OF THE ACCELERATION BALANCING LOAD.

The determination of the acceleration balancing load required the generation of a set of deceleration curves using a series of known loads (0.5 to 6.0 kg). These curves were obtained by setting the flywheel in motion by pedalling at around 150 pedal r.p.m against each frictional load and plotting the deceleration resulting from the cessation of pedalling. The curves obtained for the range of 105-0 pedal r.p.m. are shown in figure 4.2. Each deceleration curve was found to be a straight line (r²=99.6%). This is not a surprising result as this would be predicted from the equation

\[ a = \frac{T}{I} \]

where: a is the angular acceleration
Figure 4.2 Flywheel deceleration curves obtained for the range 105 to 0 pedal r.p.m. for loads of 0.5 to 6.0 kg.

Figure 4.3 Plot of flywheel deceleration against load.

regression equation:

\[ x = 4.10 + 18.1y \]
Tr is the resistive torque
I is the moment of inertia of the flywheel

When the decelerations were plotted against load a linear regression equation was obtained (figure 4.3):

\[
\text{Acceleration (rpm/s)} = 18.1 \times \text{load} + 4.10 \\
(r^2=99.7\%)
\]

It should be noted from the load lines that zero load did not result in zero deceleration as would be expected, but produced significant deceleration of the flywheel. On the ergometer tested the flywheel stopped revolving from an initial 105 pedal r.p.m. after approximately 48 seconds indicating that the system had resistance resulting from the unloaded belt and the bearings.

If a given deceleration of the flywheel results from a given load then it would be that value of load that would be required to balance any torque attempting to accelerate the flywheel at the same rate. This load is the acceleration balancing load, described above, and is derived by rearranging the above equation:

\[
\text{acceleration balancing load (kg)} = (\text{acceleration}-4.10)/18.1
\]

Not only is the flywheel speed calibrated prior to each test, as described above, but so is the acceleration balancing load. This is important as the characteristics of each ergometer and A-to-D converter can vary with temperature and state of maintenance. An example of three regression equations obtained from a cycle ergometer on 3 successive days are:

\[
\text{day 1: } y = 18.1x + 5.1 \quad (545)
\]

\[
\text{day 2: } y = 17.0x + 4.3 \quad (549)
\]
day 3: \( y = 18.2x + 4.0 \) (547)

The speed calibration factors obtained are shown in brackets.

The error due to the observed variations in the regression equations was calculated to be less than 1%.

Prior to normal testing the computer is used to monitor two deceleration curves for each of the following loads 0.5, 1, 1.5, 2 and 3 kg. The correlation coefficient for the regression line is calculated by the computer and an \( r^2 \) value of less than 99% is rejected and the entire procedure repeated. The general form of the regression equation is

\[
Y = mX + C
\]

The values of \( m \), the gradient, and \( C \), the offset are recorded on disc for automatic retrieval by the test programs.

It should be noted that this calibration technique not only incorporates those factors resulting from the moment of inertia of the flywheel but also compensates for a number of the losses caused by the rolling resistance of the flywheel and freewheel mechanism. Astrand (1971) cautioned that the calibration of mechanically braked cycle ergometers does not take into account the frictional resistance of the chain drive, "...which can be as high as 175 kpm.min\(^{-1}\) at high work loads".

During the tests the applied frictional load is known and using the above equation the instantaneous acceleration balancing load can be calculated. The instantaneous power being applied to the flywheel can, therefore, be calculated.
4:6 VERIFICATION OF THE NEW METHOD OF CALCULATION

When the flywheel continues to revolve when the subject has ceased pedalling (freewheeling) clearly there can be no power being applied to the flywheel by the subject. However, using the conventional method of calculation i.e. the product of flywheel speed and load, a value for applied external power output would be obtained. It would appear, therefore, that the subject, despite not pedalling, is continuing to provide power to the ergometer. If the new method of calculation is valid then the value calculated for applied power output must immediately drop to zero when the subject ceases pedalling.

Figure 4.4 shows the result of one subject accelerating the cycle ergometer from stationary, against a load of 1kg. After about 5 seconds the subjects stopped pedalling (point X on the figure). The flywheel continued to revolve, although decelerating, coming to a stop after about 4 seconds. Whilst the flywheel decelerated the uncorrected power output, derived from the conventional method of calculation, continued to indicate that power was being applied to the flywheel. The corrected power output, however, dropped to zero immediately. This result strongly supports the corrected method of calculation.

The value of peak power output obtained from the corrected method of calculation was over 100% higher than that obtained from the uncorrected method. Further support for the corrected method of calculation was obtained when the two shaded areas between the power curves were digitised and compared. The two areas were found to differ by only 7.6% (18.6-v-17.1) indicating that nearly all of the work done in accelerating the flywheel was the same as that recovered from the flywheel whilst it decelerated. The small difference was probably due to losses in the system manifested as heat and sound energy.
Figure 4.4 The plot of corrected and uncorrected power output for one subject accelerating the cycle ergometer from stationary, against a load of 1kg, and then suddenly stopping pedalling.
4:7 ESTABLISHING THE START POINT OF THE TEST

During the pilot studies it was found that although there were clear instructions of "GO" given to the subject to start pedalling at maximum effort the subjects were sometimes predicting the start and starting slightly early, or not reacting immediately to the command and starting slightly late. Even though this timing error was usually small it did appear to influence the results obtained. It was decided to continue to give the same instructions to the subjects but to start data logging by the computer just prior to the start of the test. The actual start point of the test was determined from the data, as shown in figure 4.5. The plot of flywheel speed was displayed on the computer screen and a cursor line was moved, on the screen, until it coincided with the point at which a change in the speed of the flywheel could be seen. The computer was then instructed to regard this point as the start of the test.

4:8 THE DISCREPANCIES IN POWER OUTPUT DURING A 'WINGATE' TEST RESULTING FROM THE TWO METHODS OF CALCULATION.

The mean (+ S.D.) values for the physical characteristics of the 10 subjects (5 males and 5 females) who took part in the study are as follows: age 25.2 (+7.1) years, height 168.0 (+10.2) cm and weight 64.5 (+11.9) kg. Each performed a single bout of 30s maximal exercise on a Monark cycle ergometer with a resistive loading of 75g/kg bodyweight, with an initial rolling speed of 70 rpm.

The saddle height used in all the tests was one in which the knee was still slightly flexed when the pedal was at the bottom of its travel.

Prior to each test the subjects warmed-up by pedalling at 30 and 40 kph for 30 seconds, against a load of 1.5kg, with a rest of 30 seconds between the two rides. Between the end of this warm-up and the start of the test the subjects
Figure 4.5 The computer display of pedalling speed, for the 30 second test, used to establish the start point of the test.
stretched for 5 minutes placing particular emphasis on the knee and hip flexor and extensor muscles.

Throughout the test flywheel speed was monitored by the computer as described above.

4.8.1 RESULTS

The results of this study are shown in Table 4.1.

4.8.2 POWER

It was found that the corrected 1s averaged peak power values were approximately 32% higher than the uncorrected ones and that they occurred on average 2.1s earlier than the uncorrected peak values. If, however, the averaging period was reduced to 0.5s then the errors became 37.5% and 3.2s, respectively. In the Wingate test the averaging period is 5s. When the peak power values were determined from the averaged 5s uncorrected values were compared with the 0.5s corrected values the errors became 51.4% and 3.8s, respectively.

4.8.3 EFFECT OF CHANGES IN THE AVERAGING PERIOD.

Figure 4.6 shows a plot of power output generated by one of the male subjects averaged over 1, 0.5 and 0.25s time periods as well as the averaged uncorrected 1s values. The corrected 1 and 0.5s outputs showed a smooth curve with a single distinct peak. However, when the averaging period was shortened to less than a pedal stroke duration e.g. to 0.25s, then within stroke variations were detected resulting in a multi-peaked plot.
<table>
<thead>
<tr>
<th></th>
<th>Averaging period (s)</th>
<th>Peak power output (W)</th>
<th>Lowest power output (W)</th>
<th>Time to peak power (s)</th>
<th>Total work done (J)</th>
<th>Wingate Test Indices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max anaerobic power (W)</td>
</tr>
<tr>
<td>uncorrected</td>
<td>5</td>
<td>663 ± 221</td>
<td>424 ± 459</td>
<td>5 ± 0</td>
<td>295.5 ± 85.0</td>
<td>663 ± 221</td>
</tr>
<tr>
<td>corrected</td>
<td>0.5</td>
<td>730 ± 241</td>
<td>494 ± 529</td>
<td>4 ± 1 ± 0.88</td>
<td>290.0 ± 83.6</td>
<td>791 ± 233</td>
</tr>
</tbody>
</table>

Table 4.1 Comparison of corrected and uncorrected values of power output and Wingate test indices obtained from a 30s maximum test on the cycle ergometer (n=10, mean ± S.D.).
Figure 4.6 Corrected and uncorrected power output generated by a subject during the first 6 seconds of a 30 second bout of maximal exercise on a cycle ergometer, with different averaging periods.
4:8.4 WORK

The values of work done showed large discrepancies between the uncorrected and corrected results for time intervals of 10s or less. For example, over the first five seconds of the sprint the corrected results averaged 20.4% higher than the uncorrected ones. In fact over any 5s period there was a statistically significant difference ($p<0.01$) between the work done calculated by the two methods, with the first 5s always being higher and the remaining 5s periods always lower for the corrected results compared with the uncorrected values. Over the entire 30s, however, no statistically significant difference was found between the values of work done determined from either method.

4:8.5 WITHIN STROKE POWER VARIATIONS.

Figure 4.7 shows a plot of the corrected power values obtained for each 0.1s of a single 30s sprint performed by an international sprint cyclist. The figure shows the profile of the power generated within each of the pedal strokes. Superimposed on the plot are the 0.5s averaged values and pedalling rate. The maximum value of within stroke power output occurred during the first pedal revolutions and declined throughout the remainder of the test despite the fact that the flywheel and pedalling speed continue to rise for the first few seconds.

Examination of the power profiles of the group as a whole showed that the maximum within stroke peak power was achieved between 1.5 and 2.5 seconds after the start of the sprint.

Closer examination of the power variation within a pedal cycle was not possible due to the relatively low sampling rate. This area of investigation was identified as one of particular interest and further developments are discussed later in this chapter.
Figure 4.7 Power output generated during a maximal bout of exercise on a cycle ergometer by an international sprint cyclist (0.1 and 0.5s averaging periods).
4:8.6 WINGATE TEST INDICES

The Wingate test indices were examine and the uncorrected and corrected values compared:

4:8.7. MAXIMAL ANAEROBIC POWER.

This is defined as the highest power output value over 5 seconds and was found to be underestimated by 16.2% when uncorrected values were used. The average corrected value was 791W and the uncorrected value was 633W. If 0.5 second averaged peak power output is investigated then the underestimation increases to 22.9% with the average corrected peak power value being 1004W.

4:8.8. ANAEROBIC CAPACITY.

Anaerobic capacity is defined as the total work done during the 30 second test. The results obtained showed no significant difference between the two methods of calculation.

4:8.9. FATIGUE INDEX.

The percentage difference between the highest and lowest 5 second power output values is defined as the fatigue index. When the corrected values are compared to the uncorrected ones the fatigue index is significantly larger (46.5% versus 33.7%, p<0.001). If the fatigue index is redefined as the percentage drop between the highest and the lowest 0.5 second averages of power output then the difference between the corrected and uncorrected values is even greater (62.8% versus 45.1%, p<0.001).
4:8.10 RELATIONSHIP BETWEEN POWER OUTPUT, FLYWHEEL ACCELERATION, AND FLYWHEEL SPEED.

Figure 4.8 shows a plot of flywheel acceleration, corrected power output and pedalling speed for one of the male subjects. Peak acceleration preceded peak power output, which in turn occurred before peak speed was attained. This sequential relationship was true for all the subjects.

4:8.11 DISCUSSION

Previous reports have suggested that the maximum work rate on a cycle ergometer occurs when the flywheel is revolving at its peak speed, which in the Wingate test has been reported to occur between 3 and 8s after the start of the sprint (Weltman et al. 1978, Katch and Weltman 1979, Kaczowski et al 1982). These findings are supported by the results of this study when the uncorrected power output values are considered with the time to both peak speed and peak power output being 4.1 ±0.89s. The corrected values, however, show that peak power output occurs approximately 1 second after the beginning of the sprint, i.e. when the flywheel is still being accelerated.

The value of peak power output obtained from the corrected computational technique is very much greater than that obtained by the conventional uncorrected, method of calculation. The absolute values obtained from both techniques are dependant on averaging time. Both techniques give increasing values with decreasing averaging periods. For the uncorrected values reducing the averaging time from 5 to 0.5 seconds resulted in an mean increase in peak power of 16.7%. The corresponding increase for the corrected values was 26.9%. Shortening the time period to individual data points resulted in a dramatic increase in the discrepancy between the two methods of calculation of peak power. Thus the shorter the averaging period the greater
Figure 4.8 A plot of flywheel acceleration, corrected power output and pedalling speed for one of the male subjects.
the difference between the uncorrected and corrected values of peak power output.

Ideally, if averaging of the power output is desired then it should not be averaged over a fixed time period but over each pedal stroke. As the pedalling frequency is constantly changing this averaging time period should also be vary. Practically the fixed time interval method of computation is the easier of the two methods to employ. The best compromise value was found to be an averaging period of 0.5s as the pedalling rate approached but never dropped below 60 rpm. This ensured that at least one whole pedal stroke was always encompassed by the averaging process.

Figure 4.9 shows a plot of uncorrected and corrected power output generated during a 30s sprint by one of the subjects. The uncorrected power output profile is identical to that which would be produced if pedalling speed were plotted. Examination of the figure shows that during the initial acceleration phase of the sprint the value of peak power exceeds that of the uncorrected value. During this phase the kinetic energy of the flywheel is being increased. When peak speed is attained, i.e. when the flywheel is no longer being accelerated, the two values of power output become equal (point X on the figure). When no acceleration is taking place the value of the accelerating balancing load is zero and, therefore, the effective load is simply the resistive load. Both methods of calculation result in the same power output value being obtained.

This is a very important finding. In many recent papers uncorrected power output is being calculated for each pedal revolution. Peak power output is a central value in these studies and as described earlier occurs at the point of fastest pedal revolution. It is indeed fortunate that when the subject has achieved peak pedalling speed there is no acceleration taking place and, therefore, at this instance uncorrected and corrected values of power output are the
Figure 4.9 A plot of uncorrected and corrected power output generated during a 30 second sprint by one of the subjects.
same. The implication of this finding is that the values of peak power output reported in these studies are correct values of power output, however, they are not the true peak values. The peak power outputs \(\text{PPO}\) reported in these studies should be re-defined as the power output at peak pedalling speed \(\text{PPO}_{\text{peak}}\). As long as the averaging time interval has been kept short (<1s) then the values of power output reported in these studies are correct.

\[
\text{PPO}_{\text{unc}} = \text{PPO}_{\text{peak}}
\]

Once peak speed has been attained the flywheel is decelerating for the remainder of the test. The torque being applied by the subject is, therefore, less than that resulting from the resistive load and kinetic energy is being lost. To prevent deceleration from occurring some of the applied resistive load would have to be reduced. The value of this acceleration balancing load is calculated and subtracted from the resistive load. The effective load is, therefore, less than the resistive load and so the calculated power output is less than that which would be obtained using the uncorrected computational method. The magnitude of the difference between the corrected and uncorrected power outputs is proportional to the acceleration of the flywheel. Careful examination of the plot shows that where the subject was able to re-accelerate the flywheel, i.e. "kicked again", during the deceleration phase, the corrected power output exceeded the uncorrected values, as would be expected.

4.8.12 MAXIMAL ANAEROBIC POWER

The results show that for all subjects the total work done in the first 5 seconds of the sprint, i.e. during the acceleration phase, using the corrected method of calculation exceeds the value obtained from the uncorrected method. Thereafter, energy is being recovered from the decelerating flywheel and the 5 second averaged values of
work done exceed the corrected values. The maximal anaerobic power, as defined by the Wingate protocol, was found to be nearly 30% higher for the corrected values than for the uncorrected values. If, however, the work done in a one second rather than a 5 second time period is considered the difference rises to a mean of 32.3%.

4:8.13 ANAEROBIC CAPACITY OR TOTAL WORK DONE

No difference was found for anaerobic capacity, defined as the total work done on the 30 second test, between the two methods of calculation. The mean pedalling speed at the start of the test was found to be 77.26 ± 6.03 rpm. At the end of the test the mean pedalling speed was 88.7 ± 11.6 rpm. The result obtained for the total work done is not surprising as these two speeds are similar and consequently the work done during the acceleration phase resulting in the increased kinetic energy of the flywheel is recovered from the flywheel during the subsequent deceleration. Had the start and end rotational speeds been very different, as would have been the case had a standing start protocol been used, then the total work done would have been different for the two methods of calculation. A lower start speed than finishing speed would result in the uncorrected total work done being underestimated, and vica-versa.

4:8.14 FATIGUE INDEX

Corrected peak power output is always greater than uncorrected peak power output, and the minimum value of power output is always lowest using the corrected computational technique. It is not surprising, therefore, that the corrected fatigue index is much greater than the uncorrected one. Using the 5 second averaged data the respective values were found to be 46.5 and 33.7%. If, however, a shorter averaging time period is considered both values of fatigue index rise: For an averaging period of 0.5s the fatigue indices were 62.8 and 45.1%, respectively,
showing the greater sensitivity of the corrected fatigue index to the averaging period.

The corrected values for peak power output, anaerobic capacity and fatigue index are of particular interest to exercise physiologists. A great deal of work has been done comparing the internal energy flux with the external work done (Boobis et al, 1983. Wootton et al, 1984). In order for such work to be valid it is important that the correct values for the external work done are measured.

The range of power scores obtained compare favourably with the power outputs for stair climbing reported by Margaria et al (1964,1966) and for isokinetic cycling (McCartney, 1983). It is clear, therefore, that the underestimations that had previously been found for cycling on friction loaded cycle ergometers, discussed by Katch and Weltman (1979), were due to errors in the measurement technique employed and not to the "limitations in terms of maximum possible resistance, establishment of resistance, and inability to maintain constant force on the pedals throughout a full pedal cycle".

4:8.15 RELATIONSHIP BETWEEN FORCE, POWER AND SPEED.

The results showed that for all the subjects peak acceleration preceded peak power output, and in turn peak power output occurred before peak speed was attained. As force is the product of mass and acceleration then peak acceleration will result from the application of peak force. Peak force will, therefore, occur at the same time as peak acceleration. If peak acceleration were replaced by peak force in Figure 4.8, the sequential relationship between peak force, peak power and peak speed, which would be expected for a freely accelerating system, would be found to hold true for the friction loaded cycle ergometer.
4:9 SENSITIVITY TO CHANGES IN PEAK POWER OUTPUT.

It is possible for physiological adaptations due to training, detraining, changes in nutritional status and many other factors to have an influence on the peak power output that can be achieved on the cycle ergometer. Figure 4.10 shows two examples of the possible changes in performance that might occur.

(a) The flywheel acceleration has remained unchanged.

In figure 4.10(a) the acceleration of the flywheel has not changed between the two tests but the peak speed achieved has increased. Using the conventional method of calculation peak power output will have increased in direct proportion to the increase in speed \((U_2-U_1)\). As the acceleration has remained unchanged the acceleration balancing load calculated by the computer for the two tests will be exactly the same and, therefore, the effective load will also remain unchanged. The peak power output calculated by the corrected method will, therefore, also increase as a consequence of the the increased maximum speed \((C_2>C_1)\). The change in magnitude of the corrected power output will be the same as that calculated for the uncorrected values. If \(dU\) is the change in the uncorrected values of peak power output that has occurred between the two tests \((U_2-U_1)\), and \(dC\) is the corresponding value for the corrected power outputs \((C_2-C_1)\) then:

\[
dU = dC
\]

Although the corrected values of peak power output are always higher than the uncorrected values, if the acceleration remains the same then the change in peak power output measured by the two methods will be the same. The time taken to reach corrected peak power output is always shorter than for the uncorrected method. If the
Figure 4.10 Two examples of possible changes in performance that might occur due to training.
acceleration of the flywheel has remained unchanged and the peak speed has increased then the time taken to reach peak speed will have increased. If $T_{U1}$ and $T_{U2}$ are the time to peak power using the uncorrected method of calculation, and $T_{C1}$ is the time to corrected peak power of the first test then the time to corrected peak power of the second test will be:

$$T_{C2} = T_{C1} \times \frac{T_{U2}}{T_{U1}} \text{ seconds}$$

It should be noted that $T_{C1}$ and $T_{C2}$ will always be less than $T_{U1}$ and $T_{U2}$, respectively.

(b) The flywheel acceleration is different between tests.

In Figure 4.10(b) the peak speed reached has not changed between the two tests but the acceleration has increased. The uncorrected peak power output in this situation will appear not to have changed as the peak speed is unchanged ($dU=0$). The value of corrected peak power output is influenced by the acceleration of the flywheel. As the acceleration has increased between the two tests, corrected peak power output will also have increased ($dC>0$).

The time taken to reach uncorrected peak power output and peak speed in test 2 will be reduced, due to the greater acceleration. This time taken for tests 1 and 2 will be:

$$T_{U1} = V_{\text{peak}} \times a_1$$
$$T_{U2} = V_{\text{peak}} \times a_2$$

where: $V_{\text{peak}}$ is the peak speed of the flywheel $a_1$ and $a_2$ are the accelerations of the flywheel in test 1 and 2 respectively.

As $V_{\text{peak}}$ is unchanged between the two tests, then:

$$T_{U2} = T_{U1} \times \frac{a_1}{a_2}$$
The time taken to reach corrected peak power output will also have decreased and will also be dependent on the new acceleration.

\[ TC2 = TC1 \times \frac{a1}{a2} \]

This situation clearly highlights the lack of sensitivity of the uncorrected method of calculation when compared to the corrected method. Although the subject has improved in performance, resulting in the increased acceleration, the uncorrected method does not indicate an increase in power output. Indeed using the 5 second blocks employed by the Wingate test the change in time to peak speed might also go undetected. This situation is by no means an artificial one as maximum leg speed can be a limiting factor influencing cycling performance particularly if the resistive load is small.

4:10 PROFILE OF POWER OUTPUT WITH RESPECT TO TIME.

It has been shown earlier in this thesis that the maximum power output that can be generated declines with the duration of the exercise. Initially the decline is rapid following an exponential type of curve. Thereafter decrease in power output diminishes gradually in a more linear fashion. The half-life of the 'decay' in power output was shown to lie between 3 and 20 seconds. A smoothed profile of corrected and uncorrected power output (0.5 second averaging) for one of the subjects is shown in figure 4.11. It can be clearly seen that the two profiles are different. The profile generated using the correct method of calculation shows the expected curvilinear decline in power output with the power output, for the whole group, dropping to half the peak value after 5.2 ±2.1 seconds. In contrast the uncorrected power output values appear to decline in a more linear fashion once the peak value has been attained.
Figure 4.11 A smoothed profile of corrected and uncorrected power output generated during a 30 second sprint for one of the subjects (0.5 second averaging period).
The power output does not drop to half the peak value by the end of the 30 second test. If the power output is assumed to continue to fall at the same rate then the half-peak value is reached after 82 ±12 seconds.

These findings give further support for the corrected method of calculation. This method gives the curvilinear decay expected and has a half-life in the range found by other researchers. The uncorrected method neither gave the decay profile expected nor a half-life in the normal range.

4:11 WITHIN STROKE POWER VARIATIONS

Figure 4.7 showed a plot of the corrected power values obtained for each 0.1s of a single 30 second sprint performed by an international sprint cyclist, and the pedalling speed. In addition the 0.5 second averaged values are shown. The shortening of the averaging period to one that was less than the duration of a pedal stroke revealed that within-stroke power output variations could be examined. It was found that the greatest power peaks were generated during the first 2s of the test when the flywheel and pedalling speed were low. As the pedalling rate increased the peak power output per stroke diminished. The within-stroke power fluctuations appear to rise as the pedalling rate drops during the latter part of the test (see 20-24s in figure 4.7), despite the onset of fatigue. These results appear consistent with the force-velocity relation of muscle. While the pedals are revolving slowly the muscle contraction speed is low and large forces can be generated, resulting in the high acceleration of the flywheel. Conversely, at the high pedalling speeds the force application is diminished due to the high muscle shortening velocities required (Hill 1922, Harrison 1970, Sargeant 1981). These results were exciting as they present a method for indirectly estimating the profile of the torque being applied during a pedal stroke.
Based on these findings a new computer program was written in which the sampling rate was increased to 40Hz (see appendix). Because of the limited memory size of the computer only 15 seconds of data could be stored.

An experiment was set up to examine the variation in the acceleration balancing load at steady paced cycling under different frictional loadings.

Six subjects (3 male and 3 female) whose ages, weight and height, mean (±S.D.) were 29.1 ±5.4 years, 67.0 ±10.0kg and 172.2 ±8.8cm, respectively, pedalled at a constant pedalling speed of 50 rpm at three different resistive loads on a Monark 864 ergometer. The loads were 2, 4 and 6kg, respectively. A typical example of the acceleration balancing load profiles obtained are shown in figure 4.12.

The dashed lines drawn on the figures below each plot show the value of acceleration balancing load that would have to be removed to prevent deceleration of the flywheel from occurring should the subject stop pedalling. This value is almost the same as the resistive load, but incorporates some of the resistive losses discussed earlier. If, over a pedal revolution, there is no net change in the angular velocity of the flywheel then the work done is simply the product of the resistive load and distance travelled. In this experiment the net flywheel speed does remain the same and, therefore, the average acceleration balancing load over a pedal revolution must be zero. The computation by the computer shows this to be true.

As the radius of the flywheel is a constant the term acceleration balancing load could be replaced by 'acceleration balancing TORQUE' by simply dividing the
Figure 4.12 Typical examples of acceleration balancing load profiles obtained for loads of 2, 4 and 6 kg.
acceleration balancing load by the flywheel radius. The resulting plot would have exactly the same shape but would have different units (Nm instead of N).

Assuming negligible losses the instantaneous value of torque being applied to the flywheel is equal to the torque being applied to the pedals by the subject, as the two are linked by the drive chain. The instantaneous value of applied torque can be calculated:

\[
\text{APPLIED TORQUE} = \text{RESISTIVE TORQUE} + \text{ACCEL. BALANCING TORQUE}
\]

where: The resistive balancing torque is simply the product of resistive load and flywheel radius.

The value of resistive torque is a constant. This means that the shape of the plots shown in figure 4.12 are exactly the same shape as the combined torque profiles that would be generated at the pedals, with the resistive torque as the offset. Figure 4.13 shows two of the acceleration balancing load profiles recalculated and redrawn as torque profiles.

The fluctuation in the amplitude of the acceleration balancing load increases with increasing load \( r^2 = 73.3\% \). This relationship is shown in Figure 4.14. As the load increases greater deceleration of the flywheel occurs between pedal strokes, and greater re-acceleration is, therefore, required during the propulsive phase of the stroke. This increasing speed fluctuation of the flywheel, during the same interval of time, results in the increasing variation in the acceleration balancing load required.

These finding have very significant and exciting implications. Researchers have attempted to examine the torque profiles that are being produced at the pedals during cycling on ergometers (Sargeant, 1980). These techniques require force transducers to be mounted on to
Figure 4.13 Two of the acceleration balancing load profiles redrawn as torque profiles (2 and 6kg load).
Figure 4.14 The relationship between acceleration balancing load and applied load at a constant pedalling speed of 50 r.p.m. (mean ±S.D., n=10)

\[ y = 9.15 + 14.1x \]
\[ r^2 = 73.3\% \]
the pedal cranks. A source of potential difference must be applied to the transducers and the output from the transducer bridge fed into an amplifier. This is by no means easy to achieve as once pedalling commences the whole system starts to revolve. Wires that are attached directly to the transducers would twist and damage would quickly follow. The conventional method of overcoming this problem is to use slip rings, such as those used in electric motors. In order to compensate for temperature drift, in the transducers, and to achieve common mode rejection of unwanted forces a minimum of two transducers arranged in a half-bridge network are required. Three connections and, therefore, three slip rings are required to this type of bridge network. A schematic diagram of the required system is shown in Figure 4.15. The researchers have discovered that the problem with this type of system is that the signal-to-noise ratio is very small. The output from the strain gauge transducers is very small compared to the noise generated by the contact bushes of the slip rings. Even using filters the quality of the signal is still poor. The results of this study indicate that the torque being applied to the pedal cranks can be measured by simply measuring the instantaneous speed of the flywheel. Simple optical encoding of the position of the cranks, which is also required in the methods described above, would allow the measurement of the torque in relation to the position of the cranks.

Using the information from the optical position encoder and the measured instantaneous value of torque the force being applied at the pedals can be calculated. If the subject is assumed to be pressing directly down on one of the pedals (see Figure 4.16) then the instantaneous value of the Torque (Tp) resulting from the force applied to the pedal (Fp) is given by

\[ Tp = Fp \times CL \times \sin(A) \]
Figure 4.15 A schematic diagram of the system required to monitor the torque being applied to the pedal cranks.
where: CL is the crank length
    \( A \) is the angle subtended by the crank and the vertical

In general, however, some force is being applied to the other pedal (Fo), and so the equation becomes

\[
T_p = (F_p - F_o) \times CL \times \sin(A)
\]

This equation also assumes the forces are being applied vertically. However, as it is the sine of the angle that is important, then a deviation from the vertical of 18 degrees would only introduce an error of 5\% into the calculation. The error would only still only be 10\% if the force was being applied at 25 degrees to the vertical. When examining the force profile of a given subject, this error would be a constant one allowing accurate measurement of any changes taking place. If it is assumed that the force being applied to the upward moving pedal is negligible, then the instantaneous value of applied force on the downward moving pedal is

\[
F_p = \frac{T_p}{(CL \times \sin(A))}
\]

The shortcoming of this new method is that it cannot differentiate between the two cranks. The values obtained are the sum of the torques being applied to the cranks. The strength of the system, however, is the ease with which the measurements can be made. By simply measuring the instantaneous speed of the flywheel and the position of the crank, a very good estimation of the force being applied to the pedal can be calculated.
Figure 4.16 Mathematical model used to determine the torques applied during pedalling.
The raw data obtained during the 15 second rides in the previous experiment were recalculated and displayed as a power profile for each load. An example of the profiles obtained for one of the subjects is shown in Figure 4.17. Both the peak and minimum values of power output were measured from the first five pedal strokes of each load. The relationship between peak and minimum power output per stroke and load is shown in figure 4.18. Each point on the plot is significantly different from any other point (P<0.001) except for the minimum power output values obtained at 4 and 6 kg loads, which are not significantly different from each other (P<0.05), but are both significantly higher than the values obtained at a loading of 2kg.

The correlation between peak power and load was very high ($r^2=90.4\%$), indicating the increased effort required to maintain pedalling speed as the load increases. It is interesting that although the correlation obtained was low ($r^2=13.1\%$), the minimum power applied per stroke also increases per stroke with increasing load. The increase found when the load was increased from 2 to 4kg was found to be significant.

To be able to interpret the findings the pedal cycle must be split into a propulsive and a recovery phase. Figure 4.19 shows these two phases. The propulsive phase is from top-dead-centre (0°) to bottom-dead-centre (180°). During this phase the powerful hip and knee extensors are combining with the plantar flexors to develop torque to accelerate the flywheel. During the recovery phase accelerating torque can only be applied by the hip and knee flexors if toe-clips are used. If, however, toe-clips are not used then recovery can only be passive.
Figure 4.17 An example of the power profiles obtained for one of the subjects for loads of 2, 4 and 6 kg.
Figure 4.18 The relationship between peak and minimum power output per stroke and applied load (mean ± S.D. n=10).
Figure 4.19 The propulsive and recovery phases of the pedal cycle.
At the light loading the deceleration of the flywheel, between propulsive phases was so small that the subjects were able to allow a period of zero propulsion and still be able to reaccelerate the flywheel sufficiently during the next propulsive phase. When the loading increased, however, the subjects attempted to prevent excessive deceleration of the flywheel by constantly applying power. This change was achieved by one or more of several available methods:

1. A change in the angle of push when the pedals are at top dead centre.

2. Pulling up with the toes on the toe clips.

3. A change in the timing of force application by each leg.

Any or all three of the above changes could be taking place.
Once this new pattern of force application had taken place, between 2 and 4kg, a further increase in the load did not result in a further increase in the contribution of this component to the overall power requirements.

The shape of the power curves obtained are similar to those obtained by McCartney (1983) from the force patterns applied to the pedals of an isokinetic cycle ergometer.

4:14 TORQUE PROFILE DURING THE FIRST FEW SECONDS OF A WINGATE TEST.

The six subjects (3 male, 3 female) described in the previous study each performed the first 15 seconds of a Wingate test against a loading of 75gm/kg bodyweight. The higher speed data logging system described above was used to monitor flywheel speed.
Figure 4.20 An example of a typical profile of acceleration balancing load against time, for the first 10 seconds of a sprint.
An example of a typical profile of acceleration balancing load, which represents the torque being applied to the pedals, is shown against time in Figure 4.20. The basic characteristics of this profile was common for all the subjects.

As can be seen the maximum value of peak acceleration balancing load occurred during the first pedal stroke. Peak acceleration balancing load declined in a non-linear fashion until peak speed was achieved. Thereafter, variation in acceleration balancing load remained relatively constant.

The same result is also true for the mean value of acceleration balancing load variation per pedal stroke. During the acceleration phase of the exercise the mean acceleration balancing load value was above zero and crossed zero when peak flywheel speed was attained. Thereafter, the mean acceleration balancing load value was close to and often slightly lower than the zero value. This is not a surprising result as during the acceleration phase of the sprint the applied torque must be greater than the resistive torque resulting in a positive mean acceleration balancing load. When peak speed is attained the mean value of applied torque must be the same as the resistive torque, therefore, no mean additional external loading is required. During the subsequent deceleration, which is at a much slower rate than the preceding acceleration, load would have to be removed to prevent the deceleration as the propulsive torque is less than the resistive torque hence the mean value of acceleration balancing load would be slightly negative, as can be seen on the plot.

The equation derived by Hill (1938) to describe the relationship between force and velocity, first investigated by Fenn (1923), can be used to interpret these findings. This equation shows that when isolated
muscles contract concentrically the relationship between the tension developed by the muscle and the speed of muscle shortening can be described by a hyperbolic curve.

\[(F + a)(V + b) = (F_{\text{max}} + a)b\]

where: 
- \(F_{\text{max}}\) is the maximum isometric tension
- \(F\) is the maximum tension developed at muscle shortening at speed \(V\)
- \(a\) and \(b\) are muscle constants

Several authors have examined the force-velocity relationship in skeletal muscle groups in situ and have found that the curve has a different shape to the hyperbolic described by Hill. One of the earliest investigations was made by Wilkie (1950). Using elbow flexion as the exercise model Wilkie developed the idea of a single muscle equivalent to the combination action of those muscles that were working. Examining a single joint angle during both static and dynamic contractions, he showed that there was a characteristic force-velocity curve, although this curve did not fit Hill’s equation. The force-velocity curve for cycling on a Krogh cycle ergometer was examined by Sjøgaard (1978). The experimental data did not fit Hill’s equation. Over the range of speeds examined (60 to 160 rpm) it was found that the peak tension per pedal thrust was almost linearly related to angular velocity. After an initial decline in force with speed the force applied to pedals did not appear to approach zero as speed was further increased (Figure 4.21). This finding is supported by Cavagna et al. (1971) who also found a levelling of the force-velocity curve during sprint running and Jorgensen (1976) and Komi (1973) who found the same result for elbow flexors and extensors. Using an isokinetic cycle ergometer Sargeant (1980) found an inverse relationship between maximum force and pedalling speed, for pedalling speeds between 23 and 171 rpm. The work done by Sargeant, using an isokinetic
Figure 4.21 Hill's equation and the results from experiments on the force-velocity relationship in cycling (Sjøgaard, 1978).
cycle ergometer, was reinvestigated by Nadeau et al. (1983) using a Monark ergometer. They found that for the range of 2 to 7kg loading the speed of contraction that could be maintained was inversely related to the load. In the Nadeau study there was no error introduced by the method of calculation as the measurements were made when the subjects were pedalling at a maximal, but near constant speed. The applied torque was, therefore, the same as the resistive torque.

As described earlier the acceleration balancing load is a function of the torque being applied to the flywheel. From the studies described above the peak torque, and therefore, the peak acceleration balancing load would be expected to fall as pedalling speed increases. The findings of the study follow this pattern. The actual shape of the curve joining the peak and mean values of acceleration balancing load will be influenced not only by the non-linear increase in the pedalling speed but also by the increasing fatigue of the muscles involved.

The rate of decline in acceleration balancing load and, therefore, torque is very close indeed to the reciprocal of the pedalling speed, as shown in Figure 4.22. This would tend to indicate that the the torque applied to the pedals is inversely related to pedalling speed. The magnitude of the peak force applied to the pedals is derived from:

\[
F_{max} = T \times CL \times k
\]

where: 
- \(T\) is the torque resulting from maximum force application
- \(CL\) is the crank length
- \(k\) is the sine of the angle between the vertical and the crank at the point where maximum force is being applied
Figure 4.22 Change in acceleration balancing load (peak and mean) and pedalling speed with time, for one subject, for the first 10 seconds of a sprint.
If the assumption is made that maximum force is being applied to the pedals at the same point in each pedal stroke then the value of peak torque will also represent the value of peak force. It should be noted, however, that peak torque will not necessarily occur at the same time that peak force is being applied. As the pedals rotate the length of the lever arm is constantly changing and, therefore, peak torque will occur when the product of applied force and the lever arm length is optimal. An error of less than 5% is introduced if the variation in the crank angle at which maximum force is applied is less than 19 degrees. As the acceleration balancing load and torque are directly related then the peak value of acceleration balancing load also represents the magnitude, but not the timing, of the maximum force being applied to the pedals. The results, therefore, indicate that there is an inverse relationship between maximum force and pedalling speed.

This finding is supported by the results found by Sargeant (1980) for subjects cycling on an isokinetic ergometer.

4:15 SENSITIVITY OF THE SYSTEM TO VARIATIONS IN TORQUE GENERATION

It would appear from the previous study that the ergometer system is sensitive to intra-stroke variations in applied torque. Figure 4.23 shows the variation in the flywheel speed when a subject pedalled with one leg against a submaximal applied load of 4kg with and without using toe-clips. The subject was asked to maintain a constant 50 pedal r.p.m. In the figure the ordinate is expressed both in pedalling speed and uncorrected power output. It can be seen that the actual pedalling speed varies during the pedal cycle, accelerating during the propulsive phase of the cycle and decelerating during the recovery phase. The
Figure 4.23 An example of the variation of pedalling speed and uncorrected power output for a constant pedalling speed of 50 r.p.m., when cycling with one leg, with and without the use of a toe-clip (load 4kg).
use of the toe-clip appears to reduce the magnitude of the variation in the pedalling speed. The system appears, therefore, to be sensitive to changes in the way in which torque is being applied. It is not surprising that the power being applied to the pedals varies throughout the pedal cycle, however, what is surprising is the apparent magnitude of this variation. When the toe-clip is used then torque and power can be applied to maintain flywheel speed during the recovery phase of the pedal cycle, however, a period of zero, or near-zero, torque and power application would be expected during the transfer from knee extensors and hip extensors to knee flexors and hip flexors. This is not seen in the figure. When toe-clips are not used no contribution from the knee and hip flexors is possible for torque generation during the recovery phase and, therefore, a very distinct period of time when no torque or power is being applied should be seen on the figure. This period is clearly not evident on the figure.

If the computer is programmed to calculate the torque that must be being applied to the pedals (i.e. corrected method of calculation) to produce the variation in pedalling speed seen in Figure 4.23 then a very different pair of profiles is obtained, as shown in Figure 4.24. When the toe-clip is not used (dashed line) the calculated torque drops to zero during the recovery phase of the cycle. A different period of recovery is seen when the toe-clip was used. Although the calculated applied torque drops to nearly zero after the completion of the propulsive phase of the stroke some torque is is being quickly re-applied by the knee and hip flexors to reduce the magnitude of the deceleration of the flywheel, as was seen in Figure 4.23. Torque then appears to be re-applied by the main propulsive muscles by a co-ordinated transfer from the flexores to the extensors. The reduction in flywheel speed variation resulting from using the toe-clip means that less propulsive torque is required during the propulsive phase of the pedal stroke. Figure 4.24 clearly shows that
the maximum torque required to maintain the constant pedalling speed is less when toe-clips are used than when they are not. The corrected method of calculation appears not only to give the profile of torque profile that would be expected but to be also sensitive to subtle variations in the way that the torque is being applied.

To examine the sensitivity of the system to changes in torque application further the subject was asked to pedal with one leg using a toe-clip at three different loads and at a constant speed of 50 pedal r.p.m. The applied loads were 2, 4 and 5 kg. Figure 4.25 shows the calculated torque profiles obtained. Clearly, the peak torque generated increased with increasing load. This is the result that would be predicted from the previous study. Close examination of the profiles reveals further interesting findings. It appears that the greater the applied load the greater the contribution of the knee and hip flexors, during the recovery phase of the cycle, to flywheel speed maintenance. When a load of only 2 kg was applied very little contribution was seen from the knee and hip flexors as relatively little deceleration of the flywheel occurred during the recovery phase. What re-acceleration of the flywheel that was required to maintain the constant pedalling speed was comfortably achieved during the propulsive phase of the cycle. As the load was increased the contribution from the knee and hip flexors increased in an attempt to reduce the magnitude of the flywheel deceleration during the recovery phase of the pedal cycle. This reduction of flywheel deceleration resulted in the peak torque required during the propulsive phase not increasing in proportion to the applied load. A doubling of the applied load from 2 to 4 kg required only an average increase of 69% in peak torque. When the load was increased from 2 to 5 kg (a 150% increase) the increase in peak torque was only an average of 101%. These results are consistent with findings by researchers using cycle ergometers with pedals that have been instrumented with
Figure 4.24 Calculated torque being applied to the pedals when cycling with one leg, with and without the use of a toe-clip.
(pedalling speed = 50 r.p.m. Load = 4kg).
Figure 4.25 The calculated torque profiles obtained when pedalling with one leg, at 3 different loads (2, 4 and 5kg, toe-clip used).
strain gauges. Sargeant and Davies (1977) asked four subjects to pedal at 50 r.p.m. on a friction-loaded cycle ergometer with each leg separately and then with both legs. In that study the ergometer used was of the fixed-wheel type in contrast to the free-wheel type used in the present study. The feet were also secured to the pedals using toe-clips. They found that the mean peak force increased with work load. The relationship between mean peak force and work load was found to be linear with a steeper slope for two-legged than for one-legged although large inter-individual differences were found. As in the present study Sargeant and Davies reported an increase in net work performed on the crank during what they termed the flexion phases of the pedal cycle with increasing load and a marked increase in flywheel speed fluctuation with load for both one- and two-legged cycling. McCartney et al (1983) further support the findings from the present study. The torque profiles obtained by instrumenting the pedals of their isokinetic cycle ergometer show the same characteristics as those from the present study.

In order to investigate the effect of pedalling speed on the correctly calculated torque profile the subject was asked to pedal with one leg against an applied load of 2kg maintaining three different constant speeds. The three pedalling speeds were 50, 70 and 90 r.p.m., respectively. The foot of the subject was attached to the pedal with a toe-clip.

Typical torque profiles from each of the three speeds are shown in figure 4.26. Subtle changes in the profile can be seen to be occurring with increasing pedalling speed. The profile obtained at 50 r.p.m. has the same characteristics as those described above. As pedalling speed increased the time available for changeover in torque production from the hip/knee extensors to the flexors decreased. Less contribution to the total cycle torque production was,
Figure 4.26 Typical calculated torque profiles obtained for three different pedalling speeds, when pedalling with one leg (50, 70 and 90 r.p.m. toe-clip used).
therefore, available from the flexors and this reduced contribution with pedalling speed can be seen in the figure. The peak torque per stroke also slightly increased with pedalling speed reflecting the inability of the hip/knee flexors to prevent flywheel deceleration during the recovery phase of the cycle.

Care must be taken in interpreting the profiles as it is clear from closely examining them that the relatively slow sampling rate is limiting the resolution of the curves. The sampling rate was limited by the rate at which the internal analogue-to-digital converter of the computer can be read. Further research in this area will require the use of external converters which are being sampled in excess of 100Hz.

It would appear from the findings of the present study that by simply monitoring the acceleration of the flywheel the torque being applied to the pedals can be calculated. This result has far reaching implications. The cycle ergometer has not been fully utilised for evaluating muscle function due to the difficulty of obtaining data about the force/torque being applied to the pedals. Using the relatively simple system described in this chapter a great deal of information on force/torque production can be obtained easily.

4:16 EFFECT OF RESISTIVE LOAD ON PEAK POWER OUTPUT.

Several investigators have examined the maximum power output that can be generated on cycle ergometers and compared the results with peak power outputs generated on other forms of ergometer (Katch and Weltman 1979, Nakamura 1986). Others have correlated the peak power output values with physiological variables (Bar-Or 1980, Kaczowski et al 1982, Inbar et al 1981), anthropometric characteristics (Katch 1974) and athletic performance (Crielard and Pirnay, 1981). The optimal setting of the load is,
therefore, important if maximum power output is to be achieved. Several studies have examined load optimisation but have all done so using the uncorrected method of power output calculation.

Previous work described in this chapter has shown that the work done in accelerating the flywheel in a maximal test is highly significant and is a function of the rate at which the flywheel is being accelerated. The magnitude of the resistive loading will influence this rate. The present study was designed to investigate the effect of different resistance settings on the peak power outputs that could be generated on a Monark cycle ergometer. Both corrected and uncorrected peak power outputs were calculated for each load, and the discrepancies between the two values examined.
METHOD

Eighteen physically active subjects (9 male and 9 female) who were fully familiarised with the test procedure participated in the study. The physical characteristics of the subjects were, mean (±S.D.): age 29.3 (±10.1) years, weight 67.6 (±9.8) kg and height 172.6 (±10.4) cm.

The tests were performed on a basket-loaded Monark cycle ergometer (Model 864) with toe clips attached to the pedals.

Following a standard warm-up - which consisted of cycling, against a load of 1.5 kg, for 30 seconds at 30 kph, 30 seconds rest and 30 seconds at 40 kph - the subjects were allowed to stretch for 5 minutes. Each subject then performed 7 six second sprints each at a different resistive load. Each sprint was performed at a rolling start of approximately 65 pedal rpm. The loads used were separately determined for each individual and were equivalent to 55, 65, 75, 85, 95 and 105 g kg⁻¹ bodyweight. The order of loading was randomly assigned by the computer. The subjects pedalled at 65 rpm with the load supported by the experimenter. The load was introduced smoothly approximately one second prior to the instruction "GO" upon which the subject attempted to accelerate the pedals as quickly as possible without rising out of the saddle. Verbal encouragement was given throughout the 6 seconds. The subjects had a minimum of 7 minutes passive recovery between sprints.

The saddle height was set for each subject prior to the warm-up and remained unchanged throughout all the trials.

The instantaneous value of flywheel speed was monitored by the microcomputer as described earlier. Both the flywheel speed calibration and the regression equation calibration routines were performed prior to each group of tests.
At the conclusion of each sprint the computer was used to calculate and display the power output integrated over each 0.5 second of the test, using both corrected and uncorrected methods of calculation. The time to peak power was also determined for both methods.

4:16.2 RESULTS

A summary of the results is shown in Table 4.2.

Figure 4.27 shows the effect of different frictional loads on both the corrected and the uncorrected peak power outputs and time taken to reach peak power output from the start of the sprint.

A paired t-test was used to compare corrected and uncorrected peak power outputs for each load, and to examine the difference between loads for each method of calculation.

An increase in the frictional loading from 55 to 95 g.kg⁻¹ bodyweight resulted in a significant (p<0.05) increase in the uncorrected peak power output. A further increase in load above 95 g.kg⁻¹ bodyweight did not result in a further increase in peak power output.

(In contrast corrected peak power output declined with increasing load. However, a minimum change in the load of 20 g.kg⁻¹ bodyweight was required before the drop in peak power output became significant (P<0.05).)

For all loads the corrected peak power output was significantly (P<0.001) higher than the corresponding uncorrected value, with the average difference ranging from 68% for the lightest load (55g.kg⁻¹ bodyweight) to 6.7% for the heaviest load (105 g.kg⁻¹ bodyweight).
<table>
<thead>
<tr>
<th>LOAD (g.kg(^{-1}) B.W.)</th>
<th>PEAK POWER OUTPUT (W)</th>
<th>TIME TO P.P. OUTPUT (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Corrected</td>
<td>Uncorrected</td>
</tr>
<tr>
<td>55</td>
<td>921.2 ± 190.9</td>
<td>592.7 ± 123.6</td>
</tr>
<tr>
<td>65</td>
<td>901.3 ± 200.1</td>
<td>652.1 ± 124.7</td>
</tr>
<tr>
<td>75</td>
<td>879.0 ± 202.2</td>
<td>705.7 ± 133.5</td>
</tr>
<tr>
<td>85</td>
<td>875.2 ± 205.1</td>
<td>749.8 ± 150.1</td>
</tr>
<tr>
<td>95</td>
<td>865.6 ± 165.2</td>
<td>765.7 ± 166.9</td>
</tr>
<tr>
<td>105</td>
<td>836.9 ± 170.7</td>
<td>768.2 ± 175.6</td>
</tr>
<tr>
<td>115</td>
<td>825.2 ± 201.1</td>
<td>770.1 ± 188.8</td>
</tr>
</tbody>
</table>

Table 4.2 Corrected and uncorrected power output and time taken to reach peak power output for different resistive loads (n=18, mean ±S.D.).
Figure 4.27 The effect of different frictional loads on both the corrected and uncorrected peak power output, and time taken to reach peak power output from the start of the sprint (mean ±S.D., n=18).
The time to peak power was always shorter for the corrected values than for the uncorrected values (P<0.001). From the start of the test the time to reach corrected peak power output increased, and the time taken to reach the uncorrected peak power output decreased, with increasing frictional load. The difference did not become significant until the load changed by 30 g.kg⁻¹ bodyweight (P<0.05) for both methods of calculation.

4:16.3 DISCUSSION

Katch et al (1977) investigated the work-output scores of 28 subjects against 3 fixed loads of 4.5 and 6 kp on a Monark cycle ergometer. Re-calculation from the data presented on the subjects results in the loads applied being approximately 54, 67 and 80 g.kg⁻¹ bodyweight. Peak power was found to increase with increasing load but that there was no statistical difference between the 5 and 6kp loads. From these results Katch et al conclude that the optimum frictional resistances are 5 to 6kp (64 to 80 g.kg⁻¹ bodyweight). Evans and Quinney (1981) also examined the resistance settings for anaerobic power testing on a Monark ergometer. Their findings, for 12 male subjects, showed that peak power output increased with increasing loads up to a mean of 7.2kp (97 g.kg⁻¹ bodyweight). A further increase in the load resulted in a decline in peak power output. Nadeau et al (1983) found that values of peak power output for male subjects was still increasing with increasing loads up to 7kg (98 g.kg⁻¹ bodyweight), but started to decline for the female subjects above 6kg (102 g.kg⁻¹ bodyweight). The findings of these studies, in which power output was calculated in the conventional manner using 5 second time blocks, are in very close agreement with those uncorrected results in the present study. It would appear that increasing the load from the recommended Wingate loading of 75 g.kg⁻¹ to around 95g.kg⁻¹ will result in the highest value of peak power output being achieved.
The results obtained for corrected peak power output, however, show the opposite trend. It would appear that the lighter the load the greater the peak power output.

Uncorrected peak power output was found to be very sensitive to changes in resistive loading up to 95 g.kg\(^{-1}\) bodyweight. This finding is supported not only by Katch et al and Evans and Quinney but also by Nakamura (1986) who proposed an optimisation routine for obtaining maximum peak power output. The corrected values, however, were found to be very much more load tolerant throughout the spectrum of loads used, requiring a minimum load change of 20 g.kg\(^{-1}\) bodyweight before a statistically significant change in peak power output was detected. This increased tolerance to load variation by the corrected method is due to the differences in flywheel acceleration at different loads. As the load is decreased the subjects were able to accelerate the flywheel more quickly. This resulted in a greater proportion of the total work being done in increasing the kinetic energy of the flywheel and less into overcoming the frictional resistance. As both the work against the frictional load and the work done in accelerating the flywheel are summed together to give the corrected value of power output the net result is one of maintaining peak power output levels.

The reduction in the differences between the values of corrected and uncorrected peak power outputs as the load increases is not a surprising result. As the frictional load increases the acceleration of the flywheel that the subject can achieve decreases. The size of the difference in power outputs calculated by the two methods is proportional to the magnitude of the flywheel acceleration. As the acceleration is reduced then the difference diminishes. If the load was increased until no flywheel acceleration occurred then the two values would be the same. At this load, however, the subject would not
be able to move the flywheel i.e. zero acceleration. It is of interest to note that the optimisation routine proposed by Nakamura (1966) using the uncorrected method of calculation predicts that very high loads would be required for maximum power output.

As reported earlier corrected peak power output is always reached earlier than uncorrected values. Corrected peak power occurs whilst the flywheel is still being accelerated. As with the peak power values the times taken to reach peak power with changing load had opposite trends depending on the method of calculation used. Whereas the time to peak power increased with load for the corrected method of calculation it decreased for the uncorrected method. As the load increased the maximum speed achieved was decreased and even though the rate of acceleration also decreased the overall time taken to reach the peak speed diminished with the time to uncorrected peak power. Therefore, decreasing with increasing load. As the load increased the proportion of the overall power being used to overcome the resistance increased and as a consequence greater flywheel speed had to be achieved before maximum corrected peak power output was achieved, hence the greater time taken to achieve it.

Irrespective of the calculation method used, the change in loading had to be at least 30 g.kg⁻¹ bodyweight before the change in time to peak power became statistically significant (p<0.05).

Why is the highest value of peak power output achieved at the lightest load? A clue to the answer may lie in the time taken to reach peak power output. As the load increases this time taken also increases (see Table 4.2). Research on isokinetic cycle ergometers (Sargeant et al 1981, McCartney et al 1983) indicate that the highest peak power output occurs at pedalling speeds of around 100-110 rpm. The time taken to accelerate the pedals to this speed
is least at the lightest loads, due to greatest acceleration, and gets progressively longer as the loading is increased. The importance of the duration of an activity on peak power output has been discussed earlier in this thesis. As duration increases peak power output decreases due to the influences of fatigue. Therefore, even though the optimum pedalling speed is achieved by all the subjects at all the loads, greater fatigue will have occurred as the loading is increased due to the greater time required to reach this speed, resulting in a decline in the peak power output generated. Further evidence for this argument is that the change in load required to cause a significant change in peak power output is similar to that required to cause a significant change in time to peak power.

From the results it appears that light loads, not heavy loads as had previously been thought, are needed if maximum values for peak power output are to be achieved. However, such loads may not be suitable for optimising maximum mean power output over a 30s test.

4:17 EFFECT OF RESISTIVE LOAD ON THE MAXIMUM MEAN POWER OUTPUT IN A 30 SECOND TEST.

The results from the previous study showed that light loads produce the highest values of peak power output but gave no indication of the effect of the load on the maximum mean power output that could be achieved in a 30 second test. Since the early work of Asmussen and Boje (1945) there have been many studies examining the relationship between the human power output generated on friction-loaded cycle ergometers and a variety of physiological characteristics. For example, the relationship between power output and aerobic and anaerobic capacities (Bar-Or et al 1980, Kaczowski et al 1982), nutritional (Tuttle et al 1949) and thermal (Jacobs 1980) status, the effect of warm-up (Inbar and Bar-Or 1975), muscle
fibre-type composition (Kaczowski et al 1982, Inbar et al 1981), anthropometric characteristics (Katch 1974) and athletic performance (Crielaard and Pirnay 1981). In all these studies optimisation of the load was important, so that maximum mean power output could be achieved.

This next study was designed to investigate the effect of resistance settings on the maximum mean power output that could be generated on a Monark cycle ergometer. The results calculated by the two different methods would be compared.

4:17.1 METHOD

The mean (±S.D.) values for the physical characteristics of the 12 subjects (six males and six females) who took part in the study are as follows: age 24.7(±5.3) years, height 168.7 (±9.8) cm and weight 65.2 (±10.1) kg.

On four successive days the subjects were asked to perform a single bout of 30 seconds maximal exercise against a different resistive loading. The loads used were determined for each subject and were equivalent to 55, 75, 95 and 105 g.kg\(^{-1}\) bodyweight. The order of loading was assigned randomly by the computer. The tests were performed on a basket-loaded Monark cycle ergometer (model 864) to which toe clips had been attached.

Prior to the first test the saddle height determined for each subject and the same saddle height was used for all four tests. A standardised warm-up was followed by each subject consisting of cycling for 30 seconds at 30 kph, 30 seconds rest and then cycling for 30 seconds at 40 kph. The load used during the warm-up was 1.5 kg. The subjects then stretched, particularly the quadriceps femoris, hamstrings and triceps surae, for five minutes. The subjects then pedalled at 65 rpm with the load supported by the experimenter. The load was introduced smoothly
approximately one second before the instruction "GO" upon which the subject attempted to accelerate the pedals as quickly as possible without rising out of the saddle. The subjects were verbally encouraged, throughout the 30 seconds, to try and maintain as high a pedalling rate as possible. The subjects were instructed prior to the test not to 'pace' themselves.

The instantaneous value of flywheel speed was monitored as described earlier. Both flywheel speed calibration and regression equation calibration were checked prior to each test day. Previous studies had shown that these calibration factors were stable. At the conclusion of each sprint the computer calculated and displayed the power output integrated over each 0.5 second of the test, using both corrected and uncorrected methods of calculation. The mean values of pedalling speed and power output were also determined.

4:17.2 RESULTS

A summary of the results obtained from this study are shown in Table 4.3.

Figure 4.28 shows the effect of different frictional loads on both the corrected and uncorrected mean power outputs generated during a 30s maximal test.

A paired t-test was used to compare corrected and uncorrected mean power outputs for each load, and to examine the difference between each load for both methods of calculation. For both methods of calculation mean power output increased with increasing load. However, only the 55 g.kg⁻¹ bodyweight loading values were found to be significantly different from all the other values (p<0.001). In addition significance (p<0.05) was found between the uncorrected values obtained at 75 and 105 g.kg⁻¹ bodyweight. At a loading of 55 g.kg⁻¹ bodyweight the
<table>
<thead>
<tr>
<th></th>
<th>LOAD (g.kg(^{-1}) bodyweight)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>55</td>
</tr>
<tr>
<td><strong>MEAN POWER OUTPUT (W)</strong></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>471.5±79.9</td>
</tr>
<tr>
<td>C</td>
<td>480.0±85.2</td>
</tr>
<tr>
<td><strong>PEAK POWER OUTPUT (W)</strong></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>5879±116.1</td>
</tr>
<tr>
<td>C</td>
<td>933.1±227.0</td>
</tr>
<tr>
<td><strong>PEAK PEDAL REVS (rpm)</strong></td>
<td>162.9±12.5</td>
</tr>
<tr>
<td><strong>MEAN PEDAL REVS (rpm)</strong></td>
<td>131.0±9.5</td>
</tr>
</tbody>
</table>

U=uncorrected, C=corrected

Table 4.3 Corrected and uncorrected power output and pedalling speeds at different resistive loads (n=12, mean ±S.D.).
Figure 4.28 The effect of different frictional loads on both the corrected and the uncorrected mean power output generated during a 30s maximal test (mean ±S.D., n=12).
values of corrected mean power outputs were higher than the uncorrected ones (p<0.01). Corrected mean power output was only just significantly higher than uncorrected mean power output at a load of 75 g.kg\(^{-1}\) bodyweight (p<0.05). Above this load no significant differences were found.

Corrected peak power output (Figure 4.29) tended to decline with increasing load, however, only the value obtained at 95 g.kg\(^{-1}\) bodyweight was significantly different from the others (p<0.05). Uncorrected peak power increased with load with all values being significantly different from one another (P<0.05). All values of corrected peak power output were significantly higher than the uncorrected ones (p<0.001).

Figure 4.30 shows a plot of the difference between the corrected and uncorrected mean power outputs in relation to the differences in the pedalling speed at the beginning and end of the test. The greater the discrepancy in the speed the greater the difference between the mean power values. The regression equation calculated was:

\[ y = 0.17x + 1.22 \quad (r^2=83.8\%) \]

The relationship between peak and mean pedalling speed with load is shown in figure 4.31. Both values declined with increasing loads. The regression equations derived were:

peak pedalling speed: \( y = 212.9 - 0.933x \) \( (r^2=64.2\%) \)

mean pedalling speed: \( y = 183.0 - 0.950x \) \( (r^2=76.1\%) \)

4:17.3 **FATIGUE INDEX**

The corrected and uncorrected fatigue indices for the
Figure 4.29 Effect of load on corrected and uncorrected peak power output generated during a 30s maximal test (mean ±S.D., n=12).
Figure 4.30 A plot of the difference between the corrected and uncorrected mean power outputs in relation to the differences in the pedalling speed at the beginning and end of a 30 second test (n=12).
Figure 4.31 The relationship between peak and mean pedalling speed with load (mean ±S.D., n=12).
different loads, expressed as the difference between the peak and end power output divided by the peak power output, are shown in Table 4.4.

Figure 4.32 shows that uncorrected peak and end power outputs increased with increasing load. The overall effect is an increasing fatigue index with load. The increase in fatigue index obtained when the loads were increased from 55 to 75, and 75 to 95 kg\(^{-1}\) were significant (p<0.001 and p<0.05, respectively). Further increases in loading did not produce significant increases in the fatigue index.

As with the uncorrected values the corrected values of end power output rose with increasing load, however, there was a decline in peak power output (Figure 4.33). The overall result was a decline in corrected fatigue index with increasing load. The value of fatigue index at the lightest load was significantly higher than those obtained at all the other loads (p<0.01), however, no significant differences was found in this index between the other loads.

At all loads corrected fatigue indices were always higher than uncorrected ones (p<0.001).
Table 4.4 Corrected and uncorrected peak and end power outputs and associated fatigue indices for different resistive loads (n=12, mean ±S.D.).

<table>
<thead>
<tr>
<th>LOAD (g·kg⁻¹·bodyweight)</th>
<th>55</th>
<th>75</th>
<th>95</th>
<th>105</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEAK POWER (W)</td>
<td>933.1±227.0</td>
<td>914.7±173.6</td>
<td>858.0±183.1</td>
<td>887.6±169.3</td>
</tr>
<tr>
<td>END POWER (W)</td>
<td>371.3±68.7</td>
<td>404.8±71.7</td>
<td>432.2±29.7</td>
<td>407.9±113.6</td>
</tr>
<tr>
<td>FATIGUE INDEX (%)</td>
<td>59.0±6.8</td>
<td>55.1±7.2</td>
<td>48.1±14.7</td>
<td>52.6±12.2</td>
</tr>
<tr>
<td>Uncorrected</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEAK POWER (W)</td>
<td>587.9±116.1</td>
<td>693.2±133.2</td>
<td>754.0±152.6</td>
<td>781.3±160.7</td>
</tr>
<tr>
<td>END POWER (W)</td>
<td>380.4±66.6</td>
<td>415.3±70.6</td>
<td>426.0±84.5</td>
<td>427.5±90.2</td>
</tr>
<tr>
<td>FATIGUE INDEX (%)</td>
<td>348±6.8</td>
<td>39.6±7.5</td>
<td>42.8±8.0</td>
<td>44.9±6.4</td>
</tr>
</tbody>
</table>
Figure 4.32 The relationship between uncorrected peak and end power output and load (mean ± S.D., n=12).
Figure 4.33 The relationship between corrected peak and end power output and load (mean ±S.D., n=12).
4:18 COMPARISON OF INSTANTANEOUS PEAK POWER AND AVERAGED PEAK POWER

The conventional method of assessing the peak power output generated on a cycle ergometer is to count the number of flywheel or pedal revolutions in a fixed time period and to express the value obtained as an average value. This conventional method of calculation assumes that there is little change in the instantaneous value of the power being applied to the flywheel. However, the studies described in this chapter have clearly shown that the instantaneous value of power output on the ergometer is constantly varying. Should, therefore, peak power output be expressed as an averaged value, or should the instantaneous peak value be used? If it can be shown that a very high correlation exists between the instantaneous and averaged values of peak power output then either value would be equally sensitive to any changes in power production taking place and, therefore, either value could be used confidently.

The present study was designed to investigate the relationship between instantaneous and averaged peak power output for non-fatigued muscle.

4:18.1 METHOD

The mean (±S.D.) values for the physical characteristics of the eight subjects (6 males, 2 females) who took part in the study were: age 26.3 ± (2.4) years, height 179.2 (± 8.7) cms and weight 73.4 ± (6.3) kg. Each subject performed a single six second sprint on the Monark cycle ergometer at a load of 75 g.kg⁻¹ bodyweight.

Following the standard warm-up each subject was asked to pedal at 60 rpm with the load being supported by the experimenter. At the command "GO" the load was introduced and the subjects pedalled at maximum intensity for six
The computer logging procedure was initiated just prior to the start of the sprint, and the flywheel speed was monitored throughout the test. At the end of the test the point at which the sprint started was established on the computer and the data for the next 6 seconds was analysed. The computer calculated and displayed the peak instantaneous value of power output and the peak power averaged over one and five seconds periods. In addition both the time taken to reach instantaneous peak power output and the pedalling speed at which instantaneous peak power output was attained was displayed.

4:18.2 RESULTS

A summary of the data obtained is shown in Table 4.5. Figure 4.34 shows the relationship between the instantaneous and averaged values of peak power output.

4:18.3 DISCUSSION

It is clear from the results that the 5 second averaging period poorly predicts the instantaneous value of peak power output. The results for the 1 second averaging are, however, more encouraging. Although the grouped data shows a high correlation ($r=0.88$) it is important to determine the extent to which the grouping of the data masks the individual variation. The $r^2$ value of 0.78 indicates that 22% of the data is unaccounted for in the correlation. It is, therefore, of interest to examine the results obtained from repeated sprints performed by a given individual so that an idea of the variability can be assessed. The experiment to examine this variability is described below.

It is of interest to note that the speed at which instantaneous peak power output was achieved, mean 129.9 r.p.m., was similar to those reported using isokinetic
Table 4.5 Corrected instantaneous and averaged peak power output values for each subject. Also shown are the pedalling speed at, and the time taken to reach, peak power output (n=8, mean ±S.D.).

<table>
<thead>
<tr>
<th>SEX</th>
<th>INSTANT. P.P.O. (W)</th>
<th>AVERAGED P.P.O. (W)</th>
<th>REVS AT P.P.O. (rpm)</th>
<th>TIME TO P.P.O. (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>3013.1</td>
<td>1215.7</td>
<td>983.9</td>
<td>142.8</td>
</tr>
<tr>
<td>M</td>
<td>2586.4</td>
<td>927.4</td>
<td>762.7</td>
<td>128.5</td>
</tr>
<tr>
<td>M</td>
<td>2622.4</td>
<td>946.7</td>
<td>757.9</td>
<td>138.8</td>
</tr>
<tr>
<td>M</td>
<td>2322.1</td>
<td>871.7</td>
<td>751.7</td>
<td>115.4</td>
</tr>
<tr>
<td>F</td>
<td>2439.0</td>
<td>718.8</td>
<td>501.6</td>
<td>124.3</td>
</tr>
<tr>
<td>M</td>
<td>3352.8</td>
<td>1239.8</td>
<td>967.3</td>
<td>130.2</td>
</tr>
<tr>
<td>M</td>
<td>2468.6</td>
<td>898.2</td>
<td>751.6</td>
<td>121.2</td>
</tr>
<tr>
<td>F</td>
<td>2862.7</td>
<td>944.9</td>
<td>753.0</td>
<td>138.2</td>
</tr>
<tr>
<td>Mean</td>
<td>2710.9</td>
<td>970.4</td>
<td>778.7</td>
<td>129.9</td>
</tr>
<tr>
<td>±S.D.</td>
<td>346.4</td>
<td>174.9</td>
<td>149.9</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Figure 4.34 The relationship between instantaneous and averaged values of peak power output (n=8).
cycle ergometers (Sargeant, 1980; McCartney et al., 1983).

4:19 EXAMINATION OF SUBJECT VARIABILITY IN INSTANTANEOUS-V-AVERAGED PEAK POWER OUTPUT.

5 subjects (4 male and 1 female), whose personal characteristics are shown in Table 4.6, were asked to perform six 6 second sprints with 24 seconds recovery between each sprint. The load used was the recommended Wingate loading of 75g.kg⁻¹ bodyweight. Each subject followed the standard warm-up procedure prior to the test and the data was collected in the same way as that described in the previous study.

4:19.1 RESULTS

Table 4.6 shows the personal characteristics of the subjects and the correlation coefficients obtained between instantaneous and the one second averaged values of peak power output.

4:19.2 DISCUSSION

The correlation coefficient obtained varied widely from one individual to another. The average of the coefficients was 0.604 which is a low value. When the data obtained for all the subjects was grouped then the correlation was very high (r=0.945) as would be expected from the previous study. Why are the individual values of peak power output so poorly correlated when the grouped data is so highly correlated? An answer to this question may lie in the mechanics of the cycle ergometer and the data collection system. All the calculations used to measure power output whether corrected or uncorrected make the same assumption - that the load being applied at any instant is constant. The load is being applied using a Sinus balance which relies on dynamic balance. This dynamic balance is achieved using a negative feedback loop. If the applied
<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>r</th>
<th>T (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>22.3</td>
<td>169.2</td>
<td>67.1</td>
<td>0.35</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>28.2</td>
<td>174.1</td>
<td>69.4</td>
<td>0.81</td>
<td>1.9</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>25.5</td>
<td>183.7</td>
<td>77.9</td>
<td>0.41</td>
<td>1.9</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>25.7</td>
<td>187.7</td>
<td>76.0</td>
<td>0.69</td>
<td>2.6</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>26.5</td>
<td>170.6</td>
<td>64.2</td>
<td>0.94</td>
<td>3.7</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>25.6</td>
<td>177.1</td>
<td>70.9</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>S.D.</td>
<td></td>
<td>2.2</td>
<td>8.2</td>
<td>5.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

T = time to peak power  
Group correlation, $r = 0.945$

Table 4.6 The personal characteristics of the subjects and the correlation coefficients obtained when instantaneous and one second averaged values of peak power output were compared ($n=5$).
load is greater than the friction on the flywheel then the friction is increased, and if the applied load is less than the friction then it is reduced. This state of balance is, therefore, achieved by constantly changing the friction being applied to the flywheel. If the applied load is closely observed, whilst the ergometer is being pedalled at a constant speed, it can be seen to oscillate as dynamic equilibrium is maintained. The actual instantaneous value of the applied load is, therefore, not known. The magnitude of the error is increased in the tests described in this chapter as the flywheel is being accelerated under heavy loads which will result in even larger fluctuations in the resistive load. The result of this is that an error will be introduced into the power calculation. As the instantaneous values of the frictional load fluctuate around the mean, i.e. the applied load, the calculated instantaneous values of power output will also vary around the correct value. An additional error is introduced by the sampling rate used by the computer. In the tests described the sampling rates are between 25 and 40 Hz. As the peak pedalling speeds achieved are around 150 rpm (300 pedal strokes per minute or 5 per second) then only 5 to 8 data points are collected per pedal stroke which although reasonable, will introduce an error in the measurement of the acceleration of the flywheel. The error due to the sampling rate, however, is less than due to the fluctuating load. An individual value of power output may, therefore, deviate from the correct value but if a large number of values are obtained the errors will tend to cancel each other out. This is what we see in the results of this study. If small numbers of values are examined then the correlation obtained is low, but grouping the data results in a high correlation.

As the actual instantaneous load is not known on such ergometers then averaging the data will result in a more accurate value of power output being calculated as very many data points are grouped together thereby reducing the
error caused by the fluctuating load. An alternative would be to measure the actual frictional load, by placing a force transducer in series with the belt, and using this value in the calculation of power output. Although this may appear to be an attractive solution to the problem it should be noted that force detection systems often have significant time lags associated with them which in turn may result in errors of measurement when high speed dynamic changes are taking place.

4:19.3 INSTANTANEOUS PEAK POWER OUTPUT

The instantaneous value of peak power output, obtained from two studies described above (mean 2710.9W, range 2468.6–3352.8W.) are very similar to, if not slightly higher than, those obtained using isokinetic cycle ergometers (McCartney et al., 1983).

4:19.4 DISCUSSION

The results indicate that, whereas maximum peak power output requires a light load, maximum mean power output is produced when the loading is heavier. This finding was found to be independent of the calculation technique employed. The results obtained for the uncorrected mean power output are in very good agreement with Katch et al (1977), who examined 40 seconds of maximal exercise. Once the ergometer flywheel has been accelerated the variation in pedalling speed with time is small and, therefore, the differences in instantaneous values for uncorrected and corrected power outputs are also small. Therefore, for the deceleration phase of the test the high load required for the maximum value of uncorrected mean power output is equally applicable for the corrected method. During the acceleration phase the peak power output was found to be relatively insensitive to load and therefore, as the cumulative work done (mean power output) during the 30 seconds is the sum of the work done in accelerating the
flywheel and the work done during the deceleration phase the higher loads required for maximum uncorrected mean power output are equally applicable to maximum corrected mean power output. Although it would appear that the heavier the load the higher the mean power output there was no statistical difference found when the load was increased above 75 g.kg\(^{-1}\) bodyweight. Katch et al (1977) recommended that the optimal frictional resistance for maximum mean power output in 40 seconds was a loading of 5 to 6 kg (67 to 80 g.kg\(^{-1}\) bodyweight for their subjects). Further supporting evidence of this statement can be obtained by carefully examining the data presented by Sargeant et al (1981) and McCartney et al (1983) who used isokinetic cycle ergometers. The findings by Sargeant indicated that the optimal pedalling speed to obtain maximal power output during short term exercise was around 110 rpm. McCartney et al found that optimal mean power output over a 30 second test was achieved when the pedalling rate was around 100 rpm. For the subjects in the present study a loading of approximately 75-82 g.kg\(^{-1}\) bodyweight would have been required to achieve a mean pedalling rate of 100-110 rpm, a similar value to the loading recommended by Katch et al.

It should be noted that both in the present study and in that by Katch et al (1983) the highest loads used did not cause a decline in the maximum mean power output and therefore, some care must be taken in making loading recommendations based on the data presented, as a further increase in the load might result in an improved performance.

4:19.5 FATIGUE INDEX

Although the highest values of corrected peak power output were achieved when the lightest loads were used, the lowest values of corrected mean power output were obtained, due to the greater rate of fatigue. At these
light loads the lowest values of end power output was measured. As with many other power values this trend is opposite to the one obtained when the corresponding uncorrected power values are calculated.

Why should the lightest loads result in the greatest decrement in power output when the highest peak power output values are achieved at these loads? These results may be due to either a greater compromise of energy provision or a greater decrease in efficiency, or indeed a combination of the two as they are not mutually exclusive.

If efficiency is assumed to remain constant, then an increase in external power output must be as a result of increased metabolic energy provision. As the time course of the activity is short the vast majority of this energy must have been derived from the anaerobic processes. This increased energy provision will, therefore, be due to an increased rate of degradation of ATP. The consequence of this is that the ADP and AMP levels will rise more rapidly and PCR stores will decrease at a greater rate. As anaerobic glycolysis is also contributing more to energy production the concentration of protons ($H^+$) will also rise at a greater rate. An increase in hydrogen ion concentration, which causes a drop in muscle pH, has been shown to inhibit glycolysis at the PFK step, if not counteracted by positive modulators, in particular ADP and AMP. The hydrogen ions enhance the decrease in PCR levels through a displacement of the creatine kinase equilibrium. An even further decline in the PCR levels results from the increased levels of ADP. (Hultman et al. 1967) using electrical stimulation reported a high correlation between the decrease in PCR levels and force decline. Since it is supposed that free ADP will rise when PCR levels drop, Hultman felt that it was quite probable that it was the ADP increase that was the primary source of decrease in force production.
Power is the product of force and velocity. The non-linear relationship between force and velocity for unfatigued muscle, discussed earlier in this chapter, results in there being a unique velocity of concentric contraction at which power output is optimised. Velocities of contraction both above and below this point result in a decrease in the maximum power output that the muscle can generate. On isokinetic cycle ergometers Sargeant et al (1981) and McCartney et al (1983) report this optimised velocity as being equivalent to a pedalling speed of 110-120 revolutions per minute. At a loading of 55 g.kg⁻¹ the mean pedalling speed was approximately 130 rpm, which is 18 to 30% higher than the reported optimum speed. As the type II muscle fibres fatigue more rapidly than type I fibres the contraction velocity at which power output is optimised may well fall as fatigue increases, as the proportional contribution of the slower twitch fibres will be increasing. The average time to peak tension will, therefore, rise and as fatigue sets in relaxation time has also been shown to increase. These factors will further reduce the optimum velocity of contraction, and will result in the pedalling speeds, at the lowest loads, being even further away from this speed, resulting in even less efficiency and lower power output values.

The overall efficiency of the muscular contraction is further impaired by the fatigue processes. The accumulation of the H⁺ and La²⁻ ions has been linked to an increased efflux of K⁺ ions into the extracellular space. This increased efflux may be related to changes in the conductance of the muscle membrane to K⁺ and/or inhibition of the Na⁺/K⁺ pump. The increased extracellular K⁺ decreases the resting membrane potential, which would decrease the amplitude of the action potential, and, therefore, a decreased force of contraction. The increased levels of ADP impair the function of ATPases (mainly the Na-K-ATPase) resulting in impaired muscle function.
All these factors combine to cause the greater observed fatigue when the lightest loads are used. The higher initial power levels result in an increased rate in both energy provision inhibition and efficiency decline. In addition the speed of pedalling is different from that required for optimum power output.

For the lighter loads the average corrected values of mean power output were higher than the average uncorrected mean power outputs. This result is due to the difference in the pedalling speed at the start and the end of the test. Because the starting pedalling rates were less than the end rates not all the energy used in accelerating the flywheel was recovered in its subsequent deceleration. The corrected method of calculation accounts for this whereas the uncorrected method does not resulting in the discrepancies found. The magnitude of the differences found in mean power output between the two methods of calculation was found to be directly related to the difference in start and end pedalling speeds ($r^2=83.5\%$).

Both peak and mean pedalling speeds were found to be related to load (Figure 4.31). The inverse relationship between force (torque) and speed on isokinetic cycle ergometers has been discussed earlier in the chapter and, therefore, the result found for mean pedalling speed is perhaps not a surprising one. What is of interest is that the gradients for peak speed and mean speed against load are nearly identical. Although it would be expected that peak speed would increase with decreasing load ($r^2=64\%$) it might not be expected that the relationship between peak speed and load is the same as for mean speed and load. It should be noted that the loads used limit peak pedalling speeds to values lower than those that would be attained at maximum muscle contraction velocities.
GENERAL DISCUSSION OF CHAPTER.

The results of the studies reported in this chapter are very exciting. They indicate that friction-loaded cycle ergometers can be used not just as a tool for providing a known workload but that they can also be used for examining many aspects of muscle function with an ease that was not previously thought possible. By simply constantly monitoring the speed of the flywheel, using a computer, the acceleration of the flywheel at any instant can be calculated. The external power output, applied force and torque of the subject, at any instant in time, can be determined. These values can be used to examine many aspects of performance, such as:

a) external power output with respect to time (i.e. exercise duration);
b) the force-velocity relationship of muscle both in the fatigued and non-fatigued state;
c) the bilateral imbalance of the propulsive muscles;
d) the modification of torque production with changes in position, crank length, seat height etc.;
e) the optimal load setting for a given individual.

In addition the ergometer can correctly measure the power output and work being done so that physiological variables can be accurately examined. It is clear that the system described in this chapter is sufficiently sensitive to detect small and subtle changes in the external power output generated by the subject.

The chapter highlighted the errors that have been made to date in the measurement of power output and work done in short-duration high-intensity exercise on such ergometers. Rather than just making a damning statement of such experiments the chapter indicates where, although incorrectly measured, the values presented by these researchers are in fact valid. It appeared that the mean
power output values obtained using the uncorrected method of calculation were very close to the correct values, when a rolling start was used. Those values of peak power output that have been reported which were obtained from averaging periods of one second or less are in fact correct values of external power output although they are not in fact peak power values. These uncorrected peak power output values represent, in fact, the power being generated when the subject is—pedalling at peak speed. Unfortunately most of the other variables measured, using the uncorrected method of calculation, in particular the actual value of peak external power output, were wrong often by large amounts.

The confusion expressed by several authors as to why peak power output generated on friction-loaded ergometers appears to be significantly lower than on other ergometers was cleared up in this chapter. The results show that the friction-loaded cycle ergometer behaves in the same way as other ergometers when the peak external power output is correctly calculated. The finding that on such ergometers the mean peak power generated is not very sensitive to the load used is a bonus to those researchers interested in examining this variable.

Not only was the friction-loaded cycle ergometer discovered to behave like other cycle ergometers with respect to peak power output but it was found to have many other similar characteristics, including:

a) An inverse relationship between peak and mean torque versus pedalling speed;

b) The highest values of peak power output were found at the lighter loads, and therefore, higher pedalling speeds, whereas the greatest values of mean power output were achieved when heavier loads were applied.

c) Peak power output was attained before peak speed is achieved.
In conclusion, Jacobs et al. (1983) state that the direct measurements of selected intramuscular metabolic concentrations, made in their study, provided further physiological support for the growing use of the 'Wingate Anaerobic Test' in the assessment of the ability to generate muscular power during short term high intensity exercise. How much more valid this statement would be if the correct values of power output were calculated and used.
CHAPTER 5

5:1 Measurement of performance in repeated short-duration maximal sprints on the friction-loaded cycle ergometer.

The previous chapter closely examined the use of the friction-loaded cycle ergometer as a tool for evaluating muscle function and human performance in a single bout of exercise, with a duration from 1 to 30 seconds. Many sports are characterised as having periods of low intensity exercise interspersed by short bouts of maximal or near-maximal effort. Some of the sports that fall into this category are soccer, hockey, rugby, basketball, volleyball, cricket. It was seen in the previous chapter that during brief high-intensity exercise changes in muscle function and in metabolism occur which result in an inability of the subject to maintain power output. This inability to maintain peak power output was described as muscle fatigue. Saltin and Essen (1971) suggested that heavy bouts of cycle ergometer exercise (400W) of 10 seconds duration, which were interspersed with 20 second recovery periods, could be sustained over long periods with little decrement in performance and little increase in blood lactate. Boobis et al. (1982) and Wootton and Williams (1983) stated that such studies, although performed at exercise intensities equal to or greater than the power output that would elicit maximal aerobic capacity, are at much lower external power outputs than would be achieved during maximal exercise. They set up a study to examine the ability to perform repeated bouts of maximal dynamic exercise with different recovery durations. Using the uncorrected method of calculation of external power output they found that the capacity to perform five repeated 6s bouts of maximal exercise was influenced by the preceding number of sprint bouts and the duration of the recovery interval. These decrements in
performance and the associated high levels of blood lactate concentrations were in contrast to the findings of Saltin and Essen. These differences were felt to reflect the power output demands of the exercise which were calculated to be 2.5 to 3.5 times that which would elicit maximal aerobic capacity.

It was shown in the previous chapter that both peak power output and the total work done in maximal tests lasting only a few seconds is greatly underestimated by the uncorrected method of calculation. A study was set up to examine the extent of this error and whether a similar decrement in performance is seen when corrected values of external power output are used.

5:1.1 METHOD

The computer program described in the previous chapter was modified to capture only 10 seconds of data. Even with this shorter capture period the data logged would exceed the capacity of the memory of the computer before the end of the test. To overcome this problem the data collected during each sprint was transferred to disc during each recovery period.

Six subjects (5 males and 1 female) whose age, weight and height (mean ±S.D.) were 26.1 ±5.4 years, 71.1 ±10.2 kg and 174.2 ±8.8 cms, respectively. All the subjects were members of the Great Britain Nordic Ski Team.

The subjects were fully familiarised with the experimental protocol.

Each subject had two warm-up rides (30s at 120 and 150 W, load 14.7 N) prior to the start of the test. The warm-up allowed the subjects to reaquaint themselves with the high pedal frequencies while causing minimal metabolic disturbance.
The exercise task consisted of six 6 second maximal sprint bouts, on a Monarch 864 cycle ergometer, with 30 seconds passive recovery between sprints. The loads used were 75g.kg⁻¹ bodyweight. Each subject was instructed to pedal at an initial pedal speed of 65 r.p.m. against little resistance. The data logging by the computer was started approximately 2 seconds prior to the "GO!" command. As the experimenter gave the command the load was quickly and smoothly applied. The subject was instructed to pedal as quickly as possible, upon hearing the command, and to maintain maximum effort for the 6 seconds. A second experimenter started a stopwatch on the command and instructed the subject to stop pedalling after 6 seconds had elapsed. The second experimenter continued to monitor the elapsed time and instructed the subject to commence pedalling at 65 r.p.m. against the minimal resistance after 25 seconds of the recovery period had elapsed. The load was then reapplied after 30 seconds of recovery with the associated commands. The subjects were instructed to remain seated throughout the test.

At the conclusion of the sixth sprint the raw data for each sprint was recovered from the disc. The power output for each second of each sprint was calculated using both the uncorrected and corrected methods of calculation. The start point of each sprint was established from the point of inflexion of the pedalling speed as described in the previous chapter. The values of peak, mean and end power output, and mean pedalling frequency for each sprint was determined.

5:1.2 RESULTS

A summary of the results are shown in Table 5.1.

An example of the power output profiles for one of the subjects for each of the six 6 second sprints is shown in
<table>
<thead>
<tr>
<th>SPRINT NUMBER</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak Power Output (W)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncorrected mean</td>
<td>750</td>
<td>737</td>
<td>724</td>
<td>709</td>
<td>697</td>
<td>686</td>
</tr>
<tr>
<td>S.D.</td>
<td>120</td>
<td>125</td>
<td>120</td>
<td>128</td>
<td>114</td>
<td>123</td>
</tr>
<tr>
<td>Corrected mean</td>
<td>960</td>
<td>980</td>
<td>943</td>
<td>933</td>
<td>899</td>
<td>874</td>
</tr>
<tr>
<td>S.D.</td>
<td>171</td>
<td>217</td>
<td>212</td>
<td>226</td>
<td>180</td>
<td>203</td>
</tr>
<tr>
<td><strong>Mean Power Output (W)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncorrected mean</td>
<td>666</td>
<td>653</td>
<td>648</td>
<td>638</td>
<td>623</td>
<td>613</td>
</tr>
<tr>
<td>S.D.</td>
<td>102</td>
<td>106</td>
<td>109</td>
<td>111</td>
<td>102</td>
<td>114</td>
</tr>
<tr>
<td>Corrected mean</td>
<td>800</td>
<td>790</td>
<td>780</td>
<td>771</td>
<td>750</td>
<td>740</td>
</tr>
<tr>
<td>S.D.</td>
<td>128</td>
<td>127</td>
<td>127</td>
<td>129</td>
<td>135</td>
<td>136</td>
</tr>
<tr>
<td><strong>End Power Output (W)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncorrected mean</td>
<td>739</td>
<td>713</td>
<td>683</td>
<td>658</td>
<td>677</td>
<td>621</td>
</tr>
<tr>
<td>S.D.</td>
<td>103</td>
<td>106</td>
<td>93</td>
<td>105</td>
<td>95</td>
<td>104</td>
</tr>
<tr>
<td>Corrected mean</td>
<td>724</td>
<td>690</td>
<td>651</td>
<td>628</td>
<td>601</td>
<td>587</td>
</tr>
<tr>
<td>S.D.</td>
<td>102</td>
<td>93</td>
<td>77</td>
<td>85</td>
<td>70</td>
<td>79</td>
</tr>
<tr>
<td><strong>Mean Pedalling Rate (r.p.m.)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>127</td>
<td>124</td>
<td>123</td>
<td>121</td>
<td>119</td>
<td>117</td>
</tr>
<tr>
<td>S.D.</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>12</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 5.1 Corrected and uncorrected power output and mean pedalling speed for each of the 6 sprints (n=6, mean ±S.D.).
Figure 5.1 An example of the corrected power output profiles for one of the subjects for each of the six 6 second sprints.
Uncorrected peak power output was found to decline steadily from the first sprint. All subsequent values are significantly (p<0.05) lower than the first value. In contrast the highest value of corrected peak power output occurred during the second sprint, although this value is not significantly higher than the first sprint. After the second sprint peak power output declined at a greater rate than the uncorrected values, however, it is not until the fourth sprint that the decline becomes significant (p<0.05). All the values of corrected peak power output are significantly higher, average 23.0%, than all the uncorrected power output values (p<0.001). Figure 5.2 shows the corrected and uncorrected values of peak power output.

Both uncorrected and corrected end power output values, shown in Figure 5.3, decline with increasing sprint number. As with peak power output the rate of decline is greater for the corrected values. All corresponding values of end power output are greater using the uncorrected method of calculation than for the corrected method, average 5.2% (p<0.001). There is not, however, total separation of the end power output values as there was for peak power output.

Although all the values of corrected mean power output are very much greater than uncorrected ones (p<0.001), both rates of decline are very similar, as seen in Figure 5.4. The average difference between the two methods of calculation was approximately 17.1%, with both showing a decrement of about 7.5 to 8% by the sixth sprint. For both methods it was not until the third sprint that the decline became significant (p<0.05).

Mean pedalling rate over the six seconds of the sprint is independant of the calculation technique. Figure 5.5 shows
Figure 5.2  The corrected and uncorrected values of peak power output for each 6 second sprint (mean ± S.D., n=6).
Figure 5.3 The corrected and uncorrected values of end power output for each 6 second sprint (mean ±S.D., n=6).
Figure 5.4 The corrected and uncorrected values of mean power output for each 6 second sprint (mean ±S.D., n=6).
Figure 5.5  The mean pedalling rate over the 6 seconds of each sprint (mean ±S.D., n=6).
the decrement in pedalling speed with sprint number. As with mean power output the drop in mean pedalling speed did not become significant until the third sprint (p<0.05).

5:1.3 DISCUSSION

As found by Wootton and Williams (1983) the ability to perform repeated bouts of maximal exercise is markedly influenced by the preceding number of sprint bouts. The findings of the present study are in contrast to those reported by Saltin and Essen (1971) and Essen (1978) who employed heavy but not maximal exercise intensities.

The results obtained for peak, end and mean power output using the uncorrected method of calculation compare very favourably with those reported by Wootton and Williams, however, each value was found to be different from those obtained when the correct method of calculation was used. The magnitude of the error was different for each variable examined.

Peak external power output was the value most underestimated. The error was found to average about 23.0%. The reason that this error value was the greatest reflected the fact that peak power output is attained when the acceleration in the pedalling rate is the high. In contrast, the deceleration taking place at the sixth second of the sprint is small, which results in a much smaller error in the end power output values (mean of 5.2%). It should be noted that, whereas peak power output was underestimated by the uncorrected method of calculation, end power output is overestimated. This was the expected result as the flywheel is decelerating. Whereas, the error in peak power output was very similar for all the sprints the error in end power output appeared to increase with sprint number. It would appear that not
only were the subjects not able to reproduce their peak power outputs but that, as a consequence of the initial effort in the sprint, they had an even faster decline in end power output. The fall in corrected peak power output averaged 10.8%, whereas the corresponding value for end power output was 19.0%. End power output may therefore, be the most sensitive indicator of fatigue. This is a most fortunate finding as this is the value that has the least error between calculation errors. This means that end power output values reported in studies such as that by Wootton and Williams are not too unreliable.

As discussed fully in the previous chapter corrected peak power output was attained earlier (2-3s) than when the uncorrected method of calculation was used (4-5s).

The variable of most interest when the metabolic effects of short duration high intensity exercise are examined is mean power output or work done. These two factors are linked by time. In the present study the duration of the exercise was six seconds and, therefore

\[
\text{Work Done (J)} = \text{Mean External Power Output (W)} \times 6 \ (s)
\]

Mean power output, using the uncorrected method of calculation, was found to be underestimated by an average of 17.1%. This mean error was found to be fairly similar for each sprint (range 16.6 to 17.5%). As uncorrected mean power output and mean pedalling rate are directly linked then it is not surprising that the decrement in performance with sprint number is the same for both variables. The error between the two methods of calculation for mean power output was found to be more influenced by the peak rather than the end power output value, reflecting that for the majority of the exercise the flywheel is being accelerated, with peak pedalling speed being achieved in the fourth or fifth second of the test. For the first sprint the mean work done was 4,800J.
(corrected) and 3996J (uncorrected). By the sixth sprint these values dropped to 4440J and 3678J, respectively. These values are significantly different (p<0.001) and will greatly influence any correlation between external power output and those variables measured of the metabolic demands of the exercise. The results show that the energy demands of such exercise are even higher than the 2.5 to 3.5 times greater than aerobic capacity estimated by Wootton and Williams.

It has been shown by Boobis et al (1982) that during one 6s cycle sprint that phosphocreatine was decreased by 35%, ATP by 9% and glycogen by 14%, whilst at the same time muscle lactate increased from 9 to 29 mM.kg\(^{-1}\) dry weight. If these rates of energy substrate utilisation continued in the multiple sprint activity described above then it is clear that fatigue could result from both a reduction in energy supply and from acidosis in the muscle cell. The increased hydrogen ion concentration present is thought to be a causal factor in fatigue either by inhibiting energy provision from anaerobic glycolysis by inhibiting the activity of phosphofructokinase (PFK) or in affecting the contractile mechanism itself (Hermansen, 1981; Sahlin et al., 1981).

The study described above indicates that the friction-loaded cycle ergometer is indeed a very useful tool for examining the metabolic changes that are taking place in the muscle in repeated short-duration maximal exercise. The total work being done has so far been underestimated and in future research the corrected method of calculation should be adopted if valid correlations been energy provision and external work done are to be obtained. It is of interest to note that if uncorrected mean power output values are used in tests then no more information is obtained than if simply total pedal revolutions are counted.
5:2 Loughborough Multiple Sprint Test.

In his Ph.D. thesis Wootton (1984) describes the effects of sprint training on the performance of repeated 6 second sprints. He found that although the peak external power output and the work done during the sprints was found to have increased as a consequence of the training the fatigue, defined as the decrement in performance from the first to the last sprint, had also increased. It would, therefore, appear that fatigue increases with training, a result that would come as a great surprise to a coach of athletics. The anomalous result is due to the subjects having to suffer the consequences of the increased power output in the initial post-training sprint tests. Wootton suggested that the higher energy requirements of the initial sprints caused a greater decline in high energy phosphates and an increase in muscle lactate than in the corresponding pre-training sprints. As a result of this each successive sprint started with greater incomplete replenishment of the phosphocreatine stores and increased acidosis than at the beginning of the corresponding pre-training sprint, causing a greater reduction in power output and, therefore greater measured fatigue.

In order to investigate correctly ability to resist fatigue and whether this ability improves with training a test is required in which the total work done per sprint, rather than the duration of the sprint, is set. This would enable the work done per sprint, set prior to the training, to be reproduced after the training. At the same time the sprints must be performed at truly maximal effort. A study was set up to see whether such a test could be developed using the friction-loaded cycle ergometer.

Several factors had to be considered in developing the test protocol:

1. The measurement of external power output must use the
correct method of calculation.

2. The amount of work to be done per sprint must be set by a prior maximal test of fixed duration.

3. The calculation of work done must be done in real time so that the subject knows when to cease pedalling.

4. As the calculation of power output must be done in real time the start point of the test must be established at the beginning of each sprint, rather than using the techniques employed in the previous studies.

The following test protocol, based on the above criteria, was developed. Prior to each test the computer-speed calibration factor and deceleration curves were established as described in chapter 4. After the standard warm-up consisting of two bouts of thirty seconds pedalling at 120 and 150W (load 14.9N), the subject performed a single maximal sprint at a loading of 55g.kg\(^{-1}\) bodyweight for six seconds from a stationary start. The load is 87% of the load recommended by the Wingate protocol and reflects the fact that a stationary start was used in the new test. It was decided to use the stationary rather than the rolling start because of the increased accuracy and ease with which it could be determined by the computer. The computer was programmed to wait until it detected movement of the flywheel. When the movement was detected the internal clock of the computer was initiated and the computer calculated the total work done during the subsequent 6 seconds. At the end of the 6 seconds the computer triggered a buzzer to indicate that the subject should stop pedalling.

Prior to the test the subject was asked to set the pedals in a starting position of his/her choosing. The position of the pedals was noted by the experimenter and the pedals were replaced to this position prior to each sprint.
At the end of the first test the total work done was displayed by the computer. In addition 70, 80, 90, 110, 120 and 130% of the work done was calculated and displayed. Knowing the total work that was done in the 6 second sprint the experimenter could now decide on the total work that he wishes the subject to perform in the repeated fixed-work sprints. This value was fed into the computer. The subject was then instructed to start to sprint as quickly as possible and pedal as hard as possible until the computer calculated that the work set had been attained at which point the buzzer was triggered instructing the subject to stop pedalling. After the prescribed recovery the subject was instructed to sprint again. This was continued as many times as required. Each sprint was performed from a stationary start.

The time taken to achieve the work set was displayed by the computer after each sprint. It was these values of time taken that were used as indicators of fatigue rather than the decrement in work done in a fixed time interval that has conventionally been used.

The present study investigated whether the above protocol was viable and the effect of different work settings on fatigue was examined.

5:2.1 METHOD

16 subjects (7 males and 9 females) volunteered to take part in this study. The ages, height and weight of the subjects (mean ±S.D.) was 21.6 ±0.9 years, 176.5 ±5.0 cm and 70.9 ±8.9 kg, respectively.

Each subject was asked to perform the initial 6 second maximum effort test and then to attempt five sets of 10 fixed-work sprints with 30 seconds recovery between sprints. Each set was performed at a different work load equivalent to 70, 85, 100, 115, and 130% of the work done during the 6
second fixed duration test. Each set was performed on a different day with the order of loads being assigned randomly.

At the beginning of each day's testing the calibration factor and the flywheel deceleration curves were determined as described in Chapter 4.

Toe clips were used to prevent the feet of the subjects from slipping off the pedals and the seat height was set so that the knee was slightly flexed at the bottom of the travel of the pedal. The seat height was noted and kept the same for each subject for each set of sprints.

For each subject the starting position of the pedals was noted and the pedals were returned to this position prior to each sprint. Before the computer was initiated prior to each sprint the experimenter made sure that the flywheel was stationary. A count of the number of sprints performed was displayed by the computer. At the end of each sprint the time taken to achieve the set work was recorded on a printer.

A test cut-off time of twenty seconds was applied. If the subject was unable to perform the set work within twenty seconds then the test was terminated. For some of the subjects this cut-off was required for the highest work settings.

5:2.2 RESULTS

Table 5.2 and Figure 5.6 summarize the results obtained from this study.

The results show that the time taken to perform the set work is dependent both on the work set and number of preceding sprints performed.
<table>
<thead>
<tr>
<th>Sprint Number</th>
<th>70%</th>
<th>85%</th>
<th>100%</th>
<th>115%</th>
<th>130%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.13</td>
<td>5.14</td>
<td>6.27</td>
<td>7.42</td>
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</tr>
<tr>
<td></td>
<td>±0.34</td>
<td>±0.29</td>
<td>±0.37</td>
<td>±0.45</td>
<td>±0.54</td>
</tr>
<tr>
<td>2</td>
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<td>6.41</td>
<td>7.88</td>
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</tr>
<tr>
<td></td>
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<td>±0.28</td>
<td>±0.29</td>
<td>±0.46</td>
<td>±0.69</td>
</tr>
<tr>
<td>3</td>
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<td>8.55</td>
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<tr>
<td></td>
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<td>±0.33</td>
<td>±0.32</td>
<td>±0.69</td>
<td>±1.08</td>
</tr>
<tr>
<td>4</td>
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<td>6.94</td>
<td>8.99</td>
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<td></td>
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<td>±0.90</td>
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<td>9.54</td>
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<td>±0.68</td>
<td>±1.22</td>
<td>±2.28</td>
</tr>
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<td>6</td>
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<td>7.48</td>
<td>10.09</td>
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<td>±0.90</td>
<td>±1.69</td>
<td>±3.01</td>
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<tr>
<td>7</td>
<td>4.23</td>
<td>5.86</td>
<td>7.73</td>
<td>10.82</td>
<td>13.63</td>
</tr>
<tr>
<td></td>
<td>±0.23</td>
<td>±0.77</td>
<td>±1.12</td>
<td>±2.31</td>
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<td>8</td>
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<td>6.20</td>
<td>8.16</td>
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</tr>
<tr>
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<td>±1.56</td>
<td>±2.80</td>
<td></td>
</tr>
<tr>
<td>10</td>
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<td>6.16</td>
<td>8.25</td>
<td>11.62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>±0.33</td>
<td>±1.07</td>
<td>±1.80</td>
<td>±2.82</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2 The time taken to achieve the work set, expressed as a percentage of the work done during the 6s test, for each of the ten sprints (n=16, mean ±S.D.).
Figure 5.6  The time taken to reach the set work for 5 different work settings (mean ± S.D., n=15)
<table>
<thead>
<tr>
<th>Fatigue Index (%)</th>
<th>Percentage of 6s maximum test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70%</td>
</tr>
<tr>
<td>Whole group</td>
<td>4.3%</td>
</tr>
<tr>
<td>Males</td>
<td>7.9</td>
</tr>
<tr>
<td>Females</td>
<td>2.0</td>
</tr>
</tbody>
</table>

*SEVEN SPRINTS ONLY*

| Time taken 1st sprint (% of 6s) | 68.8 | 85.7 | 104.5 | 123.7 | 142.2 |

Table 5.3 The fatigue indices over the ten sprints for each work setting, expressed as a percentage of the work done during the 6s test. The time taken for the first fixed work sprints are also shown (n=16, M=7, F=9; mean values only).
Table 5.3 shows the average time taken, as a percentage of 6 seconds, that the subjects took to perform the first and last sprint in each set. The table also shows that the first sprint at the lowest work setting took 68.8% of 6 seconds which is very slightly less than the 70% work value set. At the other end of the spectrum of set work, the 130% setting was achieved in 142% of 6 seconds.

The fatigue index was defined as

\[
\frac{(T_{sf} - T_{sl})}{T_{sf}} \times 100 \%
\]

where: \(T_{sf}\) is the time of first sprint
\(T_{sl}\) is the time of last sprint

At the lightest load the fatigue index was only 4.4%, which represented a non-significant increase in the time taken to perform the set work. In contrast, by the seventh sprint at the highest work setting, the last sprint that all the subjects were able to perform within the 20 seconds cut-off time, the value of fatigue was 60.3%. Other than for the 70% setting all increases in performance time of the last sprint when compared to the first sprint were significant (p<0.05). If the rate of decline was assumed to continue at the same rate then by the tenth sprint the fatigue index would have been approximately 86% at the 130% work setting.

It should be noted that the males as a group showed higher rates of fatigue than the females for all work levels set.

5.2.3 DISCUSSION

The new test protocol was proved to be viable. It was easy to operate and the subjects found no problems in performing the tests.

If we examine the first few seconds of the 30 second test
described in Chapter 4, we can see that a disproportionately large amount of work is done in the first few seconds of the sprint whilst the flywheel is being accelerated. This is reflected in the time taken to reach the work set in the first sprint of each set. From a stationary start peak pedalling speed is achieved in the fifth to sixth second of the sprint. In the tests where the work set was achieved before peak speed was achieved, i.e. work settings of 70 and 85%, the time taken to attain the work setting was approximately the same as the percentage of work set, 68.8 and 85.7%, respectively. At the work settings of 115 and 130% peak pedalling speed was achieved and some deceleration had taken place by the time the work setting had been reached. The time taken to reach the work setting, as a percentage of 6 seconds, was 123.7 and 142.2%, respectively. By the time peak pedalling speed had been achieved power output was beginning to decline rapidly, as discussed in the previous chapter, and, therefore, a greater proportion of time was needed to achieve the work setting. The 115% setting took a further 8.7% of time, and the 130% setting a further 12.2%. It is clear that the difference becomes greater the larger the percentage work setting applied, as shown in Table 5.3. If large work settings are required then the results indicate that to be able to predict the time that the fixed work tests will take, the initial fixed duration work test should be of longer duration, so that the work set in the fixed-work sprints are closer to 100% of the initial test value.

It is not surprising that the fatigue index increased with increased work setting. The subjects had to start each subsequent sprint having greater reduction in phosphocreatine stores and increased acidosis. Energy provision was, therefore, inhibited (as discussed in the previous chapter) and external power output reduced.

The difference between the male and female subjects in the fatigue index may in part be explained by the difference in
the performance of the initial fixed duration test. The differences can be seen in Table 5.3. If the total work done in the 6 seconds is divided by bodyweight then the males were found to do proportionately more work per kilogram bodyweight. This is not surprising as the males will have less bodyfat than the females (not measured) and so each kilogram of body mass will have a higher proportion of muscle to contribute to energy production. Assuming average values of body fat of 15 and 25% for males and females, respectively, then one would expect the males to generate approximately 13% more power per unit body mass. The mean difference between the males and females in power output per unit body mass was found to be approximately 27% which is higher than would be predicted using the approximations. As a consequence during the first fixed—work sprint energy production in the males was proportionately higher than achieved by the females, resulting in greater reductions in phosphocreatine and higher levels of lactic acid production. The second and subsequent sprints, therefore, started with the male subjects more disadvantaged than the females resulting in the faster decline in power output measured.

One of the main findings of this study will be of interest to those researchers investigating the metabolic energy provision in repeated short duration maximal exercise. It would appear that, for a given recovery duration, decrement in performance is not only intensity dependent but is also dependent on the duration of the exercise. All the sprints performed in this study were performed at maximum intensity. The duration of each sprint varied depending in the work set. At the 70% setting the mean time taken for the first sprint was 4.13 seconds. No statistical increase in exercise duration was found over the 10 sprints performed at this setting. At the 85% setting the first sprint took slightly longer, about 5.14 seconds. At this duration of exercise a statistical (p<0.05) increase in exercise duration was found over the 10 sprints. Further increases in the set work resulted in even more pronounced increases in the time taken
for the first sprint and even greater decrements in performance. Indeed at the 130% setting the increase was found to be significant (p<0.05) by the second sprint.

With only a 30 seconds recovery period between sprints a decrement in performance occurred when the duration of the maximal exercise was approximately 5 seconds. The study by Wootton and Williams, using the uncorrected method of power calculation, found a decrement in repeated 6 second sprints with a similar recovery period. The present study suggests that had Wootton and Williams used a test duration of 4 rather than 6 seconds then sprint performance would have been maintained. The results of the present study indicate that further work is needed to examine why an exercise duration of 4 seconds does not result in measurable fatigue, whereas, increasing the exercise duration by just one second does result in a decrement in performance.
5:3 EFFECT OF TRAINING ON FATIGUE MEASURED USING THE
NEW TEST

A training study was set up to investigate whether fatigue,
measured using the new test described in the previous
study, was affected by training.

5:3.1 METHOD

The subjects who volunteered to take part in the study were
split into two groups. The subjects in one of the groups
trained three times a week on the sprint treadmill,
described in Chapter 8, whilst the subjects in the other
group did not train, thereby acting as controls.

The training group consisted of 9 subjects (6 males and 3
females) whose weight and ages (mean ±S.D.) were 64.3
±11.2kg and 25.6 ±7.6years, respectively. The
corresponding values for the 8 control subjects were 61.6
±7.0kg and 30.8 ±7.3years.

All the subjects, who were fully familiarised with the test
protocol, performed two initial maximal 6 second sprints on
the friction—loaded cycle ergometer. The two tests were
separated by a recovery period of five minutes. The total
work done in the two sprints was calculated using the
corrected method of calculation. The highest value for work
done achieved between the two tests was regarded as the
100% 6 second value. The work equivalent to 95% of the 6
second value was calculated and used as the work setting
for the tests both before and after training. All the
subjects were then asked to do 10 maximal sprints at the
95% work setting, with 30 seconds recovery between sprints.

After the pre—training tests were completed the training
group visited the laboratory 3 times a week for 7 weeks.
During each visit the subjects did 10 six second maximal
sprints, on the sprint treadmill, with 30 seconds recovery.
between sprints. The control group continued their normal activities during this 7 week period.

At the end of the seven week training period all the subjects repeated the test protocol above. Although the new value of work done in 6 seconds was measured, the pre-training 95% value was used in the fixed work test.

5.3.2 RESULTS

Table 5.4 shows a summary of the time taken to achieve the 95% work setting for the two groups both before and after the 7 weeks training. The fatigue index obtained is expressed in two ways.

Method 1:

\[
\frac{(T_{SL} - T_{SF})}{T_{SF}} \times 100
\]

where: \(T_{SF}\) is the time taken for the first sprint
\(T_{SL}\) is the time taken for the last sprint

Method 2:

\[
\frac{(T_{SLA} - T_{SFb})}{T_{SFb}} \times 100
\]

where: \(T_{SFb}\) is the time taken for the first sprint before training
\(T_{SLA}\) is the time taken for the last sprint after training

The fatigue index for the training group using both methods of calculation described above significantly (p<0.05) decreased as a result of the training. The mean decrease in the fatigue index was 41.6%. There was no significant difference found in fatigue index for the control group. For the training group the reduction in the time taken to do the first fixed work sprint, as a result of the training, was 5.4%. The corresponding decrease in the tenth sprints was 16.9%. If the fatigue index using method 2 is
Table 5.4 A summary of the time taken to achieve the 95% work setting and the associated fatigue indices for the two groups, both before and after 7 weeks of training (TG=9, CG=8).

<table>
<thead>
<tr>
<th></th>
<th>Training Group</th>
<th>Control Group</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-training</td>
<td>Post-training</td>
<td></td>
</tr>
<tr>
<td>Sprint Number</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st</td>
<td>1st</td>
<td>10th</td>
<td>10th</td>
</tr>
<tr>
<td>mean</td>
<td>5.69</td>
<td>5.40</td>
<td>7.42</td>
</tr>
<tr>
<td>S.D.</td>
<td>0.33</td>
<td>0.37</td>
<td>2.20</td>
</tr>
<tr>
<td>Fatigue Index (mean±s.d.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Training Group</td>
<td>29.8±32.6+</td>
<td>17.7±22.3+</td>
<td>11.2±16.7°</td>
</tr>
<tr>
<td>Control Group</td>
<td>11.7±11.8+</td>
<td>15.6±18.6+</td>
<td>16.0±18.9°</td>
</tr>
</tbody>
</table>

Method 1=+, 2=°
compared to the pre-training method 1, for the training group, then the mean decrease in the fatigue index was found to be 62.4%.

The time taken for the training group to achieve the work set was found to be significantly reduced after training for both the first and last sprints (p<0.05). No significant change in performance was found over the seven week period for the control group.

Table 5.5 shows the work done in the 2 maximal 6 second tests, for the two groups, both before and after the 7 week training period. The mean total work done is significantly higher for the training group than for the control group (p<0.05), both before and after the training period. For the training group the mean work done in the second of the 6 second sprints was greater than the first both before and after training, however, only the pre-training values were found to be significantly different (p<0.05). No difference was found between the two sprints for the control group or for the combined data from the two groups.

The total work done in the 6 second test was significantly increased as a consequence of the training (p<0.01). The mean increase was found to be 7.0%.

5.3.3 DISCUSSION

The present study was set up to investigate whether the proposed new test was sensitive to sprint training and to see whether fatigue would be reduced as result of the training.

Absolute increase in performance, as a result of the training, was measured using the first part of the two part test. In this test the total work done in 6 seconds was measured and a significant increase of 7.0% was found. No change in the control group was found. It would appear that
<table>
<thead>
<tr>
<th></th>
<th>Work done in 6s test (J)</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Pre-training</td>
<td>Post-training</td>
<td></td>
</tr>
<tr>
<td>Training Group</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>3519</td>
<td>3770</td>
<td></td>
</tr>
<tr>
<td>S.D.</td>
<td>1023</td>
<td>1072</td>
<td></td>
</tr>
<tr>
<td>Control Group</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>3361</td>
<td>3351</td>
<td></td>
</tr>
<tr>
<td>S.D.</td>
<td>620</td>
<td>589</td>
<td></td>
</tr>
<tr>
<td>Sprint Number</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.5 The work done by the two groups during the two maximal 6s tests, both before and after the 7 week training period (TG=9, CG=8, mean ± S.D.).
the new test is indeed sensitive to changes in absolute performance. Further support for this is obtained when the first fixed-work sprint is examined. When the subjects were asked to perform the same amount of work, before and after the training period, the mean time taken fell from 5.65 to 5.4 seconds, a fall of 5.4%. If the last sprint is examined the improvement in performance, expressed as a reduction in the time taken to do the work set, was 16.9%. None of the corresponding values showed significant changes in the control group. Absolute improvements in performance are clearly detected by the new test.

Each 6 second test was repeated with an inter-trial rest period of 5 minutes. For all the groups slightly more work (<4%) was done in the second of the two sprints, however, only the pre-training value for the training group was significant (p<0.05). It is suggested that in future tests if the difference between the two 6 second maximum sprints is greater than 100J then a third sprint should be performed and the highest value of the three tests used to represent 100% work done.

Both before and after the training period the time taken to perform the fixed work tests increased with increasing sprint number. The results from Wootton showed an increase in the fatigue index with sprint training, when maximum fixed duration sprints were performed. In his study the fatigue index was calculated using the following formula

\[
\frac{(P_{mf} - P_{m1})}{P_{mf}} \times 100 \%
\]

where: 
- \(P_{mf}\) is the mean external power generated in the first sprint 
- \(P_{m1}\) is the mean external power generated in the last sprint.

In contrast to the increased fatigue described by Wootton the results from the present study showed a decrease in the
mean fatigue index from 27.8 to 17.7%, as a result of the training. Using the new test not only can the overall fatigue be measured but each post-training sprint can be compared with each corresponding pre-training sprint and any detected differences can be confidently regarded as resulting from the training, as the total work done prior to any given sprint will the same in both tests.

When examining the effects of training on fatigue it may well be of value not only to report the changes in the fatigue index that has been calculated within each test, but also to express post-training performance in relation to the pre-training first sprint; i.e. the last sprint after training is compared to the first sprint before training to obtain a value for the fatigue index (method 2 above). As the same total amount of work is done prior to the last sprint in both the pre- and post training tests a comparison of the last sprints with the first pre-training sprint is a valid measurement and should give an even better indication of the improvements in fatigue 'resistance' that has taken place than the intra-test fatigue index values. Using this second method of calculation the fatigue index was found to fall from 29.8 to 11.8%, an improvement of 62.4%. No change was found for the control group.

The new test has been shown to be a useful tool for investigating both the absolute improvements in performance and the changes in rate of fatigue resulting from training. The new test could be used on its own to investigate these parameters but could also be used in conjunction with other tests, such as repeated fixed duration tests, to give a more complete picture regarding the effects of training. It is clear from both this and the preceding chapter that the friction-loaded cycle ergometer still has a great deal to offer as a tool for investigating performance, muscle function and adaptations to training if the correct method of calculation is used.
CHAPTER 6

GENERAL DISCUSSION OF SECTION A

THE NATURE OF FATIGUE IN SHORT DURATION MAXIMUM SPRINTS

(In recent years the amount of research investigating the metabolic changes taking place during maximal exercise of short duration has increased. It has been noted that peak power output occurs within the first few seconds of the activity, and thereafter power output declines. A summary of the possible metabolic changes which might cause the observed fatigue are described below.)

a) A reduction in ATP concentration within the muscle.

A reduction in ATP concentration has been measured as a result of maximum exercise, however, depletion of ATP does not occur (Boobis et al., 1982; Jacobs et al., 1983; McCartney et al. 1986). Muscle fibres can continue to contract even at very low concentrations of ATP, much lower than the post-exercise levels reported by the above researchers. It is as yet not fully understood how reduced levels of ATP will affect power output but it may be due to differential reduction between different types of fibres or due to the amount of free ATP available at the site of muscle fibre contraction. Edwards (1981) stated that a reduction in muscle ATP would result in a reduced energy supply for both the contractile mechanism and membrane function.

b) A reduction in CP concentration.

In maximal activities lasting up to 30 seconds CP levels can decrease to as low as 30% of pre-exercise levels (Bergstrom, Harris, Hultman and Nordesjo, 1971); Jacobs et al., 1982; Boobis et al., 1982; McCartney et al. 1986). As CP is a major source of energy for rephosphorylation of ATP a
reduction in the concentration of CP in the muscle will result in a decrease in the capacity for rephosphorylation and, as mentioned above, a reduction in power output.

c) A decrease in muscle glycogen.

Although muscle glycogen has been shown to be decreased as a result of a single (Wootton, 1984) and repeated 30s sprints (McCartney et al., 1986) it appears that the reduction in muscle glycogen is not a factor that will influence power output during a single sprint, in subjects that start the activity with normal levels of muscle glycogen.

d) An increase in H\(^+\) concentration.

Bergstrom et al. (1971) proposed that an increase in H\(^+\) concentration inhibits the activity of PFK, thus reducing the rate of energy provision from glycolysis. Increase in H\(^-\) and the corresponding decrease in pH, during short duration maximal activity, has been reported by many researchers (Boobis et al., 1982; Costill, Barnett, Sharp and Fink, 1983; Jones et al 1985). More recently Hultman et al. (1986) proposed that it was unlikely that the main influence of pH was the inhibition of the activity of PFK. It may well be that H\(^+\) reduces power output by slowing the rate at which ATP is being utilised rather than being resynthesised. This might result from direct inhibition of the contractile mechanism (Donaldson and Hermansen, 1978; Fuchs, Reddy and Briggs, 1970). The inhibition has been postulated as being caused by a reduction in the affinity of calcium to troponin C and inhibition of ATPase activity, thus effecting uncoupling of the myofibrils, the return of calcium to the sarcoplasmic reticulum and membrane potential via the Na\(^+\)/K\(^+\) ATPase, which may in turn affect excitation.

Cheetham (1987) makes two related statements from her work on the measurement of fatigue in short duration maximal exercise.
"However, during sprint running the decrease in power output begins immediately after the attainment of peak power which is only 1-3s into the sprint when pH can have decreased only fractionally."

"These findings would suggest that at high absolute exercise intensities only a small decrease in pH may be sufficient to significantly reduce power output..."

Do the mechanisms of 'metabolic fatigue' adequately describe the decrease in power output measured during the sprint activities described in this thesis? Previously short duration maximal activity has been monitored mainly using either constant velocity cycle ergometers or friction-loaded cycle ergometers on which the power output has been incorrectly measured. Using both these test procedures the power output curve shows a steady, continuous decline once the peak value has been achieved. Close examination of uncorrected power output in Figures 4.9 and 4.11 quite clearly show this steady decline. In contrast, however, the corrected power output curves in the same Figures show a very different profile. Once peak power output has been achieved there is an initial very rapid decrease in power output followed by a slower rate of decline. Figure 6.1 shows the corrected power output data described in Figure 4.11 along with the profile of the speed of pedalling. Two lines of best fit for the power output data, slopes a and b, have been drawn on the figure. It can be seen that the slopes of these two lines are very different and that they intersect close to the point where maximum pedalling speed was attained. Figure 6.2 Shows a similar plot where the same subject performed a 30s sprint against a much heavier load. Once again two distinct lines of best fit are used to describe the results and these lines intersect close to the
Figure 6.1 The speed of pedalling and the corrected power output data from figure 4.11, with lines of best fit drawn for the power output data. (load = 55g.kg$^{-1}$ B.W.).
Figure 6.2 The speed of pedalling and corrected power output for a 30s maximum sprint on the cycle ergometer (load = 95g.kg\(^{-1}\) B.W.). Lines of best fit have been drawn for the power output data.
Figure 6.3 A plot of Figures 6.1 and 6.2 super-imposed on the same Figure, with the raw power output data points omitted.
point at which maximum pedalling speed was reached. Figure 6.3 shows the slopes from Figures 6.1 and 6.2 and the pedalling speeds superimposed upon each other.

It is clear from these figures that the rate of fatigue is different during the acceleration phase of the sprint than during the remainder of the test. This is a very different result to those reported previously. In the review of the literature the force-velocity relationship was found to be described by a curve which has a unique point at which power output is optimal, irrespective of whether the muscle group is fully described by Hill’s equation or not. Hill’s equation (1) can be re-arranged to give power output as shown in equation (2).

\[(P + a)(V + b) = (Po + a)b \quad (1)\]

\[PV = V.\{(Po + a)b/(V + b) - a\} \quad (2)\]

\[P = \text{force exerted by muscle} \]
\[Po = \text{force exerted by muscle when } V=0 \]
\[V = \text{speed of contraction} \]
\[Vo = \text{speed of contraction when } P=0 \]
\[a = \text{constant having same dimensions as } P \]
\[b = \text{constant having same dimensions as } V \]

The constant \(a\) in the above equation, varies from person to person but is approximately \(Po/3\). It follows from equation (1) that \(a/Po = b/Vo\). Maximum power output will occur when:

\[P/a = \sqrt{Po/a + 1} - 1 \quad (3)\]

Dickinson (1928) predicted that maximum pedalling speed \((Vo)\) was approximately 220 r.p.m. The results by Nakamura would tend to indicate that this value is slightly underestimated. Figure 6.4 shows the predicted power output as a function of
<table>
<thead>
<tr>
<th>Pedal rate</th>
<th>Predicted maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>220⁺ 260⁺ 320⁺</td>
</tr>
<tr>
<td>50</td>
<td>93.9 88.6 80.9</td>
</tr>
<tr>
<td>70</td>
<td>99.9 97.9 93.0</td>
</tr>
<tr>
<td>90</td>
<td>97.6 99.9 98.8</td>
</tr>
<tr>
<td>110</td>
<td>90.0 96.8 100</td>
</tr>
<tr>
<td>130</td>
<td>78.4 90.0 97.9</td>
</tr>
<tr>
<td>150</td>
<td>64.1 79.9 93.3</td>
</tr>
<tr>
<td>180</td>
<td>38.7 62.3 82.5</td>
</tr>
</tbody>
</table>

+ r.p.m.

Figure 6.4 Predicted Power-Velocity curves calculated from Hill's equation, for maximum pedalling speeds of 220, 260 and 320 r.p.m.
pedalling speed, using the maximum pedalling rate predicted by Dickinson and a slightly higher value of 260 r.p.m. It is important to note that the following assumptions have been made in obtaining these predicted values of power output:

1) the constant \( a = \frac{P_0}{3} \);
2) the velocities \( V \) and \( V_0 \) are the average velocities over a half pedal cycle;
3) the muscle groups used in cycling are described by Hill's equation;
4) all the energy is being provided solely by concentric muscle contractions.

The dashed line, in the figure, shows the curve that would be required for power output to be at a maximum at approximately 110 r.p.m., which is the speed at which maximum power was achieved on the constant velocity cycle ergometers described by Sargeant (1980) and McCartney (1983). To achieve this curve the value of \( V_0 \) would have to be approximately 320 r.p.m. Although the work by Sjogaard (1978) showed that the F-V curve for cycling deviated from Hill's equation, the basic shape of the power output profile would be similar to that shown in Figure 6.4, although shifted expanded to the right.

If the solid curves in Figure 6.4 are examined then a maxima for power output is seen to occur between 65 and 90 pedal r.p.m. If the rate of pedalling is increased above this optimum value then the decline in the maximum power output that the muscle could generate would be rapid, dropping to 50-75% of the peak value by 160 r.p.m. During the test pedalling speed changed from 65 to 173 r.p.m. for the light load and 65 to 138 r.p.m. for the heavier load. From the start of the test peak speed was reached after 2.5 and 3.5 seconds, respectively, for the two loads. If the muscle is assumed to have been influenced by metabolic changes.
then it is possible to predict from the pedalling speed profiles in Figures 6.1 and 6.2 what would have happened to power output during the first few seconds of the test. (The following description will assume a maximum pedalling speed of 260 r.p.m.). As the subject accelerated maximally the ergometer from the rolling start speed of 65 r.p.m. the power output should increase until approximately 90 r.p.m. was reached when peak power output would be generated. This would occur during the first second of the test. The subject continued to accelerate the pedals which would result in a decline in power output, which upon reaching peak pedalling speeds of 138 and 173 r.p.m. would be approximately 86 and 66% that of the peak power value, respectively. Once maximum pedalling speed had been reached a slow decline in pedalling rate occurred which should have resulted in an increase in power output. This predicted result can be compared to the data obtained. The two slopes marked 'a' in Figures 6.1 and 6.2 are contrasted in Figure 6.3. The slopes are different with the slope generated by the heavier load having the lesser gradient. The differences in the slopes reflect the relative magnitude and rate of change in pedalling speed that resulted from the two loads. With the lighter load the rate of change of pedalling speed was the greater and the resulting slope was, therefore, steeper. As the maximum speed reached was also higher for the lighter load than for the heavier load the power output at the end of the acceleration phase was also relatively lower. For the lighter load the power output dropped to approximately 55% of the peak value. The corresponding value for the heavier load was 68%. Both these values indicate a greater decline in power output than that predicted from the Figure 6.4, but are similar to that which would have been obtained had Dickinson's value of predicted maximum pedalling rate been used. It would appear that a large proportion of the fatigue occurring during the acceleration phase of the sprint can be accounted for by the force-velocity relationship of the muscle, and NOT by metabolic changes that may have taken place. It can, however, clearly be identified from the
Figures that fatigue due to metabolic changes is also occurring. Once peak speed is reached pedalling speed starts to decline. If metabolic changes had not occurred then power output would have started to rise as the pedalling speed declined towards the optimum value i.e. a positive value for slope b should have been obtained, as shown by the dotted line in Figure 6.2. However, power output did not rise, it in fact fell. This indicated that the metabolic changes that were taking place within the muscle were influencing the power being generated by the muscle. Unlike Slope a, Slope b, in the two figures, truly represented the 'metabolic fatigue' taking place in the muscle. In fact if the magnitude of the rate of fatigue was calculated from this figure it would be slightly underestimated as a correction for the drop in pedalling rate should be incorporated. To explain this statement the profiles in Figure 6.2 will be examined. Pedalling speed declined from 138 r.p.m., at peak pedalling speed, to 73 r.p.m., at the end of the test. Had no metabolic fatigue taken place then power output should have risen from 86% to 98.5% of the peak value, as shown by the dotted line. These values are derived from the power-speed relationship in Figure 6.4. In fact, rather than increasing, power output was found to decrease from 1028 to 516W. If 1028W represents 86% of peak power output then 98.5% would be equivalent to 1177W, and this would be the predicted end power output of the test. The actual end power output value should be compared to this predicted value, i.e. the magnitude of X in Figure 6.2, for a more representative figure for the 'metabolic fatigue index'. The predicted figures obtained will be different for each individual as the F-V relationship, from which it is derived, differs from one individual to another. In order to routinely make this adjustment in the fatigue index the constants in the F-V relationship must be calculated for each individual tested, and applied to equation (2). This new fatigue index (FIPp) represents the fatigue taking place during the period of the 30s test after peak speed has been achieved, which is about 85-93% of the test duration, depending on the time taken to
reach peak speed. To estimate the fatigue index over the entire test ($F_{\text{Itot}}$) the rate of fatigue that occurred before peak speed was attained might be assumed to be the same as after it was attained. The index $F_{\text{Ipp}}$ can then be normalised to 100% of the test duration, using the following equation:

$$F_{\text{Itot}} = F_{\text{Ipp}} \times \frac{T_d}{T_{\text{pp}}}$$

where: $T_d$ is the duration of the test
$T_{\text{pp}}$ is $T_d$ minus the time taken to reach peak speed.

This discussion gives some validity to the results of those researchers who have investigated fatigue using friction-loaded cycle ergometers and have used the uncorrected method of calculation. The two values of power output used to calculate the new fatigue index are power output at peak speed, which is independent of the calculation technique used as no acceleration is taking place, and end power output. At the end of the 30s test the rate of change of pedalling speed is relatively small and, therefore, the difference between the corrected and uncorrected value of end power output, and the associated fatigue index, is also small. The F-V profile for the subject must still, however, be established so that the predicted end power output can be calculated.

What does Slope $b$ tell us about the fatigue during the acceleration phase of the sprint? If it is assumed that that the rate of metabolic fatigue occurring both before and after peak pedalling speed has been achieved is the same, then by calculating a regression equation for Slope $b$ the maximum power output at the start of the sprint ($t=0$) can be predicted. The contribution of the metabolic fatigue to the measured fatigue can be estimated. The contribution for the lighter load was approximately 3%, whereas, for the heavier load the contribution was approximately 19%. The higher contribution of the heavier load reflects the longer duration of the acceleration phase (40% longer) and the
Comparison of the two lines for the two loads in Figure 6.3, obtained after peak speed was reached, highlights further interesting results. For the heavier load power output is higher than for the lighter load and the slope of the line is greater. From the F-V relationship of muscle the explanation of these findings are straightforward. For the heavier load peak speed achieved was less than that for the lighter load, thereafter the pedalling speed, was closer to the optimum speed for power output and as a consequence greater power output was generated. The rate of decline in pedalling speed was greater for the heavier load than for the lighter load, probably due to the lesser efficiency of power production. This greater decline in pedalling speed for the lighter load resulted in a reduction in the difference in pedalling with test duration, and a narrowing in the difference between the power outputs. It is of interest to note that McCartney et al. (1986) found that subjects produced greatest mean power output at around 60 pedal r.p.m. for activities lasting 30 minutes or longer on the constant velocity cycle ergometer. This is slightly slower than the value for peak efficiency in the F-V curve described in this study. The F-V curve is for the whole muscle. The muscle fibres recruited in activities of longer duration will be predominantly Type I fibres which have a greater capacity for oxidative metabolism and have a slower rise time to peak tension. If these are the muscle fibres being recruited then a shift to the left of the power-velocity curve shown in figure 6.4 would be expected, and a slower optimum pedalling speed obtained. The opposite explanation can be used to explain the higher pedalling speed found for maximum power output during a test lasting 10 seconds or less. If it is assumed that Type II fibres, which have a faster time to peak tension, are preferentially recruited during this type of activity then the power-velocity relationship will be shifted to the right. Therefore, the optimum pedalling rate will be higher.
Goldspink (1979) pointed out that the peak mechanical efficiencies of Type II and Type I fibres occur at completely different velocities. The maximum efficiency of Type II fibres appears at a higher contraction speed, whereas Type I fibres show the corresponding peak efficiency at low contraction speed. The dashed line in Figure 6.4, therefore, represents only the muscle fibres recruited and not the whole muscle.

Is there further evidence to support the statement that the fatigue taking place during the acceleration phase is due mainly to factors other than metabolic fatigue. Cycling is an activity that has the two legs working in synchrony but out of phase by 180°. During the acceleration phase of the sprint the pedalling speed for each leg will be different. If it is assumed that the fatigue in one leg is not influencing the performance of the other during the first few pedal cycles then a decrement in force and power output should be observed resulting from the mechanisms underpinning the F-V relationship of muscle. Figure 4.23 shows a profile of acceleration balancing load, which represents the torque being applied to the pedals, during the first 10 seconds of a maximum sprint on the cycle ergometer. Each successive peak represents the torque generated by each leg alternately. The first peak is greater than the second, which is in turn greater than the third, etc. This decrease in torque is happening as a consequence of the F-V relationship of the muscles and not due to metabolic fatigue. It might be argued that this result may be due to one leg being stronger than the other, however, although dynamic leg strength was not measured the same profile was observed for all the subjects investigated.
What will happen to the calculated fatigue as a function of sprint training. Wootton (1984) and Cheetham (1987) investigated the changes in performance resulting from sprint training and noted increases in peak power output, peak speed and initial acceleration. What will be the consequences of such training to the two phases of the fatigue—discussed above? The major effect of sprint training will be to cause a change in the F-V relationship of the active muscles. It has been shown that training increases the maximum force produced at the training velocities, however, as the Vo of the muscle, i.e. the maximum theoretical speed of contraction, cannot be measured it is not known what happens to this value. It is doubtful, however, that sprint training is able to significantly influence this value. The effect of the training is, therefore, to skew the F-V relationship, as shown in Figure 6.5 (curves 1 and 2), such that the intercept on the force axis is increased but that on the velocity axis remains the same. This new F-V relationship will result in a change in the power-velocity profile of the muscle. Peak power output will increase, however, there will be little effect on the speed of contraction at which peak power output occurs, as shown in Figure 6.5 (curves 3 and 4). The power output at any sub-maximal speed will also be increased. This increase in power output at a sub-maximal speed is demonstrated on the figure as a shift from point a, on curve 3, to point b on curve 4.

The changes due to training observed by Cheetham and Wootton, described above, can be explained using Figure 6.5. If training has resulted in an increase in force production throughout the range of the speeds attained during the test then the associated acceleration will also be increased. As a consequence of this increased force production all values of power output during the acceleration phase, including peak power output, will be higher as a result of the training. The peak speed achieved, which is not the theoretical maximum speed (Vo),
Figure 6.5 The possible effects of training on the F-V and Power-Velocity relationship of the active muscles.
will also increase following training. This increase can be explained as follows. Points a and d represent the power output and force production at the pre-training maximum speed. At the same speed post-training the corresponding values of both power output and force have increased, to points b and e. If the resistance to movement has remained the same then there will be an excess force which will result in the system accelerating beyond this point until the force value once again drops until it matches the resistive forces (point f). Clearly the theoretical maximum velocity does not have to be increased for there to be an increase in the real maximum speed of movement.

The new power-velocity curve will influence the fatigue measured. Although peak power output will be higher, the time taken to reach peak power will be reduced due to the increased acceleration. Also as a result of the greater acceleration and the steeper slope of the power-velocity curve, power output will decline more rapidly than before training. The pre- and post training values of power output at maximum speed will be very similar, although the speeds themselves will be different, as shown by the line joining a to c on Figure 6.5. The result of combining these events is that during the acceleration phase both the magnitude and the rate of fatigue has increased due to the training.

Throughout the remainder of the test the speed of movement gradually decreases. The fatigue measured during this phase will reflect the magnitude of the decline in speed. The pre- and post-training power-velocity curves although not parallel are very similar. A similar drop in speed both pre- and post-training will result in a similar magnitude of fatigue, i.e. the gradient of the slope marked b in figure 6.1 will remain relatively unchanged as a consequence of the training, although shifted upwards. As described previously the true magnitude of the fatigue during this phase must be corrected for predicted end power output. The combined effect of the two components is that
fatigue appears to increase as a result of sprint training, with the main change resulting from a new F–V relationship for the active muscles.

It is of interest to note that the explanation offered above for the effects of training on the components of fatigue also explains why subjects with good sprinting ability have greater apparent fatigue than subjects with an endurance bias. The higher accelerations and peak speeds achieved by the sprinters will result in a greater decrease in power output resulting from the F–V relationship of the muscle, during the acceleration phase of the sprint.

If fatigue is defined as being a decline in power output then it must be accepted that fatigue is occurring during the first few seconds of exercise, even if it not being caused by the changes in metabolism described at the beginning of this chapter. What might be the causes of this observed fatigue?

There appear to be a number of factors which interact to produce power–velocity relationship seen in Figure 6.4. These factors are discussed below.

a) Crossbridge asynchrony.

In the most widely accepted model of muscle contraction the actin filaments are pulled along by the cyclical action of crossbridges projecting from the myosin filaments (A.F. Huxley, 1974). Binding of ATP is believed to cause detachment of the crossbridge and the ATP has to be hydrolysed before the crossbridge can rebind to actin and repeat the cycle. Each myosin filament has many crossbridges working in parallel, but asynchronously. As a consequence the swinging of an individual head will not necessarily be accompanied by movement of the actin filament to which it is attached. The difference must be taken up by conformational strain within the attached
At zero speed and very low speeds there will be many crossbridges that do not have associated movement of the actin filament. The number of such inefficient crossbridges will decrease with increasing contraction velocity until a velocity is reached at which the optimum number of crossbridges formed are accompanied by movement. At this velocity power output from crossbridge formation will also be optimum. If the velocity of contraction continues to increase power output will start to decrease due to limitations of the mechanochemical coupling time of crossbridge cycling. The swinging action of the crossbridge head will become more and more inefficient in producing force resulting in a decline in power output, dropping to zero when the crossbridges are unable to cycle rapidly enough to produce force.

b) Viscosity.

The actin and myosin filaments are embedded in a fluid. This aqueous phase of the sarcoplasm is called the sarcoplasmic matrix (Astrand and Rodahl, 1970). The viscosity of this matrix provides resistance to movement of the actin filaments relative to the myosin filaments during contraction. This resistance increases exponentially with velocity of contraction resulting in increasing internal work being done to overcome the resistance, which is dissipated as heat, with less and less external force produced and, therefore, decreased external power output.

c) "Viscosity" of the muscle.

Furusawa, Hill and Parkinson (1927) stated "When a muscle shortens it changes its shape; its molecules or parts have to flow into a new configuration; the change is hindered by the hysteresis of the molecular system of the muscle substance, by what we have called its "viscosity"." They further postulated that that the viscosity of an active fibre is very much greater than for an inactive one. If the
muscles are assumed to be contracting maximally, as they are assumed to be doing throughout this thesis, then the external work being done was described by Furusawa et al. as being

\[ W = W_0(1 - \frac{v}{c}) \]

where: 
- \( W_0 \) = work done in a maximum effort at very low speed
- \( v \) = muscle shortening velocity
- \( c \) = greatest possible speed of shortening of the unloaded muscle.

From this equation it can be seen that as \( v \) increases then the external work or power output decreases, due to increasing work being done to overcome muscle viscosity.

d) Electromechanical delay.

Each muscle fibre, when activated, takes a finite time to build up tension from resting levels to maximum tension. This time course of tension build up, called the electromechanical delay (EMD) results from a combination of the actual tension build up of the contractile component of the muscle and the accompanied stretching of the series elastic component of the muscle (Jewel and Wilkie, 1958). The EMD varies from 20 to 100 ms in human experiments (Norman and Komi, 1979). At low contraction velocities the EMD is only a small proportion of the time taken for the muscle to contract. This proportion, however, increases with increasing velocity of shortening. As a consequence the average force produced, and the associated power output, over the range of movement decreases with increasing velocity of contraction. To further exacerbate the decline in force production the EMD has been shown to increase with velocity of contraction (Wilkie, 1950).
The factors discussed above combine to produce the power-speed curve seen in figure 6.4 and are the cause of the 'fatigue' seen during the first few seconds of the test.

The complexity in measuring the fatigue taking place on the friction-loaded cycle ergometer stems from the constantly changing speed of muscle contraction that is taking place during sprint activities. It would appear that fatigue would be very much more easily measured if friction-loaded cycle ergometers were replaced by constant velocity cycle ergometers which do not permit variation in the average velocity of contraction. It is, however, for precisely this reason that, despite the complexity of measurement, constant velocity ergometers should not be used to examine fatigue during sprint activities as acceleration is fundamental to these activities. In order to examine the processes of fatigue both the metabolic and the mechanochemical causes must be examined. The artificial restrictions placed on the subjects by the constant velocity ergometers do not allow these systems to function normally.

This thesis has shown that, far from increasing the complexity of measurement, the friction-loaded cycle ergometer can be used to measure many performance characteristics more simply, as long as the correct method of calculation is used. A good example of this is the examination of the torque profile generated during cycling. It has been shown that instead of having to instrument the pedals or cranks with strain gauges and associated slip rings, which is required on the constant velocity ergometer (and previously thought to be needed on the friction-loaded ergometers), the speed of the flywheel needs only to be monitored by a computer, using a small generator.
CHAPTER 5
INTRODUCTION TO SECTION B

In the previous section the use of friction-loaded cycle ergometers for investigating short duration maximal exercise was closely examined. It was found that when the correct techniques of calculation are applied then very useful results are obtained. The cycle ergometer is, however, limited in its use for evaluating sports performance because the sprint running action, which is fundamental to many sporting activities, cannot be fully reproduced on it. On the cycle ergometer the weight of the subject is being supported on the saddle. During the running stride not only has the subject to propel himself forward but he has to support and indeed elevate his body weight. Ideally, what is required is an ergometer which is as versatile as the cycle ergometer, which requires the subject to support his own body weight, which can measure external power output, and which allows the subject to reproduced the running action as closely as possible.

In the past motorised treadmills have been used to examine anaerobic performance capacity in sprint running (Thomson and Garvie, 1981). The subjects were asked to run at near maximal intensity for short periods of time. There are several major drawbacks in using the motorised treadmill for evaluating maximal sprint performance. The subjects are not free to accelerate in the same way that they would in normal activity. It is impossible to vary the treadmill speed so that the subject is running at maximum speed at every instant during the test. The subject can only maintain peak running speed for a few moments and, therefore, the treadmill cannot be set at this maximum speed as the subject would be unable to keep up with it. The treadmill must be set at a speed which will maximally tax the subject over the duration of the test, therefore, the subject will be working sub-maximally for part of the test. In addition to the speed modification problem it is
very difficult to measure external power output being generated by the subject on such treadmills (Lloyd and Zacks, 1972).

What is required is a treadmill which is propelled solely by the subject so that any change in running speed is reflected in a change in the treadmill speed. The system adopted must also allow external power output to be readily measured. There is at present, however, no generally accepted method for the examination of sprint running performance in the laboratory.

The following chapter describes the development of an ergometer, based on a non-motorised treadmill, that:

(a) allows the subjects to sprint at speeds similar to those achieved in free running;
(b) allows the same variability in instantaneous work rate during sprinting that cycle ergometers permit during cycling;
(c) enables instantaneous values of power output to be determined throughout the sprint.

The work done by the sprinter can be split into two components. The vertical component raises the centre of gravity during each stride so that leg recovery can take place. Fukunaga et al (1978) found that for a given runner, the vertical component of the work being done by the runner was independent of running speed. The horizontal or 'propulsive' component moves the runner along the ground; the greater this propulsive component the faster the sprinter will cover the ground. The sprinter, therefore, attempts to maximise his work rate in this direction. Ideally, the total work done by the sprinter, i.e. the sum of the vertical and horizontal components, should be monitored when evaluating the physiological demands of sprinting. It is very difficult to measure the vertical component of the work being done.
during sprinting. No attempt is made to measure this component and so the instrumented ergometer described in the following chapter measures only the horizontal component of the work rate, the component that actually maintains treadmill motion. The result reported by Fukunaga and colleagues for free sprinting is assumed to be valid for running on the treadmill.

The experimental chapters in this section investigate the characteristics of the sprint-treadmill ergometer and highlight its strengths and weaknesses as a tool for measuring sprint performance. Test protocols that have been developed for use on the sprint treadmill will be examined for sensitivity to changes in performance. Maximal sprint performance on the sprint treadmill will be compared to similar performance on the friction-loaded cycle ergometer and sprinting on a running track.
CHAPTER 8

CHARACTERISTICS OF THE SPRINT TREADMILL ERGOMETER.

8:1 INSTRUMENTATION OF THE TREADMILL.

A commercially available treadmill (Woodway model AB), which normally slopes backwards, was levelled by placing its rear feet on supports. All four feet were anchored securely to a base-board to prevent excessive lateral movement during use.

The hand rails provided with the treadmill were removed. New brackets were made and the rails were re-attached to the treadmill approximately 30 cms further apart and 10 cms lower than they had originally been so that the runners would not strike them with their arms while sprinting. [Figure 8.1] shows a schematic diagram of the sprint treadmill ergometer (with the handrails removed).

8:2 BELT SPEED MEASUREMENT

In order to measure the treadmill belt speed a drive system was attached to the front rolling drum of the treadmill to drive a high-precision D.C. generator [(Figure 8.2)]. A small gearbox was inserted in the drive system to give a ratio of 1:15 between drum and generator speed. Without the gearbox the output voltage from the generator, when the subjects were running at maximum speeds, was approximately 0.4 to 0.5V. The analogue-to-digital converters described later have a full range input sensitivity of 0 to 10V and so to fully utilise this sensitivity the output from the generator must be amplified 10 to 20 times. This amplification was achieved by the gearbox which resulted in the angular velocity of the shaft being increased by a factor of 15. The output voltage for a D.C. generator is given by;
Figure 8.1 The schematic diagram of the sprint treadmill ergometer, with the handrails removed.
THE SPRINT TREADMILL ERGOMETER IN OPERATION.
Figure 8.2 Diagram of the generator and gearbox driven by the front rolling drum of the treadmill.
Output Voltage = constant \times \text{angular velocity}

It is clear from this formula that the output voltage is directly proportional to the generator shaft angular velocity. The gearbox will, therefore, increase the voltage output of the generator 15-fold without affecting its linearity.

The relationship between angular velocity of the generator shaft and analogue voltage output was checked and found to be highly linear \((r^2=99.8\%)\), as shown in Figure 8.3. During each test on the treadmill the output from the generator was continually monitored by a microcomputer via a multi-channel analogue-to-digital (A-to-D) converter. In the early stages of the study the computer used was a Commodore model 4032 with a 16-channel 8-bit A-to-D (Farnell Components ADC0816). The system was later upgraded to 12-bit sensitivity using a single channel A-to-D (R.S. Components 574), multiplexed using analogue switches. The multiplexer was switched using the 1MHz port of a BBC model B microcomputer, and the output of the A-to-D was latched and read by the User Port of the same computer. In addition to being read by the computer the output from the generator was processed and used to drive a large \(\text{mA}\) meter which was positioned in front of the treadmill where it could be seen easily by the subjects. The dial of the meter was calibrated so as to display running/teadmill belt speed in m.s\(^{-1}\).

Prior to every test the output from the generator was calibrated. A 750-W, variable speed electric motor was temporarily coupled to the treadmill, by a drive belt. The motor was used to drive the treadmill belt. Whilst the belt revolved at a near constant speed, logging by the computer of the output from the generator was initiated and the number of revolutions of the treadmill belt was counted. The count and logging process was terminated at the same moment. The mean output voltage corresponding to
Figure 8.3 The relationship between applied force and belt speed and the analogue-to-digital converter value.
the known belt speed was calculated and the calibration factor determined. This calibration factor was stored on disc for automatic retrieval by the test programs.

8.3 PROPULSIVE FORCE MEASUREMENT

The measurement of the forces propelling the treadmill belt was achieved by applying Newton's third Law of Motion which states that for every action there is an equal and opposite reaction. If the subject, when running on the treadmill, is not moving relative to the ground then the force that the sprinter is applying to move the treadmill belt must be equal to the horizontal component of the restraining force in the harness. A wide tether belt was passed around the subject's waist to prevent movement of the whole body relative to the ground. The tether was connected to a force transducer (Pioden Ltd., model UF2) by two straps. The transducer was attached to a flat crossbar mounted between two vertical rails. The strap angle could be adjusted by raising or lowering the crossbar.

The Wheatstone bridge network of strain gauges within the transducer was interfaced to an amplifier and monitored by the computer via a second channel of the A-to-D converter. Known weights were suspended from the transducer prior to it being mounted on the crossbar. A high ($r^2=99.7\%$) correlation was found between applied force and the output from the amplifier [Figure 8.3].

Prior to each test the output from the force transducer was calibrated. The zero-force output was determined when no load was attached to the transducer. A known weight was attached to the transducer and suspended over a small, well lubricated, pulley so as to provide a known force [Figure 8.4]. The output from the transducer was measured for a period of 5 seconds, so that any small fluctuations in the force due to swinging of the weight would be
Figure 8.4 Method employed to calibrate the force transducer prior to each test.
averaged out. The average value obtained over the 5 seconds was used to calculate the calibration factor, which was stored on disc for automatic retrieval by the test programs.

8.4 MEASUREMENT OF POWER OUTPUT

The rate at which work was being done to move the treadmill, i.e. the horizontal power output, was calculated from the product of the restraining force and the belt speed. This calculation assumes that it is the speed of the point of force application that is being measured. On the treadmill, the points of force application and speed detection are not the same. Force is being applied at the foot/treadmill interface, whereas, it is being measured at the waist. This will result in an error in the calculation of the instantaneous value of power output. The calculation would be valid if the treadmill belt moved at a constant speed, however, during each stride the belt is accelerated and decelerated. This results in an underestimation of the instantaneous power output during belt acceleration and an overestimation during deceleration. If the force-velocity product is averaged over an entire stride-cycle then the resultant error in mean power output per stride is small.

The power being measured is only that which is being generated to propel the treadmill belt. No attempt is being made to measure the work being done to raise the centre of gravity of the runner during each stride cycle so that the legs can 'recover' after each propulsive phase. It is fortunate that research has shown that the work done against gravity is independent of running speed (Cavagna et al., 1964; Fukunaga et al. 1978), and represents up to 50% of the total power output.

Ideally the power output should be calculated from the continuous integral of horizontal force and speed, but it
is extremely difficult in practice to obtain a true integral, as data must be collected as discrete values. The Trapezoidal Method was used to approximate the integral, with the error being kept small by using a high sampling rate (>20Hz).

8:5 ESTABLISHING THE START POINT OF THE SPRINT

As with the cycle ergometer test described in Chapter 4 it was found that some of the subjects were starting to sprint either slightly before or slightly after the start command. In order to eliminate any error in the calculation that might result from this timing offset the computer logging system was initiated just prior to the start command and the actual start point of the test was determined from the data. This was done by displaying the treadmill speed data in a graphical form on the computer screen once the test was concluded. A cursor line, plotted on the screen was moved, by the experimenter until it coincided with the point at which a change in the speed of the belt could be seen (see Figure 4.5). The computer was instructed to regard this point as the start of the test.

8:6 HEART-RATE

The subject's heart-rates were also monitored by the computer throughout each sprint and during the subsequent recovery period. The output from a heart-rate recorder (Cambridge Instruments), which was proportional to the heart rate, was multiplexed with a third channel of the A-to-D converter.

8:7 PERFORMANCE DATA DISPLAY

At the conclusion of each exercise bout the computer was programmed to calculate and display the following information:
(a) the mean speed of the treadmill for each second of the sprint;
(b) the mean power generated for each second of the sprint;
(c) the mean power applied to the treadmill over the test period;
(d) the total work done in moving the treadmill;
(e) the fatigue index defined as the difference between the peak and lowest (or end) power output expressed as a percentage of the peak power;
(f) the heart-rate for each second during the sprint and for each 5 seconds during the 5-minute recovery period.

8.8 SETTING THE TREADMILL RESISTANCE

When the 750-W electric motor was coupled to the treadmill, as shown in Figure 8.5, it was found that the input power, which is a function of the current flowing through the motor armature and field coils and the potential difference across them, dropped whilst the treadmill belt speed gradually increased. This can clearly be seen in Figure 8.6 which shows the changes in the potential difference across the motor, the current flowing through it and the speed of the treadmill belt for the first 90 seconds of motor switch-on from cold. Whilst the speed of the treadmill gradually increased the power component, calculated from the product of motor potential difference and current, dropped. Both values reached near constant values after about 50 seconds. The drop in the power component was due to the fall in current flowing through the motor with the potential difference remaining constant. This fall in the power component indicated that the resistance of the treadmill was also decreasing. This was probably due to increasing temperature of the belt and bearings. Once the treadmill was warmed-up, however, the resistance became near-constant indicated by the plateauing of the speed of the treadmill and the motor input power.
Figure 8.5 The 750-W electric motor coupled to the treadmill to enable setting of the treadmill resistance and for speed calibration.
Figure 8.6 The changes in potential difference across the motor and the current flowing through it for the first 90 seconds of motor switch-on from cold.
To achieve standardisation of the treadmill resistance, prior to each test, the 750-W motor was coupled to the treadmill and run until the product of the motor voltage and current dropped to a standard value whilst the belt was revolving at a standard speed.

8:9 SUBJECT WARM-UP

Prior to each test the subjects performed a standardised warm-up procedure. This consisted of running on the treadmill for 30 seconds at 3 m.s\(^{-1}\), 30 seconds rest, and a further 30 seconds of running at 3 m.s\(^{-1}\). The subjects could tell their running speed from the dial described earlier. After the two runs the subjects were allowed to stretch for 5 minutes. They were advised to stretch the hamstring group in particular, as this muscle group is known to be highly stressed in sprint activities.

8:10 TREADMILL CHARACTERISTICS

8:10.1 SEQUENTIAL RELATIONSHIP BETWEEN FORCE, POWER AND SPEED

Ten subjects (5 male, 5 female) whose ages, weights and heights were (mean±S.D.) 29.4 ±10.8 years, 72.2 ±17.0kg, and 169.0 ±11.0cm, respectively, were asked to perform a series of maximal sprints from a standing start, so that the sequential relationship between force, power and speed could be examined.

8:10.2 RESULTS

[Figure 8.7] shows the typical sequential relation between force, power and speed generated by one of the subjects sprinting for 5 seconds from a standing start. For all the
Figure 8.7 A typical sequential relationship between force, power output and speed, generated by one of the subjects during the first 5 seconds of a sprint from a standing start.
subjects peak force was attained earlier than peak power 
\((p<0.001)\) and in turn peak power occurred before peak speed 
\((p<0.001)\).

8:10.3 DISCUSSION

These results indicate that the sprint treadmill shows the same characteristics that are common to all mechanical systems that are free to accelerate. In such systems peak force occurs at a lower velocity than peak power and, therefore, occurs earlier. Peak power, in turn, occurs whilst the system is still accelerating and is, therefore, attained before peak speed is reached. The results obtained for force and running speed are similar to those reported by Vaughan (1983) in which the displacement, velocity and acceleration curves of a sprinter was simulated

8:10.4 RELATIONSHIP BETWEEN POWER OUTPUT AND SUBJECT WEIGHT FOR A CONSTANT RUNNING SPEED

Fourteen subjects, whose range of weights ranged from 51.7 to 96.7kg, were asked to run at a constant speed of 2.87 m.s\(^{-1}\) for 30 seconds. The subjects were deliberately chosen so as to obtain a wide range of weights.

8:10.5 RESULTS

Figure 8.9 shows the plot of the relationship between horizontal force and power and body weight at a constant running speed of 2.87 m.s\(^{-1}\).

The regression equations obtained from the two plots were:

\[
\text{force (N)} = 50.0 + 0.40 \times \text{weight (kg)} \quad (r=0.93)
\]

\[
\text{power (W)} = 143.2 + 1.167 \times \text{weight (kg)} \quad (r=0.94)
\]
Figure 8.8  Simulated displacement, velocity and acceleration curves of a sprinter (adapted from Vaughan, 1983).
Figure 8.9 The plot of the relationship between horizontal force and power output and bodyweight at a constant running speed of $2.87 \text{ m.s}^{-1}$ ($n=14$).
[Figure 8.10] shows a plot of the data redrawn as power per unit bodyweight. The linear regression obtained is:

\[
power/\text{bodyweight} \ (W.kg^{-1}) = 0.542 - 0.0029 \times \text{weight (kg)} \\
(r = -0.97)
\]

As the line should theoretically be asymptotic an exponential relationship was assumed and a better line of fit was obtained:

\[
power/\text{bodyweight} \ (W.kg^{-1}) = k \times \text{weight}^{-0.454} \ (kg) \\
(r = -0.99)
\]

8:10.6 DISCUSSION

It is highly desirable to have linear relationships between variables on the ergometer, and where possible the regression lines obtained should pass through the origin. The relationships between both force and power and bodyweight, at a constant running speed, were found to be linear but they were found not to pass through the origin. This result indicates that the resistance of the treadmill increases with loading and that when the treadmill is unloaded there is still a significant value of resistance. An increase in the subject's weight would result in more force and power required to maintain running speed but the percentage increases required would not be the same as the percentage increase in weight. This result indicates the advantage that a heavier runner has over a lighter runner on the treadmill. The proportional contribution of the unloaded resistance of the treadmill decreases as the weight of the subject running increases. This is best seen in [Figure 8.10]. As the weight of the runner increases the amount of power required per unit body weight decreases. A
Figure 8.10 Plot of relationship between power output expressed per unit bodyweight and the weight of the subject (n=12).
52 kg runner must generate about 33% more power per unit bodyweight than an 80kg person, running at the same speed. This is an important finding as it will significantly influence the interpretation of inter-individual performance data, such as average running speed and total distance run in a fixed time interval, as the respective weights of the subjects must be accounted for. Both the unloaded and loaded resistance of the treadmill would have to be zero for there to be no advantage to be gained by the heavier runner. In contrast to other performance variables, power output is relatively independant of the resistance of the treadmill, thereby simplifying interpretation. If treadmill resistance increases then maximum running speed will decrease. As there is a reciprocal relationship between force and velocity then as the velocity drops the external force will increase, resulting in maintenance of the force-velocity product.

8:11 RELATIONSHIP BETWEEN FORCE AND POWER AND RUNNING SPEED

The ten subjects described above were asked to run at 3 sub-maximal speeds for 60 seconds. The three speeds were approximately 2.8, 3.4 and 4.3 m.s⁻¹. The actual running speed was accurately monitored for each subject. The mean horizontal force applied to the tether belt and the mean power output for the 60 seconds was determined for each run.

8:11.1 RESULTS

Figures 8.11 and 8.12 show the relationships between the mean force and mean power required to propel the treadmill at constant running speeds. Both force and power were found to increase with running speed. The regression equations obtained were:

\[ \text{force (N)} = 5.90 \times \text{speed (m.s}^{-1}) + 65.4 \quad (r=0.61) \]
Figure 8.11 The relationship between mean force and constant running speeds.

\[ y = 65.4 + 5.9x \]
\[ r = 0.61 \]
Figure 8.12 The relationship between mean power output and constant running speeds.
As there is no wind resistance to be overcome on the treadmill it would be expected that the force required to maintain constant submaximal running speeds would be increase in proportion to the speed of running. The results, however, show a gradual increase in average force with running speed. Luhtanen and Komi (1977) found that the time for one step cycle of the running stride decreased with increasing running speed with decreases in both contact time and flight time, at different non-linear rates. The contribution of the contact time to the step cycle time was found to increase with running speed. These findings show that the time the foot is in contact with the treadmill increases with running speed. It has been shown that the resistance of the treadmill increases with bodyweight. An increase in contact time will, therefore, increase the average resistance of the treadmill requiring an increase in the propulsive forces. This increase in average propulsive force with running speed is shown in the results. The relatively low correlation obtained reflects the inter-individual differences in stride pattern.

Power output was found to increase linearly with running speed with the increase in power output being more influenced by the increased speed than by the increased applied force. This is the result that would be expected from a friction retarded ergometer such as the non-motorised treadmill. In contrast a fluid braked devices would be expected to have an exponential relationship between power output and speed.
In order to investigate the extent of the forward lean of the subjects when running on the sprint treadmill, and the deviation of the tether belt from the horizontal during running the ten subjects described above were asked to run at a steady submaximal speed of 5 m.s⁻¹ for a minimum of 10 seconds on the non-motorised treadmill. They were also asked to run at the same speed on a motorised treadmill (Woodway model AB-927) which had the same running surface. During both tests a video camera was used to record the movement of the tether belt from the side. Three of the subjects repeated the runs with the video camera set up for a front-on view.

A 3-dimensional reference grid was used to establish both the horizontal and vertical axis on the video. The camera height was set so as to be level with the tether belt and pointing at the position where the belt crosses the mid-line of the runner's body.

The tether belt was set so that the straps were horizontal when the runner was standing upright.

Two markers were placed on the body on the side facing the camera. One was placed on the acromion process of the shoulder and the other just above where the belt would pass around the waist and in a vertical line from the anterior superior iliac crest. These markers were used to determine the extent of the forward lean of the subject. As the change in the lean was being investigated, the accuracy in the positioning of the markers was not as important as would be required if the absolute value of the lean was being measured.
Figure 8.13 The range of movement of the tether straps viewed from the side for two of the subjects.
Figure 8.14 The range of movement of the tether belt when viewed from the front, for two of the subjects.
8:12.1 RESULTS

Analysis of the recordings showed that the two attachment straps moved through an average arc of 7.7 (±2.3) degrees, when viewed from the side. Examples of the range of movement of the tether straps for two of the subjects are shown in Figure 8.12. The range of movement for the whole group was found to be from 4.0 to 11.5 degrees.

Both straps were found not to move in unison. The front view, shown in Figure 8.14, clearly shows that the tether belt was tilted, as the pelvis tilted, during the running stride due to the adduction and abduction of the hip joints. As a consequence of this tilting action the straps deviated from the mid-point in opposite directions. There was, however, a common component of movement by the straps as the whole body moved up and down during the stride cycle. Unfortunately, the exact value of the nett deviation of the tether could not be calculated from the videos but by using approximations the deviations were calculated to be less than 4 degrees.

No relationship was found between the height of the subject and degree of tether deviation.

From the video recordings it was found that if the tether was set to be horizontal when the subject was standing upright then at no time during the sprinting stride did the tether actually return to the horizontal. The point around which the tether moved was found to be 7.8 (±1.4) degrees below the horizontal, measured at the point of attachment of the tether to the force transducer.

The video analysis also showed that when running at the same speed on the non-motorised treadmill the forward lean of the upper body was more pronounced than on the the motorized treadmill, and this difference was found to be approximately 13.1 (±7.6) degrees.
8:12.2 DISCUSSION

Video analysis is noted for its inaccuracies due to the relatively slow frame rate, the long exposure duration and the curvature of the monitor screen from which the data is transposed. In this study only approximate values were required so that the order of magnitude of the errors associated with the tethering system could be calculated, and for this purpose video analysis was more than adequate.

The subjects were found to lean further forward on the sprint treadmill than when free running on the motorized treadmill. In addition to this forward lean the runner's body was found to move up and down during each stride cycle. On the sprint treadmill these two factors resulted in a small component of the bodyweight of the runner being applied to the tether at all times, which was independent of the propulsive forces derived from the legs. An assessment of the magnitude of the error caused by these two factors was made.

8:13 ERROR DUE TO THE HORIZONTAL DEVIATION OF THE TETHER

If the actual force applied to the tether is $F$ Newtons, and the angle between the tether strap and the horizontal is $A$ degrees, then the actual horizontal force ($AHF$) is a component of the applied force and is calculated from:

$$AHF(N) = F(N) \times \cos(A)$$

From the results the maximum deviation of the tether strap from the horizontal was less than 4 degrees. The cosine of 4 degrees is 0.998 and, therefore, the error introduced by deviation of the tether is less than 0.3%. Even if the deviation was twice that measured then the error would only rise to 1%.
8:14 ERROR DUE TO THE FORWARD LEAN OF THE SUBJECT.

The difference between the forward lean of the subject on the sprint treadmill and the motorised treadmill was found to be 13.1 (+7.6). If $F_v$, a component of the bodyweight, is the vertical force being applied to the tether belt, and the forward lean is $A_f$ degrees then the horizontal force ($F_h$) detected by the transducer is given by:

$$F_h (N) = F_v (N) \times \sin(A_f)$$

If $A_f$ is 13.1 degrees then 22.6% of the vertical force being applied to the tether is detected by the transducer. The vertical force ($F_v$) being applied will be determined from the instantaneous vertical force ($F_{iv}$) being generated by the runner and the deviation of the tether strap from the horizontal ($A$), using the equation:

$$F_v (N) = F_{iv} (N) \times \cos(A)$$

We know from the results that the maximum deviation of the tether strap is 4 degrees and so the maximum value of $F_v$ is 0.3% of $F_{iv}$. The combination of these equations gives a worst case value of 22.6% of 0.3%, i.e. 0.07% of $F_{iv}$. Although the vertical forces applied to the body can be very high, indeed several times body weight, the component of these forces detected by the transducer are very small.

It is clear from these results that it is the deviation of the tether belt from the horizontal that determines the magnitude of the errors. The easiest way of minimising the errors produced is to increase the length of the tether straps. The longer the straps the smaller will be the angle subtended by them due to a given absolute movement at the free end.
8:15 SETTING THE TETHER ANGLE PRIOR TO A TEST

The results show that when the tether was set to be horizontal when the subject was standing upright then at no time during the sprinting stride did the tether actually return to the horizontal. This is an interesting finding as it shows that although the centre of gravity rises and falls during the stride cycle, and even though there is time during the cycle when both feet are off the ground, the centre of gravity of the body does not get as high as when the subject is standing upright. Even though near full extension of the knee occurs, the point at which this happens is quite some distance behind the centre of gravity of the body, resulting in a pronounced forward lean, and so does not raise the body to the standing height. The extent of knee extension of the supporting leg during the running stride was investigated by Mann and Herman (1985) who showed that better sprinters do not extend their knees fully before take-off.

In order to minimise the errors due to deviation of the tether from the horizontal, the results indicate that the tether straps should be set so that they are approximately 8 degrees above the horizontal when the subject is standing. This setting is true only for the length of straps used in this study. If different strap lengths are used then the angle will be different. However, they should still be set to some angle above the horizontal when the subject is standing. This setting will ensure that the straps are as near horizontal as possible when the subject is running on the treadmill.
EFFECT OF EXTENSIBILITY IN THE TETHERING SYSTEM

If the techniques of running were reproduced exactly on the sprint treadmill then the force applied to the transducer would be expected to be zero when the runner was not touching the ground as he could not propel himself forward. When the ergometer described in this study was first set up the tether strap purchased with the treadmill was used. This strap was highly extensible and the results of the pilot studies showed that at no time did the value of force applied to the transducer drop to zero. Observation of the strap during the tests showed that the strap which was being stretched during the propulsive phase of the stride was not completely restored to its resting length between strides.

A study was set up to investigate the effect of extensibility of the tethering system on the profile of the force being applied to the transducer.

METHOD

The ten subjects previously described performed two runs for 10 seconds at a constant 5 m.s⁻¹. The first run was with the manufacturers highly extensible tether, and the second run was with a tether of reduced extensibility.

In order to examine closely the profiles of the applied force during the runs a second microcomputer was coupled in parallel to the first to act as an 'intelligent' high-speed memory. At the conclusion of each test the profiles of the applied force were plotted on a Y-t recorder at a much reduced play-back speed. This overcame the problems of pen inertia inherent in Y-t plotters.
8:16.2 RESULTS

Four examples of the force profiles generated when the highly extensible commercial tether and the comparatively inextensible tether were used are shown in Figure 8.15.

For all the subjects the mean peak forces generated when the less extensible tether was used were greater than those obtained using the highly extensible tether (p<0.001). In addition the mean minimum forces were less for the less extensible tether than for the highly extensible one (p<0.001).

A summary of the results is shown in Table 8.1.

8:16.3 DISCUSSION

Figure 8.15 clearly shows that the minimum forces generated during the stride, when the extensible tether was used, always remains statistically (p<0.001) above zero, which would be expected from free running. The mean minimum force was found to fall to an average of 70% of the mean of the peak values. The extensible tethering straps were effectively acting as low pass filters smoothing out the force peaks. The potential energy stored in the elasticity of the tether was increased during the propulsive phase of the stride and this energy was recovered during the non-propulsive phase. As a consequence the peak and minimum forces measured were smoothed values and the actual instantaneous values of applied force throughout the stride cycle incorrectly calculated.

The results from the less extensible tether show a much wider difference between the peak and minimum forces measured during running on the treadmill. The peak forces were an average of 53.8% (p<0.001) higher than those obtained using the highly extensible tether and the
Figure 8.15 Four examples of the force profiles generated when the highly extensible and the less extensible tether straps were used.
<table>
<thead>
<tr>
<th>Extensibility</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>low</td>
<td>high</td>
<td></td>
</tr>
<tr>
<td>peak</td>
<td>min.</td>
<td>peak</td>
</tr>
<tr>
<td>Force (N)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>77.1</td>
<td>15.5</td>
</tr>
<tr>
<td>S.D.</td>
<td>17.2</td>
<td>4.8</td>
</tr>
<tr>
<td>Relative Magnitude</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(%)</td>
<td>mean</td>
<td>100</td>
</tr>
<tr>
<td>S.D.</td>
<td>6.2</td>
<td>14.6</td>
</tr>
</tbody>
</table>

Table 8.1 The average peak and minimum forces measured during the constant speed run of 5 m s⁻¹ for tethers of different extensibility. The forces are expressed as absolute values (N) and relative to the maximum mean value achieved using the tether of low extensibility (n=10, mean ±S.D.).
minimum values were 43.9% (p<0.001) lower. Although much smaller the minimum values of force for the low extensibility tether were still statistically higher (p<0.001) than the zero value that would be expected. Although the tethering system was more rigid the entire framework flexed and extended during the stride indicating that there was still a great deal of elasticity in the system which would account for some of the observed results. The horizontal component of the subject's weight resulting from the forward lean required when sprinting on the treadmill, as described earlier, will also contribute to the propulsive force observed during the flight phase.

It should be noted that the subjects found the less extensible tethering system very much less comfortable than the extensible system. They felt that any further increase in the rigidity of the system would make the tether unacceptably uncomfortable. This is not surprising as the peak forces felt by the subjects in the tether belt increases with increasing rigidity. All subsequent tests were performed using the less extensible tether.

**8:17 ENERGY COST OF STEADY SUBMAXIMAL RUNNING**

In order to compare the metabolic energy requirement of running on the sprint treadmill with that of free running, at a constant submaximal speed, a group of subjects were asked to run at a constant speed of 2.88m.s⁻¹ on the sprint treadmill and at incremented speeds on the motorized treadmill. During each test expired air was collected and oxygen uptake calculated.

**8:17.1 METHOD**

The ten subjects described earlier performed the following three tests:
CONSTANT SPEED RUN ON THE SPRINT TREADMILL

In the first test the subjects were required to run at a constant 2.88 m.s⁻¹ (10 kph) on the sprint treadmill for 3 minutes. Throughout the test the subjects breathed through a rubber mouthpiece (Harvard Equipment) into a lightweight two-way valve (Jakeman and Davies, 1979) which was attached by lightweight tubing (Falconia) to a 150 litre capacity Douglas bag (Harvard Equipment) via a two-way tap. During the last minute of the test expired air was collected in the Douglas bag.

SUBMAXIMAL INCREMENTAL TEST

The second test consisted of level running for a total of 16 minutes on the motorized treadmill. From an initial speed of 2.75 m.s⁻¹ the running speed was increased by 0.5 m.s⁻¹ every 4 minutes. During the last minute of each speed expired air was collected in Douglas bags as described above.

MAXIMUM OXYGEN UPTAKE (VO₂MAX) TEST

A modification of the Taylor treadmill test was used to measure maximal oxygen uptake (Taylor, Buskirk & Henschel, 1955). The treadmill speed for all the subjects was set at 3.13 m.s⁻¹. This speed was chosen so as to exhaust the subjects in 7 to 9 minutes. The incline of the treadmill was initially set to 3.5% and incremented by 2.5% every three minutes. An expired air sample was collected during the last minute of each three minute exercise period, until the subject indicated voluntary exhaustion when a final collection of expired air was made.

The criteria used for establishing VO₂max were:

a) Subjective exhaustion;
b) an R-value of greater than 1.10 (Issekutz, Birkhead and Rodahl, 1962);
c) a heart rate close to the expected mean for the age of the subject (Astrand, 1952)

d) a ventilatory equivalent close to 30.

EXPIRED AIR ANALYSIS

i) OXYGEN ANALYSER The oxygen content of the expired air was analysed using a precalibrated paramagnetic oxygen analyser (Sybron, Taylor Servomex, Model 570A). The digital display was accurate to 0.1%.

ii) CARBON DIOXIDE The expired air was analysed for carbon dioxide content on a precalibrated infrared carbon dioxide analyser (Mines Safety Appliances Ltd.; Lira Model 303). The analogue reading obtained from this meter was converted to a percentage reading by using the calibration curve supplied by the manufacturer.

iii) GAS VOLUME The volume of the expired air was measured by evacuating the Douglas bag through a Parkinson Cowan Dry gas meter. The meter had been precalibrated using a 600 litre Tissot Spirometer (Collins Ltd.). The temperature of the expired air was measured using a thermistor mounted in the inlet pipe to the dry gas meter. The thermistor was connected to a thermometer (Edale type 2984, Model C).

iv) DETERMINATION OF OXYGEN UPTAKE Oxygen uptake was determined by converting the volume of expired air to standard temperature and pressure for a dry gas (STPD) and then applying the Haldane transformation, using the assumptions that no net uptake or production of nitrogen at the lung had occurred. Oxygen Uptake was expressed in ml.kg\(^{-1}\). min\(^{-1}\). 


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REGRESSION EQUATION FOR THE OXYGEN COST OF SUBMAXIMAL RUNNING

The linear regression equation was calculated, for the group, for the relationship between oxygen uptake (ml.kg\(^{-1}\).min\(^{-1}\)) and running velocity (m.s\(^{-1}\)) on the motorized treadmill.

8:17.2 RESULTS

The values of oxygen uptake on the sprint and motorized treadmills are shown in Table 8.2.

Figure 8.16 shows the regression line obtained from the 4 running speeds on the motorized treadmill:

\[
\text{Oxygen Uptake (ml.kg}^{-1}.\text{min}^{-1}) = 3.49 + 11.0 \times \text{speed (m.s}^{-1})\]

\[r^2 = 81.2\%\]

8:17.3 DISCUSSION

Although the subjects were running on the level on both treadmills the oxygen cost of running at a given speed was very much higher on the sprint treadmill than on the motorized treadmill. At 2.88 m.s\(^{-1}\) the oxygen cost on the sprint treadmill was an average of 51.6 ml.kg\(^{-1}\).min\(^{-1}\), compared to 35.2 ml.kg\(^{-1}\).min\(^{-1}\) on the motorized treadmill, obtained from the regression equation.

The speed of running on the motorized treadmill equivalent to running on the sprint treadmill at 2.88 m.s\(^{-1}\) was calculated to be 4.22 m.s\(^{-1}\), using the regression equation. Therefore, in order to run at the same energy cost the subjects were required to run at an average 65% faster on the motorised treadmill than on the non-motorised treadmill.
<table>
<thead>
<tr>
<th>Treadmill Speed (m.s⁻¹)</th>
<th>Oxygen Uptake +</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>±S.D.</td>
</tr>
<tr>
<td>2.75</td>
<td>33.2</td>
<td>4.3</td>
</tr>
<tr>
<td>3.25</td>
<td>39.7</td>
<td>2.9</td>
</tr>
<tr>
<td>3.75</td>
<td>44.7</td>
<td>2.4</td>
</tr>
<tr>
<td>4.25</td>
<td>49.8</td>
<td>2.2</td>
</tr>
<tr>
<td>V̇O₂max</td>
<td>53.9</td>
<td>2.7</td>
</tr>
<tr>
<td>Sprint treadmill*</td>
<td>51.6</td>
<td>3.6</td>
</tr>
</tbody>
</table>

*2.88 m.s⁻¹
+ml.kg⁻¹.min⁻¹

Table 8.2 The values of oxygen uptake for different running speeds, and the maximum oxygen uptake achieved on the motorised treadmill. The oxygen uptake measured during the second minute of a constant speed run on the sprint treadmill is also shown (n=10, mean ±S.D.).
Figure 8.16 The relationship between oxygen uptake and running speed on the motorised treadmill (mean ±S.D., n=10).

The equation is:

\[ Y = 3.49 + 11.0x \]

\[ r^2 = 81.2\% \]
It is clear that running on the sprint treadmill is very much more demanding than free running. When asked to run for 3 minutes at speeds above the test speed of 2.88 m.s\(^{-1}\), several of the subjects were unable to complete the test. This result was surprising as 2.88 m.s\(^{-1}\) is well below the speed at which these subjects habitually ran for periods in excess of 20 minutes. Examination of the results show that the mean oxygen cost of running at 2.88 m.s\(^{-1}\) on the sprint treadmill was 51.6 ml.kg\(^{-1}\) . min\(^{-1}\). This value approaches the group mean for maximum oxygen uptake of 53.9 ml.kg\(^{-1}\) . min\(^{-1}\). It is, therefore, not surprising that any attempt to increase the running speed in the sprint treadmill was found not to be sustainable.
8:18 DETECTION OF STRIDE FREQUENCY

It is often useful to know the stride rate of an individual as this may be influenced by many factors including training status, height, weight, age and fatigue. This study was designed to investigate whether the sprint treadmill system was sufficiently sensitive to variations in treadmill speed so that stride frequency could be measured.

8:18.1 METHOD

The ten subjects described earlier ran at a constant near maximal running speed of 5 m.s⁻¹ (18 kph) at their natural running frequency for 10 seconds.

A second microcomputer was coupled in parallel with the usual test computer to act as a high-speed memory. At the conclusion of each test the profiles of the belt speed were plotted on a Y-t recorder at a much reduced playback speed. This overcame the problems of the pen inertia inherent in Y-t plotters.

During the test the number of foot strikes was counted by an observer.

8:18.2 RESULTS

A typical profile of speed variation of the treadmill belt during a constant speed run (5 m.s⁻¹) from a standing start is shown in Figure 8.17. Each individual stride was identified and the total number of strides taken in the 10 seconds counted. This number was found to be the same as that obtained by the observer.

The force data stored during the test was also plotted on the Y-t recorder. A typical plot of the force profile for one of the subjects is shown in Figure 8.18. Again each
Figure 8.17 A typical profile of speed variation of the treadmill belt during a constant speed run (5m.s\(^{-1}\)) from a standing start.
force peak resulting from the stride cycle was identified and the total number of strides taken in the 10 seconds was counted. As with the treadmill belt speed variation the total of strides counted was the same as that of the observer.

A summary of the results is shown in Table 8.3.

8:18.3 DISCUSSION

The sprint treadmill system was shown to be sufficiently sensitive to both speed variation in the treadmill belt per stride, and propulsive force variation per stride, for the number of strides taken during the test to be counted.

Automation of the stride count could be achieved by the test computer by incrementing a counter each time a point of inflexion, either at a maxima or minima, is detected.

8:19 RELATIONSHIP BETWEEN STRIDE FREQUENCY AND CHANGE IN BELT SPEED PER STRIDE

The speed profiles obtained in the previous study were re-examined to see whether the sensitivity of the treadmill system was sufficiently high that changes in the magnitude of the variation of the belt speed per stride, at a constant running speed, could be detected for different runners.

8:19.1 RESULTS

Figure 8.19 shows the profiles obtained for the first five seconds for three subjects. The stride frequencies obtained from the steady speed run (5 m.s⁻¹) progressively increase from subject A to subject C.

As the duration of the test was exactly 10 seconds the
Figure 8.18 A typical profile of the variation in applied force during a constant speed run (5m.s\(^{-1}\)) on the treadmill.
Table 8.3 The mean stride frequency and change in belt speed for each subject running at a constant speed of 2.88m.s⁻¹. The data for each subject is the mean value calculated from 10s of running.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Stride Frequency (strides.s⁻¹)</th>
<th>Change in Belt Speed (m.s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.11</td>
<td>0.36</td>
</tr>
<tr>
<td>2</td>
<td>3.70</td>
<td>0.33</td>
</tr>
<tr>
<td>3</td>
<td>3.76</td>
<td>0.31</td>
</tr>
<tr>
<td>4</td>
<td>3.57</td>
<td>0.42</td>
</tr>
<tr>
<td>5</td>
<td>3.52</td>
<td>0.50</td>
</tr>
<tr>
<td>6</td>
<td>3.82</td>
<td>0.30</td>
</tr>
<tr>
<td>7</td>
<td>3.40</td>
<td>0.44</td>
</tr>
<tr>
<td>8</td>
<td>3.76</td>
<td>0.20</td>
</tr>
<tr>
<td>9</td>
<td>3.50</td>
<td>0.35</td>
</tr>
<tr>
<td>10</td>
<td>3.22</td>
<td>0.49</td>
</tr>
<tr>
<td>mean</td>
<td>3.54</td>
<td>0.37</td>
</tr>
<tr>
<td>S.D.</td>
<td>0.24</td>
<td>0.09</td>
</tr>
</tbody>
</table>
Figure 8.19 The profiles in treadmill speed variation obtained from 3 subjects for 5 seconds of constant speed running on the treadmill.
relationship between the paper speed of the plotter and time course of the data collection was accurately calculated. The distance travelled by the paper from the beginning to the end of the plot was 12.6 cms. The paper speed was, therefore, 1.26 cms per second of data collection.

The length of plot taken for 25 strides was measured from which the time taken (TT) was calculated. The stride frequency was determined from

\[
\text{stride frequency (strides.s}^{-1}) = \frac{25}{\text{TT}}
\]

The relationship obtained between change in belt speed and stride frequency is shown in Figure 8.20.

The regression equation calculated from the results was:

\[
\text{Change in belt speed (m.s}^{-1}) = 2.64 - 0.64 \times \text{stride frequency}
\]

\[
(r = -0.61)
\]

8:19.2 DISCUSSION

Changes in the magnitude of belt speed could be detected using the sprint treadmill system. The greater the stride rate the smaller the change in belt speed per stride, at a given running speed. This is the result that would be expected intuitively.

The absolute value of the change in the belt speed per stride is not only affected by stride frequency but is also a function of the ratio of the contact to flight time during the stride cycle. The greater this ratio the less will be the time spent in the air and, therefore, less will be the time available for the treadmill to decelerate. In top class sprinting the ratio varies from about 2:1 during the start, to between 1:1.3 and 1:1.5 at
Figure 8.20 The relationship between change in belt speed and stride frequency (n=10).

\[ y = 2.64 - 0.64x \]

\( r = -0.60 \)
or near maximal speed (Horsden 1964). During the initial few strides the sprinter will be in contact with the ground for about 67% of the total time. This contact time will be reduced to about 40-45% of the total stride cycle time when maximum speed is achieved. The actual stride pattern will also influence the change in belt speed per stride. The time of contact of the foot with the ground can be subdivided into two phases, namely the deceleration and acceleration phases. The initial point of contact of the foot with the ground is in front of the vertical projection of the centre of gravity of the runner (Figure 8.2). The foot then moves backwards relative to the body. While the contact point remains in front of the centre of gravity the forces generated will have a component acting to decelerate the runner. This is the deceleration phase. Once the point of contact has moved behind the vertical projection of the centre of gravity the forces generated will act to accelerate the body. The period of time that the body is being positively accelerated is called the acceleration phase. (Figure 8.2) shows the horizontal and vertical force profiles obtained from a subject running across a force platform. The direction of the horizontal component of the forces change direction at the changeover point between the deceleration and acceleration phases. Atwater (1980) studied the distances travelled by the body during the two phases in 12 top class male sprinters. She found that the average distances covered by the body as a proportion of the total stride length was 17% in the deceleration phase and 26% in the acceleration phase. The proportion of the total stride cycle spent in each of these phases will influence the magnitude of the speed changes of the runner per stride. On the sprint treadmill these changes are manifested as changes in the speed of the belt. More work is required to accelerate a mechanical system than to keep it moving at a constant velocity. If the acceleration phase of the contact time were maximised then the time available for deceleration of the treadmill would be minimised resulting in a decrease in the
Figure 8.21 The horizontal and vertical force profiles obtained from a subject running across a force platform.
magnitude of the variation of the belt speed, when maintaining a constant running speed. The forces required during the acceleration phase would be reduced and as a consequence the energy cost of running would be minimised. This logic assumes that the modifications in the running stride do not decrease the efficiency of other variables, such as the phasic storage and recovery of elastic energy in the muscle.

Fukunaga et al (1980) examined the horizontal velocity change of the centre of gravity of a group of runners during the contact phase of the running stride. The subjects ran across a force platform whilst being filmed. The results show that both the maximum and minimum horizontal velocities occur during the contact phase. On the sprint treadmill, although treadmill deceleration is taking place while the runner is not in contact with the belt, further deceleration takes place during the deceleration phase of the foot contact. The minimum belt speed is, therefore, achieved at the end of this phase. The treadmill speed increases during the acceleration phase reaching its maximum value prior to the foot leaving the belt. Therefore, maximum and minimum belt speeds are also attained during foot contact. As the subject is tethered the change in belt speed represents the change in the horizontal velocity of the centre of gravity of the subject. Fukunaga et al found that the change on the forward running velocity was given by the equation:

\[ dV_\ast = 0.00855V_\ast + 0.161 \]

where: \( dV_\ast \) is the forward speed per stride
\( V_\ast \) is the mean running speed

The subjects in the present study were running at a mean speed of 5 m.s\(^{-1}\). If this value is used for \( V_\ast \) then \( dV_\ast \) is calculated to be 0.204 m.s\(^{-1}\). From Table 8.3 the mean value of the change in belt speed per stride was found to
be 0.369 m.s⁻¹. The value obtained by Fukunaga is, therefore, only approximately 55% of the value obtained in this study, although the stride rates were very similar.

This finding indicates one of the differences between running on the sprint treadmill and free running. The greater variation in horizontal speed found in the sprint treadmill could be due to several factors:

(a) The mass of the treadmill being less than that of the runner.

Momentum is defined as the product of mass and velocity. For a given impulse the change in horizontal momentum per stride will be given by:

$$ F \times t = m \cdot dV $$

where: $F \times t$ is the impulse  
$m$ is the mass of the subject or treadmill belt  
$dV$ is the change in horizontal velocity

If the applied impulse is the same on the treadmill as free running, then:

$$ m_s \cdot dV_s = m_t \cdot dV_t $$

where: $dV_s$ is the change in speed of the centre of mass of the subject  
$dV_t$ is the change in treadmill belt speed.  
$m_s$ and $m_t$ are the masses of the subject and treadmill, respectively

then:  
$$ dV_t = m_s / m_t \times dV_s $$

From this equation it can be seen that, if no other forces are being applied, the change in belt speed is related to
the ratio of the subject and treadmill masses. Therefore, to reproduce free running the mass of the belt should be the same as that of the runner.

The rolling resistance of the treadmill belt being greater than air resistance.

The only external resistance to motion retarding the free runner is air resistance. The rolling resistance of the treadmill belt is very much greater than air resistance, resulting in greater deceleration of the belt between strides than would be experienced by the free runner.

Modification of the running stride.

If the running stride were modified so that either the deceleration or acceleration component of the contact phase per stride increased the magnitude of the variation in the horizontal speed would be increased. Except for the increased forward lean it is not known how the stride is modified on the treadmill.

All the three factors described above combine to produce the difference in the change in horizontal speed during the stride seen on the sprint treadmill. As the results indicate that the system is sensitive to changes in the belt speed then the sprint treadmill might be a useful tool for evaluating modifications in the running stride.

Closer examination of the profiles of the three runners in Figure 8.19 allows not only the changes in the magnitude of the belt speed to be measured but also the shape of the profiles produced to be evaluated. Each subject has produced a different pattern. Of particular interest is the profile produced by subject A. There appears to be a distinct difference between the magnitude of the belt speed variation between the two legs. Examination of twelve strides shows that the mean change in the belt
speed per stride for each leg was 0.55 (±0.04) and 0.33 (±0.05) m.s⁻¹, giving a ratio of approximately 5:3. The difference between the legs was highly significant (p<0.0001). When asked, the subject stated that he knew that one leg was stronger than the other, but was unaware of any assymetry of his running stride. The system, therefore, may provide a useful tool for the evaluation of dynamic leg assymetry resulting from differences in flexibility, force production, leg length or differential rates of fatigue. As described earlier the sprint treadmill may prove to be a useful tool for evaluating the dynamic state of recovery following injury.

Automation of the measurement of the change in belt speed per stride would require both points of inflexion (maxima and minima) in belt speed to be detected and their absolute difference calculated.

It is also clear from the results that stride frequency could also be counted using the force profile. Automation of the system to do this would require the detection of force maxima and minima as discussed using treadmill belt speed variation.

In conclusion, this chapter has described the characteristics of the developed sprint treadmill ergometer. Differences have been shown between running on the sprint treadmill and running on a motorised treadmill. The major difference was found to be the energy cost of running at a constant speed. Running on the motorised treadmill was found to be approximately 25% less demanding than running on the sprint treadmill. Forward lean was found to be accentuated, and propulsive forces were measured during the non-support phase of the running stride. Although running on the treadmill was shown not to be identical to untethered running, the sprint treadmill ergometer was found to be able to measure the work done during sprint running, although only the horizontal
component was measured. The vertical component is assumed to be independent of running speed. This may well be true of constant speed running, however, it is not known what happens during the acceleration phase of a sprint. The system was shown to be sensitive to modifications in the running stride and will prove to be a valuable research tool for investigating changes in the running stride due to training and fatigue. In order for the subject to reproduce more closely untethered sprinting on the treadmill two variables need to be modified. The resistance of the treadmill needs to be reduced and the mass needs to be increased. An increase in the mass might be achieved by attaching an external flywheel to one of the treadmill's drums. The effects of bodyweight on the characteristics of the treadmill are not yet fully known, however, it appears that the heavier subject is advantaged.
CHAPTER 9

THE USE OF THE TREADMILL FOR EVALUATING SPRINT PERFORMANCE.

As early as 1928 tethering systems were employed to examine the dynamics of sprint running, however, in contrast to running on the sprint treadmill, the subjects ran along a track (Best and Partridge, 1928). The subjects wore a waist harness, similar to that used on the sprint treadmill, and whilst sprinting they pulled a rope which was attached to the harness and wrapped around a flywheel. The friction applied to the flywheel could be altered so that the load against which the sprinter worked could be varied.

In the previous chapter the characteristics of the sprint treadmill ergometer was fully described. This chapter will examine the use of the sprint treadmill for evaluating short duration maximum exercise. The cycle ergometer 30 second test, described in chapter 4, has become very popular and so it was decided to see whether a similar test could be developed for the sprint ergometer. The results from two studies will be reported. The first discusses the results from the 30 second sprint test, and the second evaluates the sensitivity of the system to different groups of subjects.

9.1.1 METHOD

Twelve subjects (6 males and 6 females) who trained regularly took part in the study. The physical characteristics of the subjects were (mean ± S.D.):

males : weight 71.8 ± 6.9 kg, height 176.7 ± 8.2 cm,
        age 27.2 ± 6.3 years.
females: weight 61.2 ±7.1 kg, height 166.2 ±6.3 cm, age 25.1 ±5.5 years.

The subjects were familiarised with running on the sprint treadmill during three prior visits to the laboratory.

Before the tests both the treadmill belt speed and the force transducer were calibrated as described in the previous chapter. These calibration factors along with the force transducer zero offset value were stored on disc for later retrieval.

Five minutes before the sprint the subjects performed two 30s submaximal runs on the treadmill at 10 and 12 k.p.h., which served both to warm-up the subjects and to reaccustom them with the experimental procedure.

Just prior to the start of the sprint the treadmill was warmed-up, using an electric motor which was temporarily connected to the treadmill, until a pre-set value of resistance was attained (full details in previous chapter).

The rear cross-bar was set so that the tether straps were approximately 7 degrees above the horizontal with the subject standing upright.

Each sprint was performed from a rolling start of 2.2 m.s⁻¹. The subjects were instructed to work maximally from the start of the test, and were encouraged to do so throughout the test.

Heart rate was measured using a Rigel 302 Cardiac Monitor, and was monitored throughout the test by the computer.

The data from the sprint was recorded on disc. At the end
of the sprint the data was recalled and analysed by the computer. Data collection was started just prior to the sprint and continued for 40 seconds. The start point of the sprint was determined as being the point at which acceleration of the treadmill belt could be detected on the computer display of treadmill speed (see chapter 3 for further details). The actual duration of the sprint was determined by the experimenter using a hand held stopwatch which was started on the "GO!" command.

The speed of, and power applied to, the treadmill belt as well as the force on the tether strap was averaged and displayed for each second of the sprint. A summary of several of the performance variables were also displayed, including:

a) The total distance that the treadmill belt was moved and the mean belt speed over the 30 seconds. These were displayed as distance run and mean running speed.

b) The total work done in moving the treadmill (horizontal component) and the mean power output, expressed both as an absolute value and in relation to bodyweight.

c) The highest value of power output averaged over one second, termed peak power output, expressed both as an absolute value and in relation to bodyweight.

d) The minimum one second averaged power output.

e) Peak and minimum running speed (treadmill speed), averaged over one second.

f) The fatigue indexes for both power output and speed, defined as

$$(\text{peak value} - \text{minimum value}) / \text{peak value} \times 100 \%$$
with each value being the one second averaged figure.

The heart rate for approximately each 1.8 seconds of the test was also displayed. Any minus figures in the time column of the heart rate display indicated values of heart rate prior to the start of the sprint.

A hard copy of all the values displayed on the screen was also obtained.

Stride frequency was calculated using the unsmoothed force profile. The number of strides taken in each 5 second block of the sprint was counted from the profile. During the sprint the total number of strides taken was counted by an observer to check whether the total number of strides determined from the force profile was correct. The average stride length for each 5 second block was calculated from the total distance that the treadmill had moved by the number of strides taken.

9:1.2 RESULTS

The results from this study will be discussed in two parts. First an example from one of the subjects will be analysed and then the group data will be evaluated.

Table 9.1 and 9.2 shows an example of the printout obtained from one of the male subjects who was 24 years old and who weighed 64.5kg.

Each one second averaged value of speed, force and power is shown in a graphical form in Figure 9.1. Both peak force and power output occurred during the first second of the test, with peak speed being attained in the third second. The subject achieved 88% of his peak speed in the first second of the sprint. The arrow in this figure indicates the point at which power output had dropped to
Table 9.1 An example of the printout obtained from the 30s maximum intensity treadmill sprint.
### HEART RATE PROFILE

<table>
<thead>
<tr>
<th>TIME (S)</th>
<th>B.P.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>124</td>
</tr>
<tr>
<td>1</td>
<td>128</td>
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<tr>
<td>2.8</td>
<td>127</td>
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<td>130</td>
</tr>
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<td>6.5</td>
<td>136</td>
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<td>8.3</td>
<td>141</td>
</tr>
<tr>
<td>10.1</td>
<td>144</td>
</tr>
<tr>
<td>11.9</td>
<td>143</td>
</tr>
<tr>
<td>13.7</td>
<td>146</td>
</tr>
<tr>
<td>15.6</td>
<td>147</td>
</tr>
<tr>
<td>17.4</td>
<td>151</td>
</tr>
<tr>
<td>19.2</td>
<td>158</td>
</tr>
<tr>
<td>21</td>
<td>165</td>
</tr>
<tr>
<td>22.8</td>
<td>172</td>
</tr>
<tr>
<td>24.7</td>
<td>176</td>
</tr>
<tr>
<td>26.5</td>
<td>180</td>
</tr>
<tr>
<td>28.3</td>
<td>182</td>
</tr>
<tr>
<td>30.1</td>
<td>183</td>
</tr>
<tr>
<td>31.9</td>
<td>183</td>
</tr>
<tr>
<td>33.7</td>
<td>188</td>
</tr>
<tr>
<td>35.6</td>
<td>189</td>
</tr>
<tr>
<td>37.4</td>
<td>190</td>
</tr>
</tbody>
</table>

Table 9.2 An example of the Heart Rate printout obtained from the 30 second maximum treadmill sprint.
Figure 9.1 An example of the one second averaged values of force, speed and power for a 30 second maximal sprint on the treadmill. Data taken from Table 9.1.
Figure 9.2 The time course of power output and heart rate for a 30 second maximal sprint on the treadmill, for one subject.
half the peak value. This occurred approximately 20 seconds into the sprint.

Figure 9.2 shows the time course of power output and heart rate during the sprint. Whereas, maximum power output was achieved during the first second, heart rate rose steadily throughout the sprint, and continued to rise after the sprint had finished.

The force and torque profiles generated from the individual data points are shown in Figure 9.3. The data sampling rate was 40.5 Hz.

9:1.3 DISCUSSION OF THE RESULTS FROM THIS SUBJECT

The one second averaged data shown in Figure 9.1 has the same basic characteristics obtained for the 30 second maximal test performed on the friction-loaded cycle ergometer, and described in Chapter 4. It would appear at first glance that the expected sequential relationship for peak force and power, discussed in the review of literature, has not occurred here. Both peak force and peak power are shown to have been reached during the first second of the test. This reflects the very high rate at which the subject was able to accelerate the treadmill, achieving 88% of his maximum speed by the end of the first second. It is because of this very rapid acceleration that both peak power and speed were attained during the first second. When the averaging period was reduced from 1.0 to 0.2 seconds then peak force was found to occur 0.4 seconds into the sprint with a value of 261N, with peak power (1120W) occurring at 0.6 seconds. Thus the expected sequential relationship was observed. Figure 9.4 shows force, power and speed profiles for a second male subject who was unable to accelerate the treadmill as rapidly as the subject being discussed in this section. The variables in the figure are not displayed as absolute values, but are shown as percentages of maximum. Peak speed was
Figure 9.3 The force and power profiles (raw data) for the first 5s of a 30s maximal sprint on the treadmill, for one subject.
achieved in the 8th second of the test. Here the expected sequential relationship for peak force, power and speed is readily seen.

The time taken for power output to drop to half of the peak value was approximately 20 seconds. This result compares favourably with the results obtained for the cycle ergometer.

Careful examination of Table 9.1 and Figure 9.1 reveals that the subject finished sprinting prematurely. The profile shows a sudden downward trend for all three variables indicating that the subject had started to decelerate sometime during the 30th second of the test. This subject was asked to sprint again two days later so that his data could be used in the group results. The consequence of not completing the full 30 seconds is that the fatigue indices are disproportionally high, 70.6 and 31.4% for power and speed, respectively. When the subject repeated the test the corresponding values were found to be 59.1 and 28.0%, which are still very much higher than the group mean, shown later, reflecting the relatively large amount of work that the subject was able to do early on in the sprint.

After a slight initial fall, of one beat per minute, heart rate was found to rise steadily throughout the test and during the first few seconds of the subsequent recovery. The subject's maximum heart rate of 196 beats per minute, determined from an incremental motorised treadmill test, was not reached during the test period. One minute before the start of the test the subject's heart rate was approximately 90 beats per minute. Anticipation of the test caused an increase in heart rate to 124 beats per minute.

The force and power profiles shown in Figure 9.3 indicate that sprinting on the treadmill is very different from
Figure 9.4 The force, power output and speed profiles, calculated as a percentage of maximum, for one subject performing a maximal 30 second treadmill sprint.
pedalling on the cycle ergometer. The inter-stride variability seen in this figure was seen for all subjects, and it is this variability which is one of the major differences between the two types of ergometers. The variability reflects the greater requirement for co-ordination of movement on the treadmill. With the inertia of the treadmill being very much less than that of the body, and with the line of the centre of gravity falling in front of the mid-support point of the running stride, the treadmill seems to be 'running away', particularly during the initial acceleration phase of the sprint, making it difficult for the subjects to 'keep their feet'. Not only is the runner trying to propel the treadmill as quickly as possible but he is also trying to maintain a state of dynamic balance. The treadmill would need to have a greater mass to reduce this problem (as described in the previous chapter).

A second difference between the treadmill and the cycle ergometers is seen during the initial few seconds of the force profile. It has been shown in the previous chapter that the propulsive force does not drop to zero during the non-support phase of the running stride. This can also be seen in the force profile in Figure 9.3. Close examination of this profile shows that the base line of applied force is even higher during the first few strides of the sprint than for the remainder of the sprint. This was found for all the subjects and is probably caused by a combination of exaggerated forward lean during the initial acceleration, resulting in a greater component of bodyweight being applied to the tether, and increased energy storage in, and retrieval from, the elasticity of the system, resulting from the high propulsive values of applied force. If Figure 9.5, which is a computer/line printer plot of the applied force over the full 30 seconds of the sprint, is closely examined this increase in the baseline for the first few seconds of the sprint can be seen. What is also apparent from the figure is that the
Figure 9.5  Computer/line printer plot of the force generated by a subject during a 30 maximum treadmill sprint.
baseline continues to drift downward throughout the sprint, although not as rapidly as during the acceleration phase. A plot from another subject (Figure 9.6) shows this trend more clearly. This can be explained by either the subject running more and more upright as the sprint progresses or by a decline in the retrieved energy from the elasticity in the system resulting from less energy being stored per stride as the applied force declines. It is impossible from the data to determine which of these two possible solutions is correct. If the individual strides are examined then for those strides where a high peak force is applied to the tether a high baseline value usually follows. This might indicate support for the energy input/output theory for the elasticity in the system. The same result may also be interpreted to support the forward lean theory. It could be proposed that to generate the higher measured applied force the subject would have to lean further forward so as to shift the centre of gravity forward in order for correct acceleration of the body to take place.

The interpretation of the force profiles with increasing test duration is similar to that described for the cycle ergometer. From the force-velocity relationship of muscle, described in the literature review, a reciprocal relationship between force and velocity, would be expected. This appears to be the case. At the start of the sprint running velocity was low and high maximum force values were generated. As the treadmill was accelerated running speed increased and the maximum force that the subject could generate decreased. The time course was too short for the decline in force seen to be due exclusively to reduction in energy provision. Figure 9.1 shows that once peak speed was achieved running speed and average applied force declined at very similar rates. The decline in force production was due to the causes of fatigue discussed in chapter 2 and resulted in a decrease in both running speed and power output. As power output was
Figure 9.6 Computer/line printer plot of the force generated by a subject during a 30s maximum treadmill sprint.
calculated from the product of force and speed it is not surprising that the decline in power output was greater than that of either of its two components, once peak speed had been reached.

The large inter-stride variation in power and force seen in this study limits the value of using these individual stride values to describe performance, and indicate the complexity of movement co-ordination whilst sprinting on the treadmill. This difficulty stems mainly from the very low mass of the treadmill belt which allows rapid acceleration of the foot to take place during the contact phase of the running stride. Smoothing of the data over a number of strides is required, and the averaging time period of one second, used in this study has been found to give useful results.

9.1.4 RESULTS OF THE GROUP

[Table 9.3] shows the results for the males and females who took part in the study. The plot of the power output generated by the two groups of subjects is shown in [Figure 6.7]. There appears to be a discrepancy between the peak power output in the [Table] and that shown in the Figure, with the Figure showing the lower value. This apparent discrepancy is due to the fact that the time it took each subject to reach his or her peak power output was different. The time taken to reach peak power output from the start of the sprint averaged 3.7 seconds for the males and 4.1 seconds for the females. The males peak power outputs were approximately 177W higher than the females, which was significant (p<0.001). The slopes of the power output curves remain relatively parallel throughout the duration of the test resulting in similar levels of fatigue, 42.0 and 43.9% for the males and females, respectively. The mean power output over the test duration was found to be 549 and 395W for the males and females respectively, a difference of 154W.
<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Males: mean ±S.D.</th>
<th>Females: mean ±S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>peak</td>
<td>716 ± 93</td>
<td>539 ± 94</td>
</tr>
<tr>
<td>5</td>
<td>658 ± 91</td>
<td>491 ± 92</td>
</tr>
<tr>
<td>10</td>
<td>609 ± 93</td>
<td>452 ± 87</td>
</tr>
<tr>
<td>15</td>
<td>589 ± 82</td>
<td>431 ± 91</td>
</tr>
<tr>
<td>20</td>
<td>537 ± 104</td>
<td>369 ± 69</td>
</tr>
<tr>
<td>25</td>
<td>487 ± 77</td>
<td>330 ± 47</td>
</tr>
<tr>
<td>30</td>
<td>415 ± 89</td>
<td>302 ± 45</td>
</tr>
<tr>
<td>mean</td>
<td>549 ± 85</td>
<td>395 ± 77</td>
</tr>
</tbody>
</table>

| Fatigue Index | Males: 42.0 ± 7.9% | Females: 43.9 ± 6.7% |
| P.P.O./bodywt. | 9.97 ± 1.17    | 8.96 ± 1.57        |
| M.P.O./bodywt. | 7.64 ± 1.21    | 6.57 ± 1.28        |

| Peak speed (m.s⁻¹) | Males: 5.12 ± 0.46 | Females: 4.52 ± 0.37 |
| Time to peak speed (s) | 4.6 ± 1.2         | 5.3 ± 0.9          |
| Fatigue Index | Males: 22.1 ± 7.9% | Females: 17.1 ± 5.2% |

+diff.: males-females (p<0.01)

Table 9.3 A summary of the data from a 30s sprint on the treadmill for the whole group, showing peak power output for the whole group, showing peak power output and the power output at every 5th second of the test. The peak running speed attained is also shown (n=12, mean ±S.D.).
Figure 9.7 A plot of the power output generated by a group of males (n=6) and a group of females (n=6) during a 30 s maximum treadmill sprint (mean ±S.D.).
The difference in absolute peak and mean power output is not surprising as the males were on average 11.7kg heavier than the females and, therefore, had a greater muscle mass. In order to compare the relative strengths of the groups the power output values were expressed in relation to body weight. When power output was expressed in this way, although the males were found to produce the greater power per unit body weight the difference was found not to be significant. As body composition was not measured the power outputs could not be expressed per unit lean body mass.

A difference between the two groups was also found for running speed, shown in Figure 9.8. The peak speed of 5.12 m.s⁻¹ for the men was significantly (p<0.05) higher than the 4.52 m.s⁻¹ achieved by the females. The time taken by the males to reach peak speed was slightly shorter than for the females even though they had to accelerate the treadmill to a higher speed. As with the value of peak power output Figure 6.8 appears to underestimate peak running speed, due to the different accelerations achieved by each subject. The fatigue index for speed was less for the females than for the males, although the difference was not significant.

Comparison of the fatigue indices for power and speed reveals that the subjects are able to maintain speed very much better than they can power output. The differences in the indices are significant (p<0.001).

The heart rate response to the test for the group, shown in Figure 9.9 was very similar to that previously described for the male subject. After an initial fall the mean heart rate rose steadily until reaching a maximum approximately 5 seconds after the conclusion of the sprint.
Figure 9.8 A plot of the running speeds achieved by a group of males (n=6) and a group of females (n=6) during a 30s maximum treadmill sprint (mean ±S.D.).
Figure 9.9 The heart rate response of the whole group (n=12) to a 30 second maximum treadmill sprint (mean ±S.D.).
Stride frequency and length was examined for the group as a whole and the results are shown in Table 9.4 and Figure 9.10. The total number of strides counted by the observer and the corresponding value determined from the force trace was found to be the same. The average number of strides taken in each 5 seconds of the sprint was found to fall steadily with increasing duration of the exercise, with the fall becoming significant during the third block, i.e. after 11 seconds of sprinting. In contrast stride length was found to be shortest during the acceleration phase of the sprint. Maximum stride length was achieved during the second 5 second block falling slightly, but not significantly, thereafter.

9:1.5 DISCUSSION

The results of this study show that the sprint treadmill is a useful tool for the evaluation of human performance during sprint running. The treadmill was able to distinguish between the two groups for both power output and running speed. It was seen that absolute power output was greater for the males than for the females. This result is similar to that reported by Jacobs et al. (1983) for sprint cycling. The difference was found to due to the greater body mass of the male subjects. When power output was expressed per unit bodyweight, although the mean value for the males was still higher than for the females the difference was not significant. Had the results been expressed per unit lean body mass the differences may well have been even smaller. Although peak power per unit bodyweight was found not to be significantly different for the two groups the males achieved a significantly higher maximum running speed. This may well reflect the advantage that the heavier subjects have on the treadmill. This apparent difference was discussed in the previous chapter, and may also be one of the reasons why the males were able to accelerate the treadmill more rapidly than the females.
Figure 9.10 Stride frequency and stride length for the whole group (n=12) during a 30 second maximum treadmill sprint (mean ±S.D.).
<table>
<thead>
<tr>
<th>Time periods (s)</th>
<th>0 - 5</th>
<th>6-10</th>
<th>11-15</th>
<th>16-20</th>
<th>21-25</th>
<th>26-30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of strides</td>
<td>20.3</td>
<td>18.8</td>
<td>18.3</td>
<td>17.7</td>
<td>17.4</td>
<td>16.6</td>
</tr>
<tr>
<td>± S.D.</td>
<td>1.5</td>
<td>1.8</td>
<td>2.1</td>
<td>1.4</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Stride length (m)</td>
<td>1.29</td>
<td>1.40</td>
<td>1.33</td>
<td>1.32</td>
<td>1.29</td>
<td>1.32</td>
</tr>
<tr>
<td>± S.D.</td>
<td>0.08</td>
<td>0.12</td>
<td>0.12</td>
<td>0.11</td>
<td>0.10</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Significant at p<0.05 from a first & b second column.

Table 9.4 The number of strides taken and the average stride length for each 5 seconds of the 30s maximum sprint test (n=16, mean ±S.D.).
Figure 9.11 The force profile for one of the subjects for the first and last 8 seconds of a 30s maximum sprint on the treadmill. The magnitude of the peak values have also been shown with the numbers 1 and 2, to represent each leg.
Figure 9.12 The force profile for one of the subjects for the first and last 8 seconds of a 30s maximum sprint on the treadmill. The magnitude of the peak values have also been shown with the numbers 1 and 2, to represent each leg.
Figure 9.13 The force profile for one of the subjects for the first and last 8 seconds of a 30s maximum sprint on the treadmill. The magnitude of the peak values have also been shown with the numbers 1 and 2, to represent each leg.
Work in which the author collaborated but which has been reported elsewhere has shown that the sprint treadmill ergometer is sensitive to differences in performance, for a group of subjects, which has resulted from training. Not only is the sprint treadmill able to distinguish between males and females, as shown in this chapter, but it was shown to be able to distinguish between different groups of the same sex. For example, differences in performance were clearly measurable between a group of sprint trained and a group of endurance trained male athletes. These studies are fully reported by Cheetham (1987).

The treadmill was also found to be useful in examining the variations in the stride cycle during the course of a maximal test. The main factor influencing the decrease in running speed was stride frequency rather than stride length. This will be discussed in more detail in the next chapter.

\[9:2\] **ASYMetry of the Propulsive Forces**

Figures 9.11, 9.12 and 9.13 show the force profiles of three of the subjects for the first and last 10 seconds of the 30 second sprint on the treadmill. In order to assist with the interpretation of the figures they have been redrawn with the numbers 1 and 2 positioned to show the magnitude and timing of the peak value of the propulsive force achieved during a stride cycle. Each number indicates which leg generated the force, however, it was not possible to determine which leg was represented by which number.

The first profile (Figure 9.11) is a typical profile obtained from the majority of the subjects. The 1's and 2's are interspersed indicating no bilateral difference in the magnitude of the propulsive forces produced. Close examination of the second profile (Figure 9.12) shows that although no difference between the legs can be seen for
the first 10 seconds of the sprint there appears to be a marked difference between them for the last 10 seconds, with the 2's being always higher than the corresponding 1's. This indicates that the peak propulsive force generated during the running stride by leg 2 was greater than by leg 1. In the third profile (Figure 9.13) there appears to be a difference between the two legs from the start of the sprint, with leg 2 generating the greatest propulsive forces throughout the test. This difference between the legs became more pronounced with increasing test duration. Of the 12 subjects participating in the study bilateral differences in the peak propulsive forces produced could be easily distinguished for 5 of the subjects.

Several reasons may be postulated for those subjects who exhibited differences between the legs from the start of the test including:

a) bilateral strength imbalance;
b) bilateral differences in joint mobility;
c) bilateral differences in co-ordination;
d) bilateral differences in the force-velocity relationship of the muscles.

A differential rate of fatigue in the legs might be the cause of the differences observed in those subjects where bilateral differences did not appear until later on in the sprint.

These results not only re-inforce the findings that the system is able to detect each running stride but it also shows that the legs can be clearly differentiated. The majority of the subjects showed little difference between the legs for the peak values of the propulsive forces generated during the running stride. However, a few of the subjects did show differences either right from the start of the test or some time later. When asked some of the subjects who showed differences said that they felt
that one leg was stronger than the other. It should be noted that some of those subjects in which differences were not observed also stated that they felt that one leg was stronger than the other.

Although the treadmill has been shown to be sensitive to performance the total picture is still not complete. Three more pieces of information are still required:
1) How does a 30s maximum sprint on the treadmill compare with a 30s maximum cycle sprint?
2) How does treadmill sprinting compare with sprinting on the track?
3) Can the treadmill be used to examine performance in repeated sprints?

Examination of the peak running speeds achieved on the sprint treadmill reveals values that are significantly lower than those which would be expected from running on the track, although this is not an unexpected result in the light of the previous chapter. In order to be able to evaluate fully sprint performance using the treadmill the relationship between treadmill and track performance must be studied.
CHAPTER 10

COMPARISON OF PERFORMANCE ON THE SPRINT TREADMILL WITH PERFORMANCE ON THE CYCLE ERGOMETER AND RUNNING ON THE TRACK.

In this chapter the results of 3 studies will be reported. The first is a small study which compared maximum treadmill performance with maximum sprint cycling on the friction-loaded cycle ergometer. The second deals with a first attempt at comparing performance on the treadmill and the track. The third study also compares treadmill and track sprinting, using subjects that are good sprint athletes, and examines some of the performance characteristics in greater depth.

10:1 COMPARISON OF A 30 SECOND MAXIMUM SPRINT IN THE TREADMILL WITH THAT PERFORMED ON THE CYCLE ERGOMETER.

Twenty subjects (10 male and 10 female) volunteered to take part in this study. The characteristics of the group as a whole was (mean ±S.D.):
height 171.7 ±10.6 cm, weight 66.6 ±8.5 kg and age 29.4 ±9.2 years.
All the subjects were fully familiarised with sprinting on both the treadmill and the cycle ergometer during prior visits to the laboratory. Each subject was asked to complete a 30 second maximum sprint on the treadmill and the cycle ergometer on separate days with the order of the tests being randomised for each subject. Each subject fasted for a minimum of 4 hours prior to the tests, with each test being performed at approximately the same time of day, so as to avoid possible variations due to circadian rhythms.

The corrected method of calculation was used during the cycle test, as described in Chapter 8. On the sprint treadmill the external power output was calculated from the
product of the force applied to the transducer and the velocity of the belt, as described in chapter 6.

Prior to each test the relevant calibration procedures were followed and the subjects performed the same warm-up routines previously described for the 30 second tests. The saddle height on the cycle ergometer was set so that there was slight knee flexion at the bottom of the pedal cycle. Toe clips were used to stop the feet from slipping off the pedals. In both tests rolling starts were used which were 65 pedal r.p.m. and 2.2 m.s\(^{-1}\) for the cycle and treadmill ergometers, respectively.

In both tests external power output was expressed as an averaged figure with the averaging period being one second. On the cycle ergometer the load used was 75g.kg\(^{-1}\) bodyweight, as recommended by the Wingate protocol.

Comparisons were made between peak and mean external power output and the fatigue indices.

10:1.1 RESULTS

A summary of the results are shown in Table 10.1. Peak power output on the cycle ergometer was found to be approximately 46% higher than on the treadmill, the difference being significant (p<0.01). Figure 10.1 shows the individual relationships between peak values on the treadmill and cycle ergometer. A correlation of 0.78 was obtained for the whole group when the two values of peak power output were compared. When corresponding values of mean power output were compared the correlation rose slightly to 0.82. Figure 10.2 shows the individual data points obtained. The difference in mean external power output between the two ergometers was approximately 41%, which was also significant (p<0.01).

No significant difference was found between the two ergometers for the power fatigue index or for the time to
Table 10.1 Comparison of peak and mean power output, fatigue index and time to peak power output between the 30s maximum sprint tests performed on the sprint treadmill and the cycle ergometer (n=20, mean ±S.D.).

<table>
<thead>
<tr>
<th></th>
<th>Ergometer</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Treadmill</td>
<td>Cycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>mean ±S.D.</td>
<td>mean ±S.D.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak power (W)</td>
<td>601 ±116</td>
<td>875 ±161+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean power (W)</td>
<td>378 ±62</td>
<td>532 ±74+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue Index (%)</td>
<td>44.3 ±9.2</td>
<td>46.5 ±14.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to peak (s)</td>
<td>1.67 ±0.77</td>
<td>1.56 ±0.69</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

+sign. diff. (p 0.01)
Figure 10.1 The relationship between peak power output on the treadmill and peak power output on the cycle ergometer (n=20).
Figure 10.2 The relationship between mean power output on the treadmill and mean power output on the cycle ergometer (n=20).
10:1.2 DISCUSSION

There was a significant difference found between the absolute values of peak and mean power output. This result was not unexpected as only a proportion of the external power applied to the treadmill is being measured. The difference is further enhanced by the lack of load optimisation on the treadmill. The load used on the cycle ergometer has been shown to be one which produces near optimal values of peak and mean power output. There is at present no method of varying the characteristics of the treadmill so that optimal conditions are obtained for external power production. Other than the absolute values of external power output the other variables measured, namely fatigue and time to peak power output, showed no difference.

The results in total are very encouraging. The relationship between the two ergometers are good. Although perfect correlations between the two ergometers was not obtained the correlation coefficients obtained showed that, in general, those who generated most power on the treadmill were also those who had the highest power output on the cycle ergometer. Some variability had been expected. Had perfect correlation coefficients been obtained then the weight supported activity of cycling could be used to fully describe running. The somatotype of the subject, particularly the endomorphic component, will affect performance in running more than during cycling. In addition different muscles are being used in the two activities.

The value that would be expected to be very similar for the two ergometers is the time to peak power. This should be independent of the activity as long as the activity is maximal and the system free to accelerate. No difference was found between the ergometers.
10:2 COMPARISON OF TREADMILL AND TRACK PERFORMANCE.

In order to investigate how performance on the sprint treadmill compares to that when running untethered on the track two comparative studies were set up. The first, described below, was effectively a pilot study which used subjects with a wide range of somatotypes. In this study only running velocity data was obtained from the track, which was compared with the performance data from the treadmill.

10:2.1 METHOD

14 subjects (8 male, 6 female) participated in the study. Each subject was asked to perform a 30 second sprint on the non-motorised treadmill and a 200m sprint on the track. In a pilot study it was found that the subjects would take approximately 30s to run the 200m on the track. In both sprints the subjects were asked to run at maximal speed from the start command and to maintain maximum effort throughout the sprint. The subjects were constantly encouraged during both tests. The order of the tests was randomised.

All the subjects were fully familiarised with running on the non-motorised treadmill during three visits to the laboratory prior to the start of the tests.

Before each test the subjects followed a similar warm-up procedure consisting of one minute of jogging followed by 5 minutes of stretching. On the treadmill the warm-up followed the standard format already described. For each test the preset resistance of the treadmill was established as described previously.

On the track a stationary start was used and the time taken to run the 200m was determined using a hand-held
stopwatch. The subjects started at the 200m mark on the track ending at the finish line and ran in the inside lane. A marker was placed at the side of the track 50m from the start line and the split time for the first 50m of the sprint was also recorded on the stopwatch. Mean running speeds for the first 50m and the entire 200m was calculated from these times.

On the treadmill the usual rolling start described previously, of 2.2m/s\(^{-1}\), was used.

10:2.2 RESULTS

Table 10.2 shows some of the correlations obtained between measured performance variables. The mean time taken to run 200m on the track was found to be 30.23s. If the running speed is assumed to be constant throughout the sprint then the mean distance that would have been run in exactly 30s would have been 198.5m. The corresponding mean distance run on the treadmill was 157.9m which is an average of 79.6% of the distance achieved on the track. The average running speed on the treadmill was, therefore, also 79.6% that on the track.

One of the highest correlations (r=0.83) was obtained when the distance run on the treadmill was compared with 200m speed on the track. The 200m speed also directly represents the calculated distance covered on the track in 30 seconds. The highest correlation (r=0.84) was obtained when 200m speed/30s distance was compared to mean power output on the treadmill. This correlation was reduced to 0.74 when mean power output relative to body weight was substituted for absolute mean power output. When peak speed on the track, measured over the first 50m of the sprint, was compared to the peak speed on the treadmill, 1 second average value, a correlation of only 0.67 was obtained. A higher correlation of 0.75 was calculated when 200m speed was substituted for 50m speed.
Table 10.2 Some of the correlations obtained between measured performance variables on the treadmill and the track.

<table>
<thead>
<tr>
<th>TREADMILL</th>
<th>TRACK</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak speed (1s)</td>
<td>50m speed</td>
<td>0.67</td>
</tr>
<tr>
<td>Distance run (30s)</td>
<td>50m speed</td>
<td>0.71</td>
</tr>
<tr>
<td>Peak power/bodyweight</td>
<td>50m speed</td>
<td>0.52</td>
</tr>
<tr>
<td>Mean power/bodyweight</td>
<td>50m speed</td>
<td>0.63</td>
</tr>
<tr>
<td>Peak speed (1s)</td>
<td>200m speed</td>
<td>0.75</td>
</tr>
<tr>
<td>Distance run (30s)</td>
<td>200m speed</td>
<td>0.83</td>
</tr>
<tr>
<td>Peak power/bodyweight</td>
<td>200m speed</td>
<td>0.65</td>
</tr>
<tr>
<td>Mean power/bodyweight</td>
<td>200m speed</td>
<td>0.74</td>
</tr>
<tr>
<td>Peak power (1s)</td>
<td>200m speed</td>
<td>0.65</td>
</tr>
<tr>
<td>Mean power (30s)</td>
<td>200m speed</td>
<td>0.84</td>
</tr>
</tbody>
</table>

( ) averaging period Group mean 200m time = 30.3s
10:2.3 DISCUSSION

In general those people who performed best on the treadmill also achieved the best results on the track, however, at best only 71% of the variance was accounted for in the correlations. The best correlation was obtained when mean treadmill power output was compared to 200m track speed. This is not a surprising result. Mean power output is less sensitive to variations in the treadmill characteristics, resulting from the relationship between belt friction and bodyweight, than running speed. An increase in friction will reduce running speed, however, the force generated during the stride will increase due to this lower speed of contraction and, therefore, as power output is calculated from the product of speed and force mean power output will be maintained. When mean power relative to bodyweight was correlated with 200m running speed a correlation of 0.74 was calculated. Those subjects who could generate the highest power output per unit bodyweight ran the furthest. A higher correlation would be expected between these variables. It is possibly surprising that such a good correlation (r=0.83) was obtained when mean running speed on the treadmill (distance run in 30s) was compared to 200m running speed. This is possibly due to the wide range of abilities of the subjects used, which artificially improved the correlation obtained. Peak running speed on the treadmill and track was relatively poorly correlated (r=0.67). This may have been due to the difference in averaging period used and the error in the hand timing over the 50m distance on the track.

Of particular interest are the results obtained for relative sprinting speeds. The mean running speeds on the treadmill were found to be approximately 79.6% that achieved on the track (5.26 ±0.48 -v- 6.63 ±0.62 m.s⁻¹). It was found in chapter 5 that the running speed on the
sprint treadmill was approximately 68% of the running speed on the motorised treadmill, for the same rate of oxygen uptake. These values indicate that running on the treadmill is between 26 and 47% harder on the treadmill than on the track or motorised treadmill.

The correlations obtained between performance parameters showed that track performance could be reasonable well predicted from treadmill performance. The subjects used had a wide range of sprinting ability. This will have the effect of increasing the degree of correlation obtained. A study was, therefore, set up to discover whether track performance could be predicted from the treadmill for sprint trained subjects of similar performance capabilities. In this study additional variables were examined including stride length and stride rate.

10.2.4 METHOD

The personal characteristics of the 7 male subjects who took part in this study are shown in Table 10.3. All the subjects were club standard sprinters or sprint hurdlers, with their event best times also shown in the table.

Each subject performed two 30 second sprints, one on the treadmill and one on the track. In all the tests the athletes ran at maximum pace from the start of the test and did not pace themselves as they would in a race.

As none of the athletes had run on the sprint treadmill prior to this study each was required to visit the laboratory on three occasions before attempting the first test so as to be fully familiarised with running on the treadmill.

Prior to each test the subject performed a similar warm-up procedure, ensuring standardisation of the pre-test physiological status.
<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yrs)</th>
<th>Weight (kg)</th>
<th>Height (cm)</th>
<th>Event</th>
<th>Best Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.7</td>
<td>62.6</td>
<td>167.7</td>
<td>100m</td>
<td>10.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200m</td>
<td>20.97</td>
</tr>
<tr>
<td>2</td>
<td>19.1</td>
<td>62.7</td>
<td>174.8</td>
<td>100m</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200m</td>
<td>21.2</td>
</tr>
<tr>
<td>3</td>
<td>18.6</td>
<td>68.9</td>
<td>178.1</td>
<td>200m</td>
<td>22.3</td>
</tr>
<tr>
<td>4</td>
<td>23.4</td>
<td>73.6</td>
<td>175.0</td>
<td>100m</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200m</td>
<td>21.4</td>
</tr>
<tr>
<td>5</td>
<td>22.0</td>
<td>85.3</td>
<td>183.8</td>
<td>110mH</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>400mH</td>
<td>53.7</td>
</tr>
<tr>
<td>6</td>
<td>32.2</td>
<td>83.5</td>
<td>184.7</td>
<td>100m</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>400m</td>
<td>50.9</td>
</tr>
<tr>
<td>7</td>
<td>22.2</td>
<td>82.1</td>
<td>187.9</td>
<td>110mH</td>
<td>15.5</td>
</tr>
<tr>
<td>mean</td>
<td>22.6</td>
<td>74.1</td>
<td>178.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S.D.</td>
<td>4.6</td>
<td>9.7</td>
<td>7.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 10.3 The personal characteristics and best performances of the 7 male subjects who took part in the study.
Just before the start of each test a thumb-prick blood sample was taken after the hand had been held in warm water for three minutes. For each subject duplicate 25ul were collected, frozen and stored at -20° for later analysis.

**TREADMILL PERFORMANCE TEST**

A video camera was positioned so that the number of strides taken during the test could be monitored so that stride frequency could be calculated.

The subject jogged at 2.5 m.s⁻¹ and on the command "GO" sprinted maximally for 30 seconds. Each subject was verbally encouraged throughout the test and was informed of the elapsed time at 10 and 20 seconds.

At the end of the 30 seconds the subject was helped onto a nearby couch. During the recovery the hand was re-warmed and a post-test blood sample was taken five minutes after the end of the sprint.

Throughout the test and during the five minute recovery period heart rate was monitored by the computer.

During the test the computer monitored applied force and treadmill belt speed as described in the previous chapter. At the conclusion of the test the computer calculated, displayed and printed out the performance characteristics.

**TRACK PERFORMANCE TEST**

Prior to the test session cones were placed around the inner edge of the track at 40, 91, 136, 183, 220 metres from the start line which was drawn 256 metres from the finish line. These distances were based on the study by Thomson (1981) in which it was estimated that the athletes
would pass a cone approximately every 5 seconds, enabling split values to be calculated which could be compared to performance values generated on the sprint treadmill.

A tripod mounted video camera was positioned in the middle of the track. During the test the camera was panned round to follow the progress of the runner.

Two timekeepers were used in the test. The first noted the point reached on the track by the subject at the conclusion of 30 seconds. The second used a split timer to note the time splits between the cones.

The subject started by jogging up to the start line at a speed similar to that used on the treadmill. On reaching the line the experimenter shouted go and the athlete started his flat out sprint and the timers started their watches.

At the conclusion of the sprint the subject was seated and a hand placed in warm water. Two 25ul blood samples were taken at the conclusion of 5 minutes recovery as described above.

DETERMINATION OF BLOOD LACTATE AND BLOOD GLUCOSE CONCENTRATIONS

BLOOD LACTATE

Each duplicate 25ul blood samples was put into 250ul of 2.5% Perchloric Acid to deproteinise the sample. The sample was then centrifuged and the supinate analysed.

25ul of the supinate was added to 250ul of reaction mixture in fluorimeter tubes. The reaction mixture consisted of:
(i) 0.25 ml of Hydrazene buffer;
(ii) 2mg of Nicotinamide Adeninedinucleotide (NAD) for
each ml of Hydrazene buffer;  
(iii) 10μl of lactate dehydrogenase (LDH) for each ml of 
Hydrazene buffer. 
The supinate/reaction mixture was mixed using a whirly mix 
and left to incubate at room temperature for half an hour. 
After this period the fluorescence was read off using a 
fluorimeter and was then compared with known standards to 
determine lactate concentration.

BLOOD GLUCOSE

1 ml of Glucose Oxidase Reagent was added to 20μl of 
supinate. The samples were then left to incubate at room 
temperature for 20 minutes. The concentration was then 
read off a photometer and then compared to a glucose 
standard to produce the final values.

ANALYSIS OF THE VIDEO RECORDINGS

The video recordings obtained were analysed on a "U.Matic" video recorder which had both slow motion and still frame 
capability. The camera frame speed was 25 per second. The 
thirty second test was split into three 10 second blocks 
using the frame counter (each 10 second block was 250 
frames). The number of strides taken in each block was 
counted.

10:2.5 RESULTS

Table 10.4 summarises the performance data obtained from 
both the treadmill and track tests. The values of the 
coefficients resulting from correlating the corresponding 
treadmill and track values, as well as whether these 
values were significantly different, are also shown in 
this table. Although the distance run on the track was 
significantly (p<0.001) further than on the treadmill, 
resulting from faster peak, mean and minimum running 
speeds, the total number of strides taken were not
Table 10.4 A summary of the performance data from the 30 seconds maximum treadmill and track sprints (n=7, mean ±S.D.).
different. The average stride length was calculated by dividing the total distance run by the number of strides taken. A significant difference (p<0.01) was found between the stride length on the treadmill when compared with that on the track, with the track values being approximately 28% longer.

The drop in running velocity, defined as the percentage difference between peak and minimum running speeds, was very much greater (p<0.01) on the treadmill than on the track.

The most important performance correlation is that of the distance run in 30 seconds on the treadmill and on the track for which an r value of 0.75 was calculated.

Table 10.5 and Figure 10.3 show a more detailed breakdown of several of the performance values examined during the tests. Although the cones on the track were positioned so one would be passed by the athlete approximately every 5 seconds and, therefore, each second sone approximately every 10 seconds, the actual mean split times for each second cone were 10.70, 11.37 and 7.96 seconds, respectively. The performance values obtained during these periods were compared to those measured during the corresponding three 10 second splits on the treadmill.

The fastest average running velocity was measured during the first 10 seconds for both the treadmill and the track with a decline in velocity over the remaining time intervals. Figure 10.2 shows the speed profile for every 5 second time split on the treadmill and the track. It can be seen that the fastest average running speed was achieved during the second 5 second time interval. All the values of the track running velocities were faster than the treadmill values (p<0.001).
Table 10.5 A detailed breakdown of average running speed, stride length and stride rate for each ten seconds of the 30s maximum treadmill and track sprints (n=7, mean ±S.D.).
Figure 10.3 The speed profile averaged over every 5 seconds of a maximum sprint on the treadmill and on the track (n=7).
On the treadmill greatest stride length was attained during the second 10 second interval. On the track, however, no significant difference was found between the average stride lengths measured for the first two time splits. By the third time split the stride length was found to have shortened (p<0.01). Again all the values of stride length on the track were greater than on the treadmill (p<0.01). Although there was no difference in the mean stride rate over the entire 30 seconds, differences were found when the time splits were examined. Whereas, the stride rate on the track remained fairly constant, with the highest value achieved during the first 10 seconds, on the treadmill the athletes showed a steady decrease in stride rate with time. The highest value on the treadmill was faster than that on the track and the lowest slower (p<0.01).

No significant difference was found between the track and treadmill values for the pre-test or post-test values for the concentrations of either blood lactate or blood glucose, as shown in Table 10.6 and Figure 10.4. The post-test concentrations of both blood lactate and glucose were found to be significantly (p<0.01) greater than the pre-test values. Blood lactate concentration showed an average 800% increase with blood glucose concentration increasing by approximately 50%.

The total number of strides taken during the treadmill test was counted using the video and was found to be identical with the number calculated from both the force and the speed profiles generated by the test computer, reinforcing the findings of the study described in the previous chapter.
Table 10.6 Comparison of pre- and post-test values of blood lactate and blood glucose between the treadmill and track 30s maximum sprints (n=7, mean ±S.D.).
Figure 10.4 The pre- and post-test values of blood lactate and glucose concentrations for both the treadmill and the track (mean ±S.D., n=7).
10.2.6 DISCUSSION

Despite the fact that the group investigated in this study was more closely matched than in the previous study the level of correlation between treadmill and track performance remained high, dropping from 0.83 to 0.75. Close investigation of the results reveals that one of the reasons for this drop is the level of correlation. Earlier in this chapter mention was made of the advantage that the heavier runner had on the treadmill due to the resistance of the treadmill not being zero when it was not loaded. The range of the weights of the athletes was quite large, 62.6 to 85.3 kg. A higher correlation was obtained between average velocity (or distance run) and bodyweight on the treadmill than on the track indicating that it is the inter-individual weight differences which is slightly skewing the data. Nevertheless, a correlation of 0.75 for such a small group indicates that the sprint treadmill can be used as a predictor of track performance, especially if bodyweight is accounted for.

It is of interest to note that the mean running speed on the treadmill is approximately 75% of that achieved by the athletes on the track. Earlier in this chapter a study was described which investigated the oxygen cost of running on the treadmill compared to running on a motorised treadmill. It was reported that to run at the same oxygen cost the subjects ran at approximately 68% of the motorised treadmill speed on the sprint treadmill. This value is similar to the 75% value obtained for mean sprinting speed and indicates that it is harder by almost a third to run on the sprint treadmill than to run untethered. A more subtle examination of the results of the present study indicates that the effect of the resistance of the treadmill increases with test duration. The mean peak velocity achieved on the treadmill was approximately 78% of that reached on the track. By the third time split, however, running speed on the treadmill had dropped to only 66% of
the corresponding track value. The resulting decrement in running speed on the treadmill was 26.7% compared with only 16.7% on the track. Examination of the stride rates on the treadmill and track show how the athletes were able to achieve the high proportion of the track peak running speed despite the resistance of the treadmill. In order to minimise the deceleration of the treadmill which occurs during the flight phase of the running stride, the time that the foot is not in contact with the treadmill should be kept as short as possible. From Table 10.5 it is clear that the athletes achieved this by significantly changing their stride pattern. During the first 10 seconds of the test not only did the athletes shorten their stride length by almost 24% but they also increased their stride rate by approximately 2%. These modifications to the running stride will result in the desired reduction in the time of the flight phase, but almost certainly at the cost of decreased efficiency. As fatigue set in the athletes were, however, unable to maintain stride rate, on the treadmill, which was reduced by approximately 14% by the third time interval.

The modifications in the running pattern described above are not as a result of a conscious decision by the athlete but are as a result of several factors that have been imposed on the athlete by the treadmill:

1) Forward lean. Earlier in this chapter the results of a study which examined the extent that the subjects leaned forward when running on the treadmill were reported. It was found that the forward lean was significant and as a result the running stride will be restricted. This restriction would almost certainly result in a shortened stride length and would account for some of the change in stride length reported in this study.

2) Momentum of the treadmill. The moving mass of the treadmill is very much less than that of the subject. If it is assumed that the subject applies the same force to the
belt, during the initial part of the acceleration phase of the running stride, that he applies to the track then from

\[ \text{FORCE} = \text{MASS} \times \text{ACCELERATION} \]

It can clearly be seen that the acceleration of the treadmill belt will be very much greater than that of the body. In the previous chapters we have discussed the force velocity relationship for human muscle which we know to be non-linear. As the treadmill belt is being accelerated, i.e. the belt velocity is increasing, the force that is being applied to move the belt must be decreasing. The rate of the decrement in this propulsive force must be greater for the treadmill than for the untethered subject due to the smaller mass. This difference in the pattern of force application will result in a modification in the stride pattern.

Centre of gravity. It was noted, in a previous section of this chapter, that the centre of gravity of the runner remained below the level of the standing centre of gravity. This is not a finding that has been reported for free running and this reduction in the vertical component of the running stride will modify the stride pattern, and in particular will reduce the length of the flight phase.

Although the performances on the treadmill were different from those on the track the physiological demands placed on the athletes were found to be very similar. The end product of anaerobic glycolysis is lactic acid. The greater the energy provision from this metabolic pathway the higher will be the concentration of muscle lactate at the termination of exercise and, after diffusion has taken place, the greater will be concentration of blood lactate. If the diffusion rate for a given subject is assumed to be the same for the two tests, and if the time at which the blood sample is taken is standardised then the concentration of blood lactate will represent the
comparable extent to which anaerobic glycolysis was taxed. Peak blood lactate concentration, following 30 seconds maximal cycling, has been shown to occur at approximately 5 minutes post exercise (MacDonald et al. 1983, Wootton, 1984). Based on these findings blood samples were taken for analysis 5 minutes after the conclusion of the tests. The results show that there was no significant difference between the treadmill and the track test for both pre- and post-test concentrations of blood lactate and, therefore, the elevation in concentration was the same for both tests. The finding of no difference between the post-test levels of blood lactate was not artificially created by a large standard deviation. The very high correlation of 0.95 between the track and treadmill values shows that the statistical lack of difference is a 'true' finding. Although the contribution of both aerobic metabolism and the degradation of high energy phosphate stores was not measured it would appear that the athletes found the treadmill and the track tests equally taxing. Further evidence supporting this claim can be obtained from the measurements of blood glucose concentration. The changes in blood glucose concentrations were considerable when one considers that the athletes were only sprinting for 30 seconds. These changes may reflect the maximal rate of working during the tests and are influenced by the increase in catecholamine concentration that such exercise induces (MacDonald et al. 1983, Brooks et al. 1984). Although the changes are large no significant differences were found between corresponding treadmill and track values. Once again a good correlation (0.65) was found between the post-test values supporting the validity of this finding. The combined evidence from the blood lactate and glucose findings support the statement that the demands placed upon the systems providing energy were very similar for the treadmill and the track tests.
CHAPTER 11

USE OF THE SPRINT TREADMILL FOR EXAMINING REPEATED SPRINTS.

In Chapter 5 it was shown that the cycle ergometer is a very useful tool for investigating the power output in repeated sprint activities. This chapter will examine whether the sprint ergometer can be used to evaluate performance in repeated sprint running.

11:1.1 METHOD

12 highly trained male athletes were asked to perform ten 6 second maximal sprints on the treadmill, with a 30 seconds recovery period between each sprint. The height, weight and age of the subjects was (mean ±S.D.) 178.8 ±5.8 cm, 76.7 ±5.2 kg, and 22.7 ±1.8 years, respectively.

Each subject was familiarised on the treadmill in the morning and participated in the test in the afternoon. All the tests were completed in one day.

Prior to the first sprint of every test the treadmill was warmed up to until a pre-set value of resistance was attained, as described in Chapter 7. Each sprint was performed from a rolling start of 2.2m.s⁻¹. The subjects were asked to perform maximally during each sprint, and were encouraged to do so throughout the test. Heart rate, determined using a Rigel 302 Cardiac Monitor, was constantly monitored by the computer.

5 minutes before the first test two 30s submaximal runs were performed on the treadmill at 10 and 12 k.p.h. which served both to warm-up the subjects and to reaccustom them with the experimental procedure.
The data from each sprint was recorded on disc. At the end of the last sprint the data was recalled from the disc and analysed by the computer. Peak and mean power output attained during each sprint was calculated, with peak power output being the highest 1 second averaged value achieved during each sprint. In addition the distance that the treadmill belt was moved during each sprint was determined. This value is referred to as distance run and is equivalent to the mean running speed.

Prior to the tests the speed and force calibration factors were determined, as described in Chapter 7, and stored on disc for automatic retrieval by the computer.

Capillary blood samples were taken in duplicate at 4 minutes after the warm-up and at 1 minute after the repeated sprint test. The samples were deproteinised, frozen at -20°C and analysed at a later date for blood lactate concentration as described by Maughan (1982).

\[\text{RESULTS}\]

The results for peak and mean power output and distance run for each sprint are shown in Table 11.1 and Figure 11.1.

The highest mean value for all three variables was achieved in the second sprint. When subsequent values were compared with the second sprint significant (p<0.05) decrement in performance was found by the 4th (p<0.05) and the 3rd (p<0.001) sprint for peak and mean power output, respectively, and by the 3rd sprint (p<0.01) for the distance run.

Figure 11.2 shows peak and mean power output and distance run expressed as a percentage of the 2nd sprint. The three variables show different rates of decline. Mean power
<table>
<thead>
<tr>
<th>Sprint number</th>
<th>Peak power output (W)</th>
<th>Mean power output (W)</th>
<th>Distance run (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean ±S.D.</td>
<td>mean ±S.D.</td>
<td>mean ± S.D.</td>
</tr>
<tr>
<td>1</td>
<td>832.9  72.5</td>
<td>709.7  71.9</td>
<td>37.3  1.36</td>
</tr>
<tr>
<td>2</td>
<td>842.0  102.2</td>
<td>717.9  59.0</td>
<td>37.86 1.21</td>
</tr>
<tr>
<td>3</td>
<td>814.0  84.3</td>
<td>693.1  64.4</td>
<td>37.37 1.28</td>
</tr>
<tr>
<td>4</td>
<td>808.0  57.9</td>
<td>676.7  56.9</td>
<td>37.21 1.28</td>
</tr>
<tr>
<td>5</td>
<td>784.0  89.4</td>
<td>654.3  61.6</td>
<td>36.84 1.57</td>
</tr>
<tr>
<td>6</td>
<td>782.2  93.9</td>
<td>650.9  59.1</td>
<td>36.78 1.44</td>
</tr>
<tr>
<td>7</td>
<td>769.7  63.5</td>
<td>640.4  53.6</td>
<td>36.60 1.34</td>
</tr>
<tr>
<td>8</td>
<td>773.9  72.0</td>
<td>626.1  55.3</td>
<td>36.36 1.40</td>
</tr>
<tr>
<td>9</td>
<td>766.6  92.6</td>
<td>620.4  60.3</td>
<td>36.27 1.50</td>
</tr>
<tr>
<td>10</td>
<td>750.4  86.7</td>
<td>608.3  55.3</td>
<td>36.03 1.41</td>
</tr>
</tbody>
</table>

Table 11.1 The results for peak and mean power output and distance run for each 6 second sprint performed on the treadmill, with a 30 second recovery period between sprints (n=12, mean ±S.D.).
Figure 11.1 The mean and peak power output and distance run for each 6 second sprint (mean ±S.D., n=12).
Figure 11.2 Peak and mean power output and distance run expressed as a percentage of the best performance for each 6s sprint (mean values only, n=12).
output can be seen to decline most rapidly with the distance run being the variable best maintained.

Blood lactate levels were only very slightly elevated as a consequence of the warm-up with a mean (±S.D.) concentration of 1.29 (+0.42) mM being measured. One minute after the tenth sprint the concentration of blood lactate was significantly (p<0.001) elevated to 15.33 (+1.57) mM, a mean increase of 14.04 mM. When both absolute and change in blood lactate concentration was correlated with mean power output over the ten sprints a correlation of less than 0.1 was obtained, i.e. the variables were not correlated. Figure 11.5 shows a plot of change in blood lactate with mean power output over the ten sprints expressed per unit body weight. A poor correlation of 0.47 was obtained. This correlation was slightly reduced to 0.41 when absolute post exercise values were substituted for the delta values.

Peak values of heart rate for each sprint were achieved at approximately 18 seconds into the recovery period between sprints, with maximum heart rate being reached between sprint 5 and 6. Two examples of heart rate profiles, from two different subjects, are shown in Figures 11.4 and 11.5. To aid clarity profiles from sprints 6 to 9 have been omitted as they are difficult to differentiate from sprints 5 and 10. Careful examination of the profiles reveals that heart rate decreased during the sprint except for sprint one. This was true for all the subjects. During the first sprint a dip in heart rate at the beginning of the sprint can be seen.

At the beginning of the first sprint the mean heart rate was 134 (+11) which was significantly elevated (p<0.01) above the 89 (+9) seen 2 minutes before the start of the sprint, i.e. approximately 2 minutes post warm-up.
Figure 11.3 Relationship between the change in blood lactate concentration, measured 1 minute after the final sprint, and the average power output expressed per unit body weight (n=12).
Figure 11.4 Heart rate profile of one subject performing ten 6 second sprints with 30 seconds recovery between sprints.
Figure 11.5 Heart rate profile of one subject performing ten 6 second sprints with 30 seconds recovery between sprints.
11:1.3 DISCUSSION

Both peak and mean power outputs were significantly lower than the corresponding results from repeated sprints on the cycle ergometer described in Chapter 5 despite the fact the subjects in the present study were very much larger and more highly trained. This is the result that would be expected as, as has been previously discussed, the treadmill does not measure the total external power output of the subject but merely the 'propulsive component'. The decline in both peak and mean power output, 11.0 and 15.3%, respectively, are also less than those measured for the repeated cycle ergometer tests. The drop in performance over the 10 sprints in this study is similar to that seen after only 6 cycle sprints. Had the total work done in the 6 second sprint been able to be measured, the value obtained may still have been less than that which the subjects could have done on the load-optimised cycle ergometer. The higher work output would cause greater fatigue on the cycle ergometer and would, therefore, explain the lesser decline in performance seen in the present study for the sprint treadmill.

The variable which showed least decrement over the 10 sprints was the distance run. As the computer is calculating power output from the instantaneous product of applied force and treadmill speed then as running speed does not appear to be declining then there must be a large drop in applied force to account for the greater drop in power output. It is not possible to fully explain this mismatch between distance run and applied force with the data obtained in this study. It is possible that the subjects improved their running stride efficiency with increasing fatigue. It may be that during the first sprints efficiency is not important to the subject, in his pursuit of speed, as energy provision is not limited. Once fatigue has set in the subject may be modifying the
running stride to optimise performance. Further examination of this is necessary. A second possible reason for the mismatch in force and running speed may be that during the course of the repeated sprints the treadmill is warming up. If this is occurring then the rolling resistance of the treadmill might be decreasing resulting in less applied force being required to accelerate the treadmill. Although the percentage fall in distance run was small, about 4.8%, this fall represents just over 1.9m over 40m, which may well significantly affect the outcome of a competitive event.

The stressful nature of the exercise is shown by the high elevation in blood lactate. This increase indicates that a large contribution to energy provision is being made by anaerobic glycolysis. As was discussed in the review of energy systems in Chapter 2 the elevated concentration of the hydrogen ion will be one of the causes of the measured fatigue as it both inhibits energy provision and interferes with the contractile mechanism itself (Hermansen, 1981). Another cause of the fatigue will be the drop in CP stores shown to occur in maximal cycling exercise (Boobis et al., 1982). Both the absolute levels of blood lactate following the sprints and the change in blood lactate concentration resulting from the sprints were found to be poorly correlated with the averaged mean power output expressed per unit body weight. Taking a measurement of blood lactate after the last sprint does not allow determination of the relative rates of production and uptake of lactate for each sprint, which will be different for each subject. The net effect is to add a great deal of noise to the system resulting in the poor correlation obtained.

The drop in heart rate seen at the beginning of each sprint could be caused by:

a) an increased intrathoracic pressure resulting from breath holding which would affect the cardiac output
(Hamilton et al., 1944);

b) a significant increase in the venous return, resulting in a greater pre-filling of the heart.

c) a drop in the peripheral resistance.

In a study by the author, not reported here, the question of whether the subjects breathed during treadmill sprinting was examined. A new breath-by-breath ventilation measuring system was developed into which the subjects breathed via a lightweight mouthpiece and tubing. Although some of the subjects examined were found to breathhold the majority did not. All the subjects showed the drop in heart rate seen in the present study and, therefore, breathholding can be discounted as the cause. Further investigation is needed to determine the actual cause but it is proposed that it is probably due to enhanced venous return resulting from the start of activity. It is of interest to note that entrainment of the breathing cycle was found to occur in sprinting activities as short as 6 seconds.

The magnitude of the dip seen in the heart rate profiles is probably underestimated. Although the actual step response of the monitor is not known it has a significant signal damping. The monitor operates by continuous averaging of the time interval between successive QRS complexes, resulting in a delay to a step change in the applied signal. The monitor is designed to follow gradual changes in heart rate. The fall in the heart rate seen in this study is quite rapid and must have been as a result of a larger actual change in heart rate, possibly even due to a momentary pause in the heart beat.

Further work, not reported in this thesis, has shown that the sprint treadmill is sensitive to changes in performance due to training (Cheetham, 1987). Within 8 weeks of sprint training, peak and mean power output values, as well as mean running speed per sprint, were
found to increase. As described for the cycle ergometer the fatigue between the first and last sprint was found to have increased with training despite, or in fact as a result of, an improvement in performance.

The present study shows that the sprint treadmill is a very useful tool for evaluating multiple sprint performance, and the associated causes of fatigue. Future work on the sprint treadmill should include the development of a repeated sprint test in which the subjects perform a fixed amount of work, rather than working for a fixed time interval, similar to that described in Chapter 5 for the cycle ergometer.
HAS THE SPRINT TREADMILL ERGOMETER BEEN SHOWN TO BE A USEFUL TOOL FOR MEASURING PERFORMANCE AND POWER OUTPUT DURING SPRINT RUNNING IN THE LABORATORY ENVIRONMENT?

The short answer to this question is YES, but not with the same level of precision that was found for the friction-loaded cycle ergometer, as described in Section A.

The work in this Section of the thesis was stimulated by a need to be able to reproduce and measure, in the laboratory, the physiological stresses during sprinting that are placed on the sportsperson in the sporting arena. When blood lactate and glucose concentrations were compared both before and after 30 seconds of maximal sprinting on the track and on the sprint treadmill no differences were found, indicating that the magnitude of the physiological stress was indeed similar. It is in the measurement of the performance that differences were found between track sprinting and sprinting on the ergometer. These differences stem from four factors:

1) an inability to measure the work being done against gravity;
2) elasticity in the tethering system;
3) a difference between the momentum of the treadmill belt and the equivalent momentum of the subject running at the same speed as the treadmill belt;
4) the retarding resistance applied to the treadmill belt being very much greater than that retarding the untethered runner.

The latter two factors resulted in peak and mean running speeds on the treadmill being only approximately 65-80% that achieved on the track. A good correlation, however, was found between track and treadmill running speeds. Due to the same two factors variation in belt speed per stride was
found to be approximately twice that which would be predicted for corresponding changes in whole body speed whilst running on the track (Fukunaga, 1980).

Forward body lean was found to be accentuated on the sprint treadmill. How this lean affects performance, however, is not known. The forward lean does bring into question one of the assumptions made for the treadmill. Previous work has shown that the work being done against gravity (Wg) during running is independent of running speed (Cavagna et al., 1976; Fukunage et al., 1980). This has been assumed to be also true for the treadmill. The forward lean may, however, influence the relationship between running speed and Wg on the treadmill. In addition the measurements made of Wg on the track were made at constant running speeds. On the treadmill speed of running is constantly changing, especially during the acceleration phase of the sprint. It is not known whether Wg remains constant during acceleration. Instrumentation of the treadmill to measure actually Wg is required to answer this question.

Elasticity in the tethering system in combination with the accentuated forward lean resulted in propulsive forces being detected during the flight phase of the running stride. The propulsive forces cannot be due to muscular contraction as the runner is not in contact with the ground. The forces detected during the flight phase are due to the recovery of energy that was previously stored in the tethering system during the contact phase of the running stride. In addition a component of body weight is also being applied to the tether due to the forward lean. Only by modifying the characteristics of the treadmill will the forces measured during the flight phase be reduced.

Examination of the tethering system during running revealed that the centre of gravity remains below the level of the standing centre of gravity. This is not a finding that has been reported for free running and this reduction in the
vertical component of the running stride will modify the stride pattern, and in particular will reduce the flight phase of the stride.

It was found that, due to the low inertia of the treadmill belt, there was a large inter-stride variation in force production and power output. It has been mentioned above that the change in treadmill belt speed per stride is greater than would be expected for the whole body during running on the track. This places a greater demand on movement co-ordination whilst running on the treadmill with many compensating stride adjustments necessary. Increasing the inertia of the treadmill should reduce this problem.

The versatility of the sprint treadmill ergometer for measuring many performance variables far outweighs the limitations of the treadmill that have been mentioned above. It has been shown that stride frequency and stride length can be readily measured. In Chapter 10 the changes in the running stride during a 30s sprint were examined. Stride rates on the treadmill were found to be similar to those on the track. The difference in running speeds between the treadmill and the track could be accounted for by differences in the stride length. The treadmill also enables subtle changes in the ratio of flight time and contact time during the stride cycle to be investigated. The sprint treadmill offers exciting possibilities for investigating asymmetry of force production and power output during actual running. It may well prove to be a very useful diagnostic tool for the evaluation of bilateral imbalance which if corrected may not only enhance performance but may also reduce the risk of injury. The commercially available devices which measure dynamic muscle strength, such as isokinetic ergometers, measure muscle groups in isolation and do not permit the same acceleration of the limb found in sprint running. In addition the influence of both body weight and the co-ordination of different body segments is not evaluated. The sprint treadmill is not restricted by any
of these factors and is, therefore, a more valuable device for investigating bilateral differences in running.

Not only was the sprint treadmill ergometer found to be sensitive to bilateral imbalance in force production but it was also found to be sensitive to changes in the pattern of belt speed variation resulting in modifications in the contact phase of the running stride. It may well be possible to use the ergometer to evaluate the changes taking place in the contact phase due to changes in stride pattern and for investigating the effects of different footwear.

In the general discussion of Section A two phases of fatigue were found to occur during the performance tests on the cycle ergometer. The first phase occurred during the acceleration phase of the test, and the second phase during the remainder of the test. The same results were found for the sprint treadmill. If Figure 9.1 is examined the two phases can be clearly seen. As with the cycle ergometer the change from one phase to the other occurs when maximum speed has been achieved. The reasons for the changes in power output seen during the first phase have been fully discussed in Chapter 6 and have been attributed to the changes in running speed that are taking place and the associated force-velocity relationship of the active muscles. The results from the sprint treadmill re-inforce the findings from the cycle ergometer adding more evidence to the argument that the power output profile obtained during the acceleration phase of a sprint test is due mainly to the force-velocity and power-velocity relationship of muscle. During the acceleration phase a power-velocity profile, similar to the one proposed in Chapter 6, will influence power output until peak speed is attained. "The maximum velocity attained depends upon a balance between the propelling force, which is constant up to the onset of fatigue, and the internal resistance, which increases as the speed rises until it balances the propelling force" (Best and Partridge, 1928). The power output during the
acceleration (first) phase declines until the force produced, which is also declining as a result of the increasing speed, drops to a value which matches the resistive forces. After this point has been reached any further decline in power output must be as a result of the fatiguing processes discussed in the review of literature. As the speed of running decreases due to these fatiguing processes an increase in power output would be expected due to a shift towards the maxima in the power-velocity relationship of the muscle group. Rather than increasing, power output has been shown to decrease during this phase of the test. It is the difference between the predicted and the measured power output that should be used as a measure of the extent of the fatigue taking place.

As the accelerations discussed above occur when running on the track or the playing field then a major advantage of the sprint treadmill over the motorised treadmill for investigating sprint running is due to the fact that these changes, and the associated changes in force production and power output, which can be measured on the sprint treadmill ergometer cannot be monitored on the motorised treadmill.

Not only has the sprint treadmill ergometer been shown to be a very useful tool for investigating performance during a single sprint but also during repeated short duration sprints. The ergometer has been shown to be sensitive to variations in performance that occur with increasing sprint number. The performance tests can be carefully tailored to examine the stresses placed on the athlete in different sporting events by modifying both the length of the exercise period and the duration of the recovery period between each bout of exercise. In the repeated sprint tests peak heart rate was found to occur during the recovery period between sprints. In contrast, during the first few moments of each sprint heart rate was found to decrease slightly. This decrease was attributed to a sudden increase in venous return to the heart caused by the pumping action of the
muscles at the start of the exercise. The actual heart rate response was not known as the data filtering by the heart rate monitor masks the step changes that might be taking place. The decreases seen may have been due to a single longer interval between just two beats or an increase in the time taken for several successive beats.

The sequential relationship between maximum force, power output and speed found in all mechanical systems, that are free to accelerate, was also found to occur on the sprint treadmill ergometer. During the test peak force was measured during the first accelerating stride. Peak power output was achieved during subsequent strides with further strides needed to complete the acceleration of the treadmill to peak speed.

It would appear that the heavier subject is advantaged on the sprint treadmill. As the resistance of the treadmill does not increase in proportion to body weight the heavier subject needs to produce less force and power output per unit body mass than the lighter subject to make the treadmill move at a given speed. The extent of this advantage needs to be further investigated, and a correction factor obtained, so that track performance can be predicted more accurately from treadmill performance.

In conclusion, although not identical with sprinting on the track sprint running on the treadmill ergometer is similar. The ergometer allows the accurate determination of the horizontal forces and power outputs generated in sprint running, as well as the instantaneous values of running speeds, foot strikes and heart-rates. The decrement in the speed and the propulsive force and power of the sprinter can be measured as the instantaneous running speeds are not restricted. Both single and repeated sprints can be examined on the treadmill ergometer making it a very useful tool for the laboratory analysis of the physiological and the biomechanical demands of sprint running.
CHAPTER 13

GENERAL DISCUSSION

The results of the studies described in this thesis have been comprehensively examined both in the discussion section of each experimental chapter and in the general discussion chapters for each section. It, therefore, remains to reflect not on the work that has already been done, and described in this thesis, but to look forward to the work that needs to be done.

One of the main assumptions that was made in the calculation of power output on the cycle ergometer was that the frictional load that retarded the flywheel was the same as the load that was suspended by the loading-basket and that it remains constant. The Sinus balance is based upon a principle of dynamic balance. The balancing system uses negative feedback to maintain an average value of resistive load. The loading-basket can be seen to oscillate during exercise indicating that there is a significant response time of the feedback system. The average value of resistance may well be the same as the suspended load but the instantaneous values may vary significantly from this average. It is important, therefore, to determine the magnitude of the error by inserting force transducers into either end of the friction belt so that instantaneous measurement of the applied force can made. In future research it should be this measured frictional force, not the assumed value, that should be used in the calculation of intra- and inter-stroke torque production and power output.

In Section A it was established that the torque being applied to the flywheel could be calculated simply by monitoring the acceleration of the flywheel taking place. This claim must be verified by comparing the calculated torque with measured torque, using a torque transducer. In
order to do this synchronisation of the two profiles obtained will be required. This will be most easily achieved by using an inductive sensor to detect the passage of the teeth of the cog on the pedal crank, with a special signal generated at a fixed point in each revolution. If the system is indeed proved to be able to calculate instantaneous applied torque then intra-stroke force, torque and power output on the friction-loaded cycle ergometer can be easily and routinely measured enabling many functional and physiological measurements to be made, which have hitherto been made only with difficulty or incorrectly.

Further close examination of the effect of the force-velocity and power-velocity relationships of the active muscle groups is required so that fatigue measured both on the cycle ergometer and the sprint treadmill can be fully evaluated. It would be interesting to correlate the fibre composition of the active muscles with the acceleration of the flywheel during a single sprint. The gradient of the associated fatigue slope could be examined to see whether it reflects the fibre composition of the muscles.

The major shortcoming of the sprint treadmill was that the total external power output was not measured. The main future development of the system should be to incorporate a method for measuring the work done against gravity. An estimate could be obtained by monitoring the movement of the centre of gravity of the subject. A good approximation of this movement might be achieved by replacing the flexible tether straps by a single rigid bar. At one end it would be attached to the belt worn by the subject. At the other end the bar would be fixed to the force transducer via a goniometer. By knowing the distance from the centre of gravity (COG) of the subject to the goniometer the vertical displacement of the COG can be measured. The acceleration of the COG, at any instant, can
be calculated and the power output required to produce this acceleration determined. The error in the location of the centre of gravity can be kept small by making the tether bar long, however, the longer the bar the smaller will be its angular movement requiring increased sensitivity from the goniometer. The system would continue to measure the horizontal power output as described in Section B and the total power output would be calculated from the sum of the horizontal and vertical components.

An attempt should be made to match more closely the mass of the subject and the mass of the treadmill. This might be achieved by attaching an external flywheel to the treadmill. This will reduce the acceleration of the treadmill belt during each stride making the treadmill easier to run on and may also result in a reduced forward lean. As the intrinsic resistance of the treadmill cannot be altered in those studies where the maximum speed of movement needs to be closer to actual sprinting speeds the treadmill could be tilted backwards so that a component of bodyweight is used to overcome the friction. Although the maximum speed of running should increase, the stride cycle will be significantly modified.

Further investigation into the use of the sprint treadmill for evaluating bilateral imbalance is needed. Any imbalances measured on the treadmill should be compared to both dynamic imbalances, measured using isokinetic devices, and isometric imbalance, using a force transducer. A systematic method for determining which force peak, on the sprint treadmill ergometer printout, corresponds with which leg will be required.

* * *

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Figure 13.1 Maximum power output as a function of time of performance, using data from the studies described in this thesis.
Finally, Figure 13.1 shows how the maximum values of power output obtained from the cycle ergometer and treadmill studies described in this thesis relate to the duration of the exercise. It can be seen that the data points fit the exponential curve described by Wilkie (1960). The 3 second data point for the sprint treadmill falls below the line and reflects the fact that the point does not represent the total power output generated by the subject.

The maximum external power output decreases "exponentially with time...and continues to decline dramatically until aerobic synthesis of ATP begins to keep pace with the rate at which it is being utilised." (Nagle, 1973)


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Martin. (1914) J. Physiol. 48:15


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Appendix 1. Time course, from switch-on, of the A-to-D values obtained for a constant input voltage.
SPEED CALIBRATION PROGRAM

100 ?FEST=0:REM DDRA INPUT
105 ?FPCF=0
110 LET N=0;X%=0;Y%=0;Z%=0
120CLS
125 *DRIVE 0
130 B=OPENIN("S-CAL")
140 INPUT#0,PC
150 PC=INT((100000*(PC+0.000005))/10000)
160 CLOSE#0
170 VOU 25,1,0;0;0;
180 PRINT
190 PRINTCHR$(141);CHR$(131);CHR$(157);CHR$(132);"TREADMILL SPEED CALIBRATION PROGRAM"
200 PRINTCHR$(141);CHR$(131);CHR$(157);CHR$(132);"TREADMILL SPEED CALIBRATION PROGRAM"
210 PRINT:PRINT:PRINT
220 PRINT"THIS PROGRAM WILL ALLOW YOU TO CALIBRATE THE SPRINT TREADMILL SPEED TRANSDUCER." 
230 PRINT
240 PRINT"THE OUTPUT FROM THE SPEED TRANSDUCER IS DETECTED BY THE 12-BIT A TO D CONVERTER "
250 PRINT
260 PRINT"YOU WILL NEED TO COUNT THE NUMBER OF REVOLUTIONS THAT THE TREADMILL BELT"
270 PRINT"MAKES IN APPROXIMATELY 1 MINUTE, WHILST THE TREADMILL IS BEING DRIVEN BY THE "
280 PRINT"H.P. ELECTRIC MOTOR"
290 PRINT:PRINT
300 PRINTCHR$(132);CHR$(157);CHR$(131); "PRESS <SPACEBAR> TO CONTINUE"
310 Y=GET
320 CLS
330 PRINTCHR$(141);CHR$(131);CHR$(157);CHR$(132); "CALIBRATION ROUTINE"
340 PRINTCHR$(141);CHR$(131);CHR$(157);CHR$(132); "CALIBRATION ROUTINE"
350 PRINT:PRINT"CONNECT THE DRIVE BELT FROM THE ELECTRIC MOTOR TO THE SPRINT TREADMILL"
360 PRINT
370 PRINT"SWITCH ON THE MOTOR - push the treadmill"
380 PRINT
390 PRINT"WHEN UP TO SPEED PRESS THE <SPACEBAR> WHICH WILL START THE DATA LOGGING BY" 
400 PRINT"THE COMPUTER AND ALSO THE INTERNAL CLOCK WHICH WILL ALSO APPEAR ON THE SCREEN"
410 PRINT:PRINT"WHEN AT LEAST 30 SECONDS HAS ELAPSED STOP COUNTING AND SIMULTANEOUSLY PRESS "
420 PRINT"THE <SPACEBAR> TO STOP THE DATA LOGGING"
430 PRINT:PRINT"THE COMPUTER WILL THEN WORK OUT AND DISPLAY THE CALIBRATION FACTOR FOR THE "
440 PRINT"SPEED TRANSUDER AND STORE IT ON DISK"
450 PRINT
460 PRINTCHR$(132);CHR$(157);CHR$(131); "PRESS <S> TO START LOGGING"
470 Y=GET
471 IF Y<"S" THEN 470
480 PROCDatatog
490 PROCfactor
500 Y=GET
510 CHAIN"TRMENU"
520 END
530 DEFPROCdata	ag
540 CLS
550 T=TIME
560 PRINTTAB(0,18);CHR$(132);CHR$(157);CHR$(131); "PRESS <SPACEBAR> TO STOP LOGGING"
570 PRINTTAB(0,7)
580 T=TIME-7)/100
590 PRINTCHR$(141);CHR$(131);CHR$(157);CHR$(132);" ELAPSED TIME " ;TT
600 PRINTCHR$(141);CHR$(131);CHR$(157);CHR$(132);" ELAPSED TIME " ;TT
610 %FE6C=224
620 %FE6C=192
630 %FE6C=224
640 %FE6C=192
650 %FE6C=192
660 %FE6C=192
670 %FE6C=192
680 PRINT:PRINT
690 PRINTCHR$(141);CHR(131);CHR$(157);CHR$(132) " A-TO-O CD" ;RT;
700 PRINTCHR$(141);CHR$(131);CHR$(157);CHR$(132) " A-TO-O COUNT " ;RT.
710 N=N+1
720 Y=INKEY(-99)
730 IF Y=0 THEN 570
740 ENOPROC
750 DEFC PROCFactor
760 CALL
770 *FXIS,1
780 PRINT:PRINT
790 PRINTCHR$(131);CHR$(157);CHR$(132);"NUMBER OF REVOLUTIONS COUNTED " ;INPUTNR
800 BL=2.93
810 AR=NR*BL/TT :REM BL=BELT LENGTH
820 REM: AR=AVERAGE BELT SPEED (m/s)
830 AA=Z7/N :REM AA=AV A-TO-O COUNT
840 CAL=AR/AA
850 C=INT((100000*(CAL+0.000005))/100000
860 PRINTTAB(0,4)
870 PRINTCHR$(141);CHR$(132);CHR$(157);CHR$(131);" CALIBRATION FACTOR=";C
880 PRINTCHR$(141);CHR$(132);CHR$(157);CHR$(131);" CALIBRATION FACTOR=";C
890 PRINT:PRINTCHR$(129);CHR$(157);CHR$(130);"PREVIOUS CALIBRATION FACTOR=";PC
900 PRINT:PRINT
910 PRINTCHR$(131);CHR$(132);" RECORD THIS VALUE"
920 PRINT:PRINT:PRINT:PRINT:PRINT:PRINT:"THIS CALIBRATION VALUE IS ALSO BEING RECORDED ON THE DISC FOR AUTOMA-"
930 PRINT:PRINT:PRINT:PRINT:"RETRIEVAL BY PRINT TEST PROGRAM"
940 PRINT" (FILENAME S-CAL)"
950 F=OPENOUT("S-CAL")
960 PRINT",CAL
970 CLOSE#F
980 PRINT:PRINT:PRINTCHR$(131);CHR$(157);CHR$(132);" PRESS <SPACE3AR> FOR MENU"
990 ENOPROC
FORCE CALIBRATION PROGRAM

1076FA=30
1076PC7=0
110LETN=3;Z=3;Y=3;Z=3
120IO=3
130CLS
1400=OPEN*IN("F-CAL")
150:INPUT**,PC
160PC=INT(100000*(PC+0.00005))/100000
170DOCLOSE=0
180DOVUD2;1,0;3;
190PRINT
200PRINTCHR$(141)CHR$(131)CHR$(157)CHR$(132);" FORCE TRANSDUCER CALIBRATION"
210PRINTCHR$(141)CHR$(131)CHR$(157)CHR$(132);" FORCE TRANSDUCER CALIBRATION"
220PRINT:PRINT:PRINT
230PRINT"THIS PROGRAM WILL ALLOW YOU TO CALIBRATE THE SPRINT TREADMILL FORCE TRANSDUCER"
240PRINT
250PRINT"THE OUTPUT FROM THE FORCE TRANSDUCER IS DETECTED BY THE 12-BIT A-TO-D CONVERTER"
260PRINT:"YOU WILL NEED TO SUSPEND A KNOWN WEIGHT (around 10kg) FROM THE TRANSDUCER"
270PRINT:PRINT:"THE COMPUTER WILL THEN WORK OUT AND DISPLAY THE CALIBRATION FACTOR FOR THE"
280PRINT:"FORCE TRANSDUCER AND STORE IT ON DISC"
290PRINT:PRINT
300PRINTCHR$(132)CHR$(157)CHR$(131);" PRESS <SPACEBAR> TO CONTINUE"
320Y=GET
330CLS
340PRINTCHR$(141)CHR$(131)CHR$(157)CHR$(132);" CALIBRATION ROUTINE"
350PRINTCHR$(141)CHR$(131)CHR$(157)CHR$(132);" CALIBRATION ROUTINE"
360PRINT:PRINT:"ALLOW THE TETHER BELT TO HANG FREE SO THAT THE 0 FORCE VALUE CAN BE OBTAINED"
370PRINT
380PRINT:"WHEN READY PRESS THE <SPACEBAR> WHICH WILL START THE COMPUTER DATA LOGGING"
390PRINT
400PRINTCHR$(132)CHR$(157)CHR$(131);" PRESS <SPACEBAR> TO START LOGGING"
410Y=GET
420PRINTTAB(0,9)CHR$(131)CHR$(157)CHR$(132);" LOGGING"
430REPEAT
440PROCDataLog
450UNTIL N=500
460Z=277/N
470PRINTTAB(0,9)CHR$(132)CHR$(157)CHR$(131);" LOGGING COMPLETED"
480PRINT:PRINTCHR$(128)CHR$(157)CHR$(132);" ZERO VALUE OBTAINED (";10")"
490L=9.9
500L=L*9.01
510PRINT:PRINT:" HANG THE LOAD FROM TETHER STRAP";PRINT
520PRINT:PRINTCHR$(132)CHR$(157)CHR$(131);" PRESS <SPACEBAR> TO START LOGGING"
530Y=GET
540PRINTTAB(0,19)CHR$(131)CHR$(157)CHR$(132);" LOGGING"
550N=3;Z=0
560REPEAT
570PROCDataLog
580UNTIL N=500
590L=Z7/N
600PROCfactor
613Y=GET
619CHAIN"TMENU"
623END
640DEFPROCDatalog
650"FESC=224
660"ESC=192
670"FES=60
680"FESC=224
690"FES=60
700"Y%=16+X%/16
710Z%=Z%+R% 
720N=N+1
730ENDPROC
740DEFPROCFactor
750CLS
760=F15,1
770PRINT:PRINT
780CAL=L/((L-Z))
790C=INT(100000*(CAL+0.00005))/100000
800PRINTTAB(0,4)
810PRINTCHR$(141)CHR$(132)CHR$(157)CHR$(131);"CALIBRATION FACTOR =";C
820PRINTCHR$(141)CHR$(132)CHR$(157)CHR$(131);"PREVIOUS CALIBRATION FACTOR";C
840PRINT:PRINT
850PRINTCHR$(131)CHR$(157)CHR$(132);"PRESS (SPACEBAR) FOR MENU"
880PRINT:PRINT"RETRIEVAL BY PRINT TEST PROGRAM"
890PRINT"(FILENAME F-CAL)"
900OPENF="F-CAL"
910CLOSEF
920PRINT:PRINTCHR$(131)CHR$(157)CHR$(132);"THIS CALIBRATION VALUE IS ALSO BEING RECORDED ON THE DISC FOR AUTOMATIC CALIBRATION"
SINGLE 30 SECOND SPRINT DATA COLLECTION PROGRAM

100 len%=6950
110 DIM dat%=len%
120 ref%=dat%+50:FL2=dat%+170G:SH%=dat%+350:SL%=dat%+5000:HH%=dat%+650:HL%=dat%+
130 RH%=dat%+6750:RL%=dat%+6950
140 SS%=0:HR%=0:FX%=0:N=0:MS=3:OH=I:MR=0
150 CH=1:REM HEART RATE CAL FACTOR
160 ?SFES2=0
170 CLS
180 DDU 23,1,0,0,0;
190 PRINT
200 PRINTCHR$(141)CHR$(131)CHR$(157)CHR$(132);" SINGLE 30 SECOND SPRINT PROGRAM"
210 PRINTCHR$(141)CHR$(131)CHR$(157)CHR$(132);" SINGLE 30 SECOND SPRINT PROGRAM"
220 #DRIVE 0
230 PRINT:PRINT
240 B=OPENIN("S-CAL")
250 INPUTB,CS
260 CLOSE#9
270 BF=OPENIN("F-CAL")
280 INPUTBF,CF
290 CLOSEBF
300 PRINT:PRINT:PRINTCHR$(132)CHR$(157)CHR$(131);SPEED CAL. FACTOR = ";CS
310 PRINTCHR$(132)CHR$(157)CHR$(131);FORCE CAL. FACTOR = ";CF
320 PRINT:PRINT:PRINT:PRINTCHR$(136)CHR$(129)CHR$(157)CHR$(130);" PUT DATA DISC IN DRIVE 1:
330 PRINT:PRINT:PRINT" THIS PROGRAM WILL COLLECT THE DATA GENERATED BY A SINGLE 30 SECOND SPRINT"
340 PRINT" ON THE SPRINT TREADMILL. THE DATA WILL BE SAVED ON DISC. THE TOTAL COLLECTION"
350 PRINT" TIME WILL BE 40 SECONDS."
360 PRINT:PRINT:PRINTCHR$(131)CHR$(157)CHR$(132);" PRESS <SPACEBAR> TO CONTINUE"
370 Y=GET
380 Y=GET
390 PRINT
400 PRINTCHR$(141)CHR$(131)CHR$(157)CHR$(132);" PERSONAL DATA INPUT ROUTINE"
410 PRINTCHR$(141)CHR$(131)CHR$(157)CHR$(132);" PERSONAL DATA INPUT ROUTINE"
420 PRINT:PRINT:PRINT
430 PRINTCHR$(132)CHR$(157)CHR$(131);"SUBJECT’S NAME ";INPUTNA$
440 PRINTCHR$(132)CHR$(157)CHR$(131);"SUBJECT’S INITIALS ";INPUTNI$
450 PRINTCHR$(132)CHR$(157)CHR$(131);"SUBJECT’S WEIGHT ";INPUTW
460 PRINTCHR$(132)CHR$(157)CHR$(131);"DATE (DAY/MONTH/YEAR) "--/--/--
470 PRINTTAB(25,9);INPUTDS$
480 FS=LEFT$(NI$,2)+LEFT$(D$,2)+MID$(D$,4,2)+RIGHT$(D$,1)
490 PRINT
500 PRINTCHR$(131)CHR$(157)CHR$(132);"FILENAME FOR DATA STORAGE = ";FI$
510 PRINT:PRINTCHR$(132)CHR$(157)CHR$(131);" RECORD THIS FILENAME"
520 PRINT:PRINTCHR$(132)CHR$(157)CHR$(130);"RECOVERY HEART RATE MONITORED (Y/N)";INPUTHR$
530 IFHR$="N" THEN 520
540 IFHR$="Y" THEN PROCRecovery
550 PRINT
560 PRINT:PRINT:PRINTCHR$(131)CHR$(157)CHR$(132);" PRESS <SPACEBAR> TO CONTINUE"
570 Y=GET
580 CLS:PRINTTAB(0,5)
590 PRINTCHR$(132)CHR$(157)CHR$(131);"ALLOW THE TETHER STRAP TO HANG FREE"
600 PRINT:PRINTCHR$(131)CHR$(157)CHR$(132);" PRESS <SPACEBAR> TO CONTINUE"
610 Y=GET
620 FOR I=1TO10000
630 IFF%=0:FF%=FF%+224:FF%=FF%+192:FF%=FF%+7680:FF%=FF%+224:FF%=FF%+16:FL%=FF%
640 NEXT
650 357
DEF PROC DataCollect  
N=N+1  
IF N DIV 7 < H THEN H+1  
PRINTCHR$(132)+CHR$(157)+CHR$(131);"COLLECTING DATA" 
H=TIME  
REPEAT  
ENDPROC

DEF PROC Stor  
PRINTCHR$(131)+CHR$(157)+CHR$(132);"COLLECTION COMPLETE" 
FOR MS="Y" THEN PROC=STORE  
PRINT;PRINT;"THE DATA IS NOW BEING TRANSFERED TO THE DISC FOR PERMANENT STORAGE"  
ENDPROC
1179 DEF PROC Storage
1180 *DRIVE 1
1181 PRINT:CHR$(132):CHR$(157):CHR$(131):"FILENAME" = "FI"
1182 PRINT
1183 PRINT:CHR$(132):CHR$(157):CHR$(131):"SUBJECT NAME" = "NAME"
1184 PRINT:CHR$(132):CHR$(157):CHR$(131):"DATE" = "DATE"
1185 PRINT
1186 PRINT:CHR$(132):CHR$(157):CHR$(131):"SUBJECT WEIGHT" = "W"
1187 PRINT:CHR$(132):CHR$(157):CHR$(131):"SPEED CAL FACTOR" = "CS"
1188 PRINT:CHR$(132):CHR$(157):CHR$(131):"FORCE CAL FACTOR" = "CF"
1189 PRINT:CHR$(132):CHR$(157):CHR$(131):"FORCE CAL FACT" = "CF"
1190 PRINT:CHR$(132):CHR$(157):CHR$(131):"NO. OF DATA POINTS" = "NPP"
1191 PRINT:CHR$(132):CHR$(157):CHR$(131):"NUMBER OF SPRINTS" = "NS"
1192 PRINT:CHR$(132):CHR$(157):CHR$(131):"RECOVERY MONITORED" = "RM"
1193 PRINT:CHR$(132):CHR$(157):CHR$(131):"TIME MONITORED (S)" = "TMS"
1194 PRINT:CHR$(132):CHR$(157):CHR$(131):"NO. H.R. DATAPOINTS" = "NH"
1195 PRINT:CHR$(132):CHR$(157):CHR$(131):"NO. RECOVERY H.R. MONITORED" = "NH"
1196 PRINT:CHR$(132):CHR$(157):CHR$(131):"NH"
1197 PRINT:CHR$(132):CHR$(157):CHR$(131):"DURATION OF MONITORING (SECONDS)" = "IMPD"
1198 ENDPROC
1199 DEF PROC Recovery
1200 MR = 1
1201 PRINT:CHR$(129):CHR$(157):CHR$(131):"DURATION OF MONITORING (SECONDS)" = "IMPD"
1202 ENDPROC
1203 DEF PROC C
1204 PRINT
1205 PRINT:CHR$(141):CHR$(157):CHR$(131):"NO. OF DATA POINTS" = "NPP"
1206 REPEAT
1207 IF (TIME-T) < 4000 + CN THEN 1570
1208 IF (TIME-T) < 4000 + CN + 500 THEN 1570
1209 ?FECE=0: REM CHANNEL 3 (H.R.)
1210 IF (TIME-T) < 4000 + CN then 1570
1211 IF (TIME-T) < 4000 + CN + 500 then 1570
1212 PRINTTAB(0,5)
1213 PRINT:CHR$(129):CHR$(157):CHR$(131):"*RH*
1214 PRINTTAB(0,5)
1215 PRINT:CHR$(129):CHR$(157):CHR$(131):"*RH*
1216 UNTIL (TIME-T) > 4000 + CN + 100
1217 ENDPROC

1218 PRINT:CHR$(129):CHR$(157):CHR$(131):"*FILENAMe = "FI"
1219 PRINT
1220 PRINT:CHR$(129):CHR$(157):CHR$(131):"SUBJECT NAME = "NAME"
1221 PRINT:CHR$(129):CHR$(157):CHR$(131):"DATE = "DATE"
1222 PRINT
1223 PRINT:CHR$(129):CHR$(157):CHR$(131):"SUBJECT WEIGHT = "W"
1224 PRINT:CHR$(129):CHR$(157):CHR$(131):"SPEED CAL FACTOR = "CS"
1225 PRINT:CHR$(129):CHR$(157):CHR$(131):"FORCE CAL FACTOR = "CF"
1226 PRINT:CHR$(129):CHR$(157):CHR$(131):"FORCE CAL FACT" = "CF"
1227 PRINT:CHR$(129):CHR$(157):CHR$(131):"NO. OF DATA POINTS" = "NPP"
1228 PRINT:CHR$(129):CHR$(157):CHR$(131):"NUMBER OF SPRINTS" = "NS"
1229 PRINT:CHR$(129):CHR$(157):CHR$(131):"RECOVERY MONITORED" = "RM"
1230 PRINT:CHR$(129):CHR$(157):CHR$(131):"TIME MONITORED (S)" = "TMS"
1231 PRINT:CHR$(129):CHR$(157):CHR$(131):"NO. H.R. DATAPOINTS" = "NH"
1232 PRINT:CHR$(129):CHR$(157):CHR$(131):"NO. RECOVERY H.R. MONITORED" = "NH"
1233 PRINT:CHR$(129):CHR$(157):CHR$(131):"NH"
1234 PRINT:CHR$(129):CHR$(157):CHR$(131):"DURATION OF MONITORING (SECONDS)" = "IMPD"
1235 ENDPROC
1236 DEF PROC Recovery
1237 MR = 1
1238 PRINT:CHR$(129):CHR$(157):CHR$(131):"DURATION OF MONITORING (SECONDS)" = "IMPD"
1239 ENDPROC
1240 DEF PROC C
1241 PRINT
1242 PRINT:CHR$(141):CHR$(157):CHR$(131):"NO. OF DATA POINTS" = "NPP"
1243 REPEAT
1244 IF (TIME-T) < 4000 + CN then 1570
1245 IF (TIME-T) < 4000 + CN + 500 then 1570
1246 PRINTTAB(0,5)
1247 PRINT:CHR$(129):CHR$(157):CHR$(131):"*RH*
1248 PRINTTAB(0,5)
1249 PRINT:CHR$(129):CHR$(157):CHR$(131):"*RH*
1250 UNTIL (TIME-T) > 4000 + CN + 100
1251 ENDPROC
MULTIPLE SPRINT DATA COLLECTION PROGRAM

100 LEN% = 2259
110 DIM DAT% (LEN%)
120 REF% = DAT%*(FH% + FL% + SL% + HL% + HH% + 255) : SL% = DAT% + 550 : HH% = DAT% + 1550 : HL% = DAT%*21C
130 G% = 0 : HR% = 0 : N% = 0 : S% = 0 : DM% = 0 : H% = 1 : MR% = 0 : NN% = 0
140 CH% = 119 : REM HEART RATE CAL FACTOR
150 ? & FE6Z = 0
160 CLS
170 VDU 23,1,0;0;'3; PRINT
180 PRINT
190 PRINT CHR$(14)CHR$(11)CHR$(157)CHR$(132) ; "MULTIPLE SPRINT DATA COLLECTION PROGRAM"
200 PRINT CHR$(14)CHR$(131)CHR$(157)CHR$(132) ; "MULTIPLE SPRINT DATA COLLECTION PROGRAM"
210 CLS : PRINT
220 PRINT: PRINT
230 B = OPENIN("G-CAL")
240 INPUT*B, CS
250 CLOSE*B
260 BF = OPENIN("F-CAL")
270 INPUT#BF, CF
280 CLOSE#BF
290 PRINT: PRINT CHR$(132)CHR$(157)CHR$(132) ; "SPEED CAL. FACTOR = "CS
300 PRINTCHR$(132)CHR$(157)CHR$(131) ; "FORCE CAL. FACTOR = "CF
310 PRINT: PRINT: PRINT: PRINT CHR$(131)CHR$(157)CHR$(132) ; "PUT DATA DISC IN DRIVE 1"
320 PRINT: PRINT: PRINT "THIS PROGRAM WILL COLLECT THE DATA GENERATED BY MULTIPLE 6 SECOND SPRINTS"
330 PRINT: PRINT "ON THE SPRINT TREADMILL. THE DATA WILL BE SAVED ON DISC. THE TOTAL COLLECTION"
340 PRINT: PRINT "FOR EACH SPRINT WILL BE 12 SECONDS"
350 PRINT: PRINT: PRINT: PRINT "PRESS <SPACEBAR> TO CONTINUE"
360 Y = GET
370 CLS
380 PRINT
390 PRINT CHR$(141)CHR$(157)CHR$(132) ; "PERSONAL DATA INPUT ROUTINE"
400 PRINTCHR$(141)CHR$(157)CHR$(132) ; "PERSONAL DATA INPUT ROUTINE"
410 PRINT: PRINT
420 PRINTCHR$(132)CHR$(157)CHR$(131) ; "SUBJECT'S NAME" ; INPUTNA$
430 PRINTCHR$(132)CHR$(157)CHR$(131) ; "SUBJECT'S INITIALS" ; INPUTN$
440 PRINTCHR$(157)CHR$(131) ; "SUBJECT'S WEIGHT" ; INPUTW
450 PRINTCHR$(157)CHR$(131) ; "DATE (DAY/MONTH/YEAR)" --/--/--
460 PRINTTAB(25,9) ; INPUTD$
470 PRINTCHR$(132)CHR$(157)CHR$(131) ; "NO. OF SPRINTS <max=10 >" ; INPUTN$
480 FF = Left$(N$ (2) + Left$(D$, 2) + Mid$(D$, 4, 2) ) + "F"
490 PRINT
500 PRINTCHR$(131)CHR$(157)CHR$(132) ; "FILENAME FOR DATA STORAGE = "F$
510 PRINT: PRINTCHR$(132)CHR$(157)CHR$(131) ; "RECORD THIS FILENAME"
520 PRINT
530 PRINT: PRINT: PRINT: PRINTCHR$(131)CHR$(157)CHR$(132) ; "PRESS <SPACEBAR> TO CONTINUE"
540 Y = GET
550 CLS: PRINTTAB(0,5)
560 PRINTCHR$(132)CHR$(157)CHR$(131) ; "ALLOW THE TETHER STRAP TO HANG FREE"
570 PRINT: PRINTCHR$(131)CHR$(157)CHR$(132) ; "PRESS <SPACEBAR> TO CONTINUE"
580 Y = GET
590 FOR I = 1 TO 100
600 $FE67 = 0 : $FE6C = 224 : $FE66C = 192 : $FE60 = $FE60 : $FE68 = 224 : FL = $FE60
610 FF = FF + FH + FL / 16
620 NEXT
630 FF = FF / 100
640 PRINT: PRINTCHR$(131)CHR$(157)CHR$(132) ; "ZERO FORCE CAL FACTOR = "FO$
650 PRINT: PRINTCHR$(131)CHR$(157)CHR$(132) ; "PRESS <SPACEBAR> TO CONTINUE"
660 Y = GET
CLS
PRINT "FILENAME = ";FILE$1
PRINT
PRINT "SUBJECT NAME = ";H$1
PRINT
PRINT "DATE = ";D$1
PRINT
PRINT "SUBJECT'S WEIGHT = ";W$1
PRINT "SPEED CAL FACTOR = ";FO$1
PRINT "FORFORCE CAL FACTOR = ";CF$1
PRINT "ZERO FORCE CAL FACTOR = ";F0$1
PRINT "NO. OF DATA POINTS = ";NP$1
PRINT "NO. REC. DATA POINTS = ";NS$1
PRINT "NO. OF SPRINTS = ";NS$1
PRINT "NO. H.R. DATA POINTS = ";HN$1
PRINT "CURRENT A-T-C-D VALUES = ";FX$1
PROCDatacollection
000 PRINT "PRESS <SPACEBAR> TO CONTINUE"
010 Y$GET
020 PRINTprintCh$(111)Ch$(157)Ch$(132)" ;DATA COLLECTION ROUTINE"
030 PRINTprintCh$(111)Ch$(157)Ch$(132)" ;DATA COLLECTION ROUTINE"
040 PRINTprintCh$(111)Ch$(157)Ch$(132)" ;PRESS <S> KEY TO START COLLECTION"
050 PRINTprintCh$(111)Ch$(157)Ch$(131)" ;CURRENT A-T-GO VALUES"
060 PRINTprintCh$(111)Ch$(157)Ch$(132)" ;DATA COLLECTION"
SINGLE 30 SECOND SPRINT DATA RETRIEVAL PROGRAM

100CLS
110 MODE 1
120 VDU 27, 1, 0; 0;
130 len%=4950
140 DIM dat%, len%
150 refZ=dat%
160PRINT
170PRINTCHR$(131)CHR$(157)CHR$(132);" DATA RETRIEVAL PROGRAM";
180 *DRIVE 1
190 PRINT:PRINTCHR$(136)CHR$(129)CHR$(157)CHR$(130);" PUT DATA DISC INTO DRIVE 1"
200 PRINT:PRINT
210 PRINTCHR$(132)CHR$(157)CHR$(131);"NAME OF FILE TO BE RETRIEVED";INPUT<<
220 OSCIL"LOAD '+F14+'";STR$=dat%
230 *DRIVE 0
240 LOAD +F14+dat7.
250
260 RH%=dat%+596;FLZ=dat%+1700;SH%=dat%+3350;SL%=dat%+5080;HM%=dat%+6560;HL%=dat%+6702
270 %W=((?refZ)+100(?refZ+1))/100
280 CS=((?refZ+4)+(H%m+T%H%))/100
290 CF=((?refZ+4)*1000+(?refZ+5))/100
300 N=(?refZ+6)+(100(?refZ+7))
310 NS=(?refZ+8)
320 MR=(?refZ+9)
330 DH=(?refZ+10)+100+(?refZ+11)
340 H=(?refZ+12)
350 CM=(?refZ+13)
355 F3%(?refZ+14)
360 IF MR=0 THEN MR$="M"
370 IF MR=1 THEN MR$="Y"
380 VDU2
390 PRINT:PRINTCHR$(132)CHR$(157)CHR$(131);FILENAME = "F14"
400 PRINTCHR$(132)CHR$(157)CHR$(131);SUBJECT WEIGHT = "W"
410 PRINTCHR$(132)CHR$(157)CHR$(131);SPEED CAL. FACTOR = "CS"
420 PRINTCHR$(132)CHR$(157)CHR$(131);FORCE CAL. FACTOR = "CF"
430 PRINTCHR$(132)CHR$(157)CHR$(131);ZERO FORCE CAL FACT= "CFZ"
440 PRINTCHR$(132)CHR$(157)CHR$(131);NO. OF DATA POINTS = "N"
450 PRINTCHR$(132)CHR$(157)CHR$(131);NUMBER OF SPRINTS = "N50"
460 PRINTCHR$(132)CHR$(157)CHR$(131);RECOVERY MONITORED = "MR";
470 PRINTCHR$(132)CHR$(157)CHR$(131);TIME MONITORED (S) = "TM"
480 PRINTCHR$(132)CHR$(157)CHR$(131);NO. H.R. DATA POINTS = "HN"
490 PRINTCHR$(132)CHR$(157)CHR$(131);NO. REC. DATA POINTS = "EN"
490 VDU2
500 PRINT:PRINTCHR$(151)CHR$(157)CHR$(132);" PRESS <SPACEBAR> TO CONTINUE"
510 Y#GET#
520 CLS:CLG
530 PROCspeedplot
540 PROCframe
550 PROCprintout
560 PROCHeart
570 PROCMenu
580 END
590 DEF PROCFrame
600 MOVED,0
610 DRAw1276,0;DRAW1276,999;DRAW0,999;DRAW0,0
620 FORI=32701243 STEP 32:MOVE1,0;PLOT8,1,32:NEXTI
630 FORI=10070000STEP100:MOVE1,1;PLOT6,32,8:NEXTI
640 PRINTCHR$(131)CHR$(157)CHR$(132);"TYPE1=LEFT...2=RIGHT...Y=BREAK POINT"
650 I=40
660 MOVE1,600;PLOT8,1,40
670 X#GET#
600 MOV EI,A30;PLOT6,1,43
690 IF X$="2" THEN I=I+1:GOT0730
700 IF X$="1" THEN I=I-1:GOT0720
710 IF X$="G" THEN PROCUnw
720 IF X$="y" THEN 740
730 GOTO680
740 XI=1*N/1276
750 ENDPROC
760 DEFPROCspeedplot
770 I=0
780 REPEAT
790 I=I+1:NH=3350+1:NL=5000-I
800 SX=(?((dat%+NH)*16+7(dat%+NL))/16)*C:J=0
810 SL=(?((dat%+NH+1)*16+7((dat%+NL)))/16)*S+100
820 MOVE1276/N+1,ST:DRAW1276/N+1+1,SL:
830 UNTIL I=W
840 ENDPREC
850 DEF PROCPrintout
860 TT=40/N
870 CLS:CLS
880 PRINTCHR(131);CHR(1157);CHR(12);"INTERACTION PEDDL = ";:INPUT IP
890 CLS
900 VDU2
910 PRINT
920 PRINT"BREAKPOINT SET = ";(INT100*X)/100;" SECS"
930 PRINT
940 PRINT"TIME SPEED FORCE POWER P/SW"
950 NP=30/IP
960 SH=6:SL=100:DS=0:PD=0;PP=3:PM=100	;PW=0
970 FORAA=ITONP
980 CA=AA*IP
990 REPEAT
1000 CS=CA+AA*IP/TT
1010 SP=SP+(?,SH)+CB2) 16+7(SL+CB2)/16)*CF
1020 FP=FP+(?,F)+CB2)/16+7(FLX+CB2)/16-F0C)*CF
1030 C=CA+1
1040 UNTIL CA+IP/TT
1050 SP=SP/CA;FP=FP/CA
1060 PRINT":AA*IP;" ";(INT100*SP)/100;" ;(INT100*FP)/100;" ;(INT100*SP+FP)/100;"
1070 PRINT"DISTANCE RUN = ";(INT100*SP+FP)/100
1080 IFSP>SH THEN SH=SP
1090 IFSP<SL THEN SL=SP
1100 IFSP>PP THEN PP=SP*FP
1110 DS=DS*SP/IP
1120 PD=PD*SP/IP
1130 PW=PW*SP/IP
1140 NEXT
1150 PRINT
1160 PRINT"MEAN RUNNING SPEED m/s = ";(INT100*DS)/100
1170 PRINT"TOTAL WORK DONE (hot) = ";(INT100*W)/100
1180 PRINT"MEAN POWER OUTPUT (W) = ";(INT100*PP)/100
1190 PRINT"MEAN POWER/BODYWEIGHT = ";(INT100*PP/100)/10000
1200 PRINT"PEAK POWER/BODYWEIGHT = ";(INT100*PP)/10000
1210 PRINT"PEAK POWER OUTPUT (W) = ";(INT100*PP)/100
1220 PRINT"MIN. POWER OUTPUT (W) = ";(INT100*PP)/100
1230 PRINT"FATIGUE INDEX (POWER) = ";(INT100*(PP-RP/100))/100
1240 PRINT"MEAN RUNNING SPEED = ";(INT100*SH)/100
1250 PRINT"MIN. RUNNING SPEED = ";(INT100*SH)/100
1260 PRINT"FATIGUE INDEX (SPEED) = ";(INT100*(SH-SL)/SH*100))/100

363
I29 - END PROC
130 DEF PROCMenu
1310 CLS
1320 PRINT;PRINT;PRINT"<KEY NO.> OF DESIRED OPTION"
1330 PRINT;PRINT"<F> FOR FORCE PROFILE"
1340 PRINT"<P> FOR POWER PROFILE"
1350 PRINT"<H> FOR RAM H.R. RECOVERY DATA"
1360 PRINT"<E> FOR PROGRAM END"
1370 PRINT"<S> FOR PROGRAM RE-START"
1380 IF Y=$"="GET$ THEN PROCMenu
1390 IF Y=$"=""F" THEN PROCForce
1800 IF Y=$"=""P" THEN PROCPlot
1810 IF Y=$"=""H" THEN PROCRawr
1820 IF Y=$"=""E" THEN END
1830 IF Y=$"=""S" THEN RUN
1843 GET01710
1953 ENDPROC
1860 DEF PROC Heart
1870 VDU2
1880 PRINT:PRINT:PRINT"HEART RATE PROFILE":PRINT
1890 PRINT":TIME (s) B.P.M.
1900 HT=40/H
1910 HM=Q:HN=J00:HC=0
1920 REPEAT
1930 HC=HC+1
1940 HR=(7(HM*HC+16+7(HL*HC)/16))*.119
1960 GT=INT(10*(HC+HT-II*T))/10
1970 PRINTGT,HC
1980 UNTIL HC=H
1990 IF NR="N" THEN 220
2000 PRINT:PRINT"RECOVERY HEART RATE"
2010 HC=0
2020 REPEAT
2030 FOR J=1 TO
2040 HC=HC+1
2050 HR%=HR%+17(HM*HC+16+7(HL*HC)/16))*.119
2060 NEXT
2070 UNTIL HC=CN
2080 VDU3
2100 ENDPROC
2110 DEF PROC Rawhr
2120 IF NR="N" THEN ENDPROC
2130 HC=0
2140 VDU2
2150 REPEAT
2160 PRINT:PRINT"RECOVERY HEART RATE (RAW DATA)"
2170 HC=HC+1
2180 HR%=HR%+17(HM*HC+16+7(HL*HC)/16))*.119
2190 PRINTINT10*(HC+ST))/10,HR%
2200 UNTIL HC=CN
2210 VDU3
2220 ENDPROC
2230 VDU5
MULTIPLE SPRINT DATA RETRIEVAL PROGRAM

100CLS
110 MODE4
120 VDU 23,1,0;0;0;
130 DIM dat% len%
140 VDU dat% len%
150 ref%=dat%
160PRINT
170 PRINT CHRS(151) CHRS(157) CHRS(132) ;"DATA RETRIEVAL PROGRAM";
180 #DRIVE 1
190 PRINT:PRINT CHRS(136) CHRS(129) CHRS(157) CHRS(130) ;"PUT DATA DISC INTO DRIVE 1";
200 PRINT:PRINT
210 PRINT CHRS(132) CHRS(157) CHRS(131) ;"NAME OF FILE TO BE RETRIEVED"; INPUT F:
220 GOSFOR LOAD "*F1*";"*STR#*dat1"
230 *DRIVE
240
250 FH%#dat%:50:FL%#dat%:550:SH%#dat%:1550:SL%#dat%:1550:HH%=dat%:2050:HL%=dat%:1550
260 W=(?ref%)^100-?ref%)^100
270 CS=?(ref%)^2*100+?(ref%+1))100
280 CF=?(ref%)^4*1000+?(ref%+1))100
290 N=?(ref%)^6*100+?(ref%+1)
300 NS=?(ref%)^8
310 MR=?(ref%+1)
320 DM=(ref%+1)*100+?(ref%+1)
330 CN=?(ref%+1)
340 FN=?(ref%+1)
350 VDU 2
360 PRINT:PRINT CHRS(131) CHRS(157) CHRS(131) ;"FILENAME = ";F1$;
370 PRINT CHRS(132) CHRS(157) CHRS(131) ;"SUBJECT WEIGHT = ";W;
380 PRINT CHRS(132) CHRS(157) CHRS(131) ;"SPEED CAL. FACTOR = ";CS;
390 PRINT CHRS(132) CHRS(157) CHRS(131) ;"FORCE CAL. FACTOR = ";CF;
400 PRINT CHRS(132) CHRS(157) CHRS(131) ;"FORCE CAL. FACT = ";FO;
410 PRINT CHRS(132) CHRS(157) CHRS(131) ;"NO. OF DATA POINTS = ";N;
420 PRINT CHRS(132) CHRS(157) CHRS(131) ;"NUMBER OF SPRINTS = ";NS;
430 PRINT CHRS(132) CHRS(157) CHRS(131) ;"TIME MONITORED (S) = ";DM;
440 PRINT CHRS(132) CHRS(157) CHRS(131) ;"NO. H.R. DATA POINTS = ";H;
450 VDU 3
500 PRINT:PRINT CHRS(131) CHRS(157) CHRS(132) ;"PRESS <SPACEBAR> TO CONTINUE";
510 Y$=GETs
520 CLS:CLG
530 PROC Speedplot
540 PROC Frame
550 PROCPrintout
560 PROC Heart
570 PROC Menu
580 END
590 DEF PROC Frame
600 MOVE 0,0
610 DRAW 200,0;DRAW 200,900;DRAW 0,900;DRAW 0,0
620 FOR I=100 TO 100 STEP 100:MOVE I,0:CLG:PAUSE 100:next I
630 FOR Y=100 TO 100 STEP 100:MOVE Y,0:CLG:PAUSE 100:next Y
640 PRINT CHRS(131) CHRS(131) CHRS(131) ;"TYPE I=LEFT...2=RIGHT...Y=BREAK POINT";
650 I=40
660 MOVE 1,40
670 MOVE 1,40

366
670 X$=GET$0
680 MOVEI,603;PLOT,I,1,40
690 IF X$="2" THEN I=I+4;GOTO720
700 IF X$="1" THEN I=I-2;GOTO720
710 IF X$="6" THEN PROCDisx
720 IF X$="Y" THEN 740
730 GOTO660
740 XI=I+N/120
750 ENDPROC
760 DEFPROCDiplopIat
770 I=0
780 REPEAT
790 I=I+1;NH=I50+1;NL=I530+1
800 SI=7;datX+NH)16+7;datX+NL)/16*CS+103
810 SI=7;datX+NH+1)16+7;datX+NL+1)/16*CS+103
820 MOVE1200/N*1,SL;DRAW:200:N*1(+1),SL
830 UNTIL I=N
840 ENDPROC
850 DEF PROCPrintout
850 TT=12/N
860 CLSCLS
870 PRINTCHR$(131);CHR$(137);CHR$(132);"INTEGRATION PERIOD = ";INPUTIP
880 CLS
890 VDU2
900 PRINT
910 PRINT"BREAKPOINT SET = ";INT(100*X*I+TT)/100;" SECS"
920 PRINT
930 PRINT"TIME SPEED FORCE POWER P/Bu"
940 PRINT
950 XP=6/IP
960 SH=0;SL=100;DS=0;PB=0;PF=3;PM=100000;P=3;CBl=XI
970 FORAA=0TO(IP-1)
980 CA=0;SP=0;FP=0
990 REPEAT
1000 SP=SP+(SP+SH*X)*16+7.(SL+CB%)/16*CS
1010 FP=FP+(FP+SH*CB1)*16+7.(FL+CS%)/16*CF
1020 CA=CA+1;CBl=CA+1
1030 UNTIL CA>IP/TT
1040 SP=SP*CA;FP=FP/CA
1050 PRINT;"(A+1)*IP";"INT(100*SP)/100;";INT(100*FP)/100;"INT(100*SF*FP)/100;
1060 IFSP>SH THEN SH=SP
1070 IFSP<SL THEN SL=SP
1080 IFSP<SL THEN SL=SP
1090 IFSP<SL THEN SL=SP
1100 I=I-1;GOTO100
1110 DS=DS+SP+FP
1120 WD=WD+SP+FP
1130 PD=PD+SP+FP
1140 PW=PW+SP+FP
1150 PE=SP+FP
1153 NEXT
1160 PRINT
1170 PRINT "DISTANCE RUN = " ; INT(100*SD)/100
1180 PRINT "MEAN RUNNING SPEED m/s = " ; INT(100*68)/100
1190 PRINT "TOTAL WORK DONE (tor) = " ; INT(100*WC)/100
1200 PRINT "MEAN POWER OUTPUT (W) = " ; INT(100*PD)/100
1210 PRINT "MEAN POWER/WEIGHT = " ; INT(1000*PP/WE)/1000
1220 PRINT "MEAN POWER OUTPUT (W) = " ; INT(1000*PP/WE)/1000
1230 PRINT "MEAN POWER OUTPUT (W) = " ; INT(1000*PP/WE)/1000
1240 PRINT "MEAN POWER OUTPUT (W) = " ; INT(1000*PP/WE)/1000
1250 PRINT "MEAN POWER OUTPUT (POWER) = " ; INT(100*(PP-PE))/100
1260 PRINT "MEAN POWER OUTPUT (W) = " ; INT(1000*(SH+SP)/SH+100)/100
1270 PRINT "MEAN POWER OUTPUT (W) = " ; INT(1000*(SH+SP)/SH+100)/100
1280 PRINT "MEAN POWER OUTPUT (W) = " ; INT(1000*(SH+SP)/SH+100)/100
1290 PRINT "TOTAL WORK = " ; INT(100*(SH+SP)/SH+100)/100
1300 ENDPROC
1310 DEF PROC dump
1320 *G0.4 2 1 0 0 0 0 1279 900
1330 END PROC
1340 DEF PROC force
1350 CLS:CLG
1360 FOR I=200 TO 1000 STEP 200:MOVE I,0:PLOT 6, I, 32:NEXT
1370 FOR I=50 TO 830 STEP 50:MOVE 0, I:PLOT 6,32,1:NEXT
1380 PRINT:PRINT "FORCE PROFILE - " ; F1*
1390 I=Xt-1
1400 REPEAT
1410 I=I+1:MH=58+I:NL=550+1
1420 FZ=77{dat+NH)*16+7{(dat+NL)/16-F32]*CF
1430 F1X=7{(dat+NH+1)*16+7{(dat+NL+1)/16-F32]*CF
1450 UNTIL I>N*4+XI
1460 ENDPROC
1470 *G0.4 2 1 0 0 0 0 0
1480 ENDPROC
1490 DEFPROC plot
1500 CLS:CLG
1510 FOR I=200 TO 1000 STEP 200:MOVE I,0:PLOT 6, I, 32:NEXT
1520 FOR I=50 TO 830 STEP 50:MOVE 0, I:PLOT 6,32,1:NEXT
1530 PRINT:PRINT "FORCE PROFILE - " ; F1*
1540 I=Xt-1
1550 REPEAT
1560 I=I+1:MH=58+I:NL=550+1
1570 FZ=77{dat+NH)*16+7{(dat+NL)/16-F32]*CF
1580 F1X=7{(dat+NH+1)*16+7{(dat+NL+1)/16-F32]*CF
1600 UNTIL I>N*4+XI
1700 DEF PROCMenu
1710 CLS
1720 PRINT: PRINT: PRINT "PRESS <KEY NUM.> OF DESIRED OPTION"
1730 PRINT: PRINT: "F" FOR FORCE PROFILE"
1740 PRINT: PRINT: "P" FOR POWER PROFILE"
1750 PRINT: PRINT: "R" FOR RAW H.R. RECOVERY DATA"
1760 PRINT: PRINT: "E" FOR PROGRAM END"
1770 PRINT: PRINT: "S" FOR PROGRAM RE-START"
1780 Y$ = GET$0
1790 IF Y$ = "F" THEN PROCforce
1800 IF Y$ = "P" THEN PROCpowerplat
1810 IF Y$ = "R" THEN PROCrawhr
1820 IF Y$ = "E" THEN END
1830 IF Y$ = "S" THEN RUN
1840 GOTO 1710
1850 ENDPROC
1860 DEF PROCheart
1870 VDU2
1880 PRINT: PRINT: PRINT "HEART RATE PROFILE"
1890 PRINT: PRINT: "TIME (S) B.P.M.*
1900 HT=32/H
1910 HM=0; NN=300; HC=0
1920 REPEAT
1930 HC+HC+1
1940 HRZ=(7(HHZ+HC)/16+7(HLZ+HC)/16)*.115
1950 GT=INT(10*(HC+HT-XI+IT))/10
1960 PRINTG,T, HRZ
1970 UNTIL HC=H
1980 VDU5
2000 ENDP
SHORT MULTIPLE SPRINT RETRIEVAL PROGRAM

100 N=443
110 CLS
120 MODE0
130 NN=0
140 VDU 23,1,0;0;
150 len%=2550
160 DIM datl(len%) 1en%
170 ref%=datl%
180 SHZ=dat%+1050:SL=dat%+1550
185 FHZ=dat%+50:FL=dat%+550
190 WHZ=dat%+2050:HL=dat%+2150
190 PRINT:PRINT:"FILENAME TO BE RETRIEVED":INPUTFILE
200 NN=#STR$(NN)
210 FIS=LEFT$(FILE,6)
220 DELETE
230 OSCL"LOAD "+FILENAME+6 "DAT"
240 DELETE
250 CLS
260 PRINT"FILE BEING EXAMINED = ";FIS;" (SPEED)"
270 PRINT"PRESS (SPACEBAR) FOR NEXT FILE. <F> FOR FORCE PROFILE OF CURRENT FILE"
280 NN=NN+1
290 MOVEO,0
300 FOR=1 TO 1000:MOVEO,0:PL0T6,I,25:NEXT
310 FOR I=1 TO
320 S=7(SHZ+I)*16+(SL+I)/16
330 PRINTTAB(50,0);I,S
340 FOR I=1 TO
350 F=(FHZ+I)*16+(FL+I)/16
360 PRINTTAB(50,0);I,F
370 NEXT
380 Y$=GET$
390 IF Y$=" THEN 600
400 MOVEO,0
410 FOR=1 TO 1000:MOVEO,0:PL0T6,I,25:NEXT
420 FOR I=1 TO
430 H=(HHZ+I)*16+(HLZ+I)/16
440 PRINTTAB(50,0);I,H
450 NEXT
460 Y$=GET$
470 IF Y$=" THEN 600
480 MOVEO,0
490 FOR=1 TO 1000:MOVEO,0:PL0T6,I,25:NEXT
500 NEXT
510 Y$=GET$
520 IF Y$=" THEN 600
530 GOTO200
540 CLR:CLS
550 PRINT"FILE BEING EXAMINED = ";FIS;" (FORCE)"
560 PRINT"PRESS (SPACEBAR) FOR NEXT FILE. <H> FOR HEARTRATE PROFILE"
570 GOTO200
580 FOR=1 TO 1000:MOVEO,0:PL0T6,I,25:NEXT
590 FOR I=1 TO
600 H=(HHZ+I)*16+(HLZ+I)/16
610 PRINTTAB(50,0);I,H
620 NEXT
630 Y$=GET$
640 IF Y$=" THEN 600
650 MOVEO,0
660 FOR=1 TO 1000:MOVEO,0:PL0T6,I,25:NEXT
670 FOR I=1 TO
680 H=(HHZ+I)*16+(HLZ+I)/16
690 PRINTTAB(50,0);I,H
700 NEXT
710 Y$=GET$
720 GOTO200
MULTIPLE HEART RATE PLOT PROGRAM

100 N=0
110 VDU 27,2,0,0,0;
120 len$=250
130 DIM dat% len$
140 HH%=dat%+2050:HL%=dat%+2150
150 MODE0
160 CLG
170 CLS
180 MODE0
190 PRINT"STARTING FILENAME ":INPUTFN$;
190 PRINT"NO. OF SEQUENTIAL FILES TO BE EXAMINED ":INPUT N;
200 CLS
210 *DRIVE1
220 OSCIL*LOAD "+FI$+" "+STR$+dat$
230 *DRIVE0
240 H=? (dat%+12)
250 HT=31/H
260 IFN=N THEN180
270 MOVE0,0
280 DRAW1200,0;DRAW1200,1000;DRAW0,1000;DRAW0,0
290 FORI=0 TO I160 STEP40
300 MOVE,0;PLOT6,1,2
310 NEXT
320 X=95
330 MOVE40+X,0;DRAW40+X,1000
340 MOVE,0;DRAW1,1000
350 MOVE+40,0;PLOT21,X+360,1000
360 FORI=200 TO 0 STEP 200
370 MOVE0,1;PLOT6,32,1
380 NEXT
390 FORJ=0 TO I160
400 I=I+1
410 HZ=(? (HH%+I)*16+? (HL%+I)/16)+.115
420 HZ=(? (HH%+I+1)*16+? (HL%+I+1)/16)+.115
430 MOVEJ*HL,H;HT,(HZ-100)*10;DRAW(J+1)*HL,H;HT,(HZ-100)*10
440 NEXT
450 N=N+1
460 IF N=9 THEN 480
470 GOTO210
480 PRINTTAB(49,15);"FILE-NAME = "+LEFT$(FN$+6)
490 PRINTTAB60,30;"SECONDS"
500 PRINTTAB11,30;"100"
510 PRINTTAB11,24;"120"
520 PRINTTAB11,18;"140"
530 PRINTTAB11,12;"160"
540 PRINTTAB11,6;"180"
550 PRINTTAB11,1;"HEART-RATE"
555 PRINTTAB10,27;"SPRINT"
560 PRINTTAB46,27;"RECOVERY"
560 Z=GET
570*G0.4 2 1 0 0 0 0 0 0
APPENDIX 2
30s MAXIMAL TEST ON THE CYCLE ERGOMETER
TEST PROTOCOL SUMMARY.

1. Switch on the computer at least two hours before test.

2. Stabilise reference supply for the internal A-to-D of the computer. This is most easily achieved by placing a precision reference diode (example Type 04BJ [Radiospares]) across the reference voltage pins of the A-to-D converter. Note: the reference voltage of the precision diode must be less than 1.8 volts. The maximum potential difference applied to the A-to-D input is limited by the value of the reference diode.

3. Establish the calibration factor for the flywheel speed transducer.

4. Plot the flywheel deceleration profiles for different resistive loads. Calculate the load/deceleration regression equation.

5. Calculate the desired load for the test:
   For rolling start use $- 65g.kg^{-1}$ Bodyweight.
   For stationary start use $- 55g.kg^{-1}$ Bodyweight.

6. Establish the correct seat height for the subject. The seat such be raised to the last setting at which the subject's knee is still slightly flexed when the pedal is at the bottom of its travel. Check to see that the hips are not swinging whilst the subject is pedalling at a light load.

7. Prior to the test allow the subject to warm-up. A recommended protocol would be: Pedal for 30 seconds at 30 k.p.h. with a load of
1.5 kg. This should be followed by 30 seconds rest.
Then pedal for a further 30 seconds at 40 k.p.h. with
the same load. The subject should then be allowed
to stretch for 3 minutes, with particular emphasis
being placed on the Quadriceps and Hamstring groups.

8. Establishing the start point of the test.
The data collection by the computer should be started
just prior to the start of the sprint itself. The change
in speed detected from the speed profile should be
used to establish the start point of the test.

9. If a rolling start is used the rolling speed
should be in the range 60-70 pedal r.p.m. The subjects
should be urged to maintain this speed during the
establishment of the load.

10. In the rolling start protocol the load should be
supported by the tester whilst the subject accelerates
the flywheel up to the required speed. The tester
then counts down 3-2-1—GO!. Whilst saying "one" the
the load should be introduced quickly BUT SMOOTHLY!

NOTE - The tester much check that the load is being
correctly supported by the Sinus balance. The
ergometer was not intended to handle the high loads
used in these tests. Incorrect loading is the
main cause of error in such tests.

11. Once the load has been applied the subject is
encouraged to work maximally for the full 30 seconds.
It is not recommended that the subject is
informed of the elapsed time until at least 15
seconds into the test.

NOTE - There is a tendency for the subject to rise out
of the saddle during the acceleration phase of
the sprint. The subject should be carefully
instructed not to rise out of the saddle at any time during the test.

12. The computer should monitor the test for longer than the 30 seconds so that data from the whole test is collected. All the raw data from the test should be stored on disc for later retrieval.

13. Once the test is completed the pedalling speed and power output averaged over each second of the test should be calculated. The corrected method of calculation described in this thesis should be used to determine power output.

14. The following indices should be calculated:
   a) Peak power output: The highest 1 second averaged value of power output.
   b) Work done: The total work done during the test. Mean power output will be the total work done divided by 30.
   c) Fatigue index: This is defined as

   \[(\text{P.P.O.} - \text{E.P.O.})/ \text{P.P.O.} \times 100 \%]\n
   where: P.P.O. is peak power output
   E.P.O. is end power output.
APPENDIX 3

30s MAXIMAL TEST ON THE SPRINT TREADMILL ERGOMETER
TEST PROTOCOL SUMMARY.

1. Switch on all analogue systems at least two hours before test.

2. Establish the calibration factor for the treadmill speed transducer. A minimum of 100 revolutions of the treadmill belt should be used.

3. Determine the calibration factor for the force transducer.

4. Prior to the test allow the subject to warm-up. A recommended protocol would be:
   Run for 30 seconds at 2m.s\(^{-1}\).
   This should be followed by 30 seconds rest.
   Then run for a further 30 seconds at 3m.s\(^{-1}\).
   The subject should then be allowed to stretch for 3 minutes, with particular emphasis being placed on the Quadriceps and Hamstring groups.

5. Set the height and angle of the tether strap. The results described in this thesis show that the tether strap should be slightly above the horizontal, with the highest end attached to the subject. The actual angle will be dependent on the length of the tether strap.

6. Just prior to the test the treadmill itself should be warmed-up to standardise rolling resistance. This is best achieved by attaching an electric motor to the treadmill, which is run until the product of the potential difference across it and the current flowing through it drops to a predetermined value.
7. A rolling start should be used. A speed of $2\text{m.s}^{-1}$ was found to be suitable.

8. Establishing the start point of the test.
The data collection by the computer should be started just prior to the start of the sprint itself. The change in speed detected from the speed profile should be used to establish the start point of the test.

9. Once up to the rolling start speed the tester counts down "3-2-1-GO". On the command GO the subject attempts to accelerate the treadmill as rapidly as possible. The tendency is for the subject to lean too far forward during this acceleration phase causing problems with maintaining balance. The subject should be urged to keep as upright as is comfortable. (Plenty of familiarisation of the start of the sprint is required!)

10. Once the sprint has started the subject is encouraged to work maximally for the full 30 seconds. It is not recommended that the subject is informed of the elapsed time until at least 15 seconds into the test.

11. The computer should monitor the test for longer than the 30 seconds so that data from the whole test is collected. All the raw data from the test should be stored on disc for later retrieval.

12. Once the test is completed the running speed and power output averaged over each second of the test should be calculated.
13. The following indices should be calculated:
   a). Peak power output: The highest 1 second averaged value of power output.
   b). Work done: The total work done during the test. Mean power output will be the total work done divided by 30.
   c). Fatigue index: This is defined as

\[
\frac{(P.P.O. - E.P.O.)}{P.P.O.} \times 100 \, \% 
\]

where: P.P.O. is peak power output
       E.P.O. is end power output.

In addition stride frequency and stride rate should be determined for each 5 seconds of the test and for the test as a whole.