# ECONOMY AND EFFICIENCY OF HUMAN LOCOMOTION

BY

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# ABSTRACT

Human locomotor economy and efficiency are highly variable. This study investigated the role that stature plays in this variation, by evaluating metabolic and respiratory responses to walking and running at speeds set relative to one's stature.

Four groups of subjects: male, high $\dot{V}O_2$ max (n = 11); male, average $\dot{V}O_2$ max (n = 10); female, high $\dot{V}O_2$ max (n = 10); and female, average $\dot{V}O_2$ max (n = 11) were habituated to treadmill locomotion prior to the measurement of maximal oxygen consumption ($\dot{V}O_2$ max). The $\dot{V}O_2$ max test entailed 1 $km.h^{-1}$ increases per min from 3 to 6 $km.h^{-1}$ walking, and 7 - 17 $km.h^{-1}$ running then 1% grade increments per min until exhaustion. On each of four other occasions, the subject walked or ran at 6 of a variety of relative speeds - walking at 0.5, 0.7, 0.9, 1.1, 1.3; running at 1.5, 1.7, 1.9 and for selected subjects 2.1, 2.3 and 2.5 $statures.s^{-1}$, and grades - 0%, +3%, -3%. Steady-state respiratory and metabolic responses, and treadmill speed were monitored by an on-line computer system developed for this study. Cadence and RPE were also monitored.

All subjects demonstrated an exponential relationship between $\dot{V}O_2$ and walking relative speed ($st.s^{-1}$) (RS).

$$\dot{V}O_2\ (ml.kg^{-1}.min^{-1}) = 4.747 * e^{(1.371*RS)}$$

During running this relationship was essentially linear. The variability of economy at relative speed (9.08%) and absolute speed (9.01%) did not differ.

Male and female subjects did not differ in response to absolute speed but females were more economical at relative speeds ($p<0.05$). Those with high and average aerobic capacity did not differ in locomotor economy at relative speed. Higher freely-chosen stride length was associated with a higher $\dot{V}O_2$ response as velocity increased.

The $\dot{V}O_2$ of uphill walking was 1.4 times greater than that for downhill walking (running: 1.28 times). Stride length decreased with increasing speed in uphill locomotion but the reverse was the case for downhill.

The economy and efficiency of walking was greater than that of running. Walking economy was maximal between 0.7 and 0.9 $st.s^{-1}$. Running economy remained essentially unaffected by increased velocity.

The setting of locomotor velocity relative to stature does not minimize inter-subject variability in metabolic and respiratory response.

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# CHAPTER I

# THE PROBLEM

## INTRODUCTION

It is commonly observed (Finley and Cody 1970) that people of differing heights, walking at the same absolute velocity, adopt different locomotion strategies. The taller people, whose greater leg length enables a longer stride, take relatively fewer steps than the shorter people. To maintain the same cadence, the shorter person must take an exaggerated stride. Either way, it would seem to follow that it is more "difficult" for the shorter person to match the absolute velocity of the taller. Certainly the kinematics of locomotion differ between the taller and shorter individuals walking at the same velocity (Murray _et al_ 1964).

The scaling of locomotor response to the morphological characteristics of the animal in a variety of species has clearly indicated that body length (stature in man) plays a role in both the mechanics of locomotion and the subsequent physiological response (Taylor _et al_ 1970, Alexander 1976, Alexander 1977, Heglund _et al_ 1982). Grieve and Gear (1966) recognized the significance of stature in modifying the kinematics of locomotion and developed the concept of relative speed (RS) to equalize velocity based on stature. They defined relative speed as that fraction of body stature (m) covered overground during locomotion per second. It is commonly expressed as statures per second (st.$s^{-1}$). Since that time, researchers have employed relative speed to equalize locomotor conditions between subjects not only for the purpose of kinematic or rehabilitative analyses (Rosenrot et al 1980, Wall and Charteris 1981, Charteris 1982) but also to enable physiological assessments (Das and Ganguli 1979).

Researchers in the field of human metabolic locomotor response have largely ignored the implications of this biologically based generalization. The vast majority of studies, almost without exception, which have examined the relationship between walking and/or running velocity and the energy cost of locomotion have concerned themselves with movement at absolute velocities (Fenn 1930, Elftman 1939a, 1939b, Margaria et al 1963, Lloyd and Zacks 1972, Sakurai and Miyashita 1983). Many attempts have been made at developing equations to predict the energy cost of locomotion (Cavagna et al 1964, Cavagna and Margaria 1966, Givoni and Goldman 1971) but the precision of such predictions is hampered by the inter-subject variability in oxygen consumption at absolute velocities. This has been estimated to be in the region of 10% to 30% (Durnin and Namyslowski 1958, Shephard 1976, Mayhew 1977).

The sources of this inter-subject variability are many and varied. At the cellular level contraction-coupling efficiency, mitochondrial activity and enzyme action may differ between individuals (Whipp and Wasserman 1969, Wilkie 1974, Sjodin 1983). The fibre type composition of the active musculature varies as a function of genetic inheritance (Thorstensson 1976, Saltin et al 1977, Bergh et al 1978). Slow-twitch, oxidative muscle fibres are more efficient than fast-twitch glycolytic fibres (Crow and Kushmerick 1982). Subject-to-subject variability in fast/slow twitch fibre ratio will, thus, influence the oxygen consumption at any given locomotor velocity. The individual's inherent elasticity of muscle fibre and associated connective tissue contributes to this variability, as does the individually differing oxygen transport kinetics in the cardio-vascular system. Cell membrane permeability and partial pressure differentials may also vary from person to person (Astrand and Rodahl 1977).

Neuro-muscular patterning of bodily movement, i.e. the skill and co-ordination involved in movement, certainly differs from one person to the next, even in such a fundamentally human movement pattern as walking or running. Joint and tendon kinesthetic feedback, motor control centre patterning and perceptual-environmental cues all play a role in the differential response of individuals to locomotion at a given velocity (Winter 1978b, Rejeski et al 1982, Cavanagh and Kram 1983). Pressure, pain and stretch receptors contribute via feedback-loop mechanisms to moderate the movement pattern of an individual during locomotion (Astrand and Rodahl 1977).

The mechanics of locomotion differ from one person to the next. Morphological characteristics of the body such as mass, segmental lengths and volume, and overall stature contribute significantly to locomotor mechanics. The forces generated, the distances moved through, the angular displacements of body segments, the inertial forces overcome, the inter-segment transfers of momentum, and the vertical and lateral oscillations of the body centre of gravity vary considerably between individuals at the same locomotor velocity (Winter 1983a, 1983c, 1984). Cadence and stride length differ, as does pelvic step (Saunders et al 1953, Grieve and Gear 1966). Joint and ground-foot friction provide variable resistance to movement between, and within individuals.

Energy storage in muscle and the transfer of energy from segment to segment contribute significantly to inter-subject differences in oxygen consumption at any given velocity (Cavagna et al 1963, Winter 1979a, Ito et al 1983). The absorption of energy during eccentric muscle loading such as occurs after heel strike during braking double support is thought to play a significant, but individually variable, role in energy transfer from one stride to the next.

All of these factors play a significant role in the differences between individuals in the energy cost of locomotion at a given velocity. Furthermore, these factors contribute to the overall efficiency of human locomotion.

Efficiency, as a functional concept, has significance at both micro and macro levels.

A.V. Hill (1922) first explored the force-velocity relationship in isolated muscle, and demonstrated that the power-velocity curve, generated from this relationship, had a point of optimal power output at about 30% of maximal shortening velocity. By considering the energy cost of developing tension under various conditions, he produced a muscle efficiency-shortening velocity curve. Hill's experiments demonstrated that optimal efficiency was achieved at about 20% of maximal shortening velocity. Since that time, many researchers have explored the relationship between power output and energy cost, both in isolated muscle preparations and *in vivo*.

Any attempt to quantify "efficiency" requires, as a prerequisite, an understanding of the term. While the dictionary definition - work done divided by energy expended - is straightforward, many variations on this basic theme have clouded the issue. "Gross efficiency" (Gaesser and Brooks 1975) or "muscular efficiency" (Stainsby *et al* 1980) has been defined as the ratio of mechanical work to the metabolic energy expended. It has been recognized that some of the metabolic energy expended during locomotion is used for basic life support functions such as circulation, respiration, digestion, etc. These must occur, at a minimal level, regardless of the power output. Accordingly, in "net efficiency" the denominator is defined as "the energy expended above that at rest".

When the subject is performing work on an ergometer, overcoming the internal machine resistance to movement combined with the reciprocating work of limb movement requires an energy expenditure above that at rest. The term "work efficiency" was coined to account for this work, in which the denominator was "the energy expended above that used in working against zero added load". Another attempt to relate increases in energy expenditure to the increases in power output that bring them about was labelled "delta efficiency". This was defined as the average gradient of the energy expended versus work done curve between two specified limits for the work done (Gaesser and Brooks 1975, Stainsby et al 1980).

While this variability in terminology has some validity in physiological terms, a much more complex problem presents itself in the numerator - the work done. At first glance the work done in any task should be easy to quantify. It is, purely, a function of the acceleration of a mass through a known distance. The measurement of the forces applied and the distances through which they are applied during human locomotion, however, is a particularly difficult task. Locomotion involves reciprocal action of the extremities and the trunk. It involves the production of energy output through positive work and the absorption of energy through negative work which occurs with the rise and fall of the centre of mass of the body during every stride. Furthermore, forces are being applied by the body to the locomotor surface in sagittal, frontal and transverse planes in a variety of combinations at different stages of the step cycle. Metabolic energy is expended during each of these energy exchanges between body parts, and between the body and the locomotion surface. While it is not impossible to measure the various components of human locomotion power output, it is technically difficult and expensive (Winter 1979a) requiring force platforms and/or high speed cinematography combined with sophisticated computer-aided analysis. Because of these difficulties, and because of the relative ease of measurement of work done vertically, most workers in the field have limited their measurement of power output to that accomplished against gravity in a vertical plane (Gordon et al 1983). The omission of various components of the power output, and the differences in assumptions made regarding energy transfer have led to an enormous variability in the stated efficiency of human locomotion ranging from -120% (Margaria 1968) to +197% (Norman et al 1976). These figures are all the less believable when one considers that the efficiency for the whole process of converting foodstuff into tension through phosphorylation coupling and contraction coupling has been measured in vitro at approximately 29% (Whipp and Wasserman 1969).

Human overground locomotion involves horizontal, and, when grade walking, net vertical displacement of the mass of the body. Throughout this whole process, the centre of mass of the body is being alternately raised and lowered with every step. Each of these processes requires metabolic energy expenditure. Fractional utilization of maximal oxygen consumption ($\dot{V}O_2$ max) during locomotion has been found to be an important determinant of endurance performance (Costill et al 1973). From an efficiency point of view it is generally agreed that regardless of the $\dot{V}O_2$ max, the lower the submaximal energy cost for a given velocity of movement the better. In other words, the less energy expended to raise and lower the centre of mass of the body the better as this leaves a greater proportion of the total energy available to effect horizontal movement. Individuals vary considerably in the amount of energy to perform the same submaximal task, such as running at a given velocity. This does not necessarily imply differences in efficiency, as differing amounts of mechanical work may be performed by different subjects. Success at endurance running is highly related to the energy cost but is independent of the actual work done (Conley and Krahenbuhl 1980). Because of the practical significance of this, and the difficulty in quantifying all the work done, the term "economy" (the sub-maximal oxygen uptake per unit body mass required to perform a given task) has become an accepted criterion measure for "efficient" performance. (Cavanagh and Kram 1983).

Locomotor efficiency, locomotor economy and the velocity of locomotion are inextricably interwoven. Velocity of movement is quite simply, a function of cadence and stride length. While many of the factors, mentioned above, contribute to alterations in cadence and/or stride length, body morphology, in all its ramifications, is a major contributor. If locomotor velocity is standardized for some significant aspect of morphology, what would the effect be on the economy or efficiency of locomotion? Would the energy cost per unit velocity or per unit power output be substantially more consistent between individuals if it were?

The question addressed in this study is one of broad biological significance. Are there minima for locomotor energy expenditures when such expenditures are related to anatomical structures? In other words, what are the relationships between human energy expenditure, human allometry and locomotor power output?

## STATEMENT OF THE PROBLEM

The problem addressed in this study was to elucidate the relationship between locomotor velocity, when set according to body stature, and the consequent energy expenditure. Aspects of human economy, human efficiency and human morphology play a role in this relationship, and these traits were examined to elucidate and exemplify the relationship.

## RESEARCH HYPOTHESES

A number of hypotheses were forwarded to enable a broad examination of the relationship between relative speed and energy expenditure.

Hypothesis 1

The economy of locomotion is a linear function of relative speed from slow walking to moderate running velocities. Another way to state this hypothesis is that as relative velocity increases the change in economy divided by the change in relative velocity is a constant.

Stated statistically, the null hypothesis was:

Ho: $\rho^2$ (linear) $>= \rho^2$ (curvilinear)

Where $\rho^2$ is the population coefficient of determination for the relationship between relative speed and economy.

The alternative hypothesis was:

Ha: $\rho^2$ (linear) $< \rho^2$ (curvilinear)

Hypothesis 2

In order to evaluate the suitability of the use of relative speed as a method of equalizing effort between individuals, the following hypothesis was tested. The intersubject variability in oxygen consumption at absolute velocities is equal to the variability of oxygen consumption over a comparable range of relative speeds from slow walking to moderate running.

Stated statistically, the null hypothesis was:

Ho: $\sigma^2$ (absolute speeds) = $\sigma^2$ (relative speeds)

Where $\sigma^2$ is the population variance in oxygen consumption.

The alternative hypothesis was:

Ha: $\sigma^2$ (absolute speeds) $\neq \sigma^2$ (relative speeds)

Hypothesis 3

To explore sexual dimorphism, it was hypothesized that the economy of male subjects did not differ from the economy of female subjects at comparable relative speeds from slow walking to moderate running.

Stated statistically, the null hypothesis was:

Ho: $\mu$ (male) = $\mu$ (female)

Where $\mu$ was the population mean walking or running economy at relative speeds.

The alternative hypothesis was:

Ha: $\mu$ (male) $\neq \mu$ (female)

Hypothesis 4

To explore the effect of aerobic capability, it was hypothesized there were no differences between people with high and those with average maximal oxygen uptakes in terms of the economy of locomotion at relative speeds ranging from slow walking to moderate running.

Stated statistically, the null hypothesis was:

$$\text{Ho:} \quad \mu \text{ (high } \dot{V}O_2 \text{ max)} = \mu \text{ (avg } \dot{V}O_2 \text{ max)}$$

Where $\mu$ is the population mean economy at various relative speeds in high and low aerobic capacity groups.

The alternative hypothesis was:

$$\text{Ha:} \quad \mu \text{ (high } \dot{V}O_2 \text{ max)} \neq \mu \text{ (avg } \dot{V}O_2 \text{ max)}$$

## DELIMITATIONS

Fourty-two young adult subjects, of whom 21 were males and 21 were females, acted as subjects for this study. Half of each group were classified as having a high maximal oxygen consumption ($\dot{V}O_2$ max), while the other half had an average to low $\dot{V}O_2$ max. Each subject was habituated to treadmill walking and running with one hour of distributed practice. Body stature, sitting height, body mass, foot length and four skinfold fat measurements were obtained. Maximal oxygen consumption was measured during a progressive, continuously increasing speed test. Each subject was randomly exposed to a number of walking speeds relative to stature (0.5, 0.7, 0.9, 1.1 and 1.3 $st.s^{-1}$) and three running speeds (1.5, 1.7 and 1.9 $st.s^{-1}$) at each of +3%, 0% and -3% grade. Oxygen consumption, ratings of perceived exertion and stepping cadence were obtained during each condition.

## LIMITATIONS

The following limitations must be borne in mind while examining the implications of these experimental results and subsequent conclusions.

1. The subjects were not randomly selected. The substantial time commitment and the nature of each subject's involvement meant that potential subjects were approached with an explanation of experimental procedures and a request for voluntary participation. Every attempt was made, however, to approach as broad a spectrum of potential subjects as possible within the University student population.

2. Although every effort was made to insure that subjects had returned to resting status prior to each walk/run condition, there was no way to evaluate the cumulative effect of the six conditions per test. However, the random presentation of conditions and the variable recovery period acted to minimize the influence of one condition on another.

3. Relative speed was only calculated using overall body stature. Other aspects of morphology such as leg length, or body surface area might have been more appropriate but the setting of speeds relative to other aspects of morphology was beyond the scope of the study. Stature was selected for ease of measurement and universal applicability.

4. Subjects were not tested at the same time of day during each session. Thus, diurnal variation in exercise response might have influenced the experimental results.

5. Other than voluntary compliance with a request to maintain normal eating and exercise habits during the course of the experiment, there was no control over these external influences.

6. All of the locomotion in this experiment was carried out on the treadmill, in a laboratory setting. Extrapolation of these results to overground locomotion outside the laboratory may not be possible.

7. The contribution of anaerobic metabolism to each of the exercise conditions was not evaluated. Exercise economy was, thus, limited to the aerobic contribution during exercise only.

# CHAPTER II

# REVIEW OF RELATED LITERATURE

## MORPHOLOGY AND HUMAN LOCOMOTION

Human movement is the result of a network of causation which encompasses man's biophysical, physiological, psycho-social and conceptual being. The very act of writing these words embodies this holistic principle. Influences as disparate as visual acuity, the action of ATPase, potential and kinetic energy, concept formation, hand-eye co-ordination and motivation, amongst many others, play an important interactive role in determining the nature and scope of this manipulative skill. Human locomotion is no less complex. Form and function interact intricately with intentionality to produce the locomotor versatility we take for granted.

Allometric principles serve to introduce the relationship between form and function. Astrand and Rodahl (1977), basing their discussion of this topic on the works of Asmussen, van Dobeln, Hill, Tanner and others, point out that certain dimensions and functional capacities are determined by fundamental mechanical necessities. There exist between different parts of an organism definite allometric relationships such that if one structure changes, others will also change by amounts depending upon the nature of the relationship (Harrison et al 1977). In terms of static dimensions, areas such as body surface area and cross-sectional area of muscle are proportional to linear size raised to the second power, while volumes such as lung volume, blood volume or heart volume are proportional to linear size raised to the third power. The same applies to mass measured in units of weight since the density of biological materials is generally independent of size (Astrand and Rodahl 1977).

Length, area and volume are related, in the same way, to the dynamics of muscular contraction and the supporting cardio-respiratory system. Muscular force development is proportional to muscle surface area, and the magnitude of work accomplished is proportional to linear dimension cubed. This militates against the larger and stronger individual who is handicapped by the greater body mass he must lift vertically. The ability to perform vertical work is inversely proportional to linear body dimension. Astrand and Rodahl (1977) point out that as acceleration is equal to force divided by mass, force is proportional to length squared and mass is proportional to length cubed, acceleration is proportional to the ratio between length squared and length cubed making it inversely proportional to linear dimensions. Accordingly, the taller (and heavier) person is handicapped when it is a matter of accelerating his body mass.

The shorter the time of one step during walking the higher the step frequency. It has been pointed out that it is generally the case that the frequency of limb motion should vary as an inverse function of limb length (Hill 1950). Running speed is a function of length of stride and cadence. Maximal running speed is unrelated to stature as short limbs with short strides may move more rapidly and can cover as much ground as do longer ones moving more slowly.

Astrand and Rodahl (1977) suggest that the above reasoning, when considered in the light of the secular trend of increased body stature, would indicate that a 6% secular increase in stature means that muscular strength should be 13% higher. Furthermore, maximal work output should be 20% greater. When the oxygen transport system is the limiting factor, the taller athlete should be able to deliver 13% more oxygen to his muscles per unit of time than the smaller athlete.

Leg length, an important linear measure related to locomotion, has been measured in a variety of ways (Montagu 1960). Harrison *et al* (1977) point out that leg length obtained by stature minus sitting height is less than anatomical (trochanteric) length because the level of the acetabulum is some centimetres above the seat level. They reported sitting height/stature ratios between 45-50% in African negro peoples and Australian aborigines, and 53-54% in Chinese, Inuit, and Amerind samples.

The correlation between leg length and stature is very high. Rosenrot *et al* (1980) report a correlation higher than r = 0.99 while Harrison *et al* (1977) report a lower correlation (r = 0.864) for data from a much larger sample. Because of the difficulty in obtaining a reliable and valid measure of leg length, the ease of measuring stature and the high degree of relationship between the two when properly measured, it has been suggested that stature be used, rather than leg length, in equating the relative velocities of individuals of differing linear dimensions (Rosenrot *et al* 1980).

The relationship between leg length and the energy cost of locomotion has been explored by a number of authors. Wyndham *et al* (1971), in a study of the energy cost of treadmill and overground walking, found that 80% of the variance in oxygen consumption was related to body mass and that stature and leg length were only very slightly negatively related to energy cost.

Van der Walt and Wyndham (1973) developed prediction equations for the energy cost of walking and running partially based on morphology. The major determinants were body mass and velocity. Stride length and leg length accounted for only 2% of the total variance in oxygen consumption ($\dot{V}O_2$) but this was found to have a significant influence on $\dot{V}O_2$. While the work of Cotes and Meade (1960) identified that the vertical lift per step was a function of leg, foot and step lengths, Dean (1965) found that ankle flexion was more important that either foot or leg length in contributing to vertical trunk movement.

The relationship between stride length and leg length was investigated in an early study by Hogberg (1952a, 1952b). He found that stride length increased almost linearly with velocity in two subjects running at 8-30 $km.h^{-1}$ on a treadmill. Stride length was significantly related to leg length between 8 and 27 $km.h^{-1}$. Notwithstanding this relationship, he concluded that leg drive, not length of legs, makes the greatest contribution to lengthening the stride during fast running. In contrast to these findings, Cavanagh and Williams (1982) found there was no relationship between stride length and leg length in runners investigated while treadmill running above and below their preferred stride length. Caterisano and McMurray (1982) compared male and female runners for oxygen consumption at various walking and running speeds. They found that the energy cost of walking or running one mile was equal in males and females matched for leg length and concluded that "leg length may be an important determinant of efficiency of locomotion".

It has been shown that stride length during free walking is directly related to stature. Murray et al (1964) found that short men took significantly shorter strides than tall men. However, the effect of stature on the energy cost of locomotion is not so clearly defined. Miller and Blyth (1955) found that $\dot{V}O_2$ was proportional to gross body mass, and $\dot{V}O_2$ relative to body mass was only slightly influenced by stature and fat content. In his review of the patterns of energy expenditure in man McDonald (1961) found no relationship between either age or height and the value of heat output adjusted for walking speed and body mass. Similarly, Rasch and Pierson (1962) reported non-significant correlations of height and fat-free body mass with walking oxygen consumption. They concluded that these measures were of little value in predicting $\dot{V}O_2$. Wyndham et al (1967, 1971) found that stature was negatively correlated with $\dot{V}O_2$ max but only 3% of the variability in maximum values could be attributed to height. They concluded that stature is only a minor determinant of oxygen consumption during walking and running.

In contrast to these findings a number of researchers have reported a direct relationship between stature and locomotor energy cost. Williams et al (1966) found that tall men performed a variety of work tasks with greater efficiency than did short men. Wyndham and Heyns (1969) found that height was negatively correlated with maximal oxygen consumption and accounted for 4% of the difference between individuals. Daniels and Oldridge (1971) in a longitudinal (22 months) study on the effects of training on growing boys found that growth accounted for a 7.5% increase in stature during the test period. Maximal oxygen consumption (expressed per kg of body mass) did not change, but there was a 12.5% drop in submaximal oxygen consumption. They suggested that growth (much of it in leg length) could explain the improved economy. Stature has also been implicated in the magnitude of impact loading in running (Frederick and Clarke 1981). Based on data from a group of 1468 runners, a computer model was developed to predict peak vertical ground reaction forces at varying running speeds in individuals of varying height. Body mass was found to be proportional to height raised to the 2.5 power. This non-linear relationship causes taller individuals to experience relatively greater impact loadings during foot contact. It was felt that this might relate to greater energy cost related to negative work in the taller person.

Wyndham et al (1963) reported that gross body mass is the major determinant of oxygen consumption when men lift their body weight against gravity. This same basic principle was demonstrated in the work of Taylor et al (1972) on the oxygen consumption of mice and chimpanzees. The energy cost required to lift 1 kg was similar regardless of size. Running uphill requires a relatively smaller increase in energy expenditure over horizontal running for small versus large animals. The mice had a relatively higher energy cost for level running but the same cost per unit of body mass for lift work. In keeping with these findings, Williams et al (1966) found that lighter men were more efficient than heavier men in a variety of shovelling, cycling and pushing tasks.

Body composition clouds this issue as fat tissue adds mass to be moved but not metabolically active mass. Young sedentary females have from 22% to 28% body fat, on average, while males are approximately 10% less (Dill et al 1972, Wilmore and Brown 1974, Sparling and Cureton 1983, Wells and Plowman 1983). When these differences are experimentally (Cureton and Sparling 1980) or computationally (McDonald 1961, Dill et al 1972, Wilmore and Brown 1974, Wells and Plowman 1983, Sparling and Cureton 1983) equated, the energy cost of locomotion still remains higher in females: 7.8% in trained, and 15% in untrained subjects. The amount of sex-specific essential fat on women means they will use more oxygen per kg of fat-free mass to run at any given submaximal speed and will have a lower $\dot{V}O_2$ per kg body mass compared with men. Percent fat differences account for 74% of the differential in 12 min run performance of men and women (Sparling and Cureton 1983). Endurance trained women are characterized by a much lower percent body fat (approximately 15%) but this remains nearly 10% higher than their trained male counterparts (Wilmore and Brown 1974, American College of Sports Medicine 1979, Sinning and Wilson 1984).

Other morphological differences between males and females may influence the relative energy cost of locomotion. The average woman is shorter, weighs less and has a higher surface area/body mass ratio compared with the average male (Haymes 1984). Booyens and Keatinge (1957) noted that female acetabular fossae are more anteriorly oriented and suggested that relatively shorter iliofemoral ligaments could restrict hip extension during locomotion. Locomotor efficiency may be adversely affected in the female due to a wider pelvis, shorter legs and greater femoral convergence. Furthermore, the female's greater leg mass/body mass ratio and greater thigh fat deposition could reduce running efficiency (Pate and Kriska 1984). The work of Taylor et al (1974), however, would seem to refute this suggestion. They compared the oxygen cost of running at a constant velocity in the cheetah, gazelle and goat. These animals were selected for their substantially different limb configurations. The energy cost of running was the same as that predicted on the basis of body mass - differences in limb design had no effect on energy cost.

In quadrupedal and bipedal terrestrial animals locomotor velocity, and the mechanics of locomotion, are affected by body length (Alexander and Jayes 1980). If meaningful comparisons are to be made between animals of different sizes, an appropriate non-dimensional parameter is needed to serve as a criterion for physical similarity. The Froude number, which applies to any situation where inertia and gravity interact, is useful in this respect. The Froude number is $u^2/gl$ where u is the velocity, g the acceleration of free fall and l a characteristic length. The Froude number for terrestrial locomotion is $u^2/gh$ where h is the leg length of the animal. Considerations of physical similarities predict that the movements of animals of geometrically similar form but of different sizes will be geometrically similar only when they move with the same Froude number. Geometrically similar movements require that their stride lengths must be proportional to their linear dimensions. The theory of physical similarity further predicts that, even when the Froude numbers are not the same, the stride length to leg length ratio will be a function of the Froude number (Alexander 1977). Assessments of speed, made relative to stature in this fashion, have been employed to examine the gait characteristics of people (Alexander and Jayes 1980), of dinosaurs (Alexander 1976) and modern man compared with Australopithecus (Charteris et al 1982, Alexander 1984).

The setting of speed of locomotion relative to stature in order to compare gait characteristics in humans was introduced by Grieve and Gear (1966). They developed relationships between velocity, cadence, swing time and stride length in children and adults via chronocyclephotography and cine film. The relationship between cadence and walking speed was best described by log-log regression. They also found that the product of maximum cadence and the square root of stature is approximately constant after 5 years of age. In a subsequent publication, Grieve (1968) compared males and females at the same relative speeds. He found that the relationship between cadence and relative speed was best described as a power-fit curvilinear regression and that for an individual this relationship was very stable. The duration of swing was found to be related to cycle time and stature and it, too, was very stable within an individual. Women were found to have walked over a smaller range of relative speeds, and at any relative speed were found to take shorter relative strides than men.

Rosenrot et al (1980) asked male and female subjects to walk overground at self-selected slow, comfortable and fast speeds. They found that stride time was more highly related to relative speed (leg length.$s^{-1}$) than relative speed (st.s$^{-1}$) or absolute speed. Males chose to walk at higher relative speeds than did females. For any given relative speed female stride time was greater than male. However, when the temporal aspects of gait were expressed as a percentage of stride time, males and females did not differ. Further work from the same laboratory (Charteris et al 1982) indicated that the relationship between stride length and relative speed during walking (from 0.4 to 1.0 st.s$^{-1}$) was virtually linear. Across the same range of speeds they found that the foot lengths per stride cycle versus relative speed relationship was linear.

Das and Ganguli (1979) observed seventeen young male subjects running overground between slow and maximum speeds, and performing a stair climbing task. Their results revealed that cadence was linearly related to relative speed. Their energy cost data indicated that a single linear relationship exists between relative speed and energy cost per kg of body mass.

Relative speed has been used to set velocity for studies of habituation to treadmill walking (Wall and Charteris 1980, 1981). These studies revealed the necessity to provide an hour of distributed practice on the treadmill in order to minimize variability in the angular kinematics and temporal aspects of gait.

Charteris et al (1982) and Charteris (1982) have provided qualitative definitions of various walking relative speeds as follows: very slow (0.3 st.s$^{-1}$), slow (0.4-0.6), slow-medium (0.7), medium (0.8-1.0), medium-fast (1.1), fast (1.2-1.4), very fast (1.5 and up). It was suggested that speeds below 0.3 $st.s^{-1}$ and above 1.6 $st.s^{-1}$ are considered outside the "normal definition of walking". Based on the results of many empirical studies "preferred speed" was described as 0.85 $st.s^{-1}$, where preferred speed was that freely chosen by the subject. Preferred rhythm has been found to be very stable within a subject, both within and between days (Taguchi et al 1980).

Although most of the use of relative speed in the human locomotion literature has been based purely on stature, Alexander (1984) contends that dimensionless ratios best express empirical relationships which apply to physical systems of different sizes. The square root of an appropriate Froude number (speed/g x stature) is a more appropriate way to standardize speed than speed/stature. Frishberg (1983) used Alexander's approach to predict step length from leg length and velocity in a comparison of treadmill and overground sprinting. He found that runners with a relative step length greater than predicted reduced their relative step length on the treadmill versus overground while the reverse was the case for subjects with relative step length less than predicted by the Froude number. Regardless which method of relative speed is employed, (dimensionless, or $st.s^{-1}$), these workers are convinced that comparisons between the gait characteristics of individuals must be done on a relative speed basis, taking linear dimension into account, rather than having subjects walk or run at the same absolute speeds (Grieve and Gear 1966, Grieve 1968, Alexander 1977, Das and Ganguli 1979, Rosenrot et al 1980, Charteris 1982, Charteris et al 1982).

## LOCOMOTOR MECHANICS

"Gait can be described as an alternating loss and recovery of body equilibrium", Steindler (1955) wrote in his classic text on normal and pathological kinesiology. Human locomotion has been systematically investigated since 1836. Bresler and Frankel (1950) provide a summary of the historical background on gait research in which the Weber "Pendulum Theory", Marey's contribution - chronophotography and Fischer and Braune's classic papers on the kinetic properties of gait are presented. Fenn's work (1930), using cinematography and pressure platforms to evaluate power output in sprinters, was one of the earlier attempts to integrate the mechanics and the energetics of locomotion. Elftman (1939a, 1939b) combined similar technologies in a study of forces and torques in the legs during walking. He was the first to show that the transfer of energy within the leg and from the leg to the rest of the body could be traced by the activity of forces and torques. He was also the first to speculate that the regular alteration of reception and release of energy during locomotion suggested the possibility of partial storage of energy by the muscles. Steindler (1935) alluded to the involvement of positive and negative work (in a 2:1 energy ratio) in locomotion. He pointed out that horizontal locomotion required that work be done vertically (versus gravity), horizontally (to maintain momentum), and work be done to swing the multi-segment pendulum of the leg. Furthermore, forward acceleration increases and decreases constantly, but an average velocity is maintained.

Six major determinants of gait have been identified: pelvic rotation, pelvic tilt, knee and hip flexion, knee and ankle interaction and lateral pelvic displacement. The energy level of the body is the sum of its potential and kinetic energies. Energy expenditure in straight and level walking at constant cadence is divided approximately equally between rhythmic oscillations of the legs and elevation and depression of the centre of gravity. The knee primarily absorbs energy and does negative work while the ankle and hip do more positive than negative work. Energy transfer and storage does occur (perhaps as much as 40%) involving precise timing and very brief muscular contractions (Saunders et al 1953).

Explorations of the mechanics of locomotion through the 1960's and 70's constituted extensions of this earlier thinking (Cavagna et al 1963, 1964, 1971, 1976, Cavagna and Margaria 1966, Ralston and Lukin 1969, Cavagna and Kaneko 1977) until Winter's (1979a) landmark paper revised thinking on the nature of the mechanical work done in human movement. Since the introduction of the analysis technique involving instantaneous energy transfer within and between body segments (Winter et al 1976), other investigators have verified its utility (Fukunaga et al 1980, 1981, Williams and Cavanagh 1981, 1983, Sakurai and Miyashita 1983, 1985, Matsuo and Fukunaga 1983, Komi and Kaneko 1983). Several studies have verified the technique of using a cine camera or television system to obtain kinematic data which when combined with anthropometric measures provides accurate power flow data during locomotion (Quanbury et al 1975, Robertson and Winter 1979). Winter (1984) cautions, however, that one must not use kinematics to infer muscular causation.

Increases in locomotor velocity are a function of step frequency and stride length. Increases in either, or both, will result in higher speed. Fukunaga et al (1981) suggested that joint angle changes were related to increased stride length, and found that the changes in joint angle were linearly related to power output in sprint running. Based on six years of data collection in his laboratory, Winter (1983a) reported that within-subject joint angle patterns over the stride period are invariant and do not change with cadence. In addition, mechanical power patterns at all joints show consistent timing over the stride period. Interestingly, he provides contradictory evidence in a later paper on the variability of kinematic and kinetic patterns in locomotion (Winter 1984), in which he suggests that the low variability in ground reaction forces observed was a result of large variations in hip and knee motor patterns. This variability tends to decrease with increased cadence, and suggests that "neural control tightens" as cadence increases. Charteris (1982) used joint angle - angle cyclograms from cinematographic analysis of locomotion to demonstrate the clinical significance of this hip, knee and ankle joint angle interaction.

The stride length versus speed of locomotion relationship is linear both during walking (Charteris et al 1982) and during running (Hogberg 1952b, Knuttgen 1961, Nelson and Gregor 1976). Fenn (1930) reported that his fastest runner had the greatest stride length, lowest cadence and raised his thighs higher. Stride length during both level and grade walking was found to be dependent upon speed but practically independent of grade (Erickson et al 1946). As grade increased stride length slightly decreased. Frishberg (1983), in a study of treadmill and overground sprinting, identified that step length was a function of both body size and running speed. Foot contact time decreases with increasing speed (Cavagna et al 1976) implying that the contractile components play a progressively less important role as speed increases.

The relationship between leg length and stride length is a contentious issue. Murray et al (1964) reported that during free walking stride length is directly related to stature, with short men taking significantly shorter strides than tall men. Steindler (1955) recommended that troops running together must set cadence to the fastest possible in the person with the longest legs, and stride length to the maximum for the person with the shortest legs. Hogberg (1952a) found there was a significant relationship between leg length and stride length during running (8-27 $km.h^{-1}$) while Cavanagh and Williams (1982) found no relationship between leg length and stride length during an evaluation of distance runners.

During free running, stride length and leg length account for only 2% of the total variance in oxygen uptake but Van der Walt and Wyndham (1973) included both of these factors in locomotion energy cost equations as they significantly influenced $\dot{V}O_2$. Booyens and Keatinge (1957), on the other hand, discovered that individual variation in energy cost is unrelated to stride length, a conclusion supported by Kram et al (1985).

It has been very clearly demonstrated that running at a freely chosen stride length is less costly with respect to oxygen consumption than is running with a set over- or under-striding pattern (Hogberg 1952a, 1952b, Knuttgen 1961, Burke and Burger 1976, Cavanagh et al 1978, Zarrugh and Radcliffe 1978, Cavanagh and Williams 1982, Cavanagh and Kram 1983). "Free" gait is characterized by a proportional relation between cadence and step length. Any other "forced" cadence increases energy cost (Zarrugh and Radcliffe 1978). It has been noted that increased stride length raises oxygen consumption by a larger amount than does a decrease in stride length (Hogberg 1952a, Cavanagh and Williams 1982). The decreased economy with a greater than optimal stride length was felt to be a function of increased vertical oscillation of the centre of gravity. As Hogberg suggested, "the effort to take long strides will result in a series of jumps". In a four year longitudinal study of the mechanics of distance running, it was found that stride length and stride time decrease and cadence increases, as does non-support time, at given running velocities (Nelson and Gregor 1976). This suggests that the increase in performance with training is associated with real changes in the mechanics of running.

Clarke et al (1983) studied the effect of varied stride length on shank deceleration by placing a light weight accelerometer over the medial tibia. Normal cadence (preferred) was identified, then the subjects ran at 10% and 5% slower, and 5% and 10% faster cadence. Leg shock was significantly lower at 5% (92% of preferred) and 10% (89% of preferred) faster cadence. They concluded that increased cadence (decreased stride length) reduces the amount of shock which must be absorbed by the musculoskeletal system.

Male and female subjects differ significantly in their cadence - stride length relationship. During covert observation in an urban area men were found to exhibit a greater average velocity and step length while women, even though moving more slowly, had greater walking cadence (Finley and Cody 1970). These findings were confirmed in the laboratory by Bhambhani and Singh (1985). Regardless of the fact that female self-selected running speeds were lower than for males, cadence was higher and stride length lower. A mechanical analysis, however, revealed that there was no difference in vertical lift per stride between the sexes. At set walking velocities (1.52 and 1.79 $m.s^{-1}$) women had higher cadence than men (by 18.5% and 22.7% respectively) (Booyens and Keatinge 1957). Data on stride length per leg length showed that women walked with a lower relative stride than men (Grieve 1968, Rosenrot et al 1980). Falls and Humphrey (1976) found that for both for walking and running women had shorter stride lengths and performed less lift work than men.

Stature may be related to the energy cost of locomotion. Hill (1950) found that smaller animals consume energy at a much higher rate because of the greater cadence at any given velocity. This was supported by Slocum and James (1968) who stated that a short legged, rapid cadence runner, compared with a runner with long legs and a slower cadence, will be less efficient at the same velocity. Shibukawa et al (1983) identified that an increased ratio of non-support time to cycle time had an influence on efficiency. Taylor et al (1982), in a study aimed at elucidating the inter-species differences in energy consumption of locomotion, found that at "physiologically similar speeds" the energy cost per stride (per kg) was a constant for animals of different size. This applied equally to bipeds and quadrupeds.

Some investigators have found that cadence during walking increases linearly with velocity while it does not change much at all during running (Ogasawara 1934, Boje 1944, Knuttgen 1961). Others have found that cadence varies as the square root of velocity while walking (Dean 1965), and that cadence increases with velocity of running between 40% and 100% of maximum speed (Luhtanen and Komi 1978). Grieve (1968) found that when cadence and relative speed are related during walking, a power-fit curve best describes this very stable relationship. Grieve went on to point out that the duration of swing is related to cycle time and stature.

Freely chosen cadence is not systematically altered by grade walking (Bobbert 1960). During running, however, it has been found that cadence was higher at both positive and negative extremes of grade (8%) (Henson _et_ _al_ 1977). On the level and uphill, speed increases were accomplished by stride length at slower speeds and by cadence at higher speeds. For downhill running, this pattern was reversed - cadence accounted for increases at slower speeds and stride length at faster speeds.

Energy cost is minimized during movement at freely chosen cadence both during locomotion (Davies and Barnes 1972, Zarrugh 1981) and cycling (Seabury _et_ _al_ 1976, 1977). Zarrugh found that when different step rates are imposed at one speed the average positive work rate remains constant but energy cost is least at the freely chosen cadence. This optimum depends upon cadence being directly proportional to step length. Zarrugh _et_ _al_ (1974) found that optimal energy expenditure occurred when the step length/cadence ratio was 0.007 $m/step.min^{-1}$. During Seabury's experiment (Seabury _et_ _al_ 1976) a "most efficient" pedal rate was found to exist for each power output. This "most efficient" rate increased with power output (from 42 RPM at 41W to 64 RPM at 327W). The increase in energy expenditure observed when pedalling slower than "most efficient" rate is more pronounced at high power outputs than low, but the increased oxygen consumption in response to pedalling faster than "most efficient" is less pronounced at high power outputs than at low power outputs. Taguchi et al (1980, 1981), on the other hand, found no direct relationship between preferred tempo and mechanical efficiency pedalling at low power outputs.

Hagberg et al (1981) forwarded some reasons for the existence of the optimal phenomenon in movement frequency. They suggested that above preferred pedal speed there was a higher muscle fibre recruitment rate and below preferred speed more force was required per pedal stroke. During the unloaded cycling task all physiological responses were quadratically related to pedal frequency. At both below, and above preferred speed oxygen consumption, minute ventilation, lactate and respiratory exchange ratio were higher. Another factor involved may be muscle fibre type. Suzuki (1979) exercised two groups of subjects, one with high fast-twitch percentage and one with high slow-twitch percentage, at 60 and 100 RPM submaximally (below 80% of maximal oxygen uptake). The slow-twitch group experienced a drop in efficiency at the higher speed (down from 23.3% to 19.6%). He suggested that the predominant use of slow-twitch fibres at rapid pedal rates may require a substantial increase in energy expenditure. This is related to the fact that slow-twitch fibres become glycogen depleted first, thus the slow-twitch group must call upon the less economical fast-twitch fibres at higher speeds. The optimum phenomenon in cadence is not restricted to the lower body. In a unique experiment during which subjects pumped a car tire at freely chosen and fixed pace (10 to 60 strokes per minute), the energy cost per stroke versus work rate graph suggested there was a point of minimum energy per stroke. This point agreed with the freely chosen work pace (Corlett and Mahadeva 1970).

Cavagna et al (1976) identified that contact time decreases with increasing speed of locomotion. Alexander and Jayes (1980) expressed contact time (B) (the fraction of a stride for which each foot is on the ground) as:

$$B = 0.67 - 0.13\ (u^{2/gh})$$

where: $u$ = velocity ($m.s^{-1}$)
$g$ = acceleration due to gravity
and $h$ = leg length (m).

Contact time plays a role in efficiency in that in order for work efficiency to rise, contact time per step must approach a constant value (Ito et al 1983). Swing time, the inverse of contact time, is shorter than that due to the moment of inertia of the linked segments during walking (Grieve and Gear 1966).

Snellen (1960) walked his subject on a treadmill in an environmental chamber uphill (0.6 $m.s^{-1}$, 16% grade) for three hours and at 1.7 $m.s^{-1}$, 0% grade for one hour. He measured heat loss by evaporation and mathematically eliminated heat exchange by radiation and convection, and found that heat production exceeded heat loss during grade walking. This difference was attributable to the energy equivalent of body mass times height gained. In level walking, however, heat production equalled heat loss. He concluded that in level walking no external work is done. During level walking or running, the body returns to the same energy level once per stride and no net work is done by the body (Winter 1978a). However, a substantial amount of energy is expended during locomotion and energy is transferred from one part of the body to another. Winter defines internal work as the mechanical work done to move the body segments through the desired pattern to accomplish a given movement. External work is the mechanical work done by the body on an external load. The total work done by the body during locomotion is the sum of internal and external work (Winter 1982a). The only external work done in locomotion at 0% grade is that necessary to overcome air and ground friction. The measurement of total work requires summation of the potential, kinetic and rotational energies of each of the segments of the body. At any given point in time it is possible to have several muscles simultaneously generating and absorbing mechanical energy. The only sources of mechanical energy are muscles doing positive work during a concentric contraction, and except for the ligaments, articulating surfaces and fluids, the only 'sink' for energy absorption are muscles doing negative work during an eccentric contraction (Winter 1982a). Positive horizontal work is greater than negative work during locomotion, thus there is some loss to air and foot friction (Winter 1978a). Hamill et al (1983) supported this finding in their study of ground reaction forces during running at speeds from 4 to 7 $m.s^{-1}$. As speed increased the accelerating impulse became progressively greater than the braking impulse. They identified that ground reaction forces are speed dependent. Vertical forces, braking and propelling impulses, and lateral forces drop as speed decreases. There was a high negative correlation between peak vertical force and the duration of support time.

The importance of internal work and its inclusion in locomotion power output is illustrated by the following work. Kaneko et al (1979) studied the external work of running in place by force platform, and the internal work by cinematographic techniques. As cadence increased, internal work increased from 0.5 to 2.0 $kcal.min^{-1}$ while external work decreased from 2.7 to 1.7 $kcal.min^{-1}$. In a study of the efficiency of concentric and eccentric cycle ergometry, Morrissey et al (1983) measured both internal and external work. When the mechanical work necessary to raise, lower and change the speed of the limb segments (internal work) was added to the external work, efficiency was raised by 7%. Power output calculated from the internal plus external work per stride during locomotion was an average of 16.2% (range 2.4 to 41.7%) greater than that calculated by the centre of mass approach (Winter 1979a). Total average internal work of walking, in this study, was reported as 1.09 J per stride per kg of body mass per stride distance covered.

Examination of the relationship between ground reaction force and movement velocity indicates that power output against gravity increases very little with increases in speed but that power output horizontally increases linearly with speed, (from 4 $J.kg^{-1}.s^{-1}$ at 5 $m.s^{-1}$ to 9 $J.kg^{-1}.s^{-1}$ at 9 $m.s^{-1}$) (Fukunaga <u>et al</u> 1981, Matsuo and Fukunaga 1983). Cavagna <u>et</u> <u>al</u> (1963) reported that vertical displacement plateaus with increased speed when step length exceeds 0.9 to 1 m. Total external work was found to be lower than that due to vertical displacement because lift work is partially sustained by the inertial force of forward motion.

Most studies of the forces involved in locomotion have indicated that horizontal power output increases progressively with increased speed, while vertical power output remains constant or even decreases. Luhtanen and Komi (1978) observed that the rise and fall of the centre of gravity decreased from 11 cm to 4 cm as speed of running increased from 3.9 to 9.3 $m.s^{-1}$. This brought about a linear decrease in potential energy of the body, while at the same time kinetic (horizontal) and rotational energy increased parabolically with speed. In a later work, these same authors (Luhtanen and Komi 1980) quantified increases in limb rotation work (from 3 to 8 $W.kg^{-1}$) and horizontal work (from 11 to 35 $W.kg^{-1}$) with increased speed of running (from 3.9 to 9.3 $m.s^{-1}$). Cavagna and Margaria (1966) examined horizontal and vertical force output during overground walking. As in the above studies they found work due to velocity in the horizontal direction increases progressively with speed but vertical work stays constant. Their force platform results indicated that the foot was moving backward at heelstrike in relation to the body, thus facilitating forward progression. It was found that forward work is greater in walking than running at the same speed. They speculated that this was due to extra isometric work done while walking, extra work due to positive and negative acceleration of the upper and lower limbs which was unrelated to progression of the centre of mass, and differences in energy transfer between the two modes of locomotion.

As the velocity of running increases so does the difference between the maximum and minimum velocity observed during each stride cycle (Cavagna and Margaria 1966). Some of the work done in running is absorbed in internal fixation during the anelastic deformation of the body. The negative work phase of each step cycle (expressed as % of stride) increases with speed. Speed is limited by the deceleration of each step, air resistance and the reduced duration of push (Cavagna et al 1971). Winter et al (1976) explored the nature and extent of these within-stride variations in energy level during walking. The total body mean energy level at a velocity of 1.22 $m.s^{-1}$ (subjects of mass 59.6 kg) was 699 J while stride-to-stride changes in energy level were only 2.7% of this. These stride-to-stride changes occur twice per stride with two bursts of 2.7% of total energy added and absorbed per stride. Winter commented that "It is anticipated that the number and magnitude of these changes in energy will be a measure of the efficiency of walking".

Hinrichs and Cavanagh (1983) used three-dimensional cinematography and segmental analysis to evaluate the contribution of the arms to running. They found that the arms contribute very little angular momentum about the transverse or anterior-posterior axes but that they contribute substantially about the vertical axis. The arms counter the effect of leg angular momentum in the opposite direction. There was a substantial amount of variation in arm contribution to angular momentum which could have had an influence on efficiency. Morioka et al (1971), however, cautioned that all comparisons of efficiency between different types of muscular work must be related to the mass of the working musculature.

Van der Straaten et al (1975) combined surface and thin wire electromyography (EMG) of quadriceps, hamstrings and gastrocnemius musculature with cinematography during an examination of overground walking. Muscles demonstrated the same patterns at all speeds (2, 5 and 7 $km.h^{-1}$) but at 2 $km.h^{-1}$ more EMG was evident in the stance phase while at 7 $km.h^{-1}$ there was greater EMG activity during swing. There were substantial inter-individual variations in the patterns of muscular activity which was particularly marked at 2 and 7 $km.h^{-1}$. At 5 $km.h^{-1}$ there existed an optimal balance between intrinsic and extrinsic forces. This latter point is addressed in a review paper by Andrews (1983). He notes that the incidence of antagonist activity increases with speed of movement and force level, and decreases with increased skill. He points out that it is unlikely that a strong positive correlation will be found between the metabolic cost of muscular effort and any biomechanical quantities during activities where antagonist co-contraction is known to be significant.

Total power output during locomotion is a linear function of movement velocity (Cavagna et al 1977). They found, in investigations of various animals, that the power output per unit of body mass to maintain forward velocity is the same for all species and that the power output per unit body mass to lift the centre of gravity is independent of speed. Fukunaga et al (1980), Heglund et al (1982) and Sakurai and Miyashita (1983) concur that total power output is a linear function of velocity. Horizontal power output is a function velocity of movement squared (Fukunaga et al 1980). As this is the case it is not surprising that Hagberg and Coyle (1983) found that the $\dot{V}O_2$ - movement velocity relationship enabled the very accurate prediction of performance in competitive race walkers.

Both treadmill and overground investigations of locomotion have been conducted. Questions have been raised, in the literature, regarding the comparability of the two situations. In an examination of the mechanics of overground and treadmill running, the treadmill was characterized by longer support times, lower vertical velocity and less variable vertical and horizontal velocities (Nelson et al 1972). Support time was lower in overground locomotion and cadence was higher. Taves et al (1985) reported the opposite pattern during walking at various relative speeds. They found that cadence was greater on the treadmill, and that there were some kinematic differences between the two modes of locomotion during double support and during the early and late parts of the swing phase. Elliott and Blanksby (1976) found that treadmill - overground differences were speed dependent. Below 4.8 $m.s^{-1}$ there were no mechanical differences while above this speed stride length and the period of non-support were greater for overground while cadence was higher on the treadmill. They obtained similar results on male and female subjects. During treadmill sprinting (Frishberg 1983) the shank of the support leg was less erect at contact compared with overground sprinting. The shank also moved through a greater range of motion with greater angular velocity on the treadmill. The thigh was more erect at contact and moved with a slower angular velocity while treadmill sprinting. The overground oxygen debt was 36% greater than the treadmill debt.

Despite these differences it has been reported that there are no oxygen consumption differences between treadmill and overground running at equal velocities (up to 4.33 $m.s^{-1}$) (McMiken and Daniels 1976, Farrell et al 1979). Pugh (1970), on the other hand, found that the slope of the oxygen consumption - speed relationship was much steeper for overground than for treadmill running. The variability in oxygen consumption during road walking (coefficient of variation = 24%) is, however, significantly greater than that for treadmill walking (14%) (Wyndham et al 1971). Van Ingen Schenau (1980) criticized the errors in thinking regarding treadmill-overground locomotion differences. Many of the observed differences have been explained on the basis of the difference in frame of reference used (treadmill-fixed, overground-moving). He points out the illogic in this thinking by noting that the frame of reference must move at the speed of locomotion with the subject. He suggests that only air resistance and visual/auditory input differ between the two modes of locomotion.

Air resistance, during overground running, plays a role in the energetics of locomotion (Cavagna et al 1971, Leger and Mercier 1984). Pugh (1970, 1971) performed systematic studies of the effects of wind resistance in running. The change in oxygen uptake was found to increase as a function of relative wind velocity squared. He found that the energy cost of running against the wind was 7.5% of the total energy cost at 6 $m.s^{-1}$ and 13.6% at 10 $m.s^{-1}$. Davies (1981) measured the oxygen consumption of treadmill running with, and against the wind. As long as the running speed was below 5 $m.s^{-1}$, regardless whether running with or against a wind equal to treadmill speed, the effects on oxygen consumption were within the limits of normal biological variation.

Running on different surfaces has an effect upon energy cost. The looser the surface, the lower the resistance the foot encounters, and the higher will be the energy cost

(Givoni and Goldman 1971, Soule and Goldman 1972). These authors developed terrain coefficients which represented the increase over treadmill locomotion energy cost for moving on the other surface as: hard road 1.2, ploughed field 1.5, sand dunes 1.8, swamp 1.8, loose sand 2.1.

Habituation to unusual movement tasks such as steep downhill walking improves efficiency (Davies and Barnes 1972). Subjects in their study improved co-ordination and curtailed waste movements thus reducing energy cost by 43% at -25% grade. Other investigators, in studies of level or uphill treadmill locomotion, reported very little, if any, change in oxygen consumption with habituation (Erickson _et al_ 1946, Lloyd and Zacks 1972, Cavanagh and Williams 1982, Bates _et al_ 1979, Bates _et al_ 1981). Not only did Durnin and Namyslowski (1958) find that habituation to treadmill walking had no effect on oxygen uptake, but apprehension with respect to the apparatus had no effect, nor did the time of day or the day of the week. Wall and Charteris (1980, 1981) found that there was an initial rapid accommodation to treadmill walking and that one hour of distributed practice was necessary to achieve constancy in the biomechanical features of the gait pattern.

## METABOLIC AND RESPIRATORY RESPONSES TO LOCOMOTION

Oxygen consumption is directly related to the mass of active muscle tissue involved in exercise and both of these determine the dynamics of the cardiovascular response to exercise (Lewis et al 1983). Sargeant and Davies (1977) investigated preferred and non-preferred one-leg cycling discovering that oxygen consumption was higher in the preferred limb. However, in keeping with the previous statement, this difference disappears when standardized for the size of the active muscle mass. Gross body mass is the major determinant of oxygen consumption when men lift their body weight against gravity (Wyndham et al 1963). Further work by Wyndham et al (1967) revealed that 27% of the variation in $\dot{V}O_2$ max between individuals could be attributed to body mass. One's percent fat, however, influences the maximum oxygen consumption at any given body mass. Pollock et al (1980) pointed out, in this respect, that they found good marathon runners to have a high correlation between submaximal oxygen consumption, lean body mass and maximal oxygen consumption. The energy cost of running in mammals yields a linear relationship (slope -0.4) when plotted against body mass on a log scale (Schmidt-Nielsen 1972).

Maximal oxygen uptake testing has often been used to identify the aerobic potential of an individual. Wilmore (1984) reports that $\dot{V}O_2$ max is highly reproducible (r = 0.95) and is relatively stable over the period of a year providing the activity level remains constant. The highest reported $\dot{V}O_2$ max levels are: male - Norwegian cross-country skier (94 $ml.kg^{-1}.min^{-1}$); and female - Russian skier (77 $ml.kg^{-1}.min^{-1}$) (Wilmore 1984). A wide variety of test protocols are available to assess maximal oxygen consumption (Buchfehrer et al 1983, Shepherd 1984b) but it has been found that $\dot{V}O_2$ max was significantly higher on tests where the increment was large enough to induce test durations of 8 to 17 min. The criterion level for reaching a $\dot{V}O_2$ plateau was an increase of less than 2 $ml.kg^{-1}.min^{-1}$ in oxygen consumption for a further increase in power output. In continuous running incremental tests, however, a plateau is seldom achieved.

The effects of training on maximal oxygen uptake are well documented (Astrand and Rodahl 1977). Genetic inheritance accounts for 70 to 80% of one's $\dot{V}O_2$ max while training has been found to increase maximal oxygen consumption by a maximum of 20-30%. Bergh <u>et al</u> (1978) found there were significant differences between athletes and non-athletes in $\dot{V}O_2$ max but not much difference in the percentage of slow-twitch muscle fibres. Although maximal oxygen uptake improves with training, it is not the best indicator of training status (Cureton 1981). It is better to use anaerobic or ventilatory threshold (% of $\dot{V}O_2$ max), or muscle oxidative capacity as these are largely free of inherent biological differences between males and females and reflect, reasonably well, the state of training.

Oxygen consumption increases as the velocity of locomotion increases. While Ogasawara (1934) reported this relationship was linear for walking, and Knuttgen (1961) reported it to be a power fit relationship while running, most investigators have reported the opposite results. The oxygen cost of walking has been found to be curvilinearly related to velocity in a number of studies (Ralston 1958, Cotes and Meade 1960, Lukin and Ralston 1968, Menier and Pugh 1968, Wyndham et al 1971, Donovan and Brooks 1977, Fardy and Hellerstein 1978, Marchetti et al 1983). Most of these authors found that oxygen uptake increased as a function of velocity squared. Generally speaking the energy cost and, for that matter, the power output of running have been found to be linearly related to the speed of movement (Ogasawara 1934, Margaria et al 1963, Menier and Pugh 1968, Shephard 1969, McMiken and Daniels 1976, Mayhew 1977, Bransford and Howley 1977, Das and Ganguli 1979, Fukunaga et al 1980, Marchetti et al 1983, Leger and Mercier 1984). Studies of both bipedal (Fedak et al 1974) and quadrupedal (Heglund et al 1982, Taylor et al 1982) locomotion across a variety of species confirmed the nature of this relationship in the terrestrial animals. Interestingly, Fedak et al (1974) report that bipedal running is less efficient than quadrupedal running, estimating that the energy cost of running bipedally is twice as great as running quadrupedally in an animal the size of man.

Several investigators have noted that the energy cost of running a given distance was independent of the velocity of locomotion (Margaria et al 1963, Costill and Fox 1969, Cavanagh et al 1973). However, in a study which included both walking and running (Fellingham et al 1978), the energy cost per distance factor was found to increase with speed. This may have been related to the fact that the energy equivalent of the excess post-exercise oxygen consumption was added to the exercise energy cost in order to determine the total energy cost for the activity. This may not have been an entirely valid procedure as Gaesser and Brooks (1984) have argued that not all of the post-exercise oxygen consumption is directly related to the demands of the exercise. Lipolysis and elevated fatty acid levels, elevated calcium ion concentrations, high catecholamine levels, elevated body temperature and "ultra-slow" substrate cycling all play a part in elevating post-exercise oxygen consumption.

Grade walking and running have been found to have a significant effect upon the energy cost of locomotion. Most studies report that oxygen consumption increases as a direct linear function of increased gradient (Margaria et al 1963, Lukin and Ralston 1968, Shephard 1969, Pugh 1971, Givoni and Goldman 1971). Pugh (1971) reported, in support of this relationship, that while walking on gradients the oxygen consumption-lift work relationship was linear above 50W but curvilinear below that power output. Bobbert (1960) found, on the other hand, that the log of energy consumption increased linearly with grade (0-12%). Positive and negative grades affect the mechanics of energy exchange during locomotion in different fashions. The increase in positive work done while walking uphill is accompanied by a decrease in negative work (Pugh 1971). The opposite effect was alluded to by Saunders et al (1953). They identified that a descending grade of 4% requires little or no elevation of the body against gravity. Lukin and Ralston (1968) compared level and grade walking potential and kinetic energy patterns finding that on the level these patterns form a mirror image, while on a grade they are almost perfectly in phase. This would be a most unfavourable situation with respect to the exchange of energy.

It has been found that the excess oxygen consumption of running uphill (compared with level running) is greater than oxygen consumption difference between level and downhill running at the same speed and (negative) grade (Henson et al 1977, Howley et al 1984). Compared with level running at 3.83 $m.s^{-1}$ the oxygen consumption at -3% grade represented a energy savings of 14.7% (Howley et al 1984). However, at -6% grade the additional energy savings were only 11.1%, and only 8.5% at -9% grade. The flattening of the energy cost-gradient relationship at grades below 0% suggested that the decrease in external work with decreasing grade is countered by "an increased need to decelerate the body at impact - an energy requiring process". Not only does this process require energy, but it may also lead to injury. Schwane and Armstrong (1983) state that exercise involving total body negative work is particularly effective in causing injury to skeletal muscle. Compared with concentric, eccentric contraction produces relatively high forces per active cross-sectional area. Injury was evidenced by elevated levels of creatine phosphokinase and lactate dehydrogenase, and by necrosis of fibres. In this regard, it is interesting that the gastrocnemius electromyogram (EMG) becomes progressively silent as the down gradient increases but the anterior tibial musculature EMG is unaffected (Cavanagh et al 1973).

Taylor et al (1972) ran mice and chimpanzees on the level, and on +15 and -15 degree slopes, measuring their steady-state oxygen consumption. They found that the energy cost required to lift 1 kg through 1 m was similar in both mice and chimpanzees. Running uphill requires a relatively smaller increase in energy expenditure over horizontal running for small versus large animals as the small animals have a higher energy cost for level running but the same cost per kg of body mass for lift work. In fact, the mouse oxygen consumption was very similar at all three gradients. They pointed out that in man running at -3 degrees gradient (5.2% grade), the efficiency of energy recovery is nearly 100%.

There are substantial differences between males and females which have an influence on the metabolic responses to locomotion. Males have greater absolute lean body mass and a lower percentage fat (young females 22-26% fat, males 12-16%) (Pate and Kriska 1984). Women carry 12% of body mass as essential for normal biological function while men have only 3% essential body fat. Males have a greater hemoglobin concentration (by 15%) (Cureton 1981), a larger heart volume after adjustment for body mass, and greater blood volume compared with females (Wells and Plowman 1983, Pate and Kriska 1984). Males and females are equal in muscle fibre type distribution, however, there are no clear differences between the sexes in metabolic substate utilization. Males have greater lipid oxidation capability because of their higher mitochondrial density (Campbell _et al_ 1979). Males have larger slow-twitch and fast-twitch muscle fibres than women, with the greatest difference in the fast-twitch fibres (Wells and Plowman 1983, Pate and Kriska 1984). Cureton (1981) suggests that these differences lead to the following differentials between male and female maximal aerobic capacity: male $\dot{V}O_2$ max = 1.5 x female ($l.min^{-1}$); male $\dot{V}O_2$ max = 1.2 x female ($ml.kg^{-1}$body $mass.min^{-1}$); and male $\dot{V}O_2$ max = 1.05 x female ($ml.kg^{-1}$lean body $mass.min^{-1}$). Furthermore, he notes that male maximal arterial minus venous oxygen difference ($a\text{-}\bar{V}\ O_2$) is greater than female. Dill _et al_ (1972) concur with the Cureton suggestions, finding that male maximal oxygen uptake (per kg LBM) was 15% higher (7.8% higher - Wilmore and Brown 1974) than the female value. Cureton and Sparling (1980) added weight to male distance runners making them experimentally equivalent to a group of female runners in percent fat. This reduced the mean sex difference in treadmill running time by 32%, and 12 min run performance by 30%. This was the result of a 38% reduction in the sex difference in oxygen uptake per kg lean body weight and a 65% reduction in sex difference in $\dot{V}O_2$ max relative to mass carried. They concluded that the sex specific essential fat of women means they will use more oxygen per unit of lean body mass to run at any given submaximal speed and will have a lower $\dot{V}O_2$ per kg body mass. While these differences are significant, Wells and Plowman (1983) suggest that "although physiological values for the average man are statistically different from the average woman, differences between any two individuals of the same sex are often greater".

Haymes (1984) reviewed male - female differences from the point of view of responses to heat stress. The average woman is shorter, weighs less and has a higher body surface area to body mass ratio. These are advantages for heat loss via radiation and convection. Women have a lower total body water content, thus at equal sweat rates women lose a greater percentage of body water. At the same percentage of maximal oxygen consumption there are no differences in either temperature or sweating rate between men and women. Endurance training lowers the threshold for sweating and vasodilation equally in both sexes.

Nunneley (1978) reports that while many studies have shown that women are less heat tolerant than men, particularly when physical work is required, "much of the difference is related to women's relatively low level of physical fitness and lack of heat acclimatization which are in turn a result of their traditionally sedentary lifestyle". When work load is adjusted to individual capacity (%$\dot{V}O_2$ max) females respond to heat stress much as males do. This view is supported by the American College of Sports Medicine (1979) which states that women experience lower evaporative heat loss compared with men for the same heat load, with higher skin and deep body temperatures at the onset of sweating.

Women have been found to consume the same amount of oxygen (per kg body mass) as equally well-trained males walking and running at given sub-maximal movement speeds (Durnin and Namyslowski 1958, Krahanbuhl *et al* 1976, Wells *et al* 1981). McDonald (1961) reported that after adjustment for body mass differences, the energy cost of walking was approximately 10% less for women than men. In another study (Bhambhani and Singh 1985), the energy cost of running at preferred speed was higher in females than in males (per km), however, this was not the case for energy cost per stride. This was despite the fact that female self-selected running speeds were lower than male. Cadence was higher in females but stride length was lower. Despite these differences, there was no difference in vertical lift per stride between the sexes. It was felt that at least part of the difference noted was as a result of lower levels of fitness in the female subjects. Diamant *et al* (1980) used the same logic to explain the relatively poorer performance (compared with men) of a group of highly trained women who ran for 2.5 h on the treadmill at 64% $\dot{V}O_2$ max. Oxygen uptake, stroke volume and cardiac output drifted up, and a-$\overline{V}$ $O_2$ difference drifted down over the test period. Cadence progressively increased while stride length dropped (from 2.13 to 2.075 $m.stride^{-1}$). In addition to the fitness level differences, several authors have noted that socio-cultural differences between the sexes may have led to findings of differences between the sexes in exercise responses (Wilmore and Brown 1974, Nunneley 1978, Pate and Kriska 1984). In each case, the greater levels of habitual physical activity amongst males in Western society were used to explain at least part of the difference observed.

One of the concerns frequently raised in the literature regarding the assessment of women is the potential effect the menstrual cycle has on exercise response. Stephenson et al (1982a, 1982b) cycled female subjects at sub-maximal and maximal power outputs on day 2, 8, 14, 20 and 26 of the menstrual cycle, finding that submaximal and maximal oxygen consumption, and average work time to exhaustion were not different during different phases of the cycle. There were no changes in cardio-vascular responses, anaerobic threshold or ratings of perceived exertion across the cycle. Haymes (1984) reported that during the normal menstrual cycle resting temperature rises at ovulation (0.5 degrees) and remains elevated in the luteal phase. Despite elevated temperatures, he found that male and female skin and core temperatures, and sweat rate in response to exercise were similar at all times during the monthly cycle. He also found no difference in metabolic rate at different phases of the cycle, or any difference in exercise tolerance between men and women.

Endurance trained individuals have smaller increases in muscle and blood lactate, a slower rate of glycogen depletion, lower carbohydrate metabolism and increased fat oxidation at any given submaximal oxygen consumption compared with the untrained (Holloszy and Coyle 1984). Both Sutton (1978) and Weltman and Katch (1976) agree that the more highly trained individual uses more fat metabolism than the unfit at the same power output. Hormonal regulation of energy substrate may differ in fit and unfit subjects. The unfit subjects in Sutton's (1978) study demonstrated increases in blood glucose, blood lactate, plasma cortisol and serum growth hormone compared with the fit subjects. Serum insulin was depressed in both groups.

More highly trained subjects demonstrate a more rapid accommodation to exercise than those of lower fitness levels (Flint et al 1974, Weltman and Katch 1976). Training has the effect of raising one's maximal aerobic capacity (Flint et al 1974, Pederson and Jorgensen 1978, Saltin and Rowell 1980, Pandolf 1983) but the effects on submaximal oxygen consumption are less well defined. Some studies have shown that training reduces the submaximal oxygen consumption (Cotes and Meade 1959, Margaria et al 1963, Sjodin 1983) while others have indicated that steady-state oxygen consumption at submaximal power output remains unchanged with training (Flint et al 1974, Holloszy and Coyle 1984). In their review of ten studies which examined the oxygen cost-velocity of running relationship, Leger and Mercier (1984) state that trained subjects are more efficient than untrained. The anaerobic threshold of trained men (79.2% $\dot{V}O_2$ max) and women (73.3% $\dot{V}O_2$ max) is significantly higher than that of untrained men (66.5% $\dot{V}O_2$ max) and women (58.9% $\dot{V}O_2$ max) (deMello et al 1985).

Part of the reason for an improved oxygen uptake profile after training may be related to improved skill and co-ordination. Person (1958) used electromyography, tensiometry and electrogoniometers on elbows to monitor change in people as they learned how to file, and cut with a chisel. Pre-training EMG's and tensiograms indicated a lack of co-ordination and greater muscle action in the agonist because of antagonist co-contractions. After training there was a co-ordination of EMG and force patterns. There was a concentration of excitation in time and rest periods (quiet EMG) appeared. The pre-training activity of the antagonist is explained by irradiation of excitation, but it could also be explained by noting that it takes part in corrective movements. Post-training reduction in antagonist co-contraction would help explain the reduction in oxygen consumption which accompanies training.

## MUSCLE DYNAMICS IN LOCOMOTION

The usual relationship between slow-twitch and fast-twitch fibre composition in muscle is 50/50, however, endurance athletes have a higher number of slow-twitch fibres while sprint or power athletes have a higher concentration of fast-twitch fibres (Thorstensson et al 1977, Saltin et al 1977, Bergh et al 1978, Holloszy and Coyle 1984). Thorstensson (1976) points out that the distribution of the two main fibre types is governed by genetic factors. Edgerton (1976) reviewed the role of muscle fibre types in human movement noting that there are three main categories of muscle fibres - the two listed above and an intermediate fibre with both oxidative and glycolytic capability. There is a scarcity of these intermediate fibres in untrained individuals. Edgerton pointed out that the shortest peak-to-peak tension (and largest tension) occurs in motor units that have the largest cell body, axon and muscle fibres. Slow-twitch fibres and intermediate fibres are fatigue resistant - a characteristic which is related to isotonic contraction efficiency. The central nervous system can modify the nature of muscle output by varying: the number of motor units recruited per unit of time; the kind of motor units called upon to contract; and the frequency of activation. Fast-twitch fibres are generally recruited during strenuous activity or high speed movements (Heglund et al 1982, Holloszy and Coyle 1984). Slow-twitch fibres usually have twice the number of mitochondria of fast-twitch fibres which accounts for their high oxidative capacity. There is a direct relationship between the fatigue index (reduced endurance) and the percentage of fast-twitch fibres (Thorstensson 1976).

The metabolic cost of locomotion is determined by the intrinsic velocity of shortening of motor units and the frequency of stimulation (Heglund et al 1982). Buchthal and Schmalbruch (1970) stimulated human muscle fibres in vivo and measured the time to peak contraction. They found that slow-twitch fibres had contraction times between 60 and 100 ms while fast-twitch fibres had times between 30 and 60 ms. Suzuki (1979) supported this finding identifying that slow-twitch fibres have a longer cross-bridge engagement time. Slow-twitch fibres may, thus, offer resistance to shortening at high movement velocities as the muscle filaments do not have time to disengage. Thorstensson et al (1976) found a high correlation between isokinetic maximal torque output at top speed and the relative area of fast-twitch fibres. These findings on intact human muscle were found to be consistent with animal muscle preparations. While Komi (1984) is correct in his assertion that because our dynamometers can only reach approximately 30% of maximum muscular contraction speed, the force time relationship in humans is only weakly linked to the slow-twitch to fast-twitch ratio, others have reported that the force-velocity relationship is essentially the same as reported for in vitro muscle preparations (Parker et al 1983). They pointed out that force decreases as speed increases because speed exceeds the maximum shortening velocity of individual fibres, and that there is a positive relationship between the percentage of fast-twitch fibres and maximum limb velocity.

Hill (1922) related movement speed to theoretical maxima for efficiency through measurements of human elbow flexion power output. He suggested that the more rapidly a muscle shortens the more energy is wasted in passive and viscous processes associated with the change of form. He found there was a point of optimal efficiency for which a small increase in movement speed gives a big decrease in efficiency but a large decrease in velocity causes only a small loss of efficiency. He proposed that submaximal efforts are less efficient than maximal efforts. During a submaximal effort, contraction energy is proportional to the fraction of fibres participating but the energy wasted through passive and viscous processes is the same as for a maximal effort. While logical, this ignored the differential efficiency of fast- and slow-twitch fibres. The energy cost of maintaining tension in fast-twitch fibres is significantly greater (1.5 to 3 times) than in slow-twitch fibres (Crow and Kushmerick 1982). Wendt and Gibbs (1984) sacrificed rats from the same litters at various ages and measured maximum mechanical efficiency in a fast-twitch muscle (extensor digitorum longus) and a slow-twitch muscle (soleus). Efficiencies averaged 8% for the fast-twitch muscle and 17% for the slow-twitch muscle.

Endurance training increases muscle mitochondria and the activity of the mitochondrial enzymes. Slow-twitch fibres have double the number of mitochondria compared with fast-twitch fibres (Holloszy and Coyle 1984). Bergh et al (1978) found that there were significant differences between athletes and non-athletes in maximal oxygen uptake but not much difference in the percentage of slow-twitch fibres. This was accounted for by the finding that there is no direct link between muscle mitochondria content or enzymes, and $\dot{V}O_2$ max. The maximal $a\text{-}\overline{V}\ O_2$ difference was felt to play a role in the elevated oxygen consumption of the trained athletes (Holloszy and Coyle 1984). A further effect of endurance training was to increase the relative area of the slow-twitch fibres (Edgerton 1976, Thorstensson et al 1977). Lactate removal rate is highly variable (between subjects) and is related to slow-twitch fibre area. McGilvery (1973) reported that slow-twitch fibres have an isoenzyme of lactate dehydrogenase which favours oxidation of lactate as fuel substrate. Fast-twitch fibres have pronounced anaerobic potential and favour lactate formation. Endurance training enhances these characteristics and Sjodin (1983) suggests that the lactate produced in the fast-twitch fibres might be transferred to, and oxidized by, adjacent slow-twitch fibres.

The oxidation of glycogen is accompanied by the production of 10% more high energy phosphate per mole of oxygen consumed than a mixture of fatty acids with a composition similar to that of adipose tissue (Sjodin 1983). This higher yield is advantageous when oxygen is limited or mitochondrial electron transport becomes limiting. The effectiveness of fuel for muscular contraction depends upon the amount of fuel (limits total work) and the maximum activity of the required enzymes (limits power output). During light to moderate work there is enough free fatty acid in the blood to supply a substantial fraction of the fuel for metabolism (McGilvery 1973). Related to these findings, McDonald (1961) stated that a high intake of carbohydrate increases efficiency while high fat intake reduces efficiency.

Muscles play a significant role during locomotion as a means of transferring energy from one step to the next, both in walking and running (Winter 1982b). Segmental analysis of locomotion is the only way to get the full picture of energy transfer as the patterns of energy transfer, generation and absorption by muscle and through the joints are quite complex (Winter and Robertson 1978). Gordon et al (1980) validated the segmental analysis approach. They found that the modelling assumptions and approximations made to simplify the structure of the human body were found to be essentially valid. The rates of energy transfer through joints and muscles were comparable to the rate of energy generation and absorption by the muscles.

Energy transfer has obvious advantages with regard to the energetics of locomotion. Estimates of the total passive energy transfer within the body per step range from 50% (Inman 1966) to 65-73% (Dean 1965, Stevenson and Coolen 1978, Caldwell et al 1979, Pierrynowski et al 1980). The remainder of the energy involved in locomotion is attributed to the metabolic cost of positive and negative work performed by the muscles. Energy transfer has been found to occur in equal proportions within segments and between segments (Stevenson and Coolen 1978). Mansour et al (1982) used three dimensional cinematography to avoid past assumptions of: 1) the head, arms and trunk portrayed as a single point of mass; 2) neglect of rotational kinetic energy of segments; 3) restricting analysis to the sagittal plane; and 4) imposing symmetry between right and left limbs, in a multi-segment study of locomotion. They found a greater exchange of energy occurred between potential and kinetic energy near individually preferred walking speeds. Cavagna et al (1977) similarly found that the energy transfer per walking stride was the greatest at a moderate speed.

Morrison (1970) looked at the length-tension and force-velocity relationships during locomotion and their effect on energy transfer in biarticular musculature. He reported evidence of energy conservation of a chemical rather than mechanical nature in the biarticular action of hamstrings, gastrocnemius and rectus femoris. Speed plays a role in energy transfer in that transfer increases as speed increases (Cavagna et al 1971, Mansour et al 1982). Winter (1983b) examined ankle and knee energy absorption patterns during walking. He found that the ankle has two mechanical power phases (negative at weight acceptance, positive at push-off). The knee has four phases: negative at weight acceptance, small positive at mid-stance, major negative at push-off and early swing and a final energy absorbing phase at the end of swing. Energy absorption by the knee was found to decrease rapidly as speed decreased.

The energy transfer, alluded to above, means that during locomotion various body parts are absorbing energy, or doing negative work. The performance of negative work is considerably more economical than is positive work (Abbott et al 1952, Asmussen 1952, Kamon 1970, Pandolf et al 1978, Pierrynowski et al 1980, Williams and Cavanagh 1983, Komi 1984). The energy cost of positive work has been measured at three to five times that of negative work with increasing speed of movement related to the higher differential. Asmussen (1952) pointed out that negative work at high velocities is produced at practically no extra energy cost, and that the force-velocity relationship does not account for nearly all the extra economy of negative work.

Negative work economy is related to the finding that muscle fibre cross-bridges can develop tension during stretching without the splitting of ATP (Davies 1971, Curtin and Davies 1975, Cavanagh and Kram 1983). Muscle cells are able to accept energy during eccentric work for direct employment in the contractile processes or for re-synthesis of energy yielding compounds (Knuttgen and Klausen 1971). Cavagna _et al_ (1968) measured positive work done by muscle, both _in vivo_ and _in vitro_, after stretching and from resting length. The work done by the muscle which shortens immediately after being stretched in the contracted state was higher than work done by the same muscle during shortening from a state of isometric contraction. This work output was found to increase with increased speed and length. The extra force observed has a transient nature (Cavagna _et al_ 1975) when examined on a prolonged time scale. When a muscle is allowed to shorten immediately after being stretched while active the greatest power output appears immediately after the release from stretch. This is particularly pertinent to the absorption of energy by muscle during locomotion, a process which, to be effective in reducing energy cost, must be timed precisely (Winter 1982b).

Ralston and Libet (1953) discovered that when a frog muscle was stretched then stimulated to contract, the amplitude of the electromyographic signal was considerably lower in the stretched muscle even though maximal tension was developed at all lengths. Furthermore, the amplitude of the muscle action potential, in response to a maximal motor nerve volley, was greater in the stretched versus the unstretched muscle.

During locomotion the ankle and hip do more positive work than negative work. The knee primarily absorbs energy and does negative work (Saunders et al 1953). In jogging (Winter 1983c) the knee muscles absorb 3.6 times as much energy as they generate over the entire stride, while the ankle muscles generate 2.9 times as much energy as they absorb. It was also noted that the variability of the movement patterns was considerably less than that seen for natural walking. As grade changes, however, patterns of positive and negative work change. Margaria (1968) found that during walking below a -9% grade no positive work was done, and no negative work was done above 22% grade.

Much of the reduced energy cost of negative work has been related to the process of energy storage. Elftman (1939b) was the first to state that the regular alteration of reception and release of energy suggested the possibility of partial energy storage by the muscles. Cavagna et al (1964) measured the efficiency of running finding it to be higher than the efficiency of the contraction-coupling process in the muscles. They felt that elastic recoil and energy storage in muscle could account for the differences.

A number of experiments have explored elastic recoil and the energy storage of negative work by having subjects jump on and off force platforms and perform knee bends. Thys et al (1972) asked their subjects to perform deep knee bends with a 1.5 s gap between extension and flexion, and also with no gap (rebound exercise). In rebound exercise the maximum speed during extension was higher, time of positive work was less, and the mean power and mechanical efficiency (25.8% vs 19%) were higher compared with no rebound. They concluded that elastic energy is stored during the stretching of the contracted muscle, but that this happens only if the positive work immediately follows the negative. If the muscle is allowed to relax the elastic energy is turned into heat. In a similar experiment Asmussen and Bonde-Peterson (1974) found deep knee bends with rebound were more efficient (39%) than without (26%), and half-knee bends exhibited the same pattern (with rebound 41%, without 22%). They calculated that 34% of the energy absorbed during negative work in knee bends was re-used during the positive phase. They, too, alluded to the necessity for the positive work to follow the negative immediately and pointed out that the time to peak tension in human muscle is 74 ms. Thys et al (1975) compared the energy cost of vertical jumping, performed with and without bending the knees; and found that the positive work done by elastic energy storage might amount to 50-65% of the total positive work.

Komi and Bosco (1978) examined the utilization of stored elastic energy by having subjects perform vertical jumps from a force platform in three ways: 1) from a static position of 90 degrees of knee flexion; 2) from a standing position with a counter-movement; 3) after dropping onto the platform from various heights. The greatest rise in body centre of mass occurred with the third condition, and they found that the stretch load (drop height) was positively related to the rise in the centre of gravity. Men could jump higher, and sustain much higher stretch loads but women were able to utilize almost all (90%) of the energy produced during the pre-stretch (men only 50%). Fukashiro et al (1983) found, in a similar experiment, that there was an optimal negative work level for a person to maximize subsequent positive work. Peak efficiency in subsequent positive power output occurred with negative power outputs between 10 and 15 $W.kg^{-1}$.

In a comparison of continuous and intermittent exercise tests, Fardy and Hellerstein (1978) found that oxygen consumption was a curvilinear function of power output. They suggested that elastic recoil during walking is lower at slow speeds (because of increased contraction time leading to decreased efficiency). Elastic recoil increases with greater stretch as speed of walking increases until the point of maximum efficiency where oxygen consumption and power output attain linearity. At low speeds, muscles provide most of the power output, but at higher speeds power is sustained by energy storage during negative work (Cavagna et al 1971). Cavagna and Kaneko (1977) support these arguments. They filmed subjects walking and running between 3 and 33 $km.h^{-1}$, finding that efficiency was maximized at intermediate walking speeds (35-40%) but increased with speed in running (from 45% to 80%). The total work accomplished per unit of distance travelled while running was greater than while walking. Ito et al (1983), while finding that a substantial amount of extra work comes from elastic recoil during running, found that efficiency remained constant (55 ± 12.7%) as velocity increased. Marchetti et al (1983) compared the efficiency of race walking and running at the same speed. Race walking was considerably less efficient (21% versus 33%). It was felt that the recovery of energy stored in the elastic components of stretched muscle was not as great in race walking.

Much of the power output during the positive phase of the running cycle (up to 70%) is conserved per stride by energy storage in lengthened muscle during the negative phase (Cavagna et al 1977, Fukunaga et al 1981). Alexander and Bennet-Clark (1977), on the other hand, point out that far less elastic strain energy is saved in muscle than in tendon. The series elastic component of muscle operates only over small strains. Thus, it can store only a small part of the work done by a muscle which shortens by a large fraction of its length. They found the storage of elastic strain in muscle was 5 $J.kg^{-1}$ and in tendon 2000 - 9000 $J.kg^{-1}$.

## ECONOMY OF LOCOMOTION

Studies of walking, running and cycling have indicated the existence of an optimal point for an individual in the relationship between energy cost and speed of movement. The minimization is reported to generally coincide with preferred speed, cadence, stride length, or tempo. In cycling studies, Hagberg *et al* (1981) found that at both above and below preferred pedal frequency oxygen consumption for equivalent power outputs was higher. These findings were supported by the work of Seabury *et al* (1977) who also found that the "most efficient" pedal rate, and the efficiency, increased with increasing power output. In contrast, McCann and Gliner (1982) reported that pedalling rate (preferred, 20% above and 20% below) did not affect mechanical efficiency, a finding supported by Taguchi *et al* (1981) for very low power outputs.

During walking and running, the existence of this optimal point has been repeatedly referred to both in relation to preferred cadence and preferred stride length (Erickson *et al* 1946, Ralston 1958, Bobbert 1960, Taylor *et al* 1970, Zarrugh *et al* 1974, Zarrugh and Radcliffe 1978, Cavanagh *et al* 1978, Kaneko *et al* 1979, Zarrugh 1981). This 'most economical' speed of walking has been reported to range from 1.11 $m.s^{-1}$ (Cavagna *et al* 1963, Margaria *et al* 1963) to 1.23 $m.s^{-1}$ (Ralston 1958) to 1.31 $m.s^{-1}$ (Zarrugh 1981), to 1.35 - 1.47 $m.s^{-1}$ (Erickson *et al* 1946). Howley and Glover (1974) reported that women self-selected a lower preferred running speed (2.28 $m.s^{-1}$) than did the men in their study (3.25 $m.s^{-1}$).

Alexander (1980) found that there is an optimum combination of duty factor B (fraction of the stride for which each foot is on the ground) and Q (time course of the forces on each foot) which minimizes the energy cost of locomotion. This optimum moves abruptly from walking (high B) to running (low B). He pointed out that the storage of elastic strain energy is more effective in running than in fast walking which may explain why men change from walking to running at a lower speed than the inelastic theory predicts. Inman (1966) presents a substantial amount of data to support the hypothesis that the human body will integrate the various motions of the body so the energy required for each step is minimal. Winter (1980) confirmed this thinking for running by television system analysis of walking and jogging which produced an algebreic sum (M3) of hip, knee and ankle moments. Examination of individual subject joint moments (hip and knee) demonstrated considerable variability despite a consistent M3 pattern. The joggers demonstrated the same consistency despite variability (30-50%) at the hip and knee.

Tied in with force output is the electrogoniometric pattern of muscle action. Milner _et_ _al_ (1971) had their subjects walk at various speeds from 0.67 to 2.28 $m.s^{-1}$ with free cadence, and 1.37 $m.s^{-1}$ with cadence set at 24 to 96 steps per minute. They found that EMG rises linearly with speed. They found that there was a minimum in EMG in the speed range 0.91 to 1.52 $m.s^{-1}$. The authors suggested that their subjects selected a preferred velocity where EMG is minimized. At this optimal velocity random variations in EMG are more marked, a finding which they felt indicated a measure of on-going adaptive control.

Economy of locomotion is considered to be the steady-state oxygen consumption for a standardized running (or walking) speed (Conley and Krahenbuhl 1980, Powers _et al_ 1983, Cavanagh and Kram 1983). Dill (1963) was the first to use the concept of economy. He developed a "skill index", which was the net oxygen consumption running at 2.3 $m.s^{-1}$, to differentiate between runners of different skill levels. This was necessary as it has been noted that there is a very large range of inter-individual differences in running economy. Farrell _et al_ (1979) found that economy at 16 $km.h^{-1}$ ranged from 43.5 to 55.6 $ml.kg^{-1}.min^{-1}$. Leger and Mercier (1984), in a review of the energy cost - velocity relationship, concluded that at any given speed there is a 10 $ml.kg^{-1}.min^{-1}$ range in inter-individual differences. McMiken and Daniels (1976) found that the oxygen cost of running 1 km ranged from 160 $ml.kg^{-1}.km^{-1}$ to 227 $ml.kg^{-1}.km^{-1}$ around the mean value of 200 $ml.kg^{-1}.km^{-1}$.

Intra-individual differences in economy have been reported at a variety of levels. Passmore and Durnin (1955) reported that the coefficient of variation (CV) of economy of walking at a constant velocity was 15%. Wyndham _et al_ (1971) compared treadmill and road walking, finding that the CV of economy on the treadmill was 14% while on the road the same subjects had a CV of economy of 24%. On triplicate samples of treadmill running against a wind resistance Davies (1981) found the CV of economy to be 18%. Cavanagh and Kram (1983), in a review of efficiency and economy of locomotion, reported a 12 to 17% coefficient of variation in economy based on their search of the literature.

On the other hand, some authors have reported rather low values for intra-individual variation in economy. Pollock et al (1980) reported low CV of economy values for marathon (7.3%) and middle distance runners (8.3%) with the best runners having the lowest values (2.8%). The good marathon runners in their study had a lower sub-max $\dot{V}O_2$ than did the middle distance runners. Costill et al (1973) found that the CV of economy was higher at 14.5 $km.h^{-1}$ (4.1%) than it was at 16 $km.h^{-1}$ (3.6%). Kram et al (1985) tried to elucidate the reasons for the variation in economy by comparing the day-to-day variation in stride length with the variations in economy. The coefficients of variation in stride length at various running speeds were quite low (1.28% at 3.15 $m.s^{-1}$, 1.11% at 3.35 $m.s^{-1}$, 1.07% at 3.58 $m.s^{-1}$, 0.96% at 3.83 $m.s^{-1}$ and 0.94% at 4.13 $m.s^{-1}$). They compared these values with the 3 - 5% CV of economy between days, and the 1 - 3% CV of economy within days finding that the variation in economy was approximately four times that due to variations in stride length. Day-to-day fluctuations in running economy, it was concluded, were primarily due to factors other than stride length. Sjodin (1983) attributes variations in economy to the relative effectiveness of the different enzyme systems, from day-to-day.

Leger and Mercier (1984) summarized the findings of ten studies on the gross energy cost of horizontal overground running by suggesting that between 8 and 25 $km.h^{-1}$ a runner uses 1 MET (3.5 $ml.kg^{-1}.min^{-1}$) per $km.h^{-1}$. As economy of running data have been collected and reported at specific velocities, to enable comparisons of running economy between studies and velocities, I have followed the Leger and Mercier lead in expressing economy as oxygen consumption in $ml.kg^{-1}.min^{-1}$ per $km.h^{-1}$ of running speed. Economy of running has been found to range from 3.05 to 3.46 $ml.kg^{-1}.min^{-1}$ per $km.h^{-1}$ (Costill and Winrow 1970, Costill _et_ _al_ 1973, Farrell _et_ _al_ 1979, Wells _et_ _al_ 1981, Lafontaine _et_ _al_ 1981, Sparling and Cureton 1983, Powers _et_ _al_ 1983). In those studies where economy has been measured at different velocities, it is generally higher (i.e. lower $\dot{V}O_2$ per velocity) at the lower speeds (Costill and Winrow 1970, Costill _et_ _al_ 1973, Wells _et_ _al_ 1981).

Some authors have measured economy in male and female subjects, finding that there were no differences between the sexes (per kg of body mass) in economy (Davies and Thompson 1979, Sparling and Cureton 1983). It was concluded, however, that females must be more economical (per kg of lean body mass) considering the extra body fat they must carry. Other authors (Bransford and Howley 1977, Wells _et_ _al_ 1981) reported that males were more economical than females. This may have been due to differences in training, as trained subjects have been reported to be more economical (5 - 7%) than untrained subjects (Margaria et al 1963, Bransford and Howley 1977). When male and female subjects are equally well trained the male advantage in economy is minimal (Wells et al 1981). Bransford and Howley (1977) suggested that the greater vertical movement of their female subjects accounted for their lower economy. In their study, the oxygen cost - velocity relationships were linear for all four groups (male, female, trained, untrained) and there were no differences between the slopes of these lines. The offsets were, however, indicative of the differences in economy. Trained and untrained subjects differ in one other important aspect. Economy is quite uniform across a broad spectrum of velocities in the well trained athlete, while the untrained individual has a more curvilinear response pattern (lower economy at both low and high velocities) (Boje 1944, Costill and Winrow 1970).

Downhill running economy is greater than uphill at the same velocity (Cavanagh et al 1973). However, running at too great a downhill grade will also lower the economy. Over the range of -30% to +5% grade, grades of -5% to -10% were found to elicit the most economical performance. They found that the net cost of running 1 m was independent of speed. The amplitude of knee movement, and both quadricep and hamstring EMG increased with increasing energy cost.

Submaximal economy is extremely important as a determinant of success in athletic performance (Costill et al 1971, Costill et al 1973, Mayhew 1977, Clement et al 1979, Lafontaine et al 1981, Hagberg and Coyle 1983). Conley and Krahenbuhl (1980) found no relationship between 10 km performance time and $\dot{V}O_2$ max in a very homogeneous group of well trained runners. However, 65.4% of the variation in race performance was explained by variations in economy.

The reasons for differences in economy of locomotion between individuals are many and varied. Differences in such factors as substrate utilization, number and activity of mitochondria, effectiveness of aerobic and anaerobic enzymes, muscle and blood pH, and the muscle fibre type composition influence economy. Fast-twitch fibres have three times more ATP turnover compared with slow-twitch fibres to get the same tension (Cavanagh and Kram 1983). During heavy exercise hydrogen ion concentration and strength is high (and pH is low). Furthermore, there is a two to three times increase in free radical concentrations. At the same time the mitochondria experience a loss of respiratory control, thus, more oxygen is consumed per mole of ATP (Sjodin 1983). It was also pointed out that with respect to substrate utilization, carbohydrate oxidation yields 10% more energy than fat oxidation. Conley and Krahenbuhl (1980) speculated that the variation in performance not accounted for by the economy of the subjects (34.6%) might be due to "inter-individual differences in muscle fibre composition, anaerobic threshold, and peak muscle and blood lactate tolerance". Sjodin (1983), having found that training performed at a velocity equivalent to the onset of blood lactate accumulation improved economy at 15 $km.h^{-1}$, suggested that this could have been due to a more efficient motor unit recruitment pattern, changes in capillary density and/or alterations in enzyme activity.

We have already seen that economy is affected by stride length variations from freely chosen (Hogberg 1952a). Nelson and Gregor (1976) followed a group of track athletes through a four year period of training. Performance improved, stride length and time decreased, and cadence increased over the longitudinal period implying that perhaps a higher cadence and lower stride length are associated with improved economy.

Mechanical factors influence economy. It has been reported that the use of air sole shoes results in a 1.6% (elite runner) to 2.8% (average runner) reduced oxygen cost for running at 4.5 $m.s^{-1}$ (Stipe 1982). The reason for this was felt to be the extra cushioning provided when the heel sinks at heel strike enabling energy to be stored in mid-stance and returned at toe-off. Hagberg and Coyle (1983) compared the oxygen cost of race walking and running in experienced race walkers. They found that the steady-state oxygen cost of race walking at 10 $km.h^{-1}$ (65% $\dot{V}O_2$ max) was significantly correlated with race walking performance. However, the running oxygen cost at approximately the same percentage of maximum capacity (12 $km.h^{-1}$) was unrelated to performance. This finding, they suggested, implies that economy is more related to the biomechanics of race walking rather than the biochemistry of energy production. Williams and Cavanagh (1981) conducted an interesting experiment to elucidate the underlying reasons for differences in economy. They used the net oxygen consumption at 3.57 $m.s^{-1}$ to establish three different groups of subjects based on economy. They measured maximal oxygen uptake (67.3 $ml.kg^{-1}.min^{-1}$), elastic storage of energy during knee bends, and muscle fibre composition (61% slow-twitch). Three-dimensional cinematography and segmental analysis were used to measure energy exchange and the relative costs of positive and negative work during running. The least economical runners had the highest mechanical work rates. The most economical had better between-segment energy transfer. There were no differences between groups in maximal oxygen uptake, muscle fibre type composition or elastic storage of energy. However, a number of kinetic and kinematic parameters were significantly different between the groups.

In a review paper Frederick (1985) listed a number of factors which are either known to directly influence economy or have been shown to be significantly associated with economy. The extrinsic factors were: ambient temperature, wind, grade, circadian rhythms, surface compliance, surface resiliency, orthotics, shoe softness, shoe weight and load carriage. Intrinsic factors affecting economy were: body weight, leg length, stride length, state of relaxation, hypnotic suggestion, body centre of mass excursion, energy transfer between segments, net positive mechanical work rate, impact force, foot strike, foot contact time, less arm motion, greater trunk angle of inclination, greater shank angle, lower knee flexion velocity in support phase and less plantar flexion at toe-off.

## EFFICIENCY OF LOCOMOTION

Efficiency is a term which refers to the ratio between the energy equivalent of the work accomplished and the metabolic energy consumed to do the work. Dill (1963) refers to Brody's 1945 definitions of gross, net and absolute (work) efficiency as being the first attempt to endorse what has come to be known as "baseline subtraction" in efficiency calculations. In gross efficiency, the entire energy cost of the activity is used as the denominator. Net efficiency refers to the subtraction of resting energy cost from the total cost. Absolute (or now known as "work") efficiency used as a denominator the total cost minus the cost of "zero-load" work. Delta efficiency, a recent term, (Stainsby *et al* 1980) refers to the ratio of the change in work output divided by the change in energy consumption for the work.

The concept of "baseline subtractions", while initially attractive, has been criticized. Wilkie (1974) suggests that the confusion regarding baseline subtractions is artificial. The baseline subtracted depends upon why you are examining efficiency. If limitations imposed by oxygen consumption are the reason "then it is the total metabolism of the body that counts". Whipp and Wasserman (1969) and Stainsby *et al* (1980) examined the whole *in vitro* muscle area, finding that phosphorylation-coupling efficiency is 40-60% and contraction-coupling efficiency is 50% leading to a maximum muscle efficiency of only 30%. Efficiency measurements based on heat exchange in muscle have been reported at 25%. Such overall efficiency values cannot be reconciled with exercising man partly because of the energy storage in muscle from step-to-step. Baseline subtractions, to be correct, must rely on the base value not changing during exercise. This, however, is not the case. Baseline metabolism, or zero-load metabolism, rises during exercise with increases in ventilation, catecholamines, lactate turnover, negative work, splanchnic metabolism, gastro-intestinal activity and temperature. Wilkie (1974) states that any inferences concerning efficiency based on heat measurements are suspect because large amounts of heat are liberated in the early stages of contraction which are related to activation not transduction. Furthermore, the replenishment of substrate stocks requires energy unrelated to work output.

Anaerobic processes contribute to energy output at all levels of power output. The relative contributions and the possible differential in efficiency of aerobic and anaerobic processes play a role in our understanding of the denominator of the efficiency calculation. Some investigators have alluded to the fact that anaerobic metabolism is inefficient (Shephard 1976, Lawson and Golding 1981), however others have indicated that the efficiency of energy production is equivalent between aerobic and anaerobic pathways. Whipp et al (1970) found that if the oxygen consumption achieves a steady-state during exercise oxygen debt and deficit are equal, and that the efficiency of anaerobic work was equal to aerobic work. Their view was that one must add recovery oxygen consumption to exercise values to get the total oxygen cost of the exercise. Wasserman et al (1967), on the other hand, found that efficiency changed very little when the energy equivalent of lactate production was added to steady-state oxygen consumption. In addition, the efficiency of unsteady-state work was equal to that of the steady-state work. Gaesser and Brooks (1975) agreed with Wasserman's approach stating that recovery oxygen consumption should not be added to that of exercise to calculate efficiency. Gladden and Welch (1978) worked their subjects at maximal power output for two minutes breathing various hypoxic gas mixtures (13-21% $O_2$), as well as at 30, 50 and 70% of $\dot{V}O_2$ max. They found that exercise oxygen consumption and blood lactate were linearly related to the partial pressure of inspired oxygen. The ratio of the slopes of these lines was taken to be an empirical expression of the energy equivalent of blood lactate. They reported that this ratio was constant at all fractional capacities as well as at maximum exercise. This suggested that it was not less efficient to use ATP synthesized anaerobically.

The formulation of the numerator in the efficiency expression, the energy equivalent of the work done, is no less contentious. In the direct analysis of mechanical energy various simplifying assumptions or incorrect mechanical equations have been employed in the past, leading to locomotor efficiencies ranging from -120% (Margaria 1968) to 197% (Norman et al 1976). Fenn's pioneering attempt to relate mechanical to metabolic energy (1930) ignored two important phenomena: the energy exchange within each segment and the transfer of energy between adjacent segments. Force plate data were used by Cavagna and co-workers (1963, 1966, 1971, 1977) to calculate the energy of the body centre of mass, making the assumption that the energy of the body centre of mass was equal to the sum of all segment energies. Winter (1982a) contends that this is a major erroneous assumption as reciprocal movements of the arms and legs may not cause a change in the body's centre of mass, and thus, are not reflected in the force plate curves. Winter further suggests (1979a) that the correct total body energy will be higher than this centre of mass approach (by an average of 16%). Cotes and Meade (1960) related vertical lift work of the trunk to energy consumption. They, too, assumed that the trunk segment reflects total body energy and neglected to take account of energy exchange within and between body segments.

Ralston and Lukin (1969), modelling their approach to gait analysis on the pioneering work of Elftman (1939a, 1939b), measured and summed various segmental energies to obtain the total body energy. Winter et al (1976) expanded upon this approach, modelling the energy components of all major body segments. Winter (1979b) proposed a definition of work done in locomotion which circumvented most of the above-mentioned problems. He defined a method of obtaining "internal work" which was always positive and accounted for all potential and kinetic energy components, the exchange of mechanical energy both within and between adjacent segments, and the positive and negative work done by muscles.

Most measures of efficiency have been based on the inclusion of external work only rather than the more all-inclusive "internal work". The work was performed against the resistance of an ergometer (Garry and Wishart 1931, Abbott _et al_ 1952, Whipp and Wasserman 1969, Gaesser and Brooks 1975, Faria _et al_ 1982, Pimental _et al_ 1982, McCartney _et al_ 1983), walking or running on a treadmill against an external load (Lloyd and Zacks 1972, Asmussen and Bonde-Peterson 1974), climbing a laddermill (Kamon 1970, Pandolf _et al_ 1978), walking or running up or down a grade (Bobbert 1960, Margaria _et al_ 1963, Dean 1965, Margaria 1968, Pugh 1970, Davies and Barnes 1972) and moving against wind resistance (Pugh 1970, 1971). Such calculations do not take into account the muscle work to move the limbs and trunk of the body itself. Thus the efficiencies, so calculated, were lower than the correponding efficiency which has the additional internal work term in the numerator. Morrissey _et al_ (1983), for example, found that when the mechanical work necessary to raise, lower and change the speed of the limb segments (internal work) was added to the external cycle ergometer work efficiency was 7% higher.

Studies which have accounted for internal work (Pierrynowski _et_ _al_ 1980, Fukashiro _et_ _al_ 1983, Ito _et_ _al_ 1983, Winter 1983c, Williams and Cavanagh 1983, Sakurai and Miyashita 1985) have struggled with the question of whether to include negative work as part of the total internal work. Winter (1979b) suggested that it should be included as its metabolic cost cannot be excluded from the denominator of the efficiency equation. It seems realistic to recognize different efficiencies for positive and negative work (Margaria 1968, Winter 1979a). Komi and Kaneko (1983) compared the efficiency of concentric and eccentric exercise on a "sledge" apparatus. Net concentric exercise efficiencies were 12 to 15% while the efficiency of negative work was highly variable and much higher than for positive work (27-132%). They found that the efficiency of negative work increased with increasing mechanical work and with speed of movement. They concluded, however, that "no set value could be representative for the negative work efficiency". Kamon (1970) found that during laddermill climbing the efficiency of climbing down (negative work) was 3.8 times that of climbing up the ladder, while a later laddermill study (Pandolf _et_ _al_ 1978) placed the differential at 5.3 times. Pierrynowski _et_ _al_ (1980) found that the efficiency of locomotion, assuming equal positive and negative work efficiency, was 65%. When negative work was assumed to be twice as efficient, the positive work was 48.7% efficient and the negative work 97.4%. If the negative work was three times as efficient the efficiencies were 43.3% and 130% respectively. This anomalous situation was explained in that two mechanisms are involved during energy absorption - passive viscosity which can transform mechanical energy to heat at no metabolic cost, and energy absorption during active contraction which involves some metabolic cost. They suggested that the efficiency could lie anywhere between that for active absorption, and the infinite efficiency of passive absorption depending upon the relative contribution of each mechanism.

Williams and Cavanagh (1983) examined the various assumptions concerning the relative costs of positive and negative work, energy transfer, and the elastic storage of energy by means of three-dimensional cine-segmental analysis of 31 well-trained subjects running at 3.57 $m.s^{-1}$. They calculated widely varying power outputs (273W to 1775W), with resultant efficiencies of 31% to 197%, depending upon which assumptions were used. They found that the assumptions regarding energy transfer had the biggest effect on the calculations of power output. They concluded that the most "realistic" assumptions were that stride-to-stride energy transfer accounted for 63% of the positive power, that elastic storage of energy during running was 35%, that non-muscular sources contributed 15% to negative power and the relative efficiency of negative work was three times that of positive work. Net efficiency of running, using these assumptions, was calculated at 44%.

Various factors have been identified which have a role to play in modifying the efficiency of locomotion. Elftman (1939b) pointed out that muscles are involved in energy exchange by receiving energy, dissipating energy, doing work and transmitting energy by tendon action. He identified various muscular factors in efficiency: the cost of maintenance of tension; the extent to which tension production is due to external forces; the energy necessary to overcome frictional resistance and non-elastic deformation; and the limitations placed on muscles by the necessity of nervous co-ordination. Whipp and Wasserman's work (1969) pointed to the need to consider all the work done such as heart, breathing and reciprocal leg action as well as the external work accomplished. Passmore and Durnin (1955) have stated that efficiency is largely unaffected by anthropometric differences or temperature. Pate and Kriska (1984), however, contend that anthropometric factors such as leg length, body weight distribution, hip width and femoral convergence do influence efficiency. A wider pelvis, shorter legs and greater femoral convergence may contribute to a less mechanically efficient gait in females. A female's leg weight to body mass ratio and greater thigh fat deposition could reduce running efficiency. They (Pate and Kriska 1984) went on to point out that mechanical skill, neuromuscular efficiency, storage of elastic energy and the oxygen cost of breathing and myocardial action affect efficiency.

Mechanical factors such as the distribution of mass in limbs and the point of muscle attachment relative to the joint centre can alter efficiency. Efficiency is reduced (by an estimated 24%) by losses in the bone-muscle connections and the human-ergometer link (Cavanagh and Kram 1983). Winter (1978a) points out that rotational kinetic energy is not important in walking but it is in running, and that as positive horizontal work is greater than negative there must be some loss to air and foot friction. Hinricks and Cavanagh (1983) found that arms contribute very little angular momentum about the transverse or anterior-posterior axes during running. They contribute substantially, however, about the vertical axis to counter the effect of leg angular momentum in the opposite direction. They concluded that substantial variation in the arm contribution to momentum could influence efficiency.

The locomotor pattern may play a significant role in efficiency. It has been hypothesized that bipedal locomotion is less efficient than quadrupedal locomotion. Man has been found to use approximately twice the amount of energy to move 1 g of body mass 1 km as the amount predicted for a quadrupedal animal of the same mass. It was felt this might be the case as the quadrupedal animal might run with less alternating positive and negative acceleration. To test their hypothesis, Taylor and Rowntree (1973) measured the oxygen cost of running on four legs and on two in chimpanzees and capuchin monkeys. They found bipedal and quadrupedal gait to be equally efficient.

Running efficiency has been found to be higher than walking efficiency (Lloyd and Zacks 1972, Fardy and Hellerstein 1978), especially when the walking and running are accomplished at the same velocity (Wyndham and Strydom 1971, Marchetti et al 1983). In fact, it has been pointed out that in normal walking it becomes more efficient to run once the movement velocity exceeds 8 km.h$^{-1}$. The main reason for the differential in efficiency between the two forms of locomotion is the beneficial effect of the elastic recoil of running (Cavagna et al 1964). Elastic recoil is lower at walking speeds because the energy is absorbed due to the increased contraction time. Elastic recoil increases with greater stretch as speed of movement increases (Fardy and Hellerstein 1978). Thys et al (1972) support this point of view stating that running is so efficient (40-50%) because the stretch shortening interval is very short. Winter (1982b) reported that the mechanical cost of walking was half of that of jogging (1.09 J/kg.m versus 2.14 J/kg.m). Mechanical cost was defined as the work done per stride (J) divided by the body mass (kg) times the stride distance (m).

Speed of movement may have an effect on the efficiency of locomotion. It has been found that efficiency increases with increased running speed (Heglund et al 1982) but decreases with increased walking speed (Donovan and Brooks 1977). Others have found that efficiency drops with increasing speed of movement (Gaesser and Brooks 1975, Brooks et al 1984), while still other studies have demonstrated no speed effect at all (Ito et al 1983). Hill (1964) measured the efficiency of loaded frog sartorious muscle in vitro during isometric and isotonic contractions. While shortening at a constant velocity efficiency remained constant over a considerable range of length. Mechanical power output was greatest at 30% of maximum load and efficiency at about 40% of maximum load. Davies (1971) shed some light on the question of the speed-efficiency relationship. He suggested that muscles are less efficient at both high and low speeds. At high speeds forming a cross-bridge is less likely and it could form at less than full extension of the flexible part of the cross-bridge. At low speeds the internal work associated with back and forth action in the sarcomere lowers efficiency. He also noted that the efficiency of utilization of the maximum thermodynamic free energy available from the ATP by the muscle is 70 to 80%. The uniformity with which a runner maintains his velocity has been suggested as one factor which would raise efficiency (Fenn 1930).

Donovan and Brooks (1977) explored the effects of grade and horizontal (trailing weight) work while treadmill walking at 3, 4.5 and 6 $km.h^{-1}$. They found that energy expenditure increased exponentially with increased load and speed. Efficiency thus dropped as speed increased. They felt that added speed meant that greater internal work had to be done, and that the shift from slow-twitch to fast-twitch fibre utilization might help explain the speed-efficiency relationship.

Suzuki (1979) divided his subjects into a high fast-twitch muscle fibre group (76% F-T) and a high slow-twitch fibre group (78% S-T) and asked each group to pedal slowly (60 RPM) and quickly (100 RPM) against sub-maximal resistance. The groups were equal in efficiency at 60 RPM but the fast-twitch subject group had a higher efficiency at the high pedal speed. In fact, the slow-twitch subject group had a lower efficiency at the higher speed than at 60 RPM (19.6% versus 23.3%). It was felt that this was the case because slow-twitch fibres become glycogen depleted first, thus, the slow-twitch subject group had to call upon the less economical fast-twitch fibres at the higher speed.

A number of cycle ergometer studies have shown that gross and net efficiencies decline with increases in pedal speed while work and delta efficiencies rise (Garry and Wishart 1931, Banister and Jackson 1967, McCartney et al 1983). In contrast with these findings, Faria et al (1982) found that gross efficiency was unaffected by changes in pedal speed. McCann and Gliner (1982) reported similar findings and concluded that mechanical efficiency does not play a role in determining preferred tempo. The results of Taguchi et al (1980) supported this conclusion. They established preferred cadence in cyclists pedalling against zero resistance and compared this with the freely selected cadence when pedalling against selected moderate resistances. They found that personal rhythm was very stable within and between days but that there was no relationship between personal rhythm and mechanical efficiency or, for that matter, between the variability in personal rhythm and the observed variability in efficiency. Subsequent experiments (Taguchi et al 1981) confirmed this lack of relationship. Others (Dickinson 1929, Seabury et al 1977) have found that a "most efficient" pedal rate exists for each power output and that efficiency is maximized at moderate (66 RPM) speeds.

Zarrugh (1981) supported the Davies (1971) suggestion of an inverted "u" shape to the walking speed-efficiency relationship with his work on the segmental summation of energy during "free" and "forced" cadence walking. Efficiency rose from a low of 9% at 0.84 $m.s^{-1}$ to a maximum of 23% at 1.7 $m.s^{-1}$ then decreased to 18% at 2.35 $m.s^{-1}$. He found that the minimum energy cost per unit distance occurred at 1.31 $m.s^{-1}$. The work rate of the head, arms and trunk was minimized near the freely chosen cadence and maximum efficiency results at the free step rate.

Grieve and Gear (1966), in their investigations of walking at various relative speeds, found that males come nearest to having the same cadence (lowest standard deviation) at 0.6 $st.s^{-1}$ while for females this point of minimal inter-subject variability occurs at 1.0 $st.s^{-1}$. They noted that (for males) this velocity coincided with the velocity at which maximum walking efficiency was found. They speculated that females might show maximum efficiency at a relative speed of approximately 1.0 $st.s^{-1}$.

Most studies which have examined the relationship between increases in power output and efficiency have found that gross and net efficiency increase with power (Gaesser and Brooks 1975, Faria _et al_ 1982, Pimental _et al_ 1982). Interestingly, however, when "work" or "delta" efficiencies are measured, they remain constant or drop as power output increases (Gaesser and Brooks 1975, Gladden and Welch 1978, Stuart et al 1981, Powers et al 1984). It was felt that these efficiencies more adequately reflected the true state of muscular activity, and that extra metabolism not directly related to power output brought about the decreased efficiencies noted. McCartney et al (1983), however, found that the efficiency of cranking an isokinetic bicycle ergometer was independent of load as long as speed stayed the same. Henry and Demoos (1950) found that increased power output at the same pedal speed during cycling brought about a small decrease in efficiency. As an aside, the Powers et al (1984) work on arm cranking demonstrated very similar efficiencies (16%) to leg work (17%) at the same percentage of maximal oxygen consumption.

The speed - power output interaction effect on efficiency is seen clearly in the work of Seabury et al (1977). Efficiency rose with power output (15% at low power output to 24% at high power). Furthermore, the "most efficient" pedal rate (of the eight conditions between 30 and 120 RPM) rose progressively with increasing power output. The higher oxygen cost observed at RPM's below "most efficient" was relatively greater at higher RPM's. They suggested that as speed of pedalling increased the energy transfer from one revolution to the next may be greater, thus, relatively less muscular contraction is needed.

The duration of short-term exercise has no effect on efficiency as long as recovery oxygen consumption is not taken into account (Crowden 1934, Wasserman et al 1967). However, the work efficiency of short tests has been found to be less than that of longer steady-state tests when recovery oxygen consumption is included with the exercise oxygen cost (Katch and Park 1975). The same oxygen debt, when added to a longer duration exercise pro rata, will lead to a reduced oxygen cost per unit of power output. They did point out that recovery oxygen consumption seemed to be independent of exercise energetics, and it would, thus, seem inappropriate to add it to the exercise cost. One factor, related to duration, has a positive effect on efficiency. Muscle temperature rises from the beginning of exercise and efficiency rises with increases in temperature (Fardy and Hellerstein 1978).

Biological rhythms show up as circadian (1 day), circseptan (7 days) and circalunar cycles. Arousal has been found to be maximized in the later afternoon with improvements in pattern recognition, reaction speed and muscle force as indicators. Body temperature peaks at approximately this time and ratings of perceived exertion are lower. Heart rate responses mirror the temperature responses. Predicted maximal oxygen uptake and work capacity (PWC 170) are minimal in mid-afternoon but measured maximal oxygen uptake shows no diurnal change. Similarly, there is no diurnal variation in exercise efficiency. In women, the rise in temperature with the second half of the oestrous cycle has no effect on maximal oxygen consumption or anaerobic threshold. The pre-menstrual increase in body hydration has a small negative effect on physical working capacity but the oestrous cycle has been shown to have no effect on athletic performance or on ratings of perceived exertion (Shephard 1984a).

One's state of training can influence the efficiency of locomotion. Weltman and Katch (1976) compared a group of subjects with high aerobic capacity (65.4 $ml.kg^{-1}.min^{-1}$ $\dot{V}O_2$ max) with a lower capacity group (49.7 $ml.kg^{-1}.min^{-1}$) on a ten minute, 120W cycle ride. They examined submaximal oxygen consumption and time to steady-state. The high capacity group achieved steady-state faster but both groups were approximately equal in submaximal oxygen consumption. The high capacity group was somewhat more efficient (24% versus 22%) and had a lower respiratory exchange ratio (0.87 versus 0.94). This implied that greater fat metabolism was employed, producing fewer kJ of energy from substrate. They suggested that the increased efficiency was most likely related to the need for less energy for temperature regulation, ventilation and circulation.

It has been reported that endurance training brings about improvements in running efficiency (Margaria _et al_ 1963). Mayhew (1977) measured the oxygen consumption of nine trained runners at various speeds from 2.2 to 4.9 $m.s^{-1}$ and used the slope of the oxygen consumption - running speed regression as a measure of efficiency. He found there was a difference in slopes between the most, and least efficient of his runners. It was interesting that amongst this group of well-trained athletes those with the higher maximal oxygen uptakes were less efficient. He suggested that the greater maximal oxygen uptake of superior runners allows them to be somewhat less efficient while running and yet maintain oxygen supply commensurate with demand at higher speeds. He also reported that there was a distinct optimal running speed at 3.1 $m.s^{-1}$ where oxygen consumption ($ml.kg^{-1}.km^{-1}$) was minimized. This optimal point occurred at a mean relative speed of 1.76 $st.s^{-1}$.

It has been suggested that one's movement skill level influences efficiency. Garry and Wishart (1931) compared the ratio of unloaded cycling oxygen cost to overall work $\dot{V}O_2$ in trained and untrained cyclists. This ratio was very much higher in the untrained cyclist (62%) compared with the trained person (41%). They suggested that skill allows the trained person to use fewer accessory muscles to hold his body in the working position. Pimental et al (1982) found that walking downhill backward (an unaccustomed activity) was less efficient than its mirror image of uphill forward walking. Williams et al (1966) suggested that "skill" accounted for inter-individual differences in the energy cost of a variety of lifting and moving tasks. In another unusual movement task, walking down quite steep grades, subjects improved substantially in movement efficiency (by 43%) with task habituation. They improved co-ordination and curtailed waste movements with habituation (Davies and Barnes 1972). Rejeski et al (1982) suggested that training improves neural control parameters, and proposed that the improved efficiency achieved through co-ordinated action may alter ratings of perceived exertion.

Winter (1978b) identified a number of sources of inefficiency during locomotion: 1) co-contractions of agonist and antagonist; 2) isometric contractions against gravity; 3) jerky, unco-ordinated movements; 4) generation of energy at one joint at the same time as absorption at another joint (such as during double support push-off).

Given the wide variety of factors listed above, and the potential interactions which might influence efficiency, it is not surprising that there is considerable intra- and inter-subject variability in efficiency and its constituants. The variability in ground reaction forces has been reported to be relatively low, both running (Hamill et al 1983) and walking (Winter 1984) (horizontal forces CV = 20%, vertical forces CV = 7%). It has been reported that swing time during running is quite variable (Grieve and Gear 1966) but that the coefficient of variation in hip and knee moments drops as cadence increases (Winter 1983a). Bates et al (1979) found that the mean absolute deviation between all measures of temporal and kinematic parameters of gait on three consecutive foot falls during running at 4.47 $m.s^{-1}$ was 5%. Luhtanen and Komi (1980) reported coefficients of variation in the horizontal power output of walking, running and jumping to range between 11.7 and 16%. Thorstensson et al (1976) had 25 young male subjects perform repeated maximal knee efforts on an isokinetic dynamometer, finding that the coefficients of variation of maximum torque averaged 10% within days and 13.5% on separate days. This includes methodological and biological variation (estimated at

8.5% CV). The coefficient of variation of integrated EMG in the leg musculature of adolescents during walking has been reported to range between 15% and 24% (Wands et al 1980). Brooke et al (1982) reported that the coefficient of variation of force output during cycling ranged between 3% and 12%. It was highest at the transition from the recovery to the power phase, and lowest at peak force output. The mean coefficient of variation, based on 29 000 movement cycles, remained constant at 9% as force output increased. This is consistent with McCann and Gliner's (1982) finding that the coefficient of variation of tempo during cycling remained constant at all power outputs.

Variability in efficiency has been reported to range from 29.5% (Erickson et al 1946) to 2.5% (Williams et al 1966). Shephard, in a review of a number of studies reported that the variability of efficiency of cycling was 4-5%, of stepping was 7% and of treadmill locomotion was 10% (Shephard 1976). Men and women have been reported to have very similar within- and between-days variability in efficiency (overall CV for men = 9.6%, women = 10.8%) of grade and level walking (Durnin and Namyslowski 1958). In fact, Mahedeva et al (1953) reported that age, sex, race and food intake combined only contributed approximately 6% variability to stepping and walking exercise oxygen consumption after the effects of body mass were taken into account. Similarly, Katch et al (1982) reported that the total variability on 8 to 20 $\dot{V}O_2$ max tests conducted over a four week period was 5.6%, of which 90% was due to biological variation. Mayhew (1977) suggested that the coefficient of variation in efficiency was minimal running at 4 $m.s^{-1}$ but that it was above 30% at slow (2.7 $m.s^{-1}$) and fast extremes (6.3 $m.s^{-1}$).

In summary, quotations drawn from several earlier papers are equally applicable to our state of understanding of locomotor economy and efficiency today. Winter and Robertson (1978) proposed that "There is no concensus as to how mechanical energy of movement should be calculated and interpreted". "Our knowledge of the subject (efficiency) remains unsatisfactory both theoretically and experimentally" (Wilkie 1974).

# CHAPTER III

# EXPERIMENTAL METHODS AND PROCEDURES

## THE ON-LINE COMPUTER-AIDED DATA ACQUISITION SYSTEM

### Theory and Development

The indirect assessment of metabolic response to exercise has come a long way since the early days of A.V. Hill and R. Margaria. The collection of expired air in glass syringes and it's subsequent analysis by chemical gas analysers was a laborious time-consuming process. Micro-Scholander or Haldane analysis of oxygen and carbon dioxide fractions of each sample would typically consume up to a half-hour of technician time. Although the results were precise and accurate, the number of experiments conducted, and the nature of such experiments, was limited by the technology (Consolazio et al 1963).

With the advent of electronic gas analysers and accurate, reliable volumeters, researchers proceeded to modify the sample collection technique in a variety of ways. Aliquots of gas were collected in a computer-assisted rotary fashion that permitted a more sensitive analysis of respiratory transients (Wilmore and Costill 1974). Other investigators employed a continuous flow analysis of expired air through a 3.5 to 5 l mixing chamber with the results appearing on an analogue recorder (Wilmore and Costill 1974, Graham et al 1980, Rejeski et al 1982, Powers et al 1983). This concept has been taken one step further by the introduction of a microcomputer to assist in the collection and interpretation of the data (Kissen and McGuire 1967, Wilmore and Haskell 1972, Beaver et al 1973, Wilmore et al 1976, Fellingham et al 1978). The most recent advances in computer-assisted data acquisition involve breath-by-breath analysis of inspired and expired air flow and composition (Yeh et al 1983).

While these systems have been validated against traditional methods and found to be superior in many respects, the sophistication of the technology and the high cost have prevented many laboratories from acquiring them. The obvious advantages of computer-aided data acquisition and the dramatic reductions in computing equipment costs prompted the author to develop a low cost alternative system. A similar system is described in the literature (Cordain et al 1982). The experimental protocol utilized in the present study was made possible by the development of this system. The quantity of data collected, the time sequencing of samples and the internal consistency of the system all made the present protocol possible.

## System Hardware

The hardware configuration (Figure 1, page 101) enabled the subject to inhale ambient air through the inlet port of the Mijnhardt dry gasmeter where inspired volume was measured. The air was drawn from the outlet of the gasmeter through

Collins ridged tubing (3 cm diameter) to a Hans Rudolph #2700 pulmonary valve. Total inspiratory resistance in this system was quite low at 0.3 to 0.5 cm water pressure depending upon the air flow. Expired air was directed, through similar ridged tubing, to a 4 l Perspex mixing chamber. Within the chamber, a small circulating fan ensured the smooth mixing of the air which was sampled from the chamber at the rate of 300 $ml.min^{-1}$ for analysis. After leaving the flow-through mixing chamber, the air passed through a 1 m section of ridged tubing before venting to the room. This prevented the contamination of the contents of the mixing chamber with room air. The 4 l volume of the chamber was chosen as approximately twice the maximum tidal volume expected during exercise. In this fashion wide fluctuations in the gas fractions were avoided while ensuring a reasonably sensitive response to real changes in air composition. Inspired air temperature was measured by a solid state thermister located inside the gasmeter. Previously calibrated Gould Capnograph Mark III carbon dioxide and Applied Electrochemistry S3A oxygen analysers were used for expired air analysis.

Analogue signals from the temperature sensor, the two gas analysers and the cardiotachometer were fed into a multiplexor and then into a 12-bit, 8-port analogue-to-digital (A-to-D) converter (locally manufactured). The subsequent digital signals were sequentially sampled, at a rate of approximately 220 times per minute, by a South West Texas 6800 microcomputer

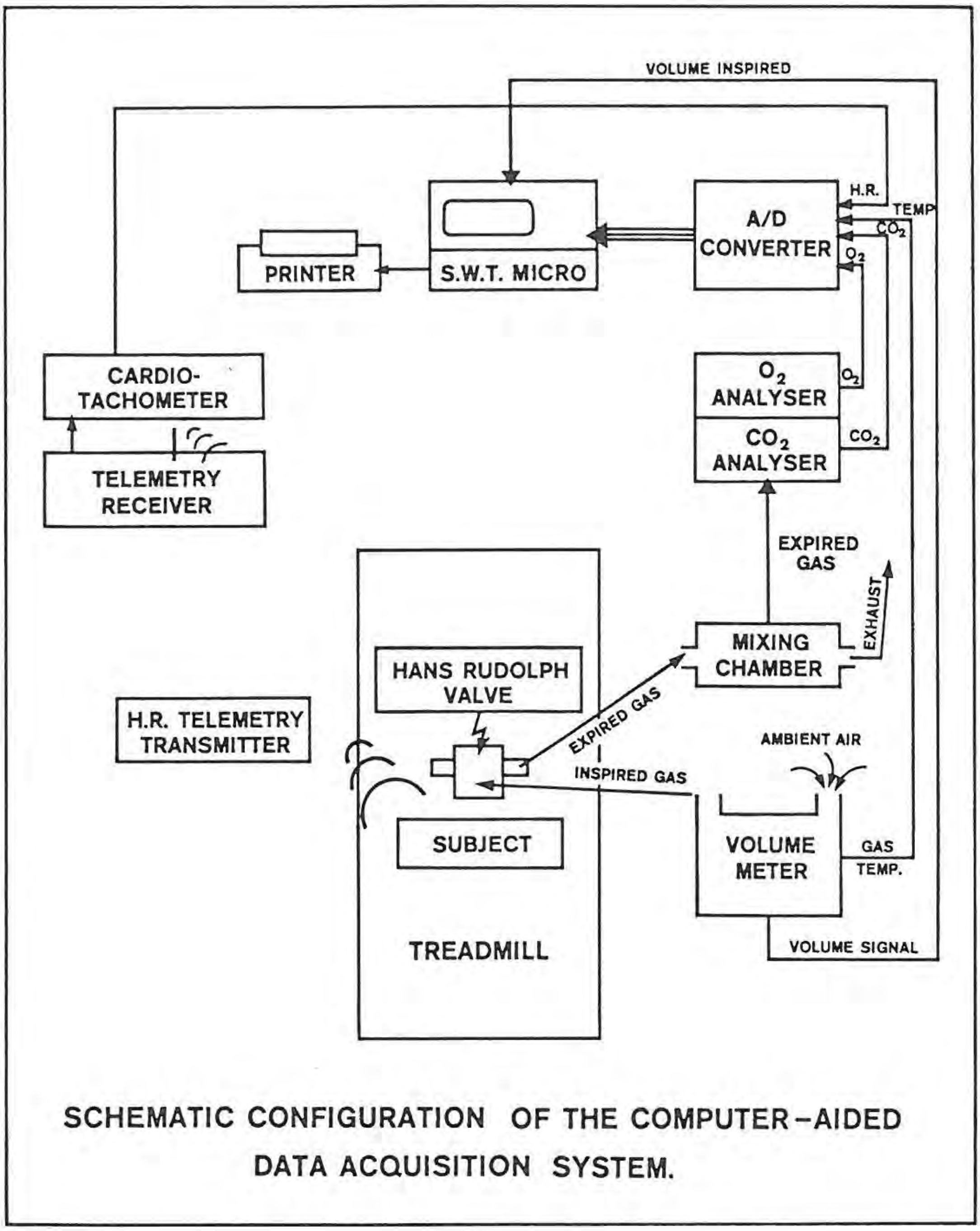


Figure 1 The on-line system

(32-K core memory). On-going visual feedback of oxygen consumption, rate of change of oxygen consumption, respiratory exchange ratio, percent of maximal oxygen consumption and elapsed time were provided on the computer's video display terminal. A permanent record of all measured and computed parameters was output to a Centronics dot matrix printer immediately after each sample.

During the development phase, all aspects of the hardware were calibrated against known standards. Volume calibration was performed, in a pulsatile manner, against a Singer gasmeter previously calibrated by the negative pressure water removal method. The mixing box fractions were compared to bags of expired air collected simultaneously. The computer sample timer was compared to several external digital clocks. The gas temperature probe was compared with a precise mercury thermometer immersed in a water bath and found to be linear from 0 to 38 degrees. Ventilation rate was compared with that obtained by conventional visual observation techniques.

After completion of the validation study and the pilot study, treadmill speed output from the Quinton control panel was interfaced with the computer through the A-to-D converter. From a knowledge of belt counts per timed period, the length of the treadmill belt and the voltage output from the controller, a regression equation between absolute belt speed and voltage was developed. This relationship was programmed into the on-line system software enabling the accurate and reliable assessment of treadmill belt speed.

## System Software

The software, written in BASIC, for this system enabled either continuous sampling ("CONT30") or discontinuous automatic ("AUTO") or manual ("MANUAL") sequence sampling. It not only performed data collection and averaging functions for a variety of cardio-respiratory variables, but also computed many derived variables and output these to both a video terminal and a hard copy printer. The "CONT30" programme was designed for use during the maximal oxygen uptake testing, and the "AUTO" and "MANUAL" programmes were designed to evaluate the steady-state responses during the walk/run testing in this study. The equations used in the software are outlined in Appendix 1 (page 259). Programme listings and a written description of the flow of the programme appear in Appendix 2 (page 262).

## Protocol for Validity Assessment

Estimates of the validity of any new technological system must be based on comparisons with established standards (Bosco and Gustafson 1982, Clarke and Clarke 1984). The established standard technique for the estimation of respiratory gas exchange by indirect methods is the collection of expired air in bags for later analysis of gas concentrations and volume (Consolazio *et al* 1963). In order to validate the system 10 well-trained long distance runners (69 ± 5.5 kg, 24 ± 4.5 y), ran on the treadmill on two occasions. The protocol for each run was exactly the same. The subject jogged at 0% grade and 8 $km.h^{-1}$ for 5 min, at which time, and every minute thereafter, the treadmill speed was increased by 1 $km.h^{-1}$ until the subject was running at 17 $km.h^{-1}$. The treadmill grade was then increased by 2.5% grade every minute until exhaustion. During one run, expired air was collected and analysed in the traditional manner. Meteorological balloon bag collections (30 s) took place at 3.5 and 4.5 min of the 8 $km.h^{-1}$ run, and further collections at 10, 12, 14, and 16 $km.h^{-1}$ during the last 30 s at each velocity. Depending upon the ease with which the subject was tolerating the load at 17 $km.h^{-1}$, samples were then taken either every minute or every 2 min until the point of exhaustion. The contents of the meteorological balloons were analysed as they were collected to obviate gas diffusion. During the other run, all data were collected using the on-line computer-aided system. Because of the ease of data collection, 30 s samples were collected every minute starting at 3.5 min and sampling continued until subject exhaustion terminated the run. The order of presentation of treatments was entirely random (6 subjects had the computer first, 4 had the bag first). The second test was conducted exactly one week after the first at the same time of day.

During the bag collection test, the subjects inspired through the Mijnhardt gasmeter just as they did during the computer test. During the bag collection test the expired air was directed through a Collins high velocity "Y" valve into the meteorological balloon. During the computer test the expired air was directed into the mixing chamber from the same piece of tubing as was used in the bag test. The unavoidable problem of removing the meteorological balloon from the "Y" valve to install the next entailed the loss of 300 ml of expired air and its replacement with an equal aliquoit of room air when the sampling stopper was placed in the neck of the bag. Gas volume removed from the bag during analysis was carefully monitored and added computationally to the volume reading.

A two factor ANOVA (Ferguson 1981) was applied to the two 8 $km.h^{-1}$ samples to assess the computer system's validity for steady-state work. Student's "t" tests were applied to the bag and computer data at all comparable points from 10 $km.h^{-1}$ to $\dot{V}O_2$ max to validate the performance of the computer system during unsteady-state work.

### Validation of the On-Line System

When the on-line system and the laboratory standard Douglas bag system were compared, the substantial overlap of the standard deviation bars and the small mean differences between the two methods supported the validity of the on-line system, both for steady- and unsteady-state exercise response (Figures 2-4, pages 107 to 109). Astrand and Rodahl (1977) point out that for repeated determinations of maximal oxygen uptake on the same subject, the variation (standard deviation) due to biological and methodological variables is 3%. In the present study, using a different technology for assessment on the repeat test, the mean differences between data collected on the two tests (for all power output conditions combined) ranged between 0.5% and 3.1% (Table I, below).

Table I  Overall mean responses (± SD) of subjects to progressive treadmill running during on-line system validation

| Variable | Douglas Bag | | On-Line | | % Diff |
|---|---|---|---|---|---|
| | $\overline{X}$ | SD | $\overline{X}$ | SD | |
| $FEO_2$ | 0.1677 | 0.0015 | 0.1668 | 0.0015 | 0.5 |
| $FECO_2$ | 0.0425 | 0.0011 | 0.0430 | 0.0014 | 1.2 |
| $\dot{V}I$(STPD) ($l.min^{-1}$) | 83.40 | 5.39 | 83.47 | 3.72 | 0.1 |
| $\dot{V}O_2$($l.min^{-1}$) | 3.24 | 0.16 | 3.34 | 0.13 | 3.1 |
| $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$) | 48.1 | 1.47 | 49.5 | 1.53 | 3.1 |
| $\dot{V}CO_2$ ($ml.kg^{-1}.min^{-1}$) | 3.50 | 0.15 | 3.49 | 0.14 | 1.4 |
| R | 1.08 | 0.04 | 1.05 | 0.02 | 2.3 |

When $\dot{V}O_2$ and R bag collection values were corrected for the 300 ml dilution factor, the differences between the two methods dropped substantially (to 1.2% for $\dot{V}O_2$, and 0.9% for R).

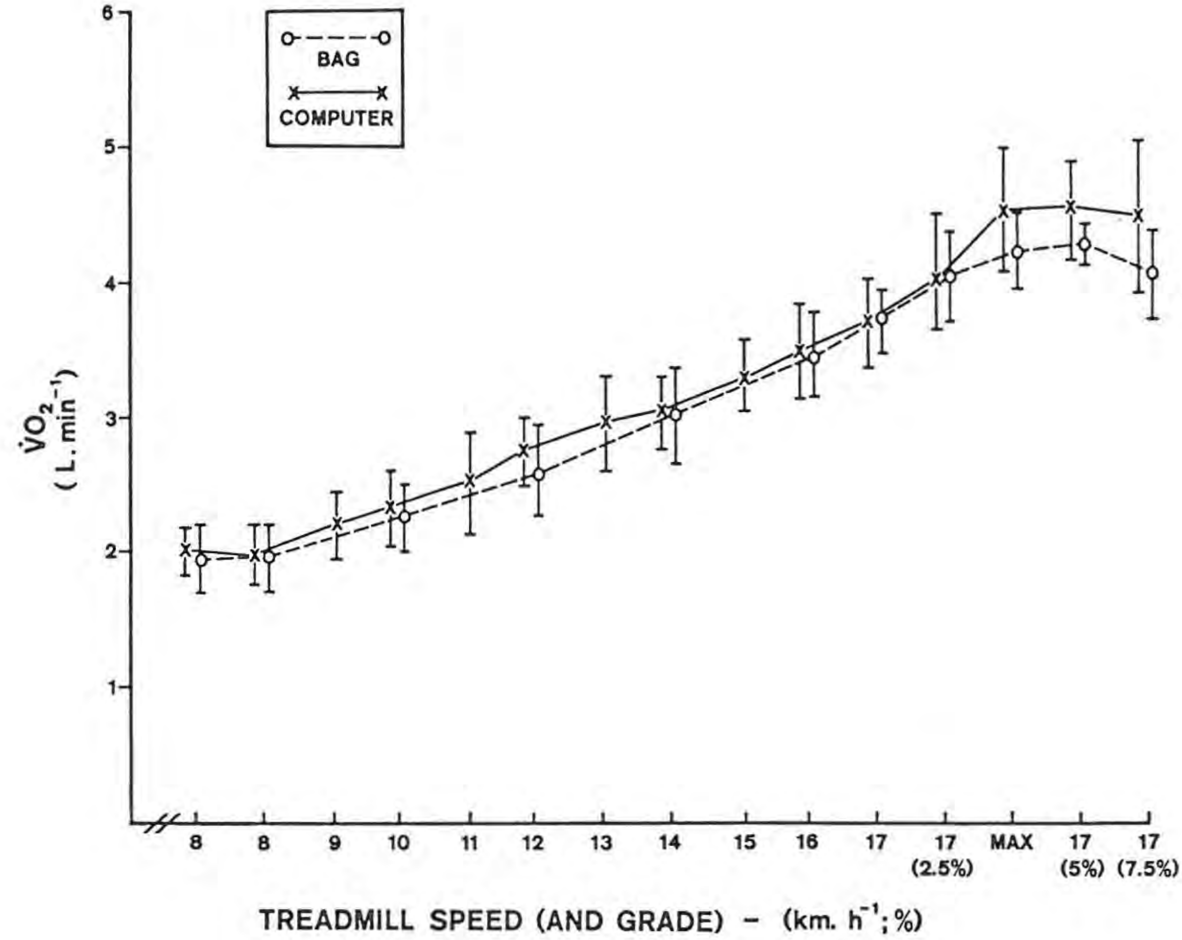


Figure 2 Oxygen consumption in response to steady-state and progressive power outputs during on-line system validation.

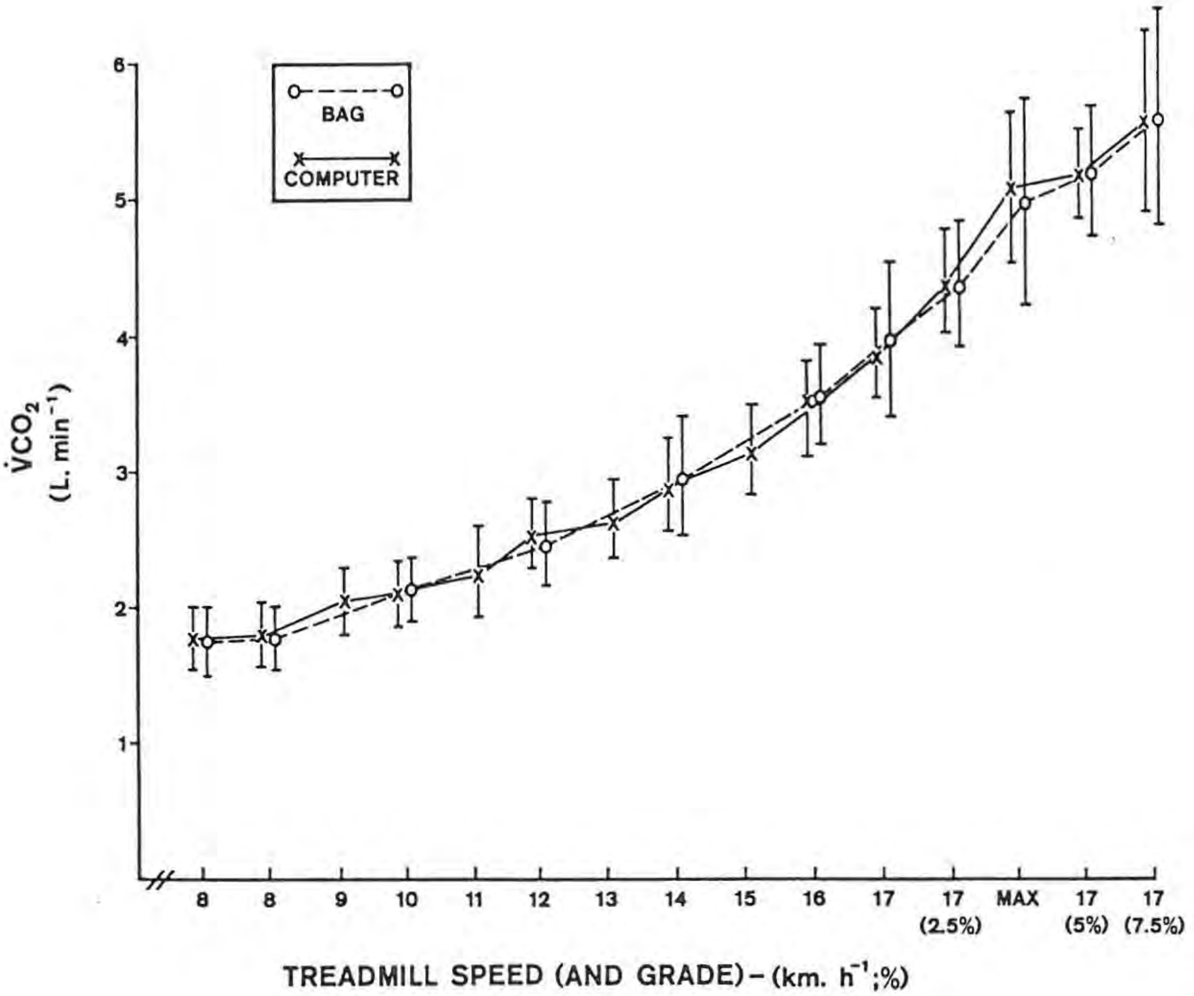


Figure 3 Carbon dioxide production in response to steady-state and progressive power outputs during on-line system validation.

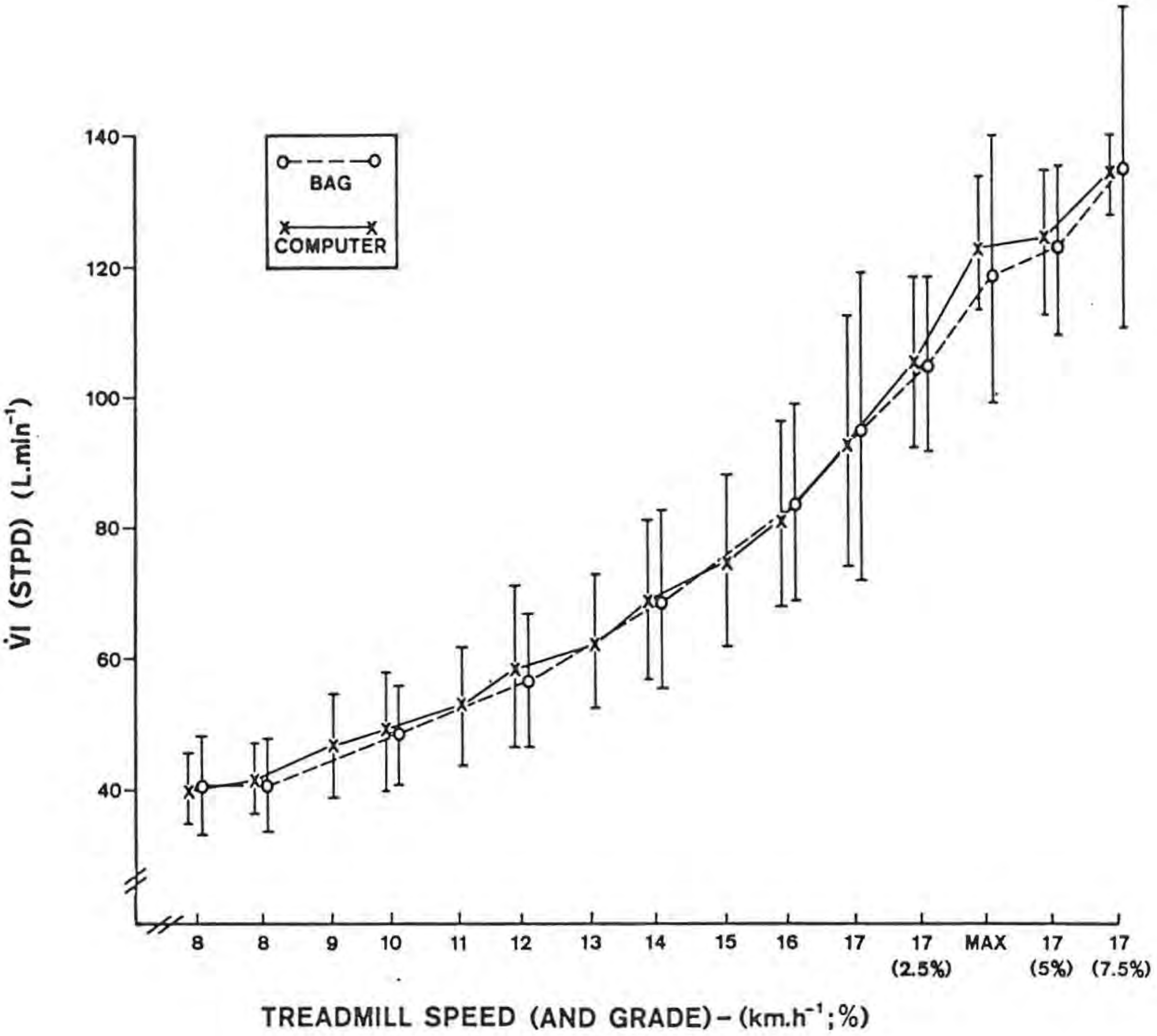


Figure 4 Inspired volume (STPD) in response to steady-state and progressive power outputs during on-line system validation.

Based on actual conditions during the above data collection, it was estimated that the average time to complete the analysis of a 15 min treadmill run using the bag collection technique was 35 min for gas analysis, plus 15 min for calculation of all parameters. The same test conducted on the computer system was finished, with a print-out in hand, as soon as the subject stepped off the treadmill. In addition to this time saving, the number of technical assistants for a computer run was reduced to one from the three required for bag collection. It was concluded that the on-line computer-assisted data acquisition system was not only providing valid results, but that it did so with substantial ease and efficiency. Similar results were obtained by Powers et al (1983) using a mixing chamber system, when they compared 30 s samples with Douglas bag collections during exercise up to maximum.

## ANTHROPOMETRIC METHODS AND PROCEDURES

### Somatometry

The following measurements of the dimensions of the body were obtained on each subject:

Stature - A Holtain Stadiometer was used to measure the distance from the vertex in the mid-sagittal plane to the floor (to the nearest mm). This measurement was made with the subject standing barefoot in the military position at attention, head erect, looking straight ahead, so that his visual axis was parallel to the surface of the floor. Montagu suggests that the latter is the best free approximation to the Frankfurt Plane (Montagu 1960).

Sitting Height - A Holtain Stadiometer was used to measure the distance from the vertex to the surface upon which the subject was seated (to the nearest mm). A box, high enough to keep the subject's feet away from the ground was placed against a wall, and the subject was instructed to take his seat in such a manner as to enable him to swing his legs freely over the front of the box, while his scapular and sacral regions were resting vertically against the surface of the wall. In this position the measurement was taken from the vertex to the box. The subject sat erect with the head aligned as described above.

Body Mass - A Seca beam balance scale was used to measure body mass to the nearest 0.1 kg. After the scale was calibrated against known masses of containerized water (± 0.3% error) and zeroed at the balance point, the subject stood quietly on the scale barefoot in his exercise clothing. An investigator moved the sliding counter-weights and recorded the body mass.

Foot Length - Harpenden sliding flat calipers were used to measure from the most posteriorly projecting point on the heel (akropodion) to the tip of the most anteriorly projecting toe (pternion), when the subject was standing erect (Montagu 1960).

## Skinfold Fat Measurements

Skinfold fat measurements were obtained using a Harpenden caliper at the four sites as indicated below. The procedure for all measurements involved the following steps. The skinfold was grasped between the thumb and index finger 1 cm above the prescribed site and pressure applied. The skinfold was raised and maintained with the thumb and finger, with the crest of the fold following the specified alignment. The caliper jaws were applied at right angles to the prescribed site and the spring handles released fully. The measurement was taken after the full pressure of the caliper jaws had been applied and the drift of the needle had stopped (recorded to the nearest 0.1 mm). The measurements were taken twice. If the difference was greater than 1 mm, a third measure was obtained and the mean of the closest pair recorded.

Biceps Skinfold - This was measured on the front of the right pendant upper arm over the biceps at a level midway between the acromion and the tip of the elbow. The skinfold was lifted parallel to the long axis of the upper arm.

Subscapular Skinfold - This was measured about 1 cm below the lower angle of the right scapula with the subject standing erect. The crease of the skinfold that was lifted ran at an angle of about 45 degrees down from the spine.

Triceps Skinfold - This was measured on the back of the unclothed pendant right arm at a level midway between the tip of the acromion and the tip of the elbow. The midpoint was established with the elbow flexed at 90 degrees. The skinfold was lifted parallel to the long axis of the arm. The subject then lowered the forearm and the caliper jaws were applied.

Supra-Iliac Skinfold - Measured 3 cm above the iliac crest with the fold running parallel to the crest, this fold was taken at the midline of the body.

The procedures for obtaining these skinfolds and methods to calculate body specific gravity are outlined by Durnin and Womersley (1974). Percent body fat was calculated using the Siri formula (1956). The specific equations used in these procedures appear in Appendix 6 (page 298).

## Derived Parameters

The following derived parameters were calculated based on the raw data collected. Equations and relationships used in developing these derivations appear in Appendix 6. Percent body fat was calculated from skinfold fat readings. Body surface area (BSA) was computed (Consolazio et al 1963) from stature and body mass. Lean body mass (LBM) was derived from percent fat and body mass. Leg length was calculated from the difference between sitting and standing stature (Montagu 1960). Relative leg length and relative foot length were calculated as proportions of overall stature and overall leg length respectively.

A number of derivations were formulated based on the exercise test data. Fractional oxygen uptake (%$\dot{V}O_2$ max), relative oxygen uptake ($\dot{V}O_2$ $ml.kg^{-1}.min^{-1}$ and $\dot{V}O_2$ $ml.kg\ LBM^{-1}.min^{-1}$), and absolute and relative economy (oxygen uptake per absolute velocity and oxygen uptake per relative velocity) were computed to assist in testing the research hypotheses.

## PERCEPTION OF EXERTION

Perception of exertion has received considerable attention since Borg (1962) first proposed its inclusion as a psychological compliment to physiological responses during exercise. Much of the earlier work, in which Borg's (1970) category rating scale (RPE) was used, was devoted to assessing the validity and reliability of the RPE scale (Pandolf 1978). These studies demonstrated a linear relationship between RPE and heart rate during cycling, and treadmill locomotion. As researchers examined this relationship more thoroughly it became increasingly apparent (Pandolf 1978) that perception of exertion was affected by a complex interaction of many influences, and that the perception of exertion was highly related to fractional oxygen consumption (Robertson 1982).

The Borg RPE scale (1970) was applied during each walk/run test to evaluate the effect of relative speed locomotion on the perception of effort. The 6 to 20 point scale has been reproduced in Appendix 3 (page 282).

## PILOT TESTING PROTOCOL

In order to establish the reliability of the on-line computer-aided data acquisition system as it was to be used in the present investigation, and to enable the circumvention of any data collection complications during the study, the procedures described below were employed (see Appendix 5 for the Data Collection Sheet used for Pilot Testing, page 292).

### Treadmill Velocity Reliability

To examine the effect of the subject moving on the Quinton Treadmill (model 24-72) on pre-set treadmill velocity, two male and two female subjects walked and ran on the treadmill. Belt counts per 30 seconds (see Appendix 4, page 288) were used to pre-set treadmill velocity at relative speeds of 0.5, 1.1, 1.5 and 1.9 $st.s^{-1}$. Subjects walked or ran at 0% and 3% grade at each velocity. Belt counts per 30 s were recorded with the subject off and on the treadmill. A related Student's "t" test was employed to assess the observed differences.

## Maximal Oxygen Consumption Reliability

Concurrent users of the on-line system, who were employing the same maximal oxygen uptake test protocol as that used in the present study, from 8 km.h$^{-1}$ upwards, have reported no difference in maximal oxygen consumption ($\dot{V}O_2$ max) upon repeat testing (Rorke 1985). There was less than 4% difference between successive determinations of $\dot{V}O_2$ max. Oxygen consumptions at comparable sub-maximal power outputs were similar throughout repeat testing.

## Walk/Run Oxygen Consumption and Initial Heart Rate

In order to avoid the cumulative effects of fatigue during repeated application of discrete exercise sessions, recovery periods should allow heart rate to drop to within 10 bpm of initial rest value (Gordon et al 1983). In order to evaluate this factor, and, at the same time, allow for an assessment of the reliability of measures of economy during repeat exercise sessions on the treadmill, four subjects (2 male, 2 female) were asked to walk or run at relative speeds of 0.5, 1.1, 1.5 and 1.9 st.s$^{-1}$. They moved at 0% and +3% grade at each velocity. Exercise sessions of randomly selected walks were interspersed with randomly selected running conditions to enable the eight conditions to be completed in one test period. Each exercise session was 4 min in duration with a variable length rest/recovery period between. Oxygen consumption was evaluated from 2.5 to 3.0, 3.0 to 3.5 and 3.5 to 4.0 min. Heart rate was measured before the initial session, and periodically during the recovery period between each session until heart rate was below the criterion measure. The criterion measures to be met were: recovery heart rate to return to within 10 bpm of initial rest value; and delta oxygen consumption between the last two exercise samples to be less than 2 $ml.kg^{-1}.min^{-1}$. Should these criteria be met, one can assume all exercise sessions started from the same physiological baseline, and oxygen consumption had achieved a steady value by the third minute of exercise.

This entire procedure was repeated to assess the reliability of this protocol. Reliability coefficients were calculated between representative points and related Student's "t" tests were applied to the data to establish the repeatability of data collection. Only single testing sessions for each condition would, thus, be necessary given adequate test - re-test reliability.

### Anthropometric Measurement Reliability

Foot length, stature, body mass, sitting height, and four skinfold fat measurements were obtained on four subjects (2 male, 2 female) on five occasions. Intra-subject coefficients of variation less than 3% and no significant difference between first and fifth measures of the parameter (via related Student's "t" test) would indicate the methods of measurement were substantially reliable.

Pilot Testing

During the pilot testing phase it was apparent that the action of the subject walking or running on the treadmill had the effect of reducing the pre-set speed slightly (by an average of 0.25 belt-cycle counts per 30 s). This was a significant difference ($p<0.05$), and accordingly, pre-set speed was set 0.25 belt-cycle counts per 30 s higher than the level necessary to obtain any given speed on an unloaded treadmill for the experiment proper. Once the treadmill speed was being monitored by the on-line system, this was accomplished by setting the speed to achieve a voltmeter speed reading 0.005 volts higher than required before the subject stepped onto the treadmill.

The technique of employing a variable recovery period was found to be quite successful in allowing the subject to start each walk/run session from within 10 bpm of resting heart rate. Taking both pilot test sessions into account, subjects were within 8 bpm of mean resting heart rate ($\overline{X}$ = 64 bpm) before each session. The comparison of oxygen uptake samples obtained between minutes 2.5 and 3 (25.62 ± 11.9 $ml.kg^{-1}.min^{-1}$), 3 and 3.5 (26.16 ± 12.0 $ml.kg^{-1}.min^{-1}$) and 3.5 and 4 min (26.24 ± 12.0 $ml.kg^{-1}.min^{-1}$) revealed that the subjects had achieved a stable oxygen consumption by minute 2.5 of each walking or running test. The justifiability of obtaining a 1 min (min 3 to min 4) $\dot{V}O_2$ sample for all subsequent testing was thus confirmed.

One of the main purposes of the pilot testing was to assess the reliability of the data collection system. Taking all conditions into account, from the slowest walk at 0% grade to the fastest run up a +3% grade, it was clear that upon repeat testing the oxygen uptake response was the same ($p<0.05$). The average $\dot{V}O_2$ of test 1 (26.0 ± 12.5 $ml.kg^{-1}.min^{-1}$) compared very favourably with that of test 2 (26.1 ± 11.9 $ml.kg^{-1}min^{-1}$). Repeated testing of anthropometric measures revealed a similar pattern. There were no differences ($p<0.05$) between test 1 and test 5 on any of the anthropometric measures. Coefficients of variation for length measures (0.24%), body mass (0.06%), four skinfolds (4.71%) and the sum of four skinfolds (2.39%) were well within acceptable limits (Montagu 1960, Lohman et al 1984). The lack of variability on repeat testing of oxygen consumption was a surprising finding, as others (Katch et al 1982, Shephard 1984b) have reported 4-6% intra-subject variability.

This pilot testing confirmed the reliability of the apparatus, and the protocol. Furthermore, data obtained on single occasions during the experimental phase could be viewed as being reliable and representative of a subject's normal response to walking or running on the treadmill.

## HABITUATION PROCEDURE

It has been clearly demonstrated that the kinematics of treadmill locomotion alter as the novice learns how to walk on the moving belt surface (Wall and Charteris 1980). Furthermore, it has been shown that these changes, while rapid initially, continue towards a stable gait pattern with distributed practice over a period of one hour (Wall and Charteris 1981). These authors have suggested that there may be metabolic correlates of these progressive changes. The changes in skill level may result in a lowering of the energy cost of gait as the novice becomes an accomplished treadmill walker. While the present study was not designed to evaluate this thesis, it was considered sufficient to habituate the subjects to treadmill locomotion with an hour of distributed practice. Each subject was exposed to all experimental conditions during these habituation sessions as outlined below.

Session 1

1) Informed consent was obtained (See Appendix 3, page 279).
2) Stature (cm) was measured.
3) Getting on and off treadmill safely was demonstrated.
4) The subject practiced this several times at 0.5 st.s$^{-1}$.
5) The subject walked for 5 min at 0.5 st.s$^{-1}$, 0% grade.
6) The subject ran for 5 min at 1.7 st.s$^{-1}$, 0% grade.
7) The subject walked for 5 min at 1.3 st.s$^{-1}$, +3% grade.
8) For 5, 6, and 7, above, the subject stepped off the treadmill while speed and grade were changed.

Session 2

1) Foot length, stature, body mass, sitting height and four skinfolds were measured.

2) The subject walked for 5 min at 1.1 $st.s^{-1}$, 0% grade.

3) The subject walked for 5 min at 0.7 $st.s^{-1}$, +3% grade.

4) The subject ran for 5 min at 1.7 $st.s^{-1}$, -3% grade.

5) The subject was instructed in taking the mouthpiece into the mouth during (3) above and wore it during minutes 4 and 5 of the walk at 0.7 and the run at 1.7 $st.s^{-1}$.

6) The subject stepped off the treadmill for every change of condition.

Session 3

For each of the following conditions the subject stepped off the treadmill for each change and wore the mouthpiece during minutes 4 and 5:

1) The subject walked for 5 min at 0.9 $st.s^{-1}$, -3% grade.

2) The subject ran for 5 min at 1.9 $st.s^{-1}$, +3% grade.

3) The subject ran for 5 min at 1.5 $st.s^{-1}$, -3% grade.

## THE EXPERIMENTAL PROTOCOL

Each subject, having completed the initial habituation, was tested for maximal oxygen uptake during a progressively increasing speed test on the treadmill. This test accomplished several purposes; it identified the subject's maximal aerobic capacity, his ventilatory threshold (V.T.), his maximum rating of perceived exertion (RPE), his submaximal economy at a number of absolute walking and running velocities, and placed him in one of the two aerobic capacity categories (high $\dot{V}O_2$ max or average

$\dot{V}O_2$ max) for further testing. In addition, it rounded out the final phase of the habituation process.

Following the test of maximal oxygen uptake, the subject returned to the laboratory on four separate occasions to enable measurement of walking and running economy at a variety of relative speeds ($st.s^{-1}$). Slow (0.5 and 0.7 $st.s^{-1}$), medium (0.9 $st.s^{-1}$) and fast (1.1 and 1.3 $st.s^{-1}$) walking speeds, as defined by Wall and Charteris (1980), and slow (1.5 $st.s^{-1}$), moderate (1.7 $st.s^{-1}$) and medium (1.9 $st.s^{-1}$) running speeds were used at -3%, 0% and +3% grade to evaluate economy across a broad spectrum of locomotor velocity conditions. The running speeds were selected in accordance with an effort to keep subjects at or below 80% of maximum capacity. Selected subjects with high maximum oxygen uptakes (above 55 $ml.kg^{-1}.min^{-1}$) were asked to perform three additional runs at 2.1, 2.3 and 2.5 $st.s^{-1}$ at 0% grade as they were the only subjects capable of performing this task at or below 80% of their maximum capacity. The 15 walking and 9 running conditions were randomly chosen, first a walk then a run, by selection from two closed containers without replacement. In this fashion, each subject performed either 3 walks alternating with 3 runs or two sets of 2 walks and a run per testing session. A single blind technique was employed to keep the subject from obtaining knowledge of each exercise condition. Subjects were asked to maintain their usual eating and exercise habits during the entire experimental period.

## Maximal Oxygen Uptake Test Protocol

Subjects were asked to refrain from any heavy exercise during the 24 hours prior to the max test. The following procedures were followed during the progressive test of maximal oxygen uptake:

1) The pre-test questionnaire was administered (see Appendix 3, page 278).
2) The subject's body mass was measured.
3) Laboratory barometric pressure and relative humidity were measured.
4) The on-line system programme "CONT30" (see Appendix 2, page 273) was loaded and initialized which allowed assessment of oxygen consumption for 25 s out of every 30 s.
5) The treadmill was set to 3 $km.h^{-1}$ at 0% grade.
6) The subject started walking on the treadmill with the mouthpiece in place.
7) After 1 min, to allow adequate expired air mixing, both the computer and the external timer were started.
8) At the end of each minute the speed was increased by 1 $km.h^{-1}$.
9) The subject walked until 6 $km.h^{-1}$ and ran at 7 $km.h^{-1}$ and above.
10) If the subject had not achieved maximum by the time he had completed a minute at 17 $km.h^{-1}$ the grade was raised by 1% at the end of each minute until the end of the test.

11) The end of the test was defined by a combination of:
    A) subjective exhaustion
    B) respiratory exchange ratio greater than 1.00
    C) delta oxygen consumption from the last 30 s of each minute to the next less than 100 $ml.min^{-1}$ or 1.5 $ml.kg^{-1}.min^{-1}$ (Astrand & Rodahl 1977).
12) Cadence was counted by visual inspection during the last 30 s of each minute.
13) The subject came off the mouthpiece at the end of the test but continued to run as the treadmill speed was reduced to a walking level. Immediately after coming off the mouthpiece the subject reported an RPE score for the highest speed/grade combination achieved.
14) The subject continued to walk for 5 min to "cool off".

### Relative Speed Walk/Run Test Protocol

Subjects were asked to refrain from heavy exercise during the 24 h prior to each laboratory visit. On each of four occasions when subjects were tested at relative speeds the following procedure was used:

1) 3 walking and 3 running conditions, alternating, were randomly selected, without replacement, from a closed container and the order recorded.
2) The pre-test questionnaire was administered.
3) Subject body mass and resting heart rate were measured as were laboratory barometric pressure and relative humidity.

4) The on-line programme "MANUAL" (See Appendix 2, page 269) was loaded and initialized to enable a 60 s sample starting at 3 min of each 4 min exercise period. The external timer was started.
5) Walking or running speed was adjusted by computer feedback after the subject started a four minute walk or run on the treadmill. He went onto the mouthpiece at 2 min and remained on the mouthpiece until 4 min.
6) Cadence was measured after three minutes for 30 s.
7) The RPE was obtained from the subject at minute 3.
8) The subject stepped off the treadmill and recovered while quietly sitting until heart rate was within 10 bpm of initial resting value.
9) Heart rate was measured periodically during recovery.
10) When the heart rate was within 10 bpm of the initial rest value, the subject started the next speed/grade condition. Steps 5 through 9, above, were repeated.
11) These procedures were followed until the subject had completed all six conditions.

## STATISTICAL ANALYSIS

A number of dependent variables, both those obtained directly from the subjects and those derived from the initial data, were treated statistically to evaluate the effects of the independent variables - relative speed, sex and aerobic capacity. Specifically, the research hypotheses were dealt with as follows:

Hypothesis 1:

Linear and curvilinear regression analysis techniques were applied to the economy of locomotion data at relative speeds and absolute speeds to evaluate the nature of the relationship between oxygen consumption and locomotion power output (Ferguson 1981).

Hypothesis 2:

Coefficients of variation for oxygen consumption (per unit velocity) were computed, for all subjects, at each absolute speed ($km.h^{-1}$) and each relative speed ($st.s^{-1}$) across a comparable range of velocities. A repeated measures ANOVA (Ferguson 1981) was used to test the hypothesis that there was no difference between the inter-subject variability in oxygen consumption when locomotor speed was set at relative and absolute velocities.

Hypotheses 3 and 4:

A two-factor ANOVA (Ferguson 1981) was used to test the hypotheses that there were no differences between the sexes, or between those of high and average aerobic capacity in the economy of locomotion. Each factor comprised two levels: Sex - male and female; aerobic capacity - high and average $\dot{V}O_2$ max. This analysis, conducted at each speed, also enabled examination of the interaction between the levels of both factors.

## Statistical Confidence

The 0.05 level of probability was employed throughout the statistical treatment of the data to test the significance of differences, variability and/or relationship. Judgements based on the results of these analyses must, therefore, be tempered with the knowledge that there were still 5 chances out of 100 that a Type I error could have been committed. In other words, the probability of rejecting a true hypothesis was set at 0.05. It was felt that this was a reasonable and acceptable level of risk attached to any decisions taken regarding the hypotheses. Astrand and Rodahl (1977) point out that intra-subject day-to-day variability in oxygen consumption due to biological variation is approximately 3%. Shephard (1984b) pointed out that "intra-individual day-to-day variation in a well performed direct measure of maximum oxygen intake is between 4 and 6%". This was supported by the finding that over four weeks of repeat testing with eight to twenty repeat $\dot{V}O_2$ max determinations, intra-subject variability was 5.6% with 90% of that due to biological variation (Katch et al 1982). It is the author's experience, both in the past (Brooke and Goslin 1985) and in the present study (see pilot test data, page 119), that repeated measurement of physiological response to human performance, when all efforts are made at standardization, elicits coefficients of variation in the 4% to 6% range. Thus, at the 5% level of confidence, chance alone could influence the outcome of a statistical test.

The chances of committing a Type II error - that of failing to reject a false hypothesis - are dependent upon the number of subjects tested. While the probability of committing a Type II error is lower at the 0.05 level than at a higher level of probability (0.01), the reasonably small number of observations in the present study leaves this probability at a moderately high level. The logistics of habituation and data collection, and the time demands placed on subjects necessarily kept subject numbers reasonably low.

Thus, in relation to Type I and II errors, and considering the inherent variability of the dependent variables and the limitations related to subject availability, the choice of the 0.05 level of probability was considered a justifiable compromise.

## SELECTION OF SUBJECTS

Young male (n = 21) and female (n = 21) subjects were selected for this study from the general student population of Rhodes University. The subjects were further divided into two more subgroups based on their maximal oxygen consumption ($\dot{V}O_2$ max). The subject groupings were: male, high $\dot{V}O_2$ max (n = 11); female, high $\dot{V}O_2$ max (n = 10); male, average $\dot{V}O_2$ max (n = 10); and female, average $\dot{V}O_2$ max (n = 11). Suitability for selection was based on willingness to participate for the full six hours of experimentation, evidence of general good health and absence of illness or injury which could adversely affect treadmill locomotion. Each subject provided written informed consent, in keeping with the University policy on ethical standards in experiments involving human subjects (see Appendix 3, page 279).

## Subject Characteristics

The male and female subjects in this study exhibited expected variation attributable to sexual dimorphism (Ross and Ward 1982, Haymes 1984) (Table II, page 130). The males were taller, heavier and had greater body surface area than the females ($p<0.05$). Because of the height differences between male and female subjects, the males moved at a significantly ($p<0.05$) higher absolute speed ($km.h^{-1}$) than the females at any given stature normalized relative speed ($st.s^{-1}$) (See Figure 5, page 131). The females exhibited higher %fat than the males ($p<0.05$) but both groups were well within the normal range of %fat (Wilmore and Brown 1974, Sparling and Cureton 1983).

Table II Anthropometric and performance characteristics of the male and female subjects

| Parameter | Male | | Female | | |
|---|---|---|---|---|---|
| | $\overline{X}$ | SD | $\overline{X}$ | SD | p |
| Age (years) | 21.7 | 3.2 | 21.1 | 2.2 | - |
| <u>Anthropometry:</u> | | | | | |
| Stature (cm) | 177.3 | 7.5 | 167.0 | 4.9 | $<0.05$ |
| Body mass (kg) | 71.2 | 6.5 | 60.4 | 7.2 | $<0.05$ |
| Leg length (cm) | 83.6 | 5.7 | 78.8 | 2.7 | $<0.05$ |
| Leg length/stature (%) | 47.1 | 1.6 | 47.2 | 0.9 | - |
| Foot length (cm) | 26.0 | 1.3 | 23.9 | 1.1 | $<0.05$ |
| Foot length/leg length (%) | 31.2 | 1.6 | 30.2 | 1.5 | $<0.05$ |
| % Fat | 15.2 | 3.3 | 23.7 | 4.0 | $<0.05$ |
| Lean body mass (kg) | 60.3 | 5.5 | 45.9 | 4.6 | $<0.05$ |
| Body surface area ($m^2$) | 1.88 | 0.12 | 1.68 | 0.11 | $<0.05$ |
| <u>Performance:</u> | | | | | |
| $\dot{V}O_2$ max ($ml.kg^{-1}.min^{-1}$) | 57.7 | 5.5 | 47.7 | 4.7 | $<0.05$ |
| V.T. (%$\dot{V}O_2$ max) | 64.7 | 8.2 | 62.9 | 8.2 | - |
| V.T. ($ml.kg^{-1}.min^{-1}$) | 37.4 | 6.1 | 30.1 | 6.2 | $<0.05$ |
| V.T. velocity ($km.h^{-1}$) | 11.5 | 2.3 | 8.9 | 1.8 | $<0.05$ |
| RPE max | 17.2 | 1.6 | 17.3 | 1.3 | - |

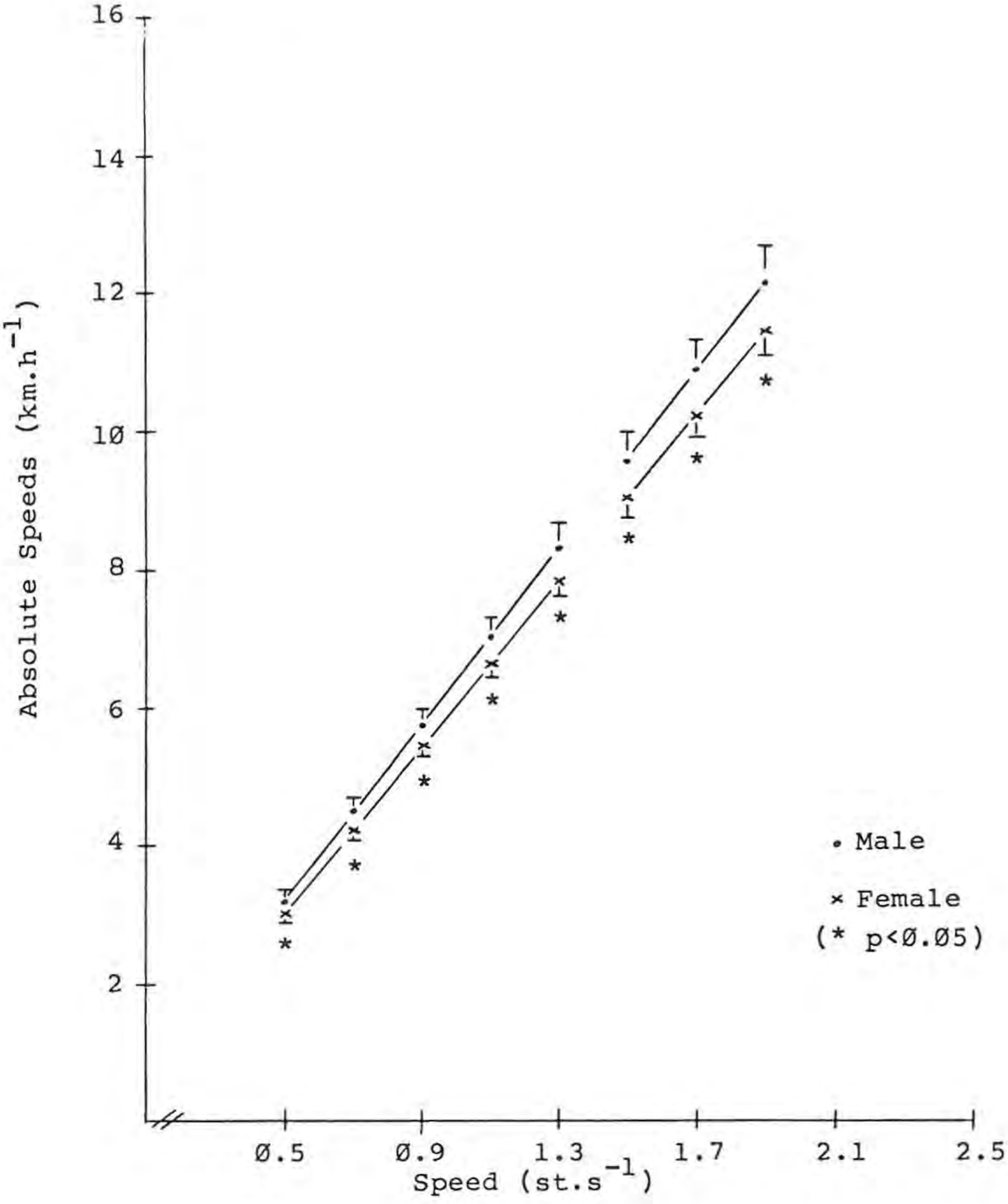


Figure 5 Absolute speeds at the relative speeds used in this study - males and females compared.

There was no difference between the male and female subjects in the ratio of leg length to stature ($\overline{X} = 47.1\%$). This is an unusual finding considering that in the normal population males have significantly longer legs relative to their stature than females (Roche and Malina 1983). Based on data collected on a control group of Canadian University students the ratio of leg length to stature in males (47.5 ± 1.83%) was significantly ($p<0.01$) greater than in females (46.7 ± 1.62%) (Ross and Marfell-Jones 1982). Further support for this finding was presented in a compilation of physical characteristics of children. It was reported (Roche and Malina 1983) that young adults (17 and 18 y) in the United States and Canada had ratios (males 47.9%, females 46.9%) comparable to the Canadian University sample. Females active in sport, however, exhibit a leg length to stature ratio much closer to that of the average male. Data reported by Spurgeon et al (1981) (48%), Eiben (1981) (47.9%), Hebbelinck et al (1981) (47.2%) and Beunen et al (1981) (48.2%) on female basketball, volleyball and handball players, gymnasts and olympic rowers support this contention. These figures are not far from the average ratio of leg length to stature reported for male olympic athletes (n = 136) of 48.1% (Tanner 1964). The lack of difference between males and females in the present study in the ratio of leg length to stature indicates that the female subjects were, by chance selection, more masculine in this respect.

In performance parameters, these two groups followed the normal pattern. Male maximal oxygen consumption ($\dot{V}O_2$ max) exceeded female $\dot{V}O_2$ max by a considerable margin, and both groups demonstrated maximal aerobic capacities in the above average category for their age group (Astrand and Rodahl 1977). Male subjects achieved their ventilatory threshold (V.T.) running at a much higher absolute velocity than females ($p<0.05$), but in terms of the $\%\dot{V}O_2$ max at which V.T. occurred there was no difference between male and female subjects. Both groups exhibited a ventilatory threshold in the normal range for untrained subjects (McArdle et al 1981) indicating that the high maximal oxygen consumption seen during the max test was more related to genetic factors than plastic response training. Both groups exhibited similar high ratings of perceived exertion at the end of the $\dot{V}O_2$ max test (Borg 1962).

Throughout Chapter IV subject responses are plotted, and discussed by category, i.e. male, female and high $\dot{V}O_2$ max, average $\dot{V}O_2$ max. The above data, and those presented in Chapter IV are tabulated by subject group, i.e. male high $\dot{V}O_2$ max, male average $\dot{V}O_2$ max and female high $\dot{V}O_2$ max, female average $\dot{V}O_2$ max in Appendix 7 (pages 306 to 350).

# CHAPTER IV

# RESULTS AND DISCUSSION

## THE ENERGY COST - VELOCITY RELATIONSHIP

The relationship between the energy cost of walking and movement velocity is clearly curvilinear (Figure 6, page 135). The upper graph in Figure 6 depicts the results from the $\dot{V}O_2$ max test in which all subjects were required to walk and run at the same absolute speeds ($km.h^{-1}$). The lower graph in Figure 6 shows the relative speed test results in which all subjects were required to walk and run at specific speeds normalized to their individual statures. Thus, during the relative speed tests all subjects walked or ran at differing absolute speeds for any given relative speed. Figure 6 and all subsequent similar Figures display subject responses separately for absolute speed (upper graph) and relative speed (lower graph) tests. Additionally, each of these Figures depicts walking data separately from running data by a break in the continuity of each graph. That the relationship between energy cost and movement velocity appears to differ depending upon whether one is moving at absolute or relative speeds is simply an artifact of the experimental protocol in this study. During the $\dot{V}O_2$ max test all subjects were required to start running at 7 $km.h^{-1}$. However, during the relative speed tests, subjects walked at 1.3 $st.s^{-1}$ (at an average of 8.06 $\pm$ 0.40 $km.h^{-1}$) and only began running at 1.5 $st.s^{-1}$

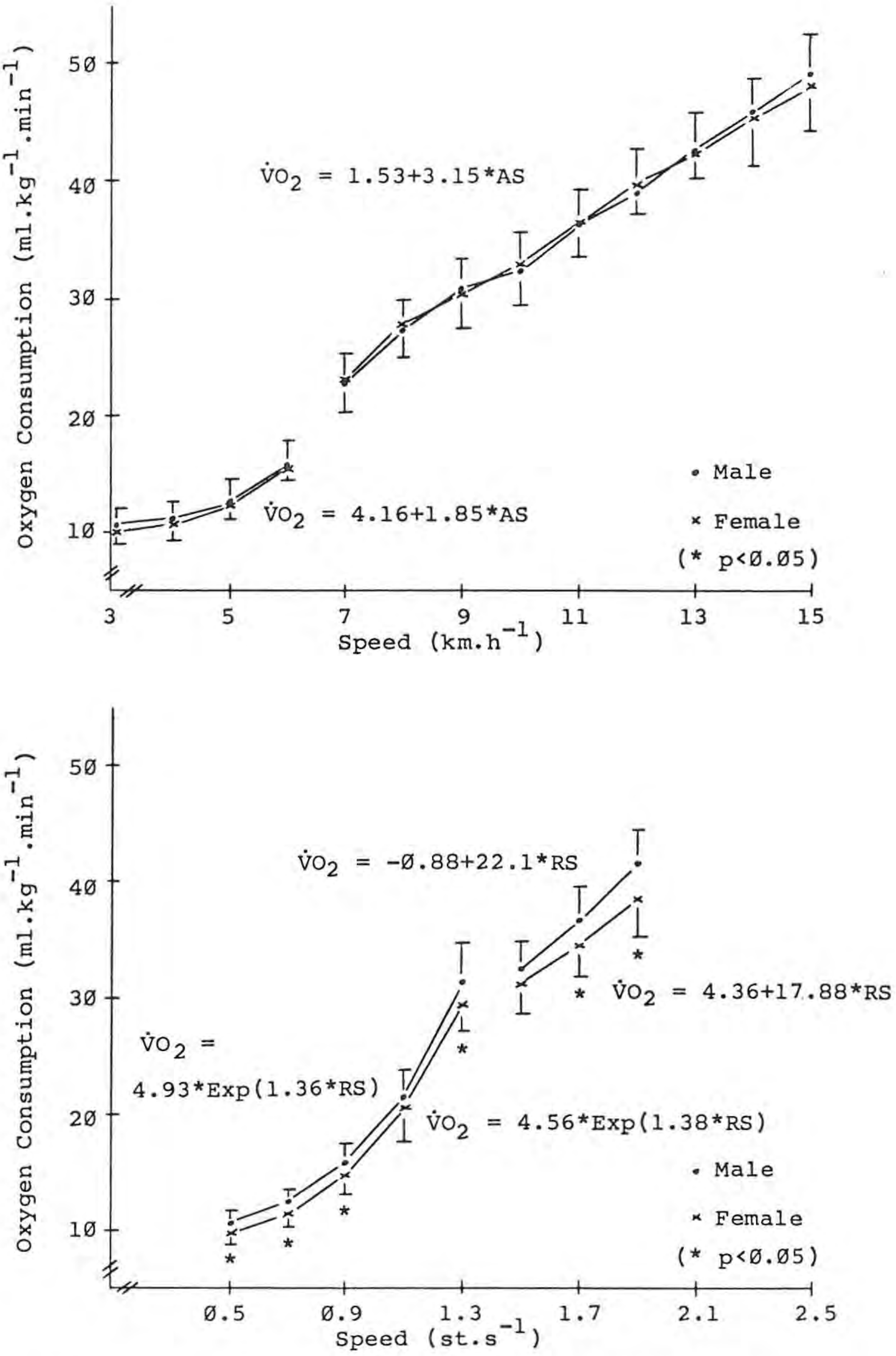


Figure 6 Oxygen consumption versus locomotion velocity at absolute and relative speeds - males and females compared.

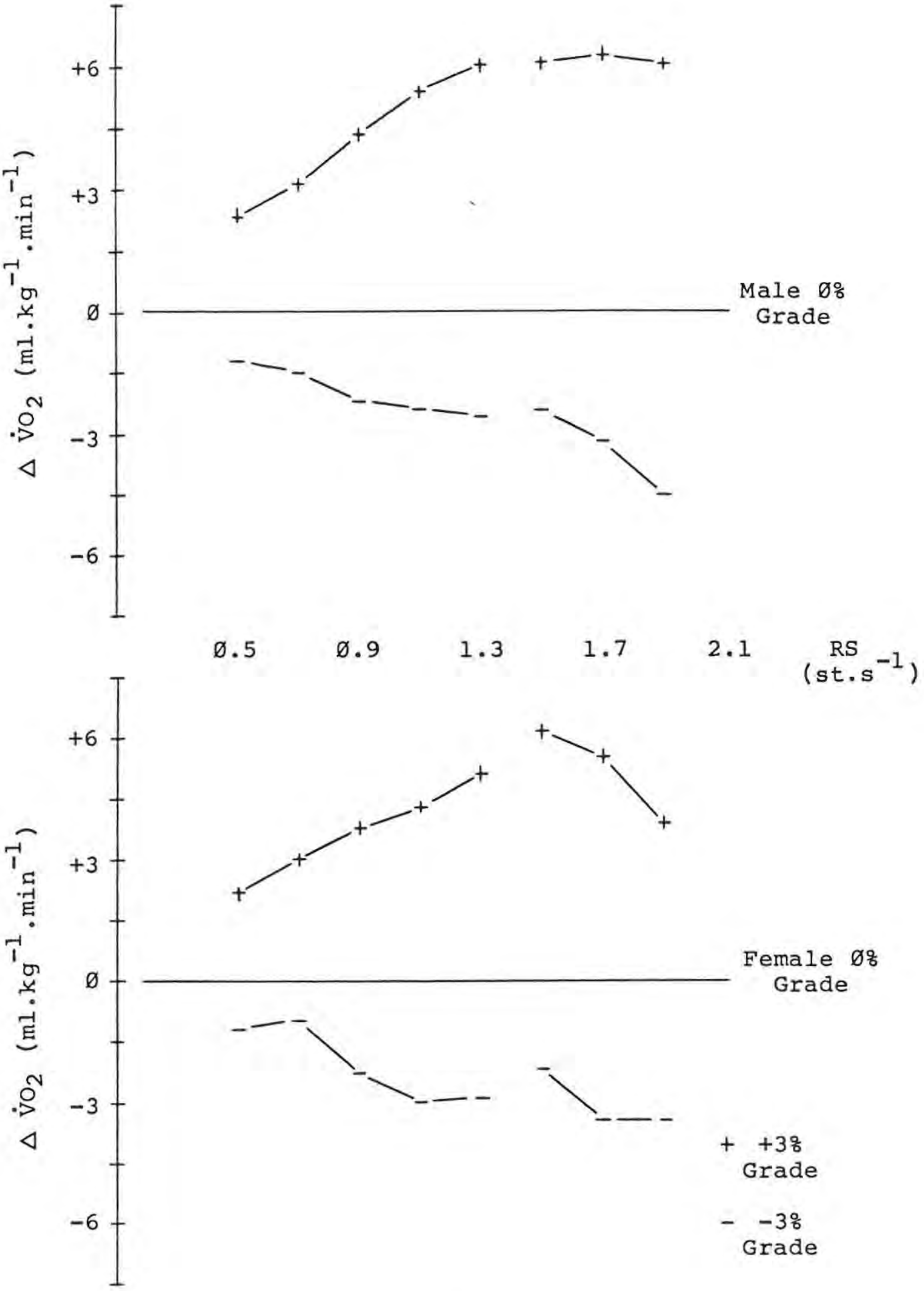


Figure 7 Change in oxygen consumption during grade walking and running at relative speeds in males and females. Data points plotted are differentials from the oxygen consumption observed at 0% grade for that velocity.

Table III Regression analysis summary for $\dot{V}O_2$ (ml.kg$^{-1}$.min$^{-1}$) (Y) versus RS (st.s$^{-1}$) (X) by subject group

| Subject Group | Best Fit | Coefficients | | Equation Form |
|---|---|---|---|---|
| | | A | B | |
| <u>Walking:</u> | | | | |
| High male | exponential | 5.1259 | 1.3432 | Y=A*Exp(B*X) |
| High female | exponential | 4.7431 | 1.3557 | Y=A*Exp(B*X) |
| Avg male | exponential | 4.7316 | 1.3822 | Y=A*Exp(B*X) |
| Avg female | exponential | 4.3860 | 1.4038 | Y=A*Exp(B*X) |
| ($\bar{X}$ standard error of coefficient A = 0.056, B = 0.059) | | | | |
| <u>Running:</u> | | | | |
| High male | linear | .9839 | 21.1645 | Y=A+B*X |
| High female | logarithmic | 17.1354 | 34.8994 | Y=A+B*Ln(X) |
| Avg male | exponential | 12.2840 | .6341 | Y=A*Exp(B*X) |
| Avg female | exponential | 14.0075 | .5197 | Y=A*Exp(B*X) |
| ($\bar{X}$ standard error of coefficient A = 0.14, B = 0.082) | | | | |

(at an average of 9.30 ± 0.50 $km.h^{-1}$) (see Figure 5, page 131).

The nature of the curvilinear relationship between energy cost and walking velocity is exponential (Table III, page 137) for all subjects and all subject groupings. Most of the research into this relationship has indicated that oxygen consumption increases as a function of velocity squared - a least-squares power fit (Lukin and Ralston 1968, Wyndham et al 1971, Fardy and Hellerstein 1978, Marchetti et al 1983). The discrepancy observed in the present study (exponential versus power fit) may be due to the fact that in most of the previous work, the subjects did not walk at extremely fast speeds (1.3 $st.s^{-1}$), and a power fit may be more appropriate for slower speeds. Alternatively, it is possible that the equalizing of speeds relative to stature is a procedure sufficient to slightly modify the nature of this curvilinear relationship from power to exponential in nature. The overall correlation obtained for the power fit ($r = 0.927$) provided the second best coefficient of determination after the exponential fit ($r = 0.957$), indicating very little difference between these forms in best describing the nature of the data in this study.

The data collected while running, depicted in Figure 6 (page 135), and all subsequent Figures, as set apart from the walking data, do not present as clear a picture regarding the nature of the oxygen consumption - velocity relationship as do the walking data. It can be seen

(Table IV, below) that both exponential and logarithmic equations provided the best least-squares fit in describing individual subject oxygen consumption - relative speed relationships. However, the coefficients of determination for all four equation forms were very similar. When the subject's responses were grouped, however, a pattern did emerge. The two average $\dot{V}O_2$ max groups displayed a best fit by exponential equations, while the two high $\dot{V}O_2$ max groups displayed a linear or almost linear, logarithmic relationship (Table III, page 137, Figure 27, page 187).

Table IV Frequency distribution of coefficients of determination for individual subject regressions between VO2 and RS while running

| Subject Group | Form of Equation | | | |
|---|---|---|---|---|
| | Linear | Exponential | Logarithmic | Power |
| High $\dot{V}O_2$ Male | 0 | 5 | 3 | 3 |
| Avg $\dot{V}O_2$ Male | 0 | 5 | 5 | 0 |
| High $\dot{V}O_2$ Female | 0 | 5 | 4 | 1 |
| Avg $\dot{V}O_2$ Female | 1 | 4 | 4 | 0 |
| Totals | 1 | 19 | 16 | 4 |

It was observed that a number of individuals in the high $\dot{V}O_2$ max group had a more uniform increase in oxygen consumption per unit of movement velocity compared with those in the average $\dot{V}O_2$ max group. This observation is supported by the regression analysis and the movement economy data (Figure 41, page 203). Thus, those with higher maximal oxygen consumptions may be more uniform in running economy. However, this perception may have been influenced by the fact that the average $\dot{V}O_2$ max group was not tested at speeds above 1.9 $st.s^{-1}$. It has been reported (Boje 1944, Costill and Winrow 1970) that the well trained athlete is more uniform in economy compared with the untrained person who exhibits lower economy at both high and low velocities.

The majority of research into the relationship between running velocity and oxygen consumption has indicated that this is a linear relationship (Margaria et al 1963, Shephard 1969, McMiken and Daniels 1976, Leger and Mercier 1984). The results of the present study are not in substantial disagreement with prior findings. All four subject groups exhibited linear or nearly linear running $\dot{V}O_2$ - velocity relationships, with the linear equation taking an almost identical form to the weighted average equation which Leger and Mercier (1984) presented based on the results of ten published studies.

Leger and Mercier (1984):

$$\dot{V}O_2\ (ml.kg^{-1}.min^{-1}) = 2.209 + 3.163*Velocity\ (km.h^{-1})$$

Present study:

$$\dot{V}O_2\ (ml.kg^{-1}.min^{-1}) = 1.528 + 3.153*Velocity\ (km.h^{-1})$$

The same relationship (running $\dot{V}O_2$ - velocity) expressed in relative speed terms must be presented separately for males and females.

Males:

$$\dot{V}O_2\ (ml.kg^{-1}.min^{-1}) = -0.876 + 22.095 * RS\ (st.s^{-1})$$

Females:

$$\dot{V}O_2\ (ml.kg^{-1}.min^{-1}) = 4.363 + 17.879 * RS\ (st.s^{-1})$$

It is interesting to note that, although walking and running are significantly dissimilar forms of locomotion, when walking and running data were combined the linear equation provided the best fit, and took a form similar to the above:

$$\dot{V}O_2\ (m.kg^{-1}.min^{-1}) = -2.75 + 3.55 * Velocity\ (km.h^{-1})$$

## THE USE OF RELATIVE SPEED

Earlier studies used relative speed to "factor-out" the differences in stature or leg length, as it was realized that human morphological variability affects normal walking characteristics (Grieve and Gear 1966, Grieve 1968, Rosenrot _et al_ 1980, Charteris 1982). While the mechanical, temporal and distance characteristics of locomotion are undoubtedly affected by stature and leg length variability, the untested assumption hinted at in these works was that the variability in the metabolic correlates of the mechanical features of gait was similarly minimized. The male and female data from the present study do not support this contention.

The male and female subjects demonstrated exactly the same oxygen consumption (per kg of body mass) at the same absolute velocities despite significant differences in both leg length and stature (Figure 6, page 135). The oxygen consumption of the males was clearly ($p<0.05$) greater than that of the females at the same relative speeds.

In order to evaluate inter-subject variability more precisely, measures of economy were computed at every velocity (both AS and RS) used in the study. Economy was expressed as oxygen consumption ($ml.kg^{-1}.min^{-1}$) per unit of: absolute velocity ($km.h^{-1}$) (Figure 21, page 168); relative velocity ($st.s^{-1}$) (Figure 23, page 170); and relative velocity ($leg\ length.s^{-1}$) (Figure 22, page 169). Coefficients of variation were computed within each subject group for each method of expressing economy at each velocity. It was found that there was no difference between the inter-subject variability in economy per $km.h^{-1}$ ($\overline{X} = 9.01\%$) and economy per $st.s^{-1}$ ($\overline{X} = 9.08\%$). However, the variability in economy per leg $length.s^{-1}$ was significantly greater ($\overline{X} = 9.91\%$) ($p<0.05$). A further breakdown of these data, by subject group, is found in

Table V (page 144) which relates the variability in morphology to the variability in gait characteristics. It can be seen that inter-subject variability in leg length was greater than the variability in stature. This may be related to the finding of a higher CV of economy (per leg length.$s^{-1}$). There was no relationship between variability in stature or leg length and the variability in gait performance variables. Furthermore, the CV of stride length, cadence and economy was greater ($p<0.05$) at both relative and absolute speeds compared with the CV of stature. It was found that the CV of economy was significantly greater than the CV of stride length and cadence. Kram et al (1985) reported similar findings during running. They pointed out that the variability in economy was significantly higher than that of stride length and concluded that the day-to-day fluctuations in running economy were due, primarily, to factors other than stride length. It seems apparent that the setting of movement velocity relative to either stature or leg length does not reduce inter-subject variability in stride length, cadence or locomotion economy. In fact, in the case of stride length, it seems to have the opposite effect.

In order to explore these relationships further, relative stride length (Grieve and Gear 1966) was calculated at each absolute and relative speed. Relative stride length is the number of statures covered per stride during locomotion (stride length/stature). It has been proposed that the use of relative stride length, which factors out differences in morphology between individuals (Grieve and Gear 1966,

Table V Mean coefficients of variation for selected anthropometric and performance variables indicating the disparity between anthropometric and performance variability

|  | CV's for Subject Groups |  |  |  |
|---|---|---|---|---|
| Variables | Male | Female | High $\dot{V}O_2$ | Avg $\dot{V}O_2$ |
| Stature | 4.2 | 2.9 | 5.4 | 4.1 |
| Leg length | 6.8 | 3.4 | 6.8 | 5.3 |
| Stride Length: |  |  |  |  |
| -at AS | 5.5 | 5.7 | 5.5 | 5.4 |
| -at RS | 7.7 | 7.0 | 8.7 | 6.5 |
| p (of AS-RS) | $<0.05$ | $<0.05$ | $<0.05$ | $<0.05$ |
| Relative Stride Length: |  |  |  |  |
| -at AS | 4.8 | 5.6 | 5.7 | 5.9 |
| -at RS | 5.0 | 5.3 | 5.5 | 4.7 |
| p (of AS-RS) | - | - | - | $<0.05$ |
| Cadence: |  |  |  |  |
| -at AS | 5.4 | 5.4 | 5.3 | 5.3 |
| -at RS | 5.2 | 5.2 | 5.1 | 4.4 |
| p (of AS-RS) | - | - | - | - |
| Economy: |  |  |  |  |
| -at AS | 9.3 | 9.7 | 9.2 | 8.7 |
| -at RS | 9.5 | 9.8 | 9.4 | 8.8 |
| p (of AS-RS) | - | - | - | - |

Grieve 1968), is a more appropriate measure than absolute stride length at any given velocity. It can give an indication of whether one person is "striding-out" relative to body size to a greater extent than another individual.

The inter-subject variability in relative stride length (Table V, page 144) was virtually the same during both absolute and relative speed tests. Furthermore, the CV of relative stride length was comparable to the CV of absolute stride length at absolute speed. The CV of relative stride length was, however, lower than the CV of absolute stride length at relative speed. Thus, taking differences in stature into account, subjects displayed similar amounts of variation in stride length whether asked to walk and run at absolute speeds or at speeds adjusted to their stature. However, the CV of absolute stride length at absolute velocities was significantly ($p<0.05$) less than that at relative speed. This was not the case for cadence or economy. This implies that people adjust to locomotion at relative speeds by varying their stride length more than their cadence. One note of caution, however, must be applied to this reasoning. The absolute speed data were collected on only one occasion (the max test) while the relative speed data were collected on up to four different days spread out over a one to two week period. It has been reported that within-day coefficients of variation are lower than between-days CV's (Thorstensson et al 1976, Katch et al 1982, Kram et al 1985). Inter-subject differences, however, do not influence day-to-day variability. Males and females have been reported to have very similar CV's of economy both within- and between-days (Durnin and Namyslowski 1958).

MALE AND FEMALE RESPONSES

Males and females did not differ in their oxygen consumption resonse to increasing absolute speeds but males had a higher ($p<0.05$) $\dot{V}O_2$ response to relative speed across the entire range of walking and running speeds (Figure 6, page 135). Males and females responded to graded locomotion in the same fashion. For both subject groupings oxygen consumption increased in response to uphill (+3%), and decreased for downhill (-3%) grade locomotion (Figure 7, page 136). The women worked at a significantly ($p<0.05$) higher percentage of their $\dot{V}O_2$ max at absolute velocities and, despite their lower $\dot{V}O_2$ submax response, at relative velocities compared with the men (Figure 8, page 147).

Males and females did not differ in energy cost ($kJ.kg^{-1}$) per step across the range of absolute speeds but at relative speeds the women were using less energy per step at both moderate walking and running speeds ($p<0.05$) (Figure 10, page 149). These data are supported by the stride length (Figure 11, page 150) and cadence (Figure 15, page 154) responses of the male and female subjects. Despite the finding that the males were absolutely taller, and had longer legs than the females ($p<0.05$) there was no difference in cadence between males and females for either

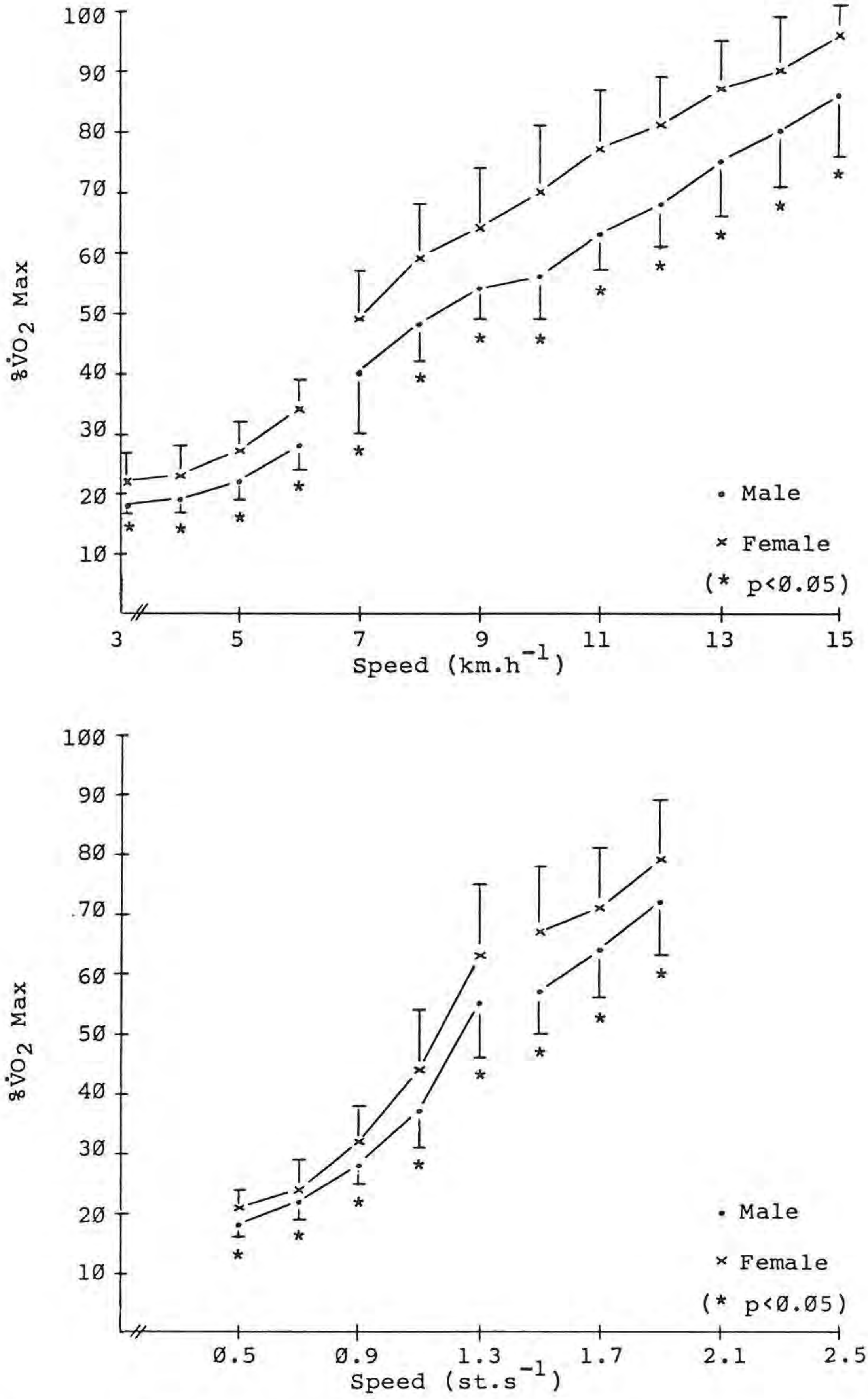
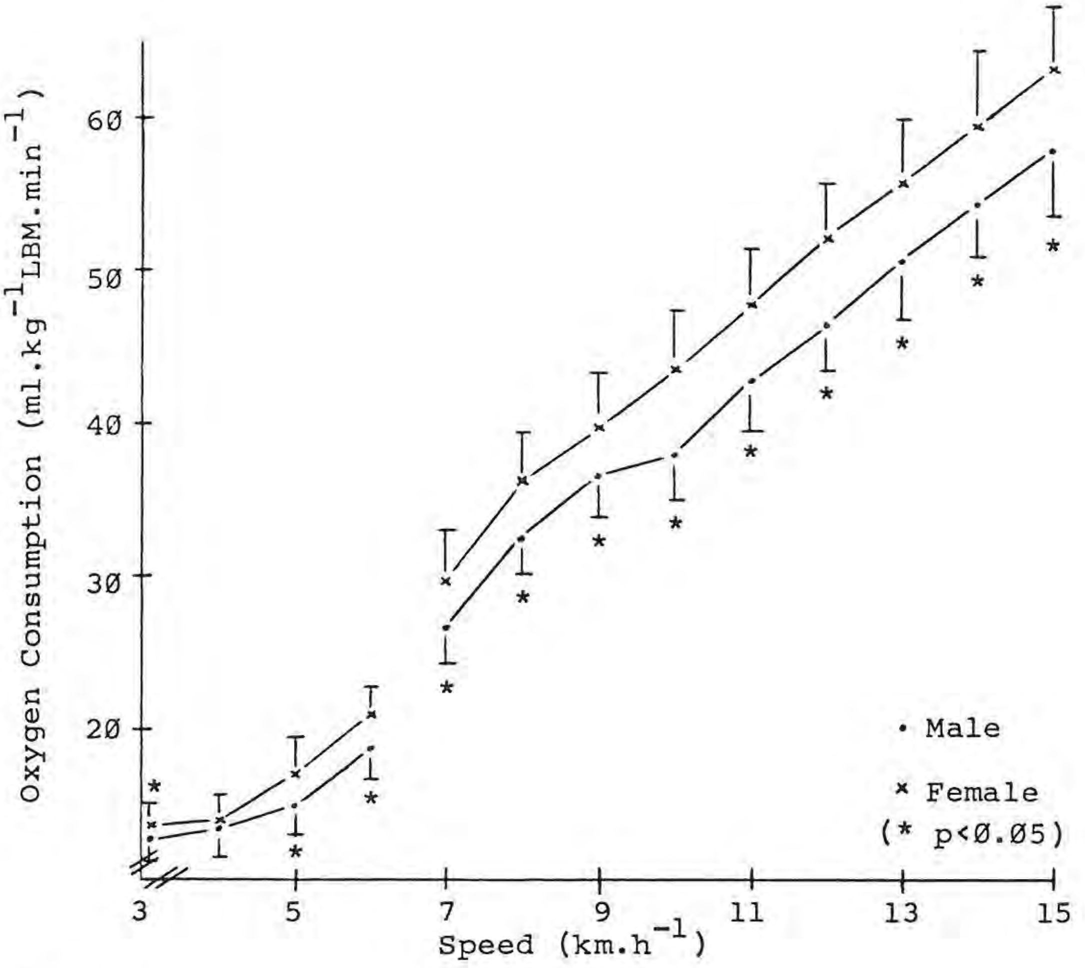


Figure 8 Percent of maximal oxygen consumption versus locomotion velocity at absolute and relative speeds - males and females compared.



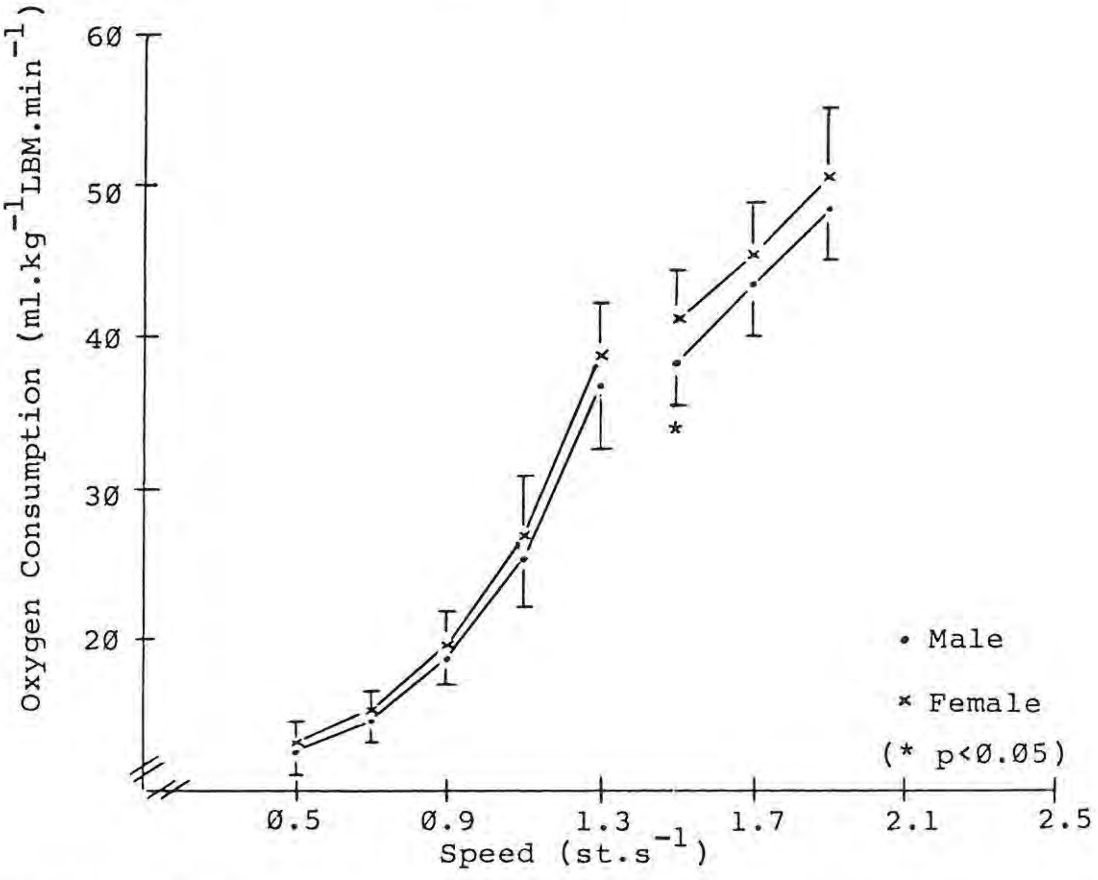
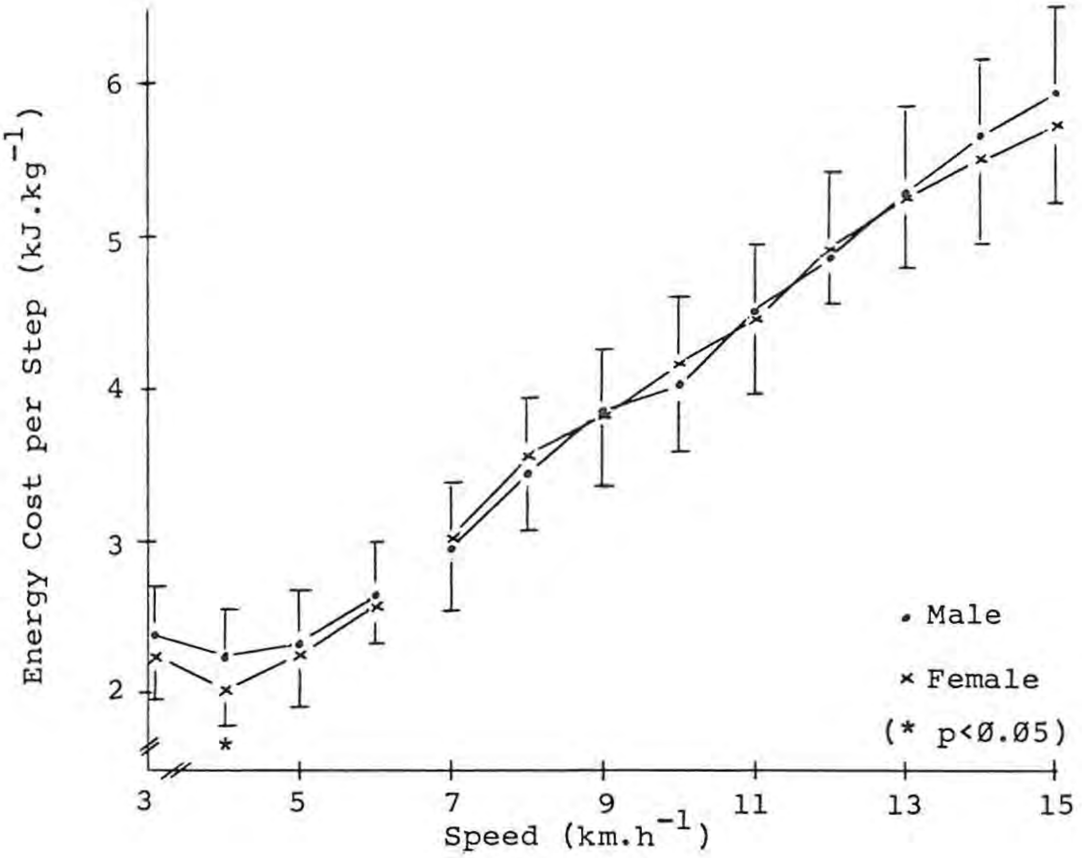


Figure 9 Oxygen consumption (per kg of lean body mass) versus locomotion velocity at absolute and relative speeds - males and females compared.



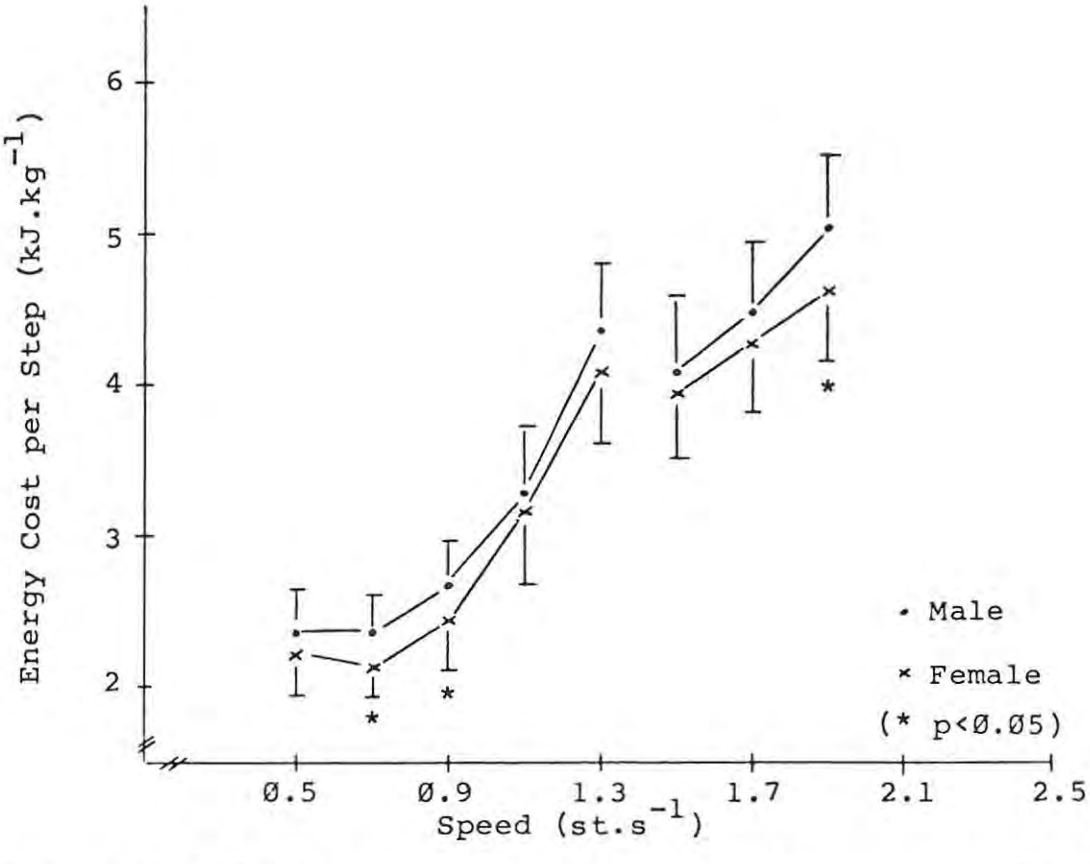


Figure 10 Energy cost per step versus locomotion velocity at absolute and relative speeds - males and females compared.

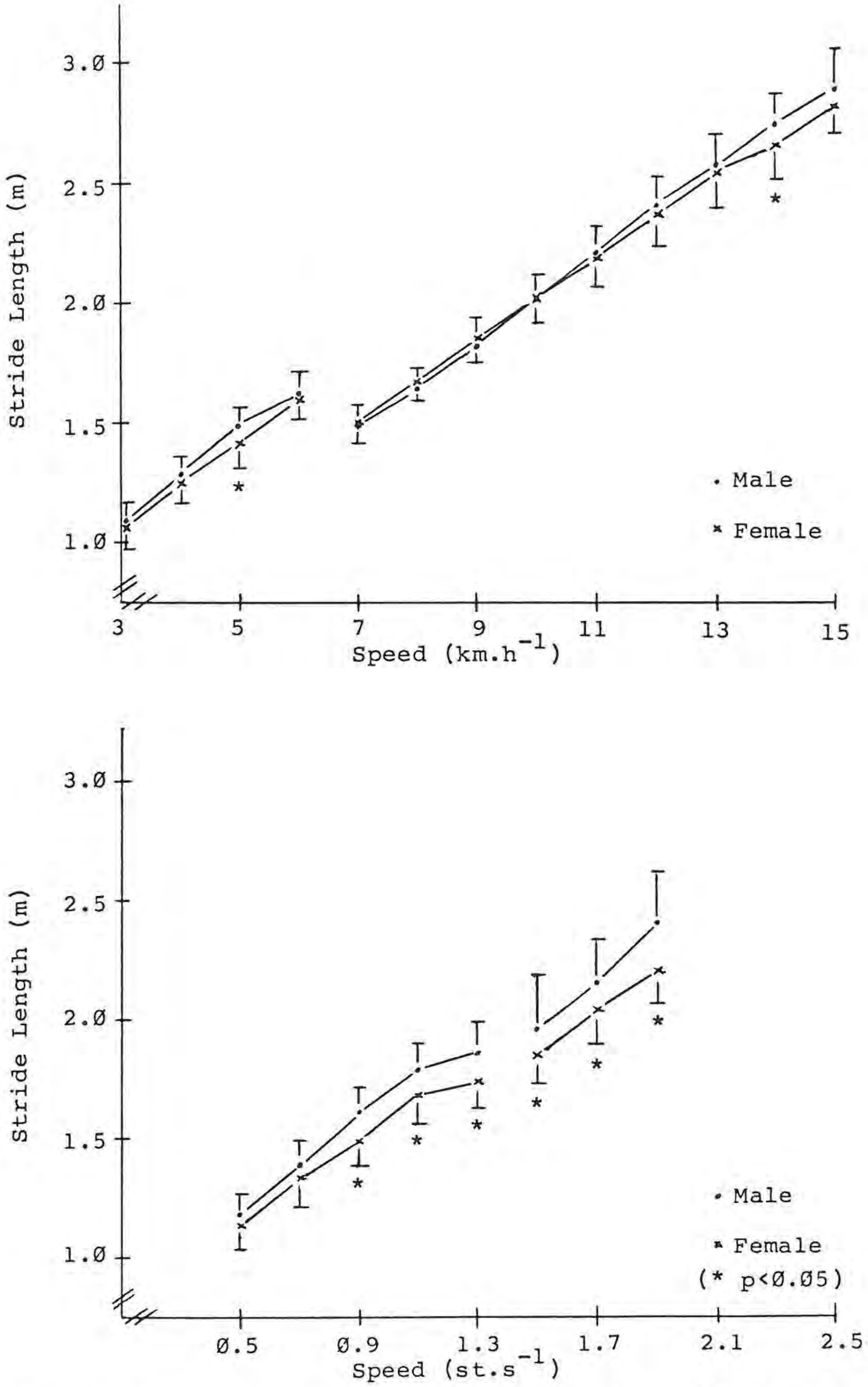


Figure 11 Stride length versus locomotion velocity at absolute and relative speeds - males and females compared.

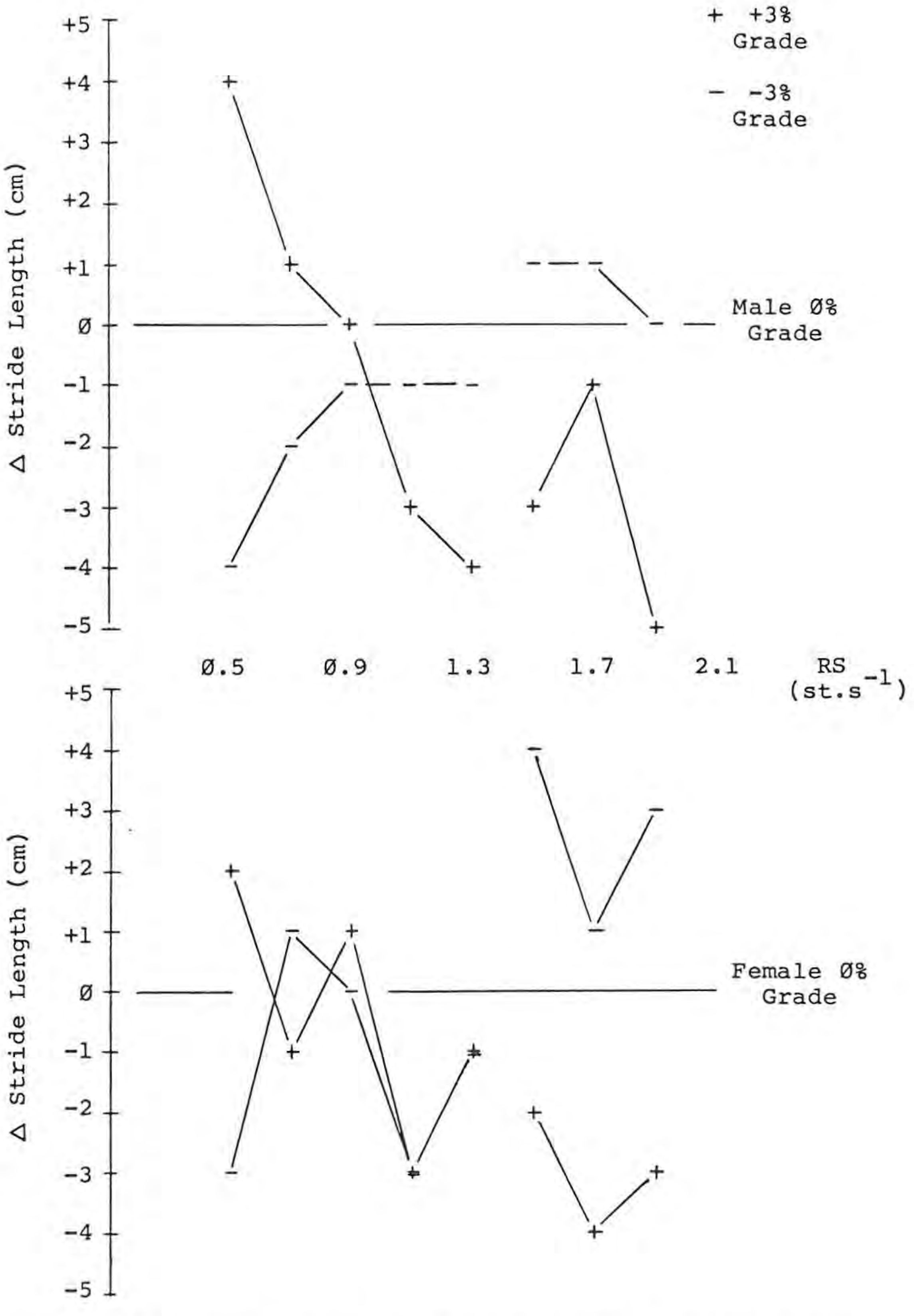


Figure 12 Change in stride length during grade walking and running at relative speeds in males and females. Data points plotted are differentials from the stride length observed at 0% grade for that velocity.

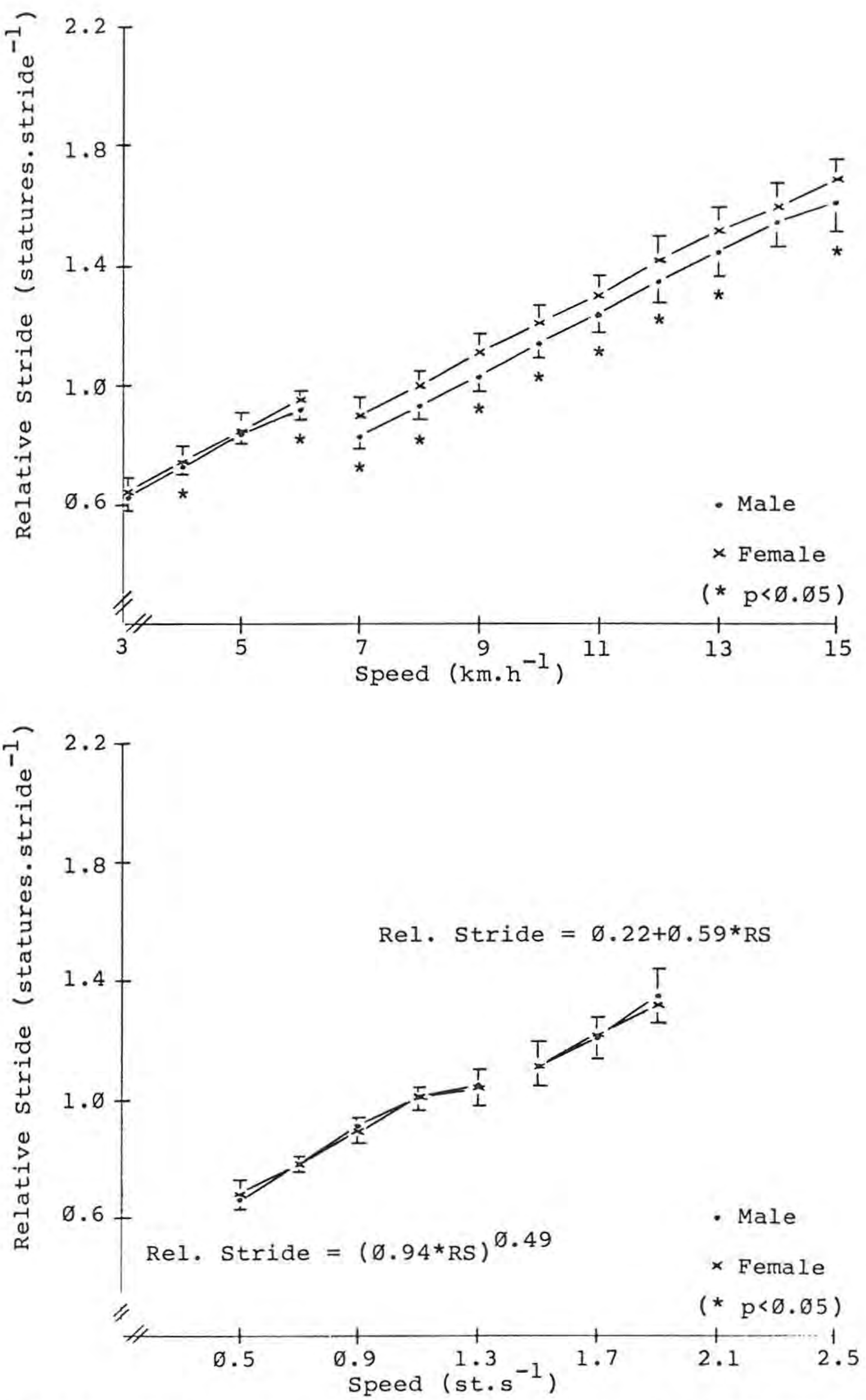
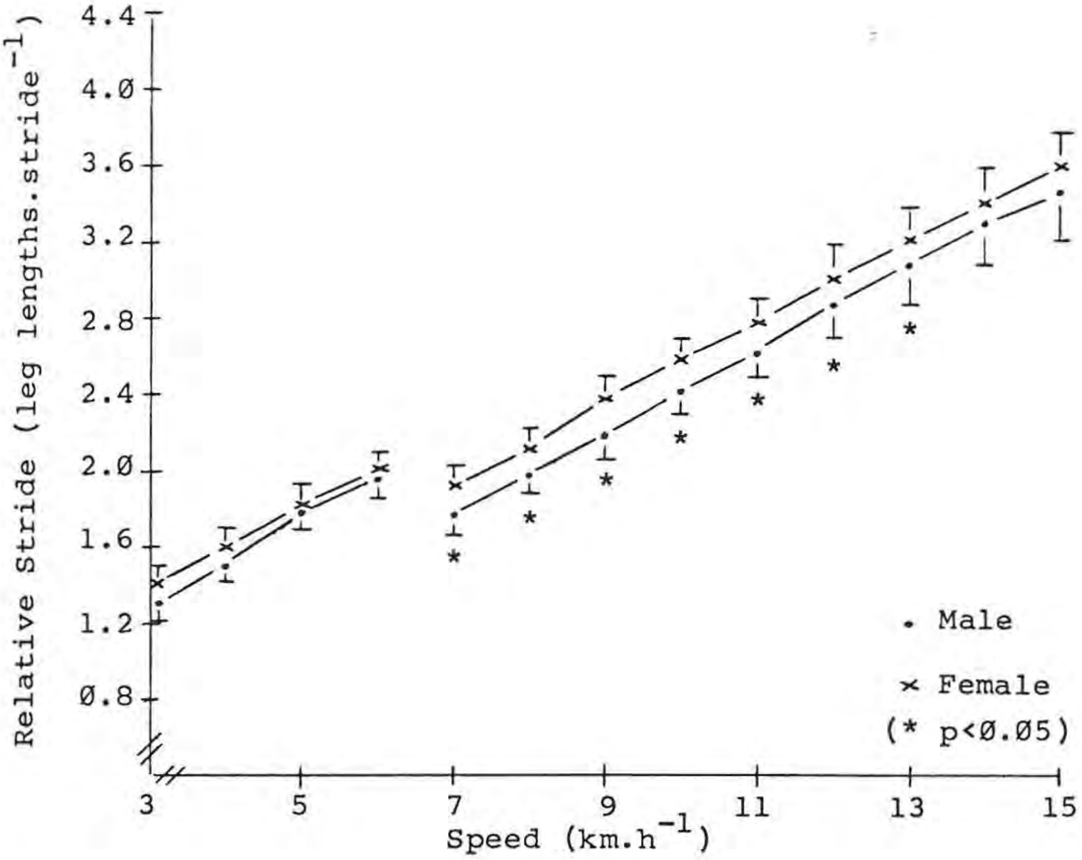


Figure 13 Relative stride (statures per stride) versus locomotion velocity at absolute and relative speeds - males and females compared.



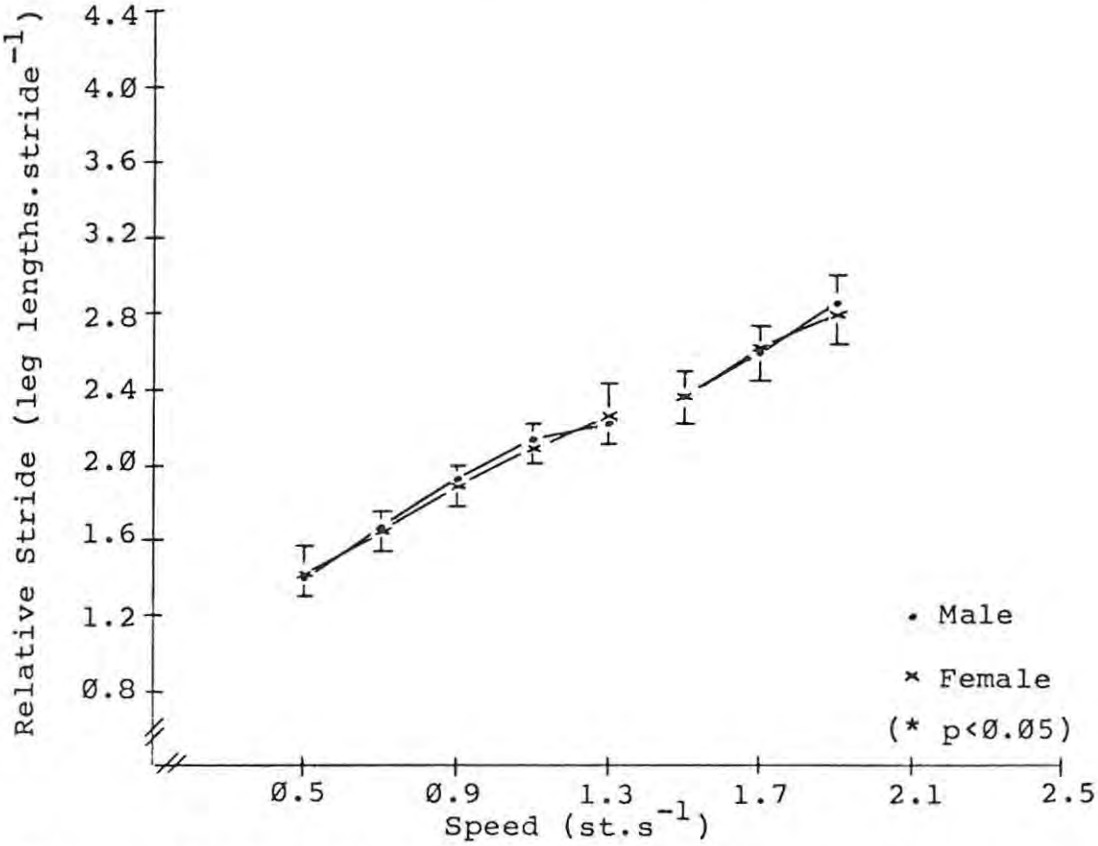


Figure 14 Relative stride (leg lengths per stride) versus locomotion velocity at absolute and relative speeds - males and females compared.

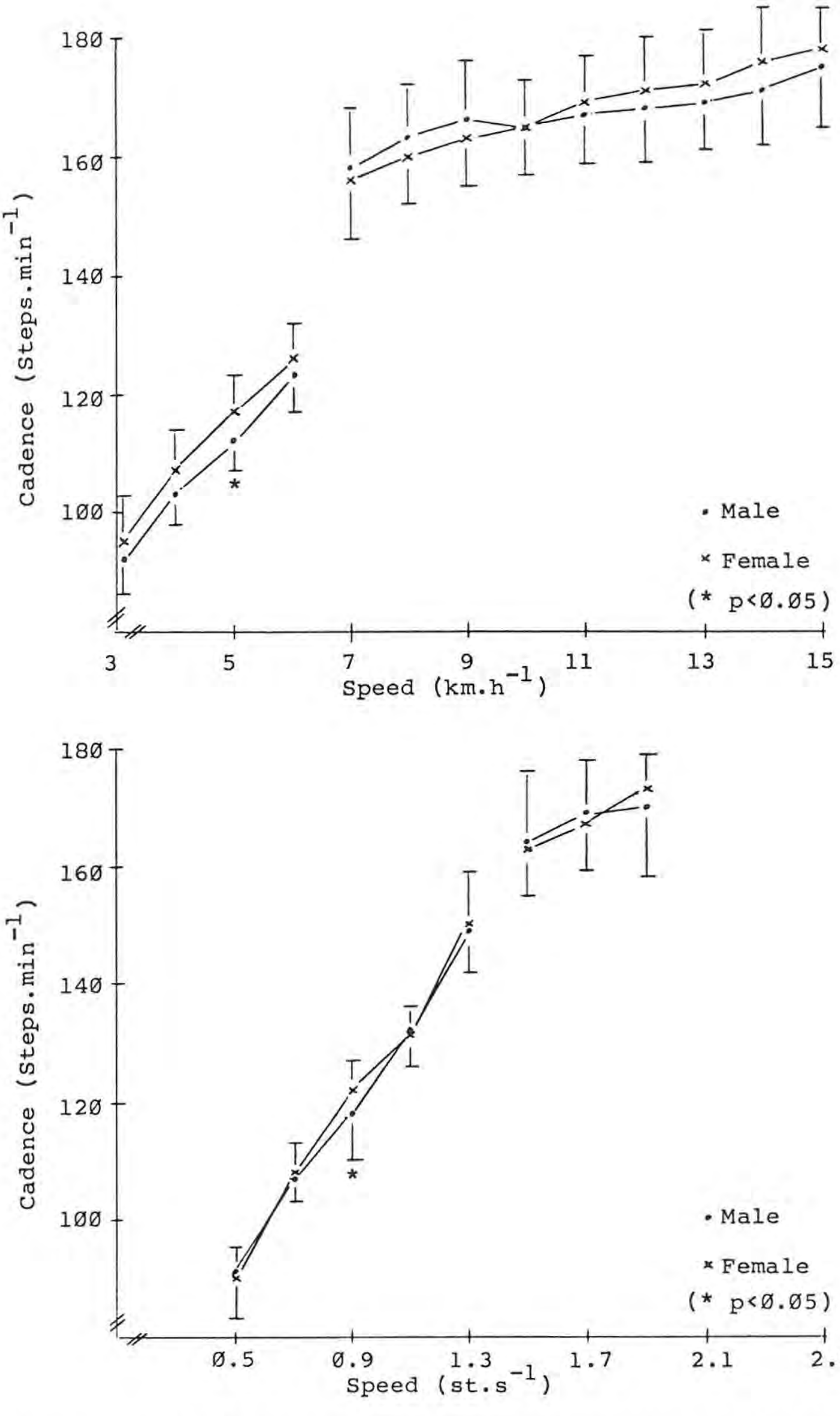


Figure 15 Cadence versus locomotion velocity at absolute and relative speeds - males and females compared.

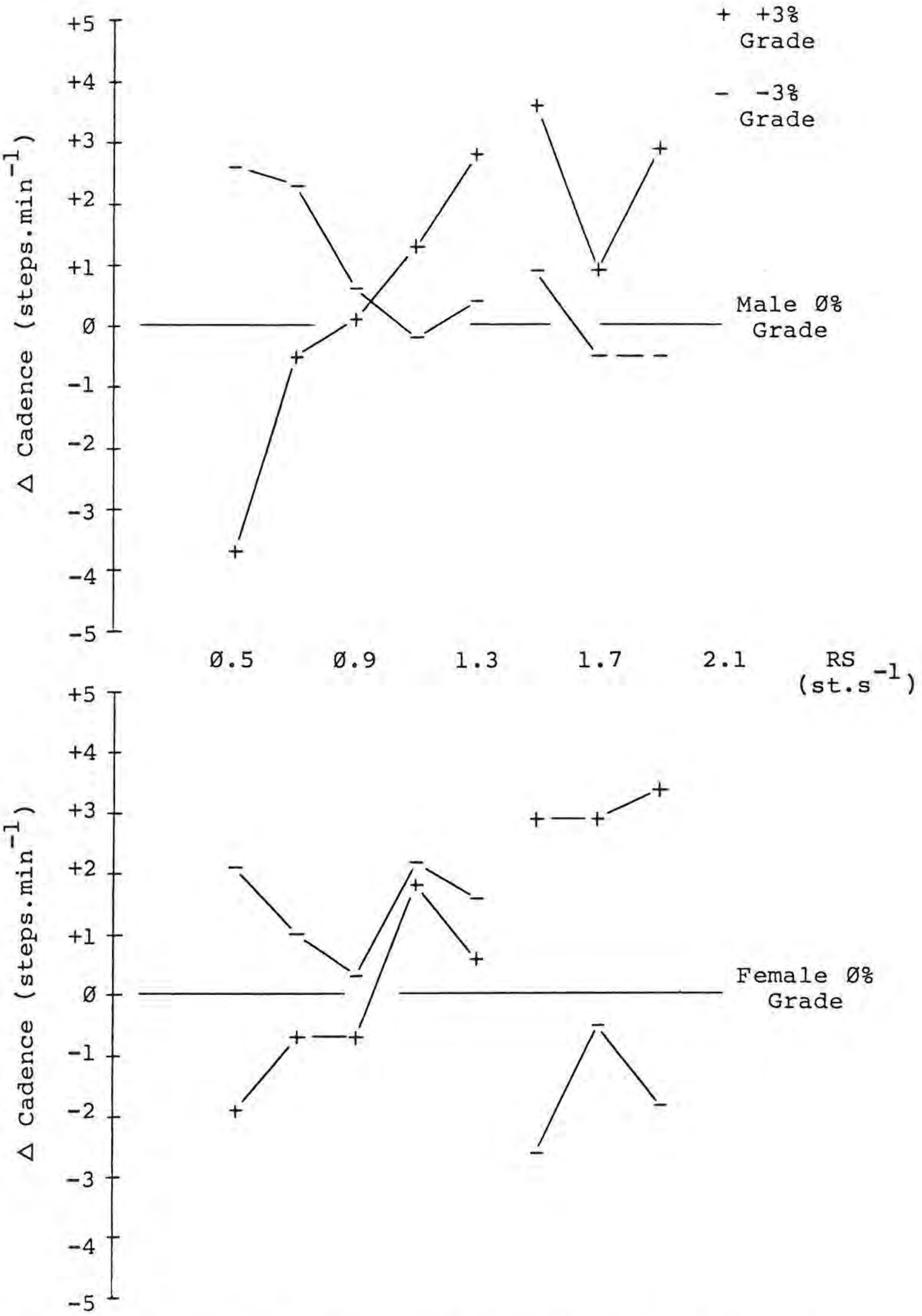
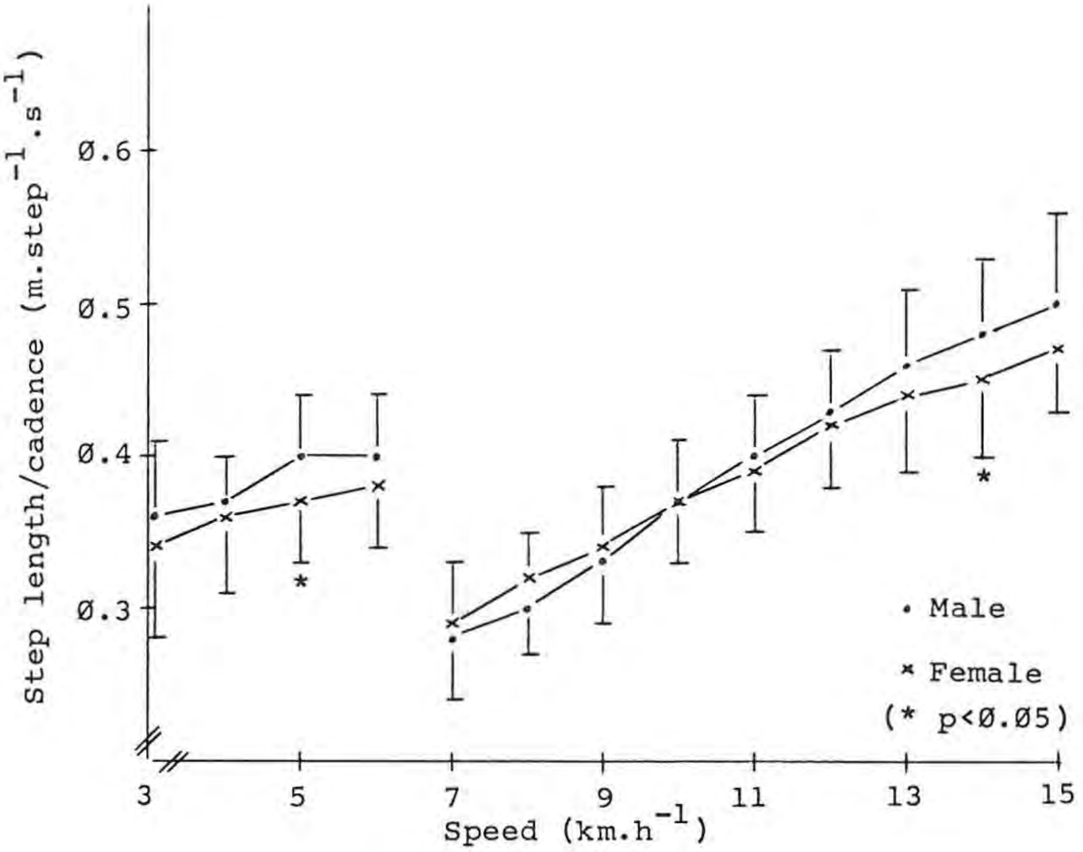


Figure 16 Change in cadence during grade walking and running at relative speeds in males and females. Data points plotted are differentials from the cadence observed at 0% grade for that velocity.



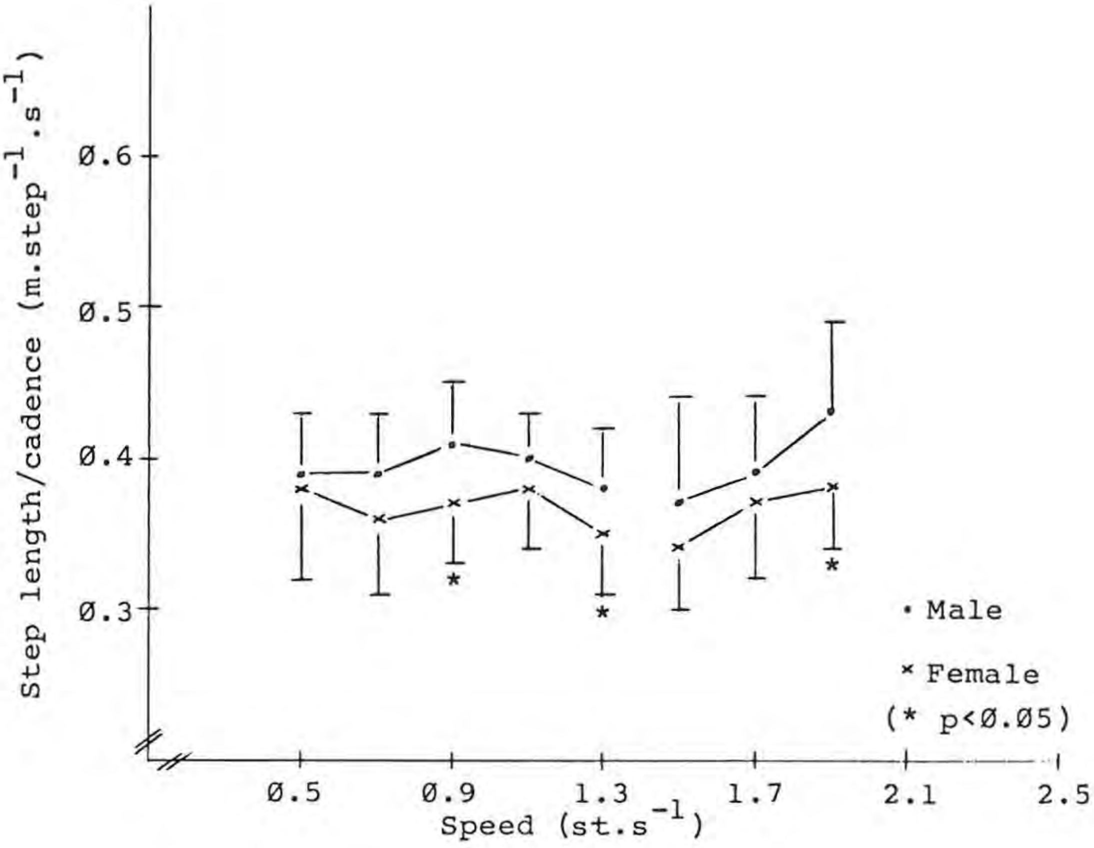


Figure 17 Step length/cadence ratio versus locomotion velocity at absolute and relative speeds - males and females compared.

absolute or relative speed tests. In this regard, the cadence response of present subjects differed from the findings of other researchers who have consistently reported that at equal absolute speeds females, with absolutely shorter statures and relatively shorter legs than men, walk with a higher cadence (Booyens and Keatinge 1957, Finley and Cody 1970, Falls and Humphrey 1976). This discrepancy may have been due to the finding that the males and females in the present study had equal relative leg lengths (leg length/stature). The females were within the normal male range. More so than leg length or stature, relative leg length may be a prime determining factor in the choice of cadence during locomotion. Males, being taller and therefore moving at higher velocities, had significantly ($p<0.05$) longer stride length under the relative speed conditions than did females.

It might be argued that difference in stride length at relative speed was the result of the males using a different locomotor pattern considering the finding that males and females had equal relative leg length. In order to explore this possibility, a proportional analysis of the male and female data was performed. The men were 6.2% taller than the women and had 6% longer legs. During walking at relative speeds which were absolutely 6.05% faster than for the women, the men took 6.2% longer strides and used 6.6% more oxygen. During running at relative speeds which were absolutely 6.26% faster than for the women, the men took 6.7% longer strides and used 6% more oxygen. The males and females in this study used the same locomotor pattern, with absolutely higher speed implicated in both stride length and oxygen consumption differences between the sexes.

The implication in the cadence, stride length and energy cost responses is that stride length increases tend to drive increases in oxygen consumption to a greater extent than do cadence increases. To evaluate this contention, correlations were computed between cadence and oxygen consumption at each relative speed (Table VI, page 159). Although these correlations were insignificant, the clear trend was that of an inverse relationship: as cadence decreased and stride length increased at any given speed, oxygen consumption tended to rise. This finding was supported by those studies which have imposed variations in stride length on subjects (Hogberg 1952a, Zarrugh and Radcliffe 1978, Cavanagh and Williams 1982). Imposed lengthening or shortening of stride length (relative to freely-chosen stride length) raises the energy cost of locomotion. However, it has been reported that increased stride length raises oxygen consumption by a larger amount than does a decrease in stride length (Hogberg 1952a, Cavanagh and Williams 1982). Although the present subjects freely chose their stride lengths, it may be that those with a naturally-chosen longer stride length consume more oxygen as a result. Certainly the male - female comparison in the present study, with the males both moving faster and using a longer stride length to do so, would seem to support this contention.

Table VI Correlations (r) between cadence and oxygen consumption at specific walking and running relative speeds

| WALKING | | | RUNNING | | |
|---|---|---|---|---|---|
| RS(st.$s^{-1}$) | r | p | RS(st.$s^{-1}$) | r | p |
| 0.5 | 0.023 | - | 1.5 | -0.198 | - |
| 0.7 | -0.076 | - | 1.7 | -0.140 | - |
| 0.9 | -0.263 | - | 1.9 | -0.193 | - |
| 1.1 | -0.156 | - | 2.1 | -0.027 | - |
| 1.3 | 0.070 | - | 2.3 | -0.568 | - |
| | | | 2.5 | -0.692 | $<0.05$ |

Relative stride length data, both relative to stature (Figure 13, page 152) and to leg length (Figure 14, page 153), clearly indicated that at any given absolute velocity the females were "striding-out" relative to their morphology to a greater extent than were the men. At relative speeds, however, males and females were "striding-out" by the same relative amounts. The finding that oxygen consumption was the same in males and females at equal absolute velocities, and that male oxygen consumption exceeded that of female at the same relative velocities (Figure 6, page 135) would indicate that the energetics of locomotion are related to absolute stride length not relative stride length.

The relationship between relative stride ($st.stride^{-1}$) and relative speed ($st.s^{-1}$) in the present study is similar to that of a normal, young adult sample from the Human Biology Gait Laboratory, Guelph, Canada (Charteris 1985):

$$\text{Rel. Stride} = (0.9896 * RS)^{0.4635} \qquad \text{(walking)}$$

Present Study:

$$\text{Rel. Stride} = (0.9377 * RS)^{0.4884} \qquad \text{(walking)}$$

$$\text{Rel. Stride} = 0.2209 + 0.5885 * RS \qquad \text{(running)}$$

It is apparent that the use of relative speed equalized cadence in male and female subjects. This supports previous findings in the literature (Grieve and Gear 1966, Grieve 1968, Rosenrot _et al_ 1980). Grieve and Gear (1966) suggested that there might be a relationship between optimal efficiency and the point of minimal inter-subject variability in cadence. They pointed out that their male subjects had minimal CV of cadence at 0.6 $st.s^{-1}$ while their female subjects displayed this characteristic at 1.0 $st.s^{-1}$. This suggestion is not supported by the data in the present study. Males demonstrated the lowest CV of cadence at 1.1 $st.s^{-1}$ while for females it was found at 0.9 $st.s^{-1}$. In both cases optimal efficiency occurred at 0.7 $st.s^{-1}$ (Figure 24, page 171).

Zarrugh et al (1974) investigated optimal locomotor energy expenditure finding that optimum was dependent upon cadence being directly proportional to stride length. They reported that optimal energy cost occurred when the step length/cadence ratio was 0.42 $m.step^{-1}.s^{-1}$. No such clear pattern of relationship appeared in the present study. During walking the step length/cadence ratio remained relatively unchanged as velocity increased. It did, however, increase with velocity during running (Figure 17, page 156). It did not follow the pattern of economy or efficiency, and although the ratios were not far below that reported by Zarrugh at the point of optimal efficiency (male 0.39, female 0.36), there was no relationship between this ratio and locomotor economy (compare Figures 17 and 21, pages 156 and 168).

Males and females did not differ in energy cost per unit of distance travelled (when expressed per kg body mass) (Figure 18, page 162). This was the case for both absolute and relative speed tests. During running, the energy cost per metre slowly decreased, although only by a very small amount. This is consistent with the majority of the literature (Margaria et al 1963, Costill and Fox 1969, Cavanagh et al 1973). Fellingham et al (1978), however, found that this variable increased with speed of running. They added the excess post-exercise oxygen consumption to the exercise $\dot{V}O_2$. This was not done in the present study as most of the exercise was carried out near or below the ventilatory threshold, with respiratory exchange ratios

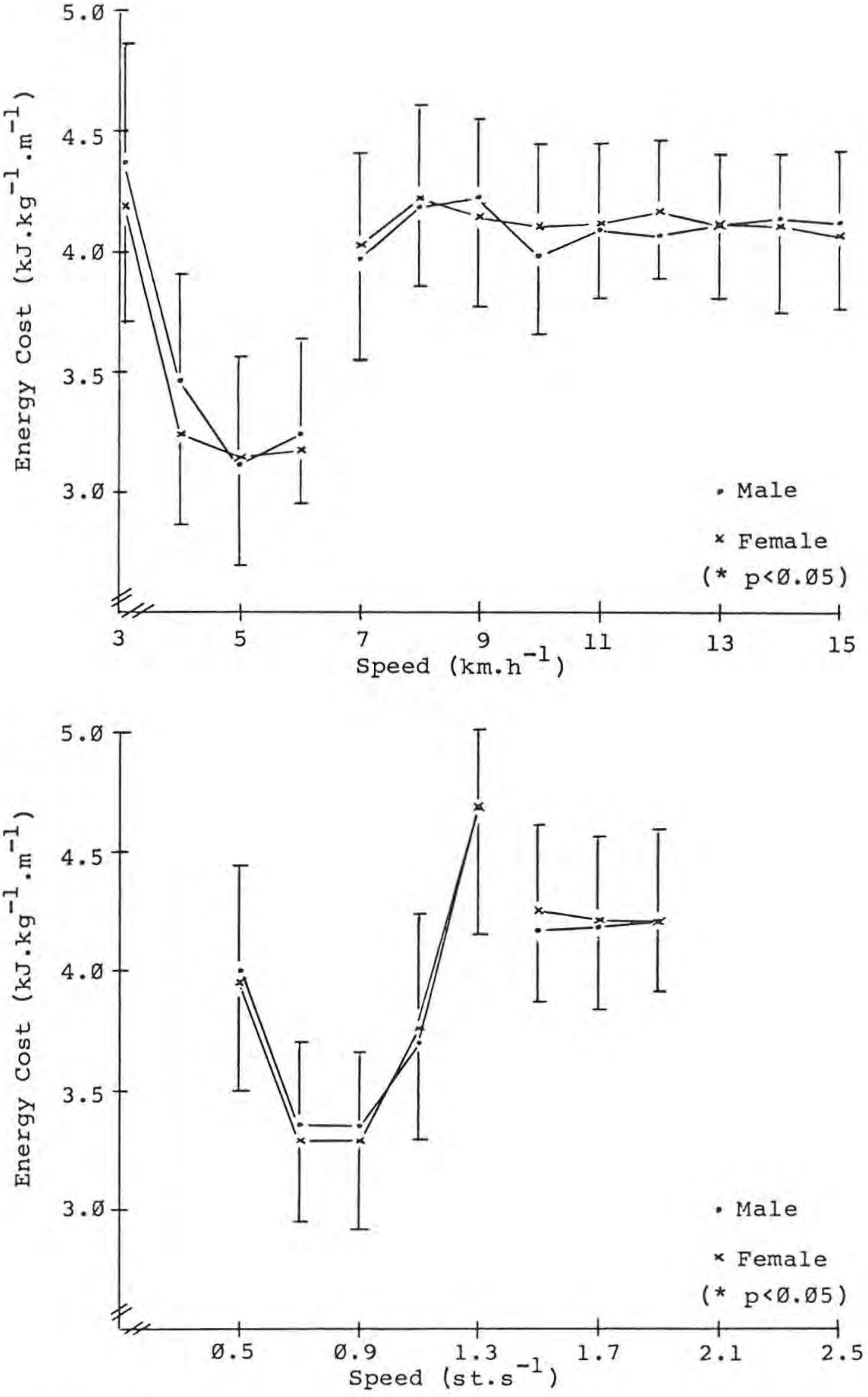


Figure 18 Energy cost per unit of distance travelled versus locomotion velocity at absolute and relative speeds - males and females compared.

below 1.0 (Figure 19, page 165). During walking, the energy cost per distance follows the same pattern as economy when plotted against velocity. The "u" shape identified 0.7 to 0.9 $st.s^{-1}$ as the least costly movement velocities. This does not support the contention, referred to in the literature, that the same amount of energy is expended to cover a certain distance regardless of velocity (Margaria et al 1963, Astrand and Rodahl 1977, McArdle et al 1981). Clearly, moderate walking speeds demand less energy per unit distance than running or, for that matter, very slow or very fast walking.

Zarrugh (1981) reported that the minimum energy cost per unit distance occurred at 1.31 $m.s^{-1}$ in his subjects. In the present study this took place between 1.21 and 1.55 $m.s^{-1}$ in the relative speed test, and at 1.39 $m.s^{-1}$ in the absolute speed test. Contrary to findings here reported, it has been stated that females have a higher energy cost per unit distance than do males (Bhambhani and Singh 1985).

The maximal oxygen uptake of the males in the present study was greater than the $\dot{V}O_2$ max of the females, and remained so (by 8.5%) when expressed per kg of lean body mass ($p<0.05$). Dill et al (1972) (15% higher) and Wilmore and Brown (1974) (7.8% higher) reported similar findings. When the effect of carrying extra fat is eliminated, the females in this study demonstrated a significantly greater oxygen consumption (per kg LBM) than the males at the same absolute velocities (Figure 9, page 148). However, at relative speeds males and females were equal in this respect. Allometric principles indicate that lean body mass is proportional to stature raised to the third power (Astrand and Rodahl 1977). When velocity of movement is set according to stature the oxygen consumption per unit of metabolically active tissue (muscle) should be consistent among subjects of different morphology. Taylor et al (1982) reported that the metabolic energy consumed per kg of muscle mass per stride is a constant in animals of different size moving at "physiologically similar speeds". This information, applied to the present study, would imply that relative speeds ($st.s^{-1}$) are "physiologically similar" since while males and females differed in energy cost per step at moderate walking and running relative speeds (Figure 10, page 149), their energy cost per unit of muscle mass was similar (Figure 9, page 148).

Ratings of perceived exertion (RPE) are related to the relative intensity of an activity (%$\dot{V}O_2$ max) (Robertson 1982). When "local" sensations of muscle or joint discomfort are significant, however, the RPE - %$\dot{V}O_2$ max relationship can be significantly altered (Pandolf 1978, Pandolf 1982). Both of these phenomena are apparent in the present data. Comparisons of the RPE - relative speed relationship (Figure 20, page 166) with the %$\dot{V}O_2$ max - relative speed relationship (Figure 8, page 147) reveal a similar pattern. The RPE at 1.3 $st.s^{-1}$, however, is out of proportion with the relative intensity (%$\dot{V}O_2$ max). It was felt that "local" sensations of discomfort accentuated the RPE response at this very fast walking speed. Most

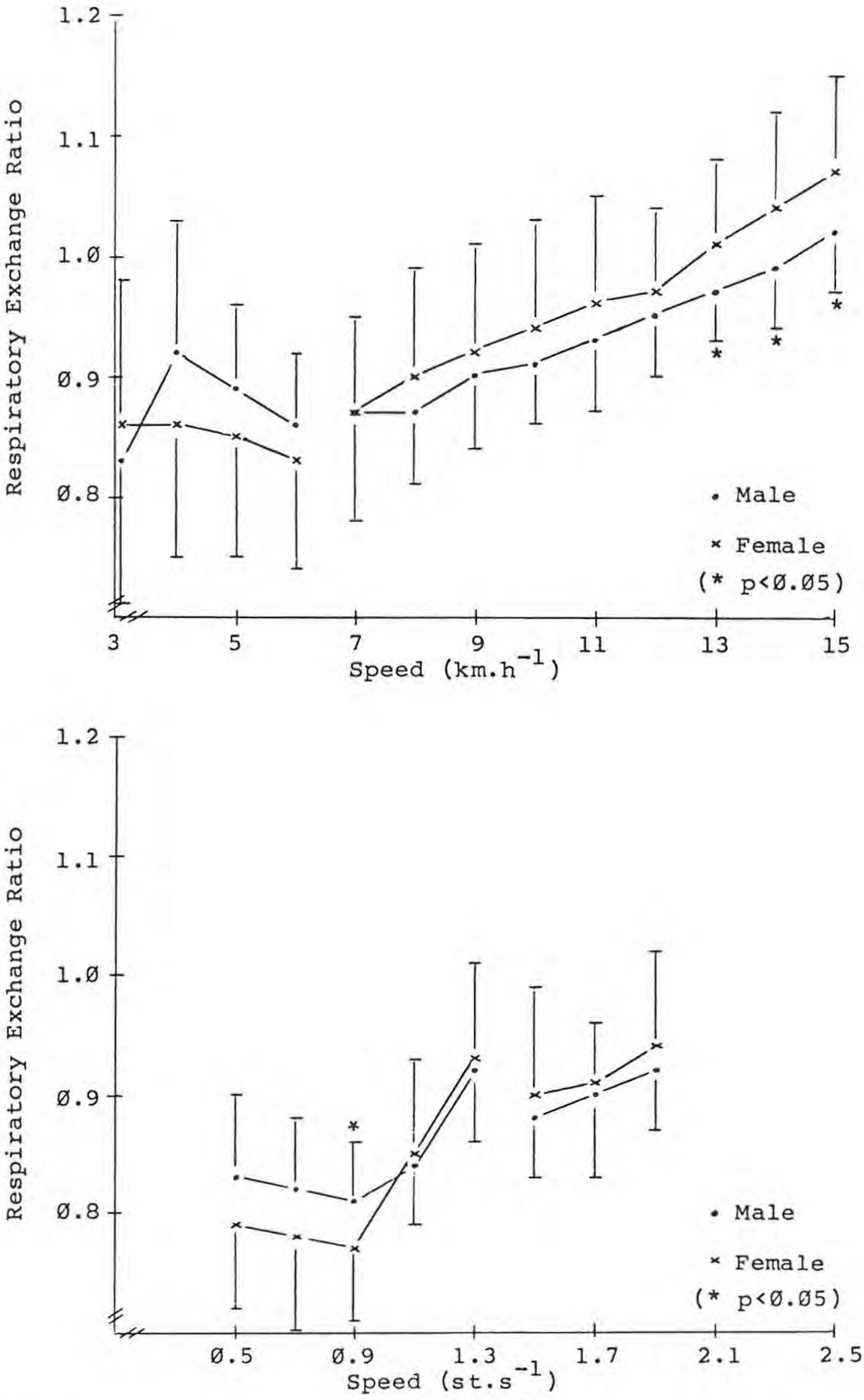


Figure 19 Respiratory exchange ratio versus locomotion velocity at absolute and relative speeds - males and females compared.

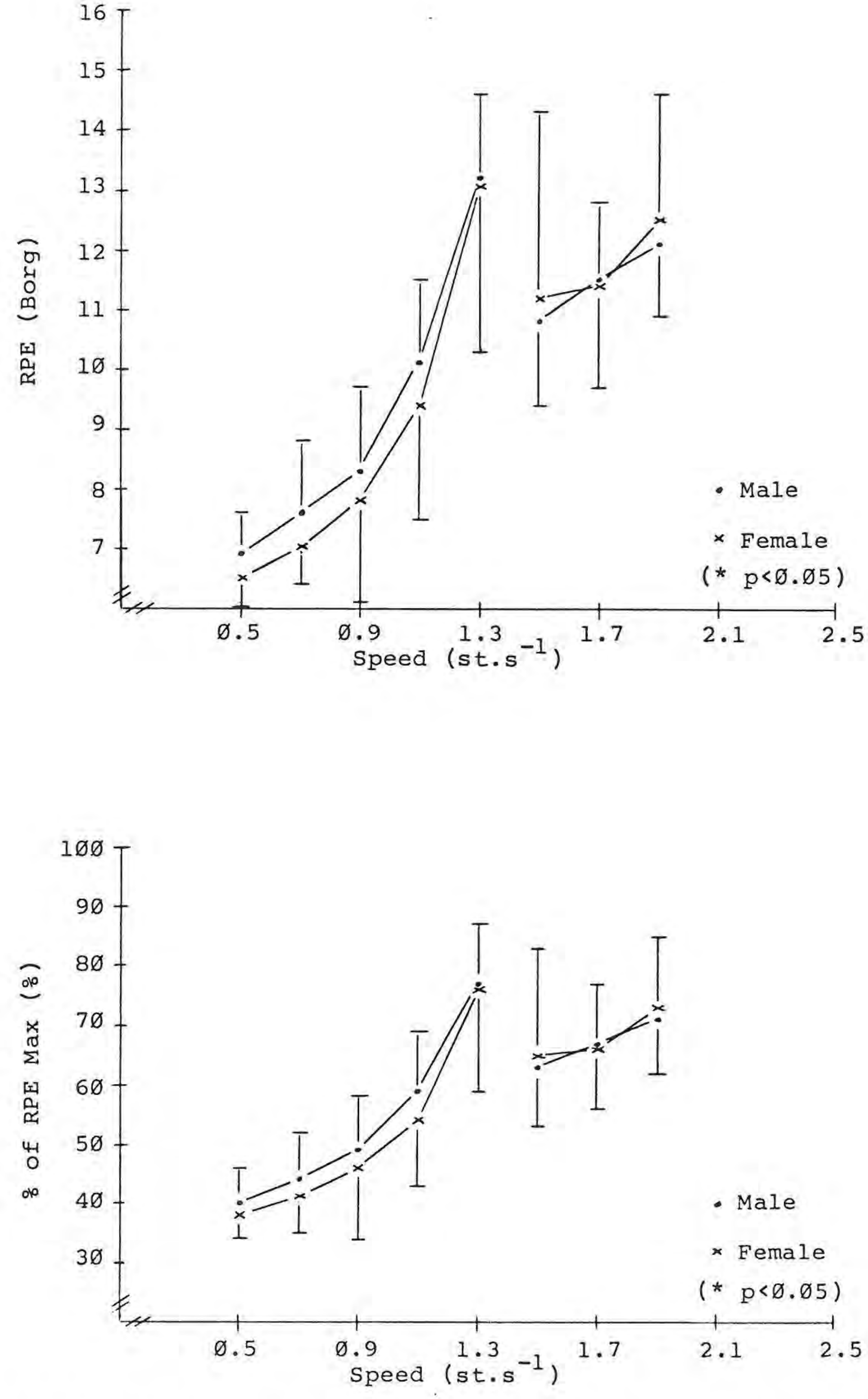
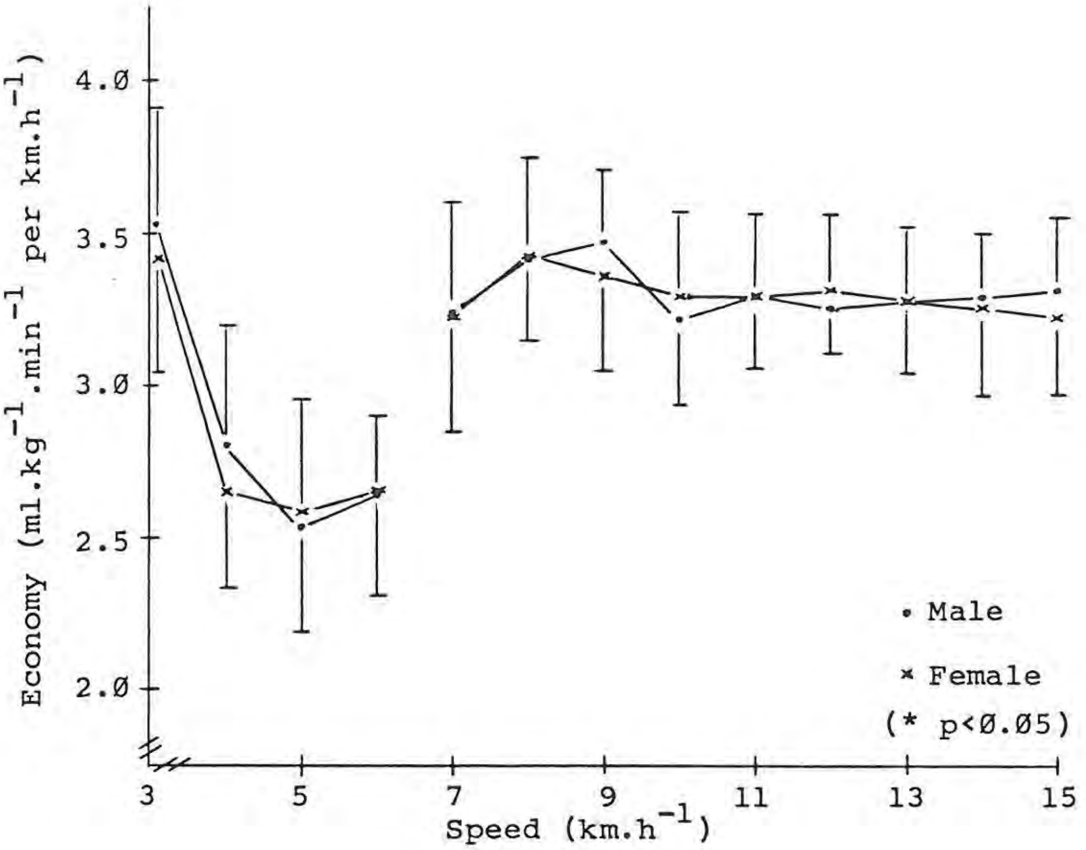


Figure 20 Ratings of perceived exertion versus locomotion velocity at relative speeds - males and females compared.

subjects complained that the walk was "too fast" and many nursed tender anterior tibial musculature after their walks at 1.3 $st.s^{-1}$. Several subjects likened it to their "late for the bus" walk.

The pattern of walking economy differs considerably from that for running (Figures 21, 22, 23, pages 168 to 170). During walking there is a distinct "u" shape with economy minimized at the extremes of movement velocity (both slow and fast), and a point of optimal economy at moderate walking speed. During running, economy is relatively unaffected by velocity, with only slight increases occurring with speed. In examining the economy data it must be pointed out that a lower oxygen consumption per unit of velocity indicates greater movement economy. It is also clear that the economy of walking at moderate speeds is substantially greater than the economy of running.

The coefficient of variation of economy, in this study, averaged 9% (Table V, page 144) which was somewhat less than that reported in the literature (Shephard 1976, Mayhew 1977). However, the variation between subjects in the present study was quite considerable and would have significant consequences for movement potential. The range in oxygen consumption (from the most to the least economical subject) increased from 3.66 $ml.kg^{-1}.min^{-1}$ at 0.5 $st.s^{-1}$ to 11.2 $ml.kg^{-1}.min^{-1}$ at 1.3 $st.s^{-1}$. During running the range of values at 1.9 $st.s^{-1}$ was 12.6 $ml.kg^{-1}.min^{-1}$. This agrees with the reported range of 10 $ml.kg^{-1}.min^{-1}$ at running speeds (Leger and



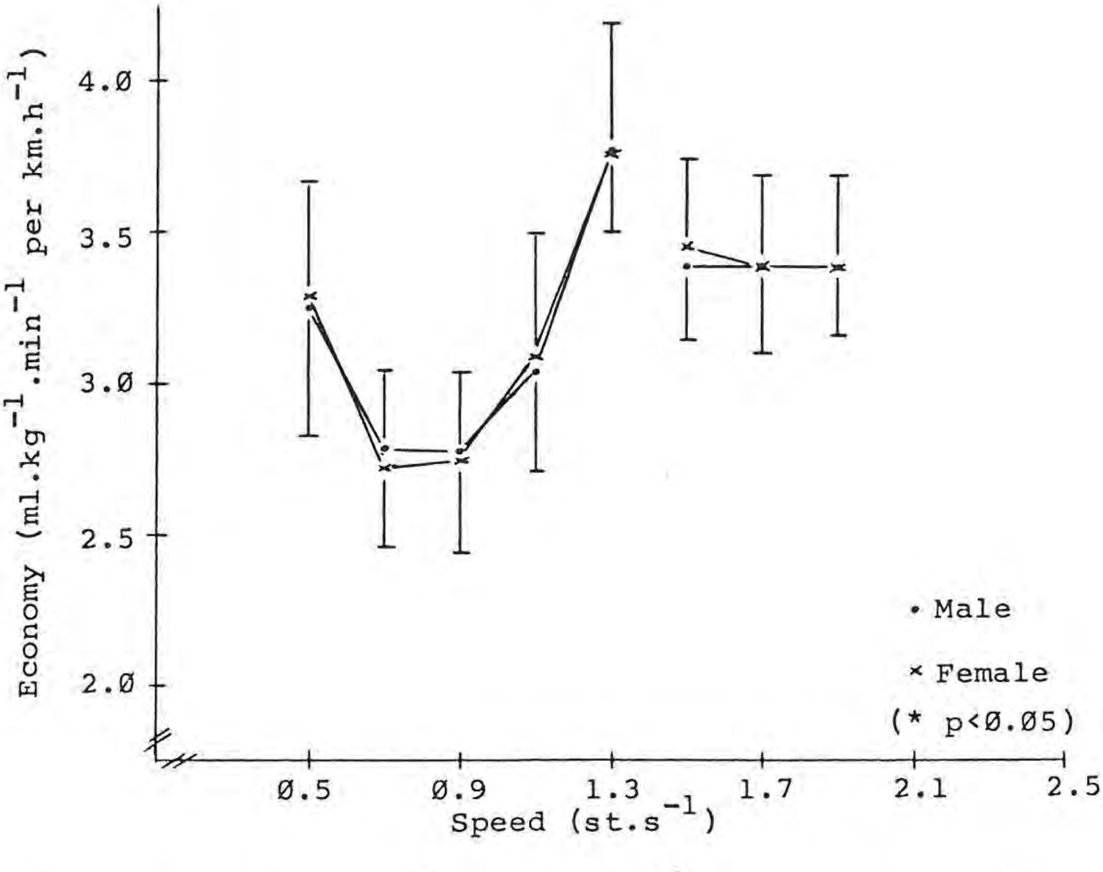
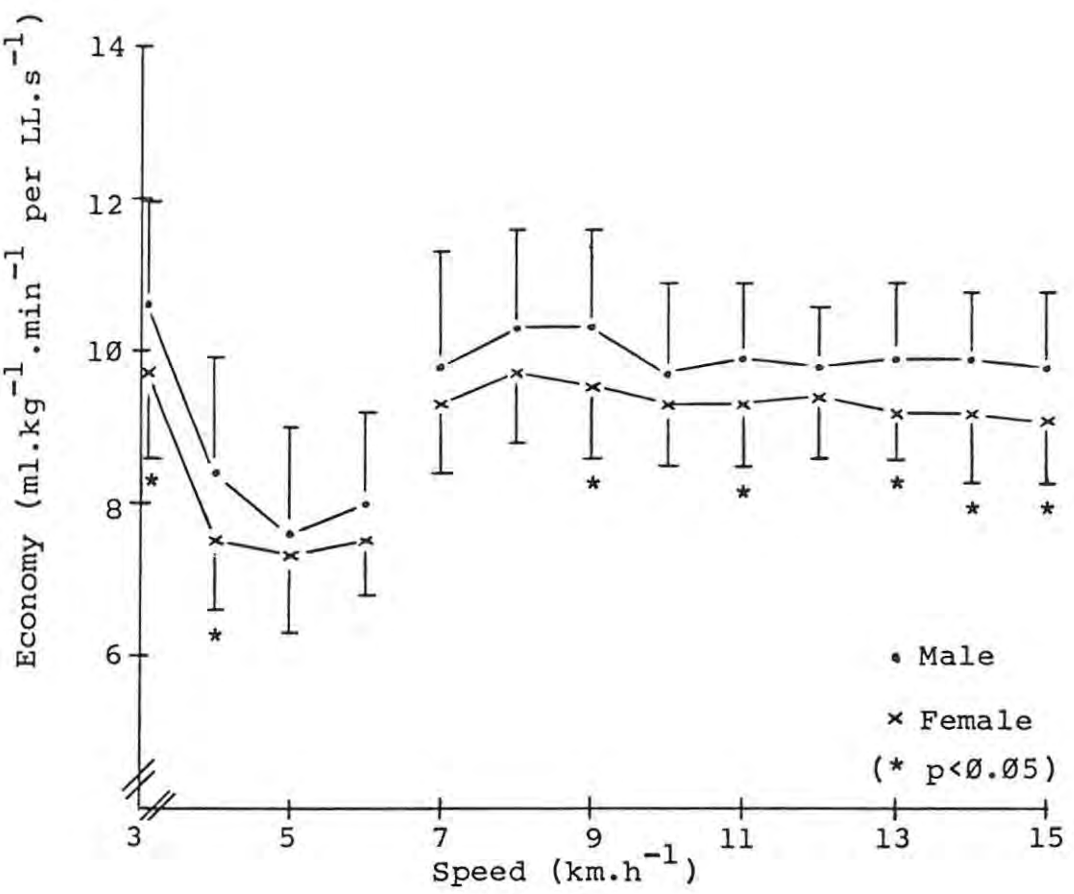


Figure 21 Economy ($\dot{V}O_2$ per km.h$^{-1}$) versus locomotion velocity at absolute and relative speeds - males and females compared.



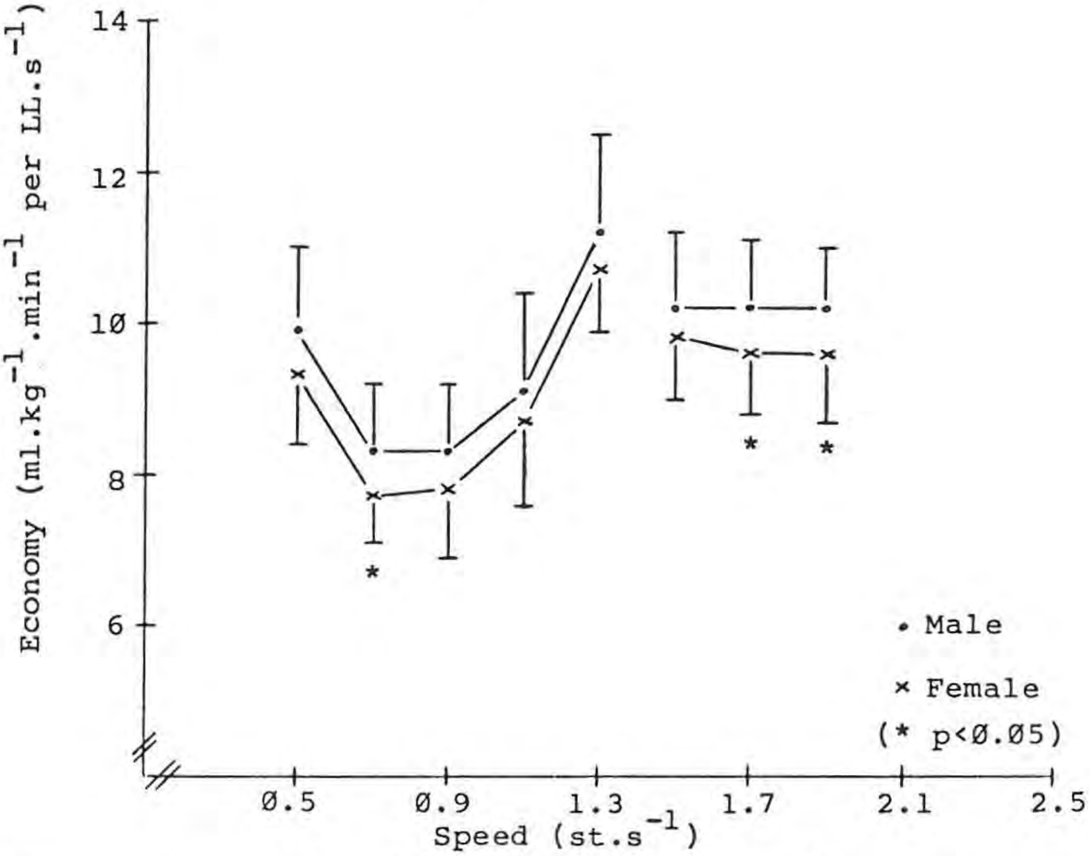


Figure 22 Economy ($\dot{V}O_2$ per leg length.s$^{-1}$) versus locomotion velocity at absolute and relative speeds - males and females compared.

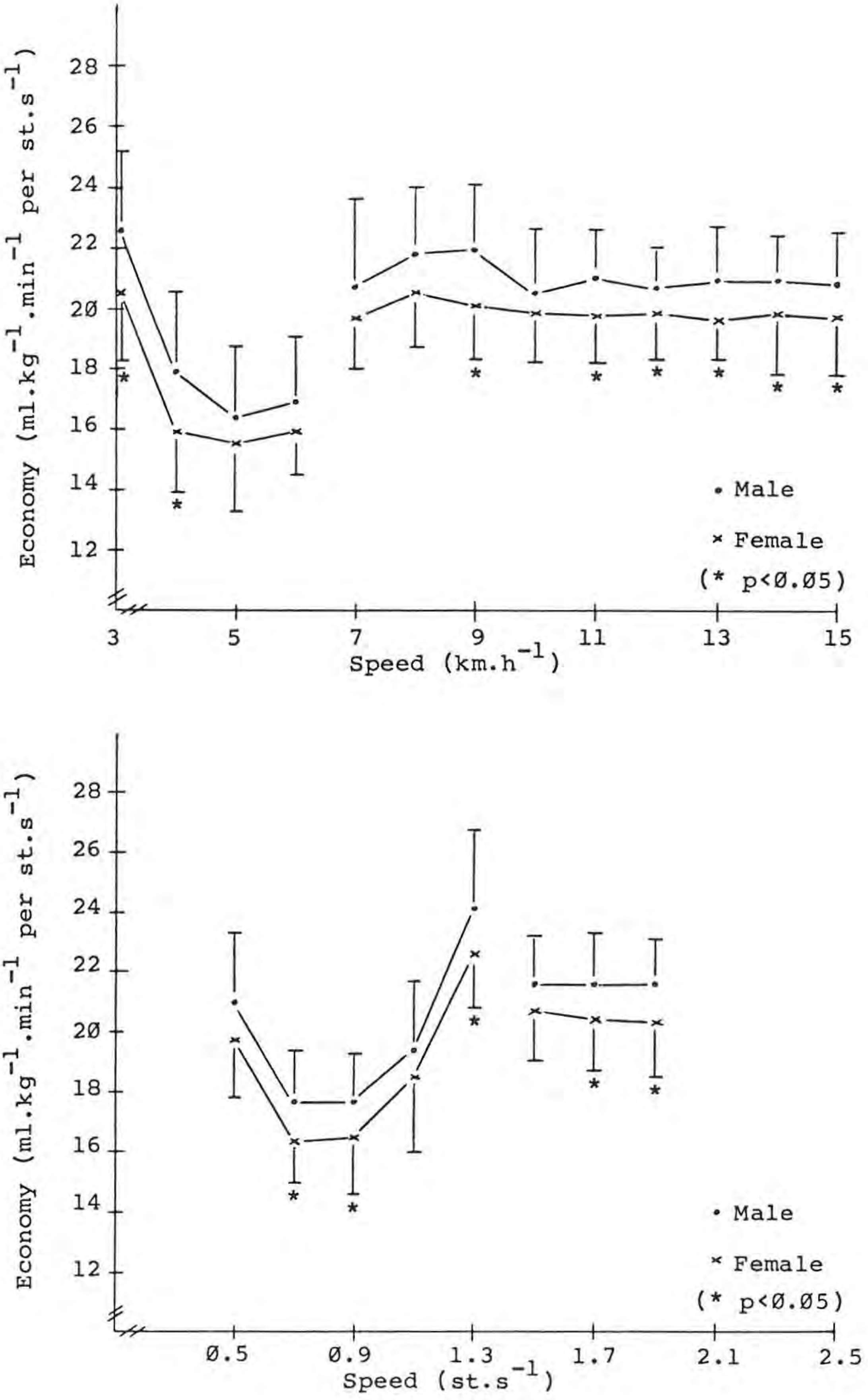
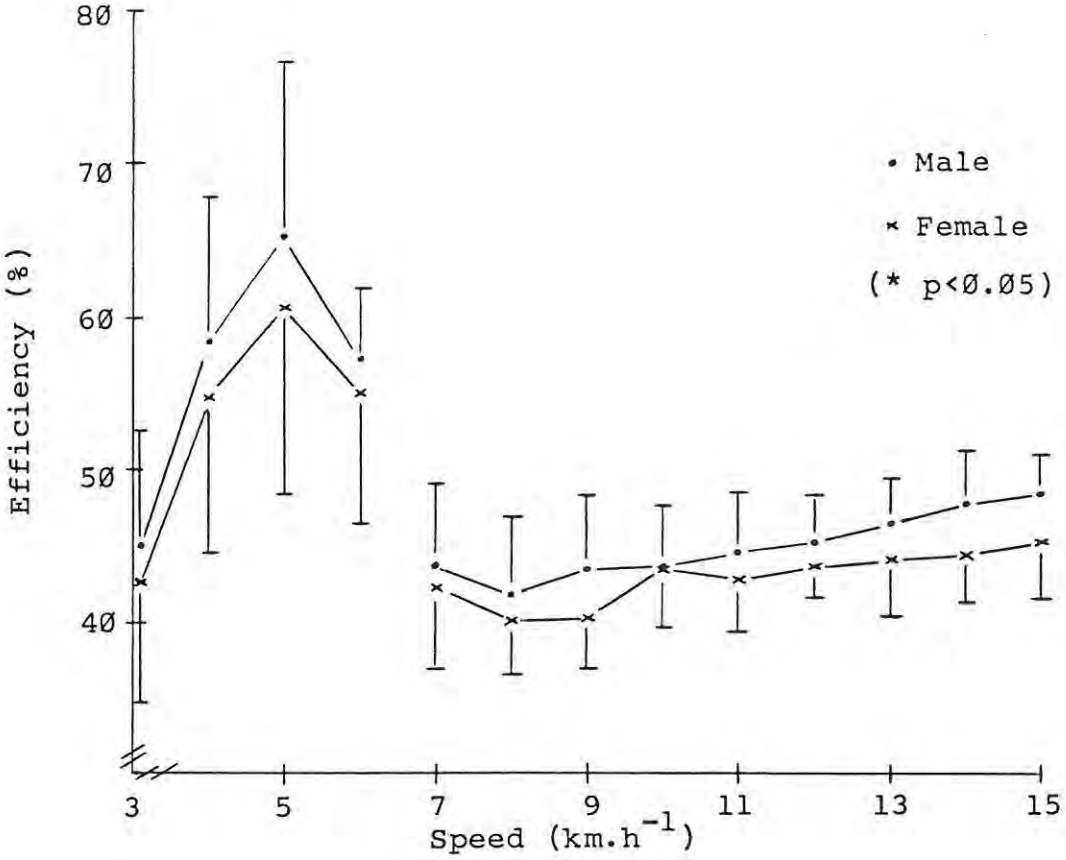


Figure 23 Economy ($\dot{V}O_2$ per $st.s^{-1}$) versus locomotion velocity at absolute and relative speeds - males and females compared.



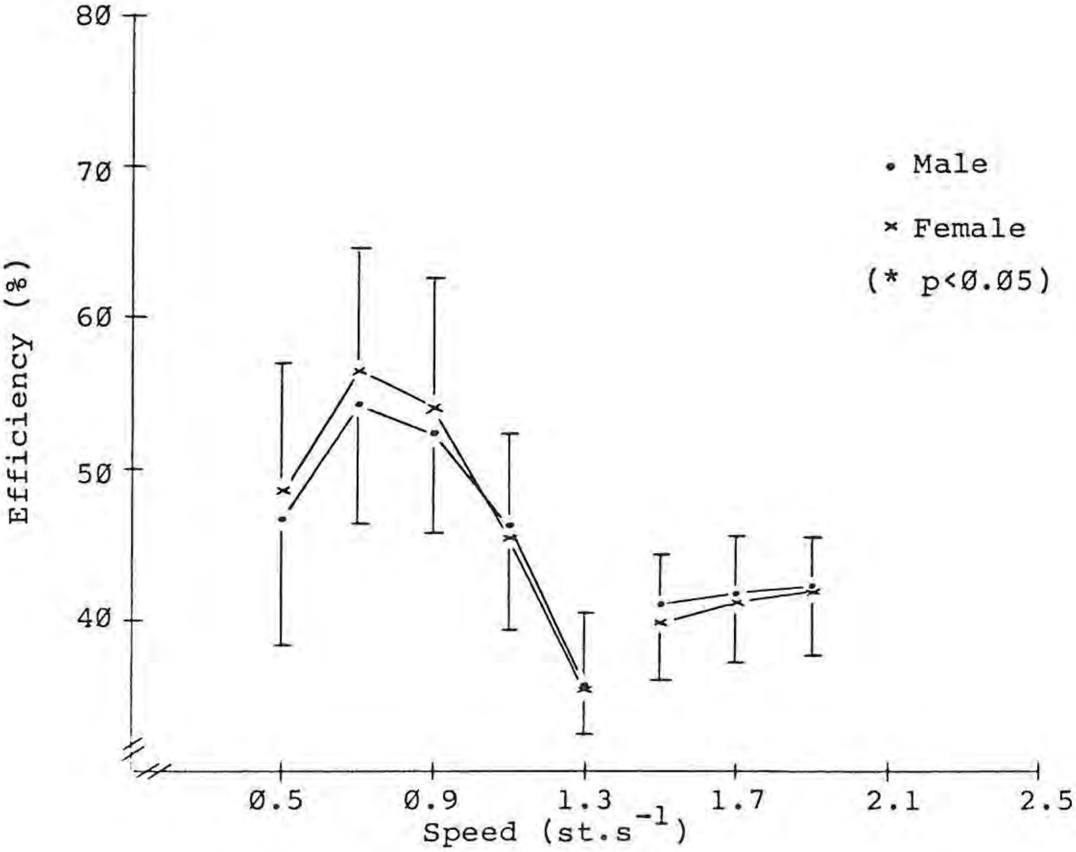


Figure 24 Estimated efficiency versus locomotion velocity at absolute and relative speeds - males and females compared.

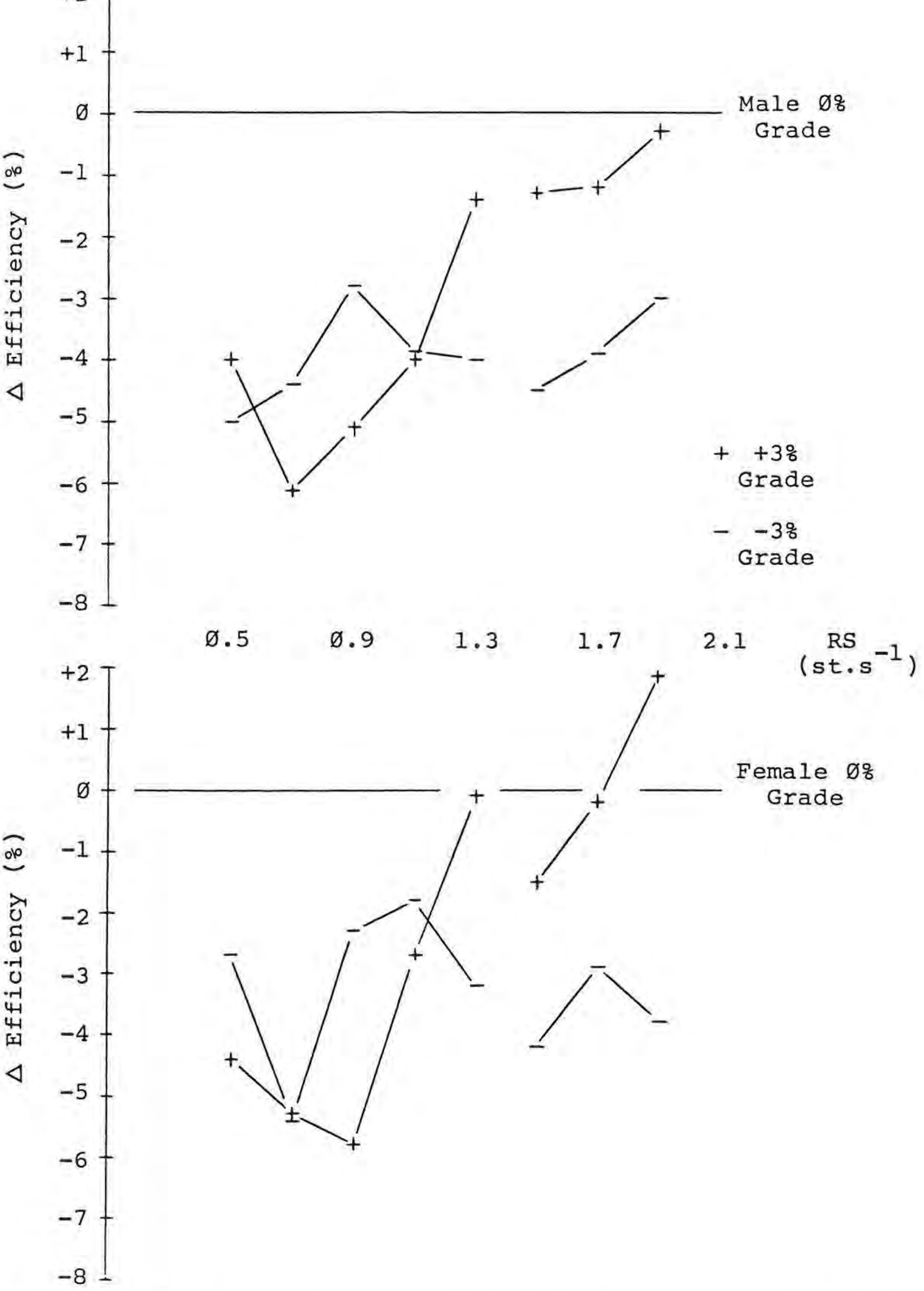


Figure 25 Change in efficiency during grade walking and running at relative speeds in males and females. Data points plotted are differentials from the efficiency observed at 0% grade for that velocity.

Mercier 1984). These data would imply that the most economical subject in the present study would have almost 25% more oxygen consumption reserve while running compared with the least economical. Given these responses it is little wonder that economy is considered to be an important determinant of endurance performance (Costill et al 1973, Conley and Krahenbuhl 1980).

During the relative speed tests the male subjects were most economical at 1.24 $m.s^{-1}$, and the female subjects exhibited this trait at 1.17 $m.s^{-1}$. During the $\dot{V}O_2$ max test this point was achieved at 1.39 $m.s^{-1}$ for both subject groups. This is consistent with the values for velocity at maximum economy reported to range from 1.11 $m.s^{-1}$ (Margaria et al 1963) to 1.31 $m.s^{-1}$ (Zarrugh 1981). These speeds coincide with "preferred" speed of 0.85 $st.s^{-1}$ (Charteris 1982), implying a direct relationship between economy and "preferred" speed. Cavagna et al (1977) reported that the energy transfer, between kinetic and potential energy, per walking stride was greatest at a moderate speed. In a similar vein, Mansour et al (1982) found that the greatest energy exchange occurred near individually preferred walking speeds. The greater the energy transfer, from stride-to-stride, the smaller is the necessity to provide energy for progression from metabolic sources. Cavagna et al (1971) pointed out that at low speed muscular action must provide most of the power output while at higher speed power is sustained by energy storage during negative work. This is another energy saving mechanism which contributes to the economy of locomotion at moderate speeds.

Mechanical factors almost certainly contribute to the low economy of both fast and slow walking. During fast walking excessive upper body action unrelated to the progression of the centre of mass would raise the energy cost while during very slow walking the "almost-held" postures during slow progression would bring about excess oxygen consumption (Cavagna and Margaria 1966). Davies (1971) suggested that at high velocity muscle tissue is less effective since forming a cross-bridge is less likely, and it might form at less than full extension of the flexible part of the cross-bridge. He went on to point out that at low speeds the internal viscous work lowered the efficiency of the sarcomere. Milner et al (1971) found that there was a minimum in EMG in the speed range 0.91 to 1.52 $m.s^{-1}$, and in light of the above points, suggested that their subjects selected a preferred velocity where EMG is minimized.

At absolute speeds ($km.h^{-1}$) males and females were equally economical (Figure 21, page 168). However, at relative speeds (leg $length.s^{-1}$ and $st.s^{-1}$) females were more economical than males (Figures 22 and 23, pages 169 and 170). During the $\dot{V}O_2$ max test this was the case because of the equal male and female $\dot{V}O_2$ response to absolute velocities, which were higher relative speeds for the women. During the relative speed tests this was a function of higher male oxygen consumption at equivalent male and female relative speeds. The distinctive "u" shape of the walking economy response is a direct function of the exponential nature of the $\dot{V}O_2$ - velocity relationship (Figure 6, page 135).

It is of interest to note that the Figures portraying economy (21, 22 and 23, pages 168 to 170) are almost mirror images of the efficiency plot (Figure 24, page 171) - a minimal oxygen consumption per unit of velocity implies a maximal efficiency. This is not surprising as the Heglund et al (1982) equation (see below) which was used to estimate the mass-specific power output required of muscles and tendons to maintain the observed oscillations in total energy is based purely on the velocity of locomotion.

$$\text{Power } (\text{W.kg}^{-1}) = (0.478 * v^{1.53}) + (0.685 * v) + 0.072$$

Where $v$ = velocity ($\text{m.s}^{-1}$)

(from Heglund et al 1982)

This equation was selected in preference to other possible choices because of two factors. The equation is independent of body size and applies equally well to quadrupedal and bipedal animals. Secondly, it provides reasonable estimates of human power output without the necessity to measure "internal work" via expensive and technologically sophisticated apparatus (Winter 1979a, Winter 1982a). Williams and Cavanagh (1983), in their excellent synthesis of information on the efficiency of locomotion, combined and tested various assumptions regarding energy transfer, negative work and elastic storage of energy in locomotion. They used 3-D cinematography and segmental analysis to actually measure internal and external work done by 31 well-trained subjects running overground at 3.57 $\text{m.s}^{-1}$. After a thorough and logical process of establishing the most "realistic" assumptions concerning energy transfer (63% per stride), elastic energy storage (35% of total energy), non-muscular absorption of negative work (15% of total energy) and the relative efficiency of negative work (3 times positive), they computed total power output and net efficiency. The average power output for their athletes was 5.85 $W.kg^{-1}$. The Heglund _et_ _al_ (1982) equation estimate of power output at this velocity was 5.87 $W.kg^{-1}$. The net efficiency reported by Williams and Cavanagh was 44% which compares very favourably with the net efficiency obtained in the present study (43.96%) at a comparable velocity (13 $km.h^{-1}$).

The effectiveness of the Heglund _et_ _al_ (1982) equation was also evaluated for walking velocities by comparison with studies reported in the literature which employed segmental analysis and measurements of internal and external work. The data presented by Winter (1979b) at 1.4 $m.s^{-1}$ indicated a power output of 1.838 $W.kg^{-1}$ compared to the Heglund estimate of 1.831 $W.kg^{-1}$. In another example (Pierrynowski _et_ _al_ 1980), power output (at 1.54 $m.s^{-1}$) was measured at 2.3 $W.kg^{-1}$ with the Heglund estimate being 2.052 $W.kg^{-1}$. In the latter case the differential may be due to the assumption used in Pierrynowski's work that negative work was only twice as efficient as positive work. The equation presented by Heglund _et_ _al_ (1982) would, thus, seem to be applicable across a broad range of locomotor velocities, and provide quite reasonable estimates of power output without the necessity to actually measure the work done.

The present data indicated that walking efficiencies (except extremely fast velocities; 1.3 st.$s^{-1}$) were higher than running efficiencies. Furthermore, running efficiency was seen to slowly increase with velocity (Figure 24, page 171). There are a significant number of conflicting reports in the literature regarding walking and running efficiency. While most authors agree that the energy cost of walking demonstrates an optimal point and the energy cost of running increases linearly with velocity, as previously discussed, substantial disagreement exists regarding the work done during locomotion. Cavagna and Kaneko (1977) reported that power output during running progressively increases (per unit of distance travelled) leading to a progressive rise in efficiency (45 to 80%) as velocity increases to maximum. These data are suspect, however, as Winter (1979a) has shown that it is erroneous to assume that the energy level of the centre of mass is equal to the sum of the segmental energies. Others have found that power output increases almost linearly with velocity of running producing relatively constant or slowly rising efficiencies (Fukunaga et al 1981, Matsuo and Fukunaga 1983, Ito et al 1983). Still others have reported parabolic increases in the horizontal and limb rotational energies during progressive increases in running speed (Luhtanen and Komi 1978, 1980). Most researchers agree, however, that there is considerably greater energy transfer between segments, and energy storage during negative work while running compared with the slower form of locomotion - walking (Cavagna et al 1971, Thys et al 1972, Fardy and

Hellerstein 1978, Alexander 1980). This is particularly apparent in examining the efficiency of walking and running at the same velocity (Wyndham and Strydom 1971, Marchetti et al 1983).

Other factors, however, intervene to lower the efficiency of running. While most investigators agree that the vertical power output during running remains constant or drops somewhat as velocity increases (Cavagna et al 1963, Luhtanen and Komi 1978, Fukunaga et al 1981), it still remains approximately twice that of walking. As velocity increases: arm and leg rotational energy increases parabolically (Luhtanen and Komi 1980); there is a less effective force-velocity relationship (Davies 1971); and the involvement of less efficient fast-twitch muscle fibres increases (Donovan and Brooks 1977, Crow and Kushmerick 1982, Wendt and Gibbs 1974).

It would seem logical that the best estimate of the efficiency of horizontal locomotion is the ability to move one's body mass at any given velocity with the lowest energy expenditure. In this respect economy should reflect efficiency. The present data support this contention. Furthermore, the Heglund et al (1982) method of estimating locomotor power output appears to provide a valid basis for the estimation of efficiency. The close congruence of the present efficiency data with those from the literature (Pierrynowski et al 1980, Williams and Cavanagh 1983) which have been based on the widely-accepted integrative summation of segmental energies approach (Winter 1979b) lends credibility to the results of this study.

In order for the effect of grade on locomotion response to be fully appreciated it is necessary to view pairs of Figures. For example, 0% grade oxygen consumption data are plotted against relative speed in Figure 6 (page 135). The differences from the oxygen consumption at 0% grade for uphill (+3% grade) and downhill (-3% grade) locomotion are plotted against relative speed in Figure 7 (page 136). In this fashion, the general trend is appreciated along with specific information on the differential effects of grade (+3% and -3%) on performance and the effect of increases in velocity on the relative response. All of these data are plotted relative to male and female responses to 0% grade at each velocity (Figure 6, page 135). The significance of differences observed while grade walking is reported with the tabular data in Appendix 7 (pages 343 to 350).

An examination of this pair of Figures (6 and 7, pages 135 and 136) for oxygen consumption reveals that the average oxygen cost of walking up a +3% grade was 1.4 times the $\dot{V}O_2$ of walking down a -3% grade. This differential was greatest at mid-range velocities (1.48 times at 0.9 $st.s^{-1}$) and least at the two extremes (1.38 at 0.5 $st.s^{-1}$ and 1.30 at 1.3 $st.s^{-1}$). This was the case because the relationship between $\dot{V}O_2$ and RS while walking uphill was somewhat more linear than the primarily exponential curve for walking downhill. In other words, locomotion was more adversely affected by uphill grades than it was by downhill grades near "preferred speed" (Charteris 1982). This may be a function of the finding that during uphill walking potential and kinetic energy patterns are in phase, while on the level these patterns form a mirror image (Lukin and Ralston 1968). Downhill walking may simply be a continuation of this effect.

The average oxygen cost of <u>running</u> up a +3% grade was found to be 1.28 times the $\dot{V}O_2$ of running down a -3% grade. Here there was no similar speed effect, the differential was the same at all speeds. The differential between +3% and 0% grade decreased as speed increased while the effect for downhill was the opposite. It was felt that this may have been due to the provision of an increasing amount of anaerobic energy at uphill grades as speed increased; thus apparently reducing the energy cost of the activity relative to locomotion at 0%. In support of this suggestion, most subjects were working above their ventilatory threshold at the fastest uphill condition (1.9 $st.s^{-1}$, +3% grade) (see Figure 8, page 147).

The change in oxygen consumption relative to 0% grade locomotion provides some interesting insights. The $\dot{V}O_2$ at +3% grade increased by approximately twice the $\dot{V}O_2$ decrease at -3% grade (Figure 7, page 136). This was a consistent pattern across all walking speeds. $\dot{V}O_2$ increased by approximately 21% from 0% grade to +3% grade while it decreased by an average of 10.7% from 0% grade to -3% grade. The general response to grade walking is a linear change in oxygen consumption with increased gradient

(Margaria et al 1963, Lukin and Ralston 1968, Givoni and Goldman 1971). However, as in the present study, it has been found that the excess oxygen consumption of uphill locomotion is greater than the savings of energy observed when moving downhill at the same speed and grade (Henson et al 1977, Howley et al 1984). The economy of negative work is primarily a function of the storage of energy during eccentric loading and the assistance of gravity (Cavagna et al 1968, Davies 1971, Cavanagh and Kram 1983). Cavanagh et al (1973) reported that while economy was greater for downhill running compared with uphill, running at too great a downhill grade will reduce economy. This may have been a function of the greater leg shock absorption necessary at the steeper downhill grades which Howley et al (1984) point out is an "energy requiring process".

The efficiency of uphill and downhill walking was found to be less than that for level walking (Figure 25, page 172). At running speeds, however, uphill and level locomotion were equally efficient. The efficiency of downhill locomotion remained approximately the same amount below that of level locomotion across all speeds. In contrast, the efficiency of uphill locomotion progressively improved relative to 0% grade efficiency as speed increased. One possible explanation for the lower efficiency of grade locomotion would be the relative unfamiliarity with the task compared with 0% grade and, thus, possibly less efficient energy transfer from stride to stride. However, a more likely explanation lies in the method of computing efficiency. The power output for grade walking was calculated by simply adding the vertical power output to the Heglund et al (1982) equation's estimate of 0% grade locomotion power output (see Appendix 6, page 301). This was added in the case of positive grade and subtracted in the case of negative. Although this is a common practice, it ignores any extra work done horizontally and laterally due to alterations in the mechanics of locomotion attendant to grade locomotion. This method does not take into account relative changes in segmental energies or for that matter, changes in the relative amounts of positive and negative work done within strides at uphill and downhill grades. Margaria (1968) found that positive work progressively decreased as negative grade increased until, below -9% grade, no positive work was being done during walking. He found that during uphill walking the contribution of negative work progressively decreased until, at 22% grade, no positive work was being done. The technique of adding the vertical work done on or by the centre of mass to level work to obtain the total work of grade locomotion has weaknesses. The efficiencies, so calculated, should be viewed with a moderate amount of skepticism.

The changes in stride length (Figure 12, page 151) and cadence (Figure 16, page 155) in response to grade locomotion provide interesting insights into their role in movement economy. As speed increased the stride length at +3% grade decreased, and the cadence increased, relative to locomotor patterns for 0% grade. These effects were significant ($p<0.05$) only at running velocities. During downhill locomotion the opposite pattern was observed. As speed increased stride length increased and cadence decreased relative to 0% grade. In light of the previous discussion regarding the possible economy of higher cadence, these responses may indicate an effort to conserve energy as the metabolic demands increase in uphill locomotion. Bobbert (1960) found that freely chosen cadence was not affected by grade walking. Henson et al (1977), however, found that running cadence was higher at both uphill and downhill grades (8%) than in level running.

Another interesting observation is that grade has little effect on cadence and stride length at moderate walking (0.9 $st.s^{-1}$) and running (1.7 $st.s^{-1}$) velocities. Perhaps this is an indication that energy optimization patterns in freely-chosen cadence are strongly tied to velocity despite the effects of grade.

## HIGH AND AVERAGE $\dot{V}O_2$ MAX GROUPS

The subjects in this study were arbitrarily divided into two categories based on their maximal oxygen consumption. The high $\dot{V}O_2$ max group (n = 21) and the average $\dot{V}O_2$ max group (n = 21) contained approximately equal numbers of males and females. The maximal oxygen consumption data (Table VII, page 185) indicate that these groups were significantly different ($p<0.05$). It is of interest that there was no difference in ventilatory threshold (V.T.)

despite the difference in $\dot{V}O_2$ max. This would imply that the high $\dot{V}O_2$ max group were not necessarily more cardio-vascularly "fit" (Costill <u>et al</u> 1971, Costill <u>et al</u> 1973, Conley and Krahenbuhl 1980). The two groups were similar in stature which meant that average velocities during the relative speed tests were very much the same (Figure 26, page 186). The subjects in the average $\dot{V}O_2$ max group were heavier and had a greater % body fat ($p<0.05$) than the high $\dot{V}O_2$ max group, but in all other respects these two subject groups were similar (Table VII, page 185). The ratio of leg length/stature, while not different between the two groups, was higher and more in the normal "male" range in the high $\dot{V}O_2$ max group, and was lower and more in the normal "female" range in the average $\dot{V}O_2$ max group.

At absolute speeds the high $\dot{V}O_2$ max group was consistently higher than the average group in $\dot{V}O_2$ response ($p<0.05$) but at relative speeds both groups were the same (Figure 27, page 187). However, as a percentage of $\dot{V}O_2$ max the average group was working relatively harder under both conditions (Figure 29, page 189). The average $\dot{V}O_2$ max group worked at a higher respiratory exchange ratio (Figure 39, page 201) at the higher velocities during the absolute speed test. The RPE data (Figure 40, page 202) support the general impression that the average $\dot{V}O_2$ max group was working relatively harder particularly at the running velocities.

Table VII Anthropometric and performance characteristics of the high and average oxygen consumption (mixed sex) subject groupings

| Parameter | High $\dot{V}O_2$ $\overline{X}$ | High $\dot{V}O_2$ SD | Average $\dot{V}O_2$ $\overline{X}$ | Average $\dot{V}O_2$ SD | p |
|---|---|---|---|---|---|
| Age (years) | 20.8 | 1.5 | 22.1 | 3.5 | - |
| Anthropometry: | | | | | |
| Stature (cm) | 172.6 | 9.3 | 171.7 | 7.1 | - |
| Body mass (kg) | 63.4 | 8.0 | 67.8 | 9.1 | $<0.05$ |
| Leg length (cm) | 82.0 | 5.6 | 80.3 | 4.3 | - |
| Leg length/stature (%) | 47.5 | 1.2 | 46.8 | 1.3 | - |
| Foot length (cm) | 24.9 | 1.7 | 25.0 | 1.6 | - |
| Foot length/leg length (%) | 30.3 | 1.4 | 31.1 | 1.7 | - |
| % Fat | 17.5 | 5.4 | 21.7 | 5.4 | $<0.05$ |
| Lean body mass (kg) | 52.8 | 8.4 | 53.5 | 9.5 | - |
| Body surface area ($m^2$) | 1.76 | 0.15 | 1.80 | 0.15 | - |
| Performance: | | | | | |
| $\dot{V}O_2$ max ($ml.kg^{-1}.min^{-1}$) | 57.5 | 6.3 | 47.9 | 6.6 | $<0.05$ |
| V.T. (%$\dot{V}O_2$ max) | 63.6 | 6.7 | 64.0 | 9.6 | - |
| V.T. ($ml.kg^{-1}.min^{-1}$) | 36.7 | 6.1 | 30.8 | 6.9 | $<0.05$ |
| V.T. velocity ($km.h^{-1}$) | 10.9 | 2.5 | 9.6 | 2.2 | - |
| RPE max | 17.5 | 1.5 | 17.0 | 1.3 | - |

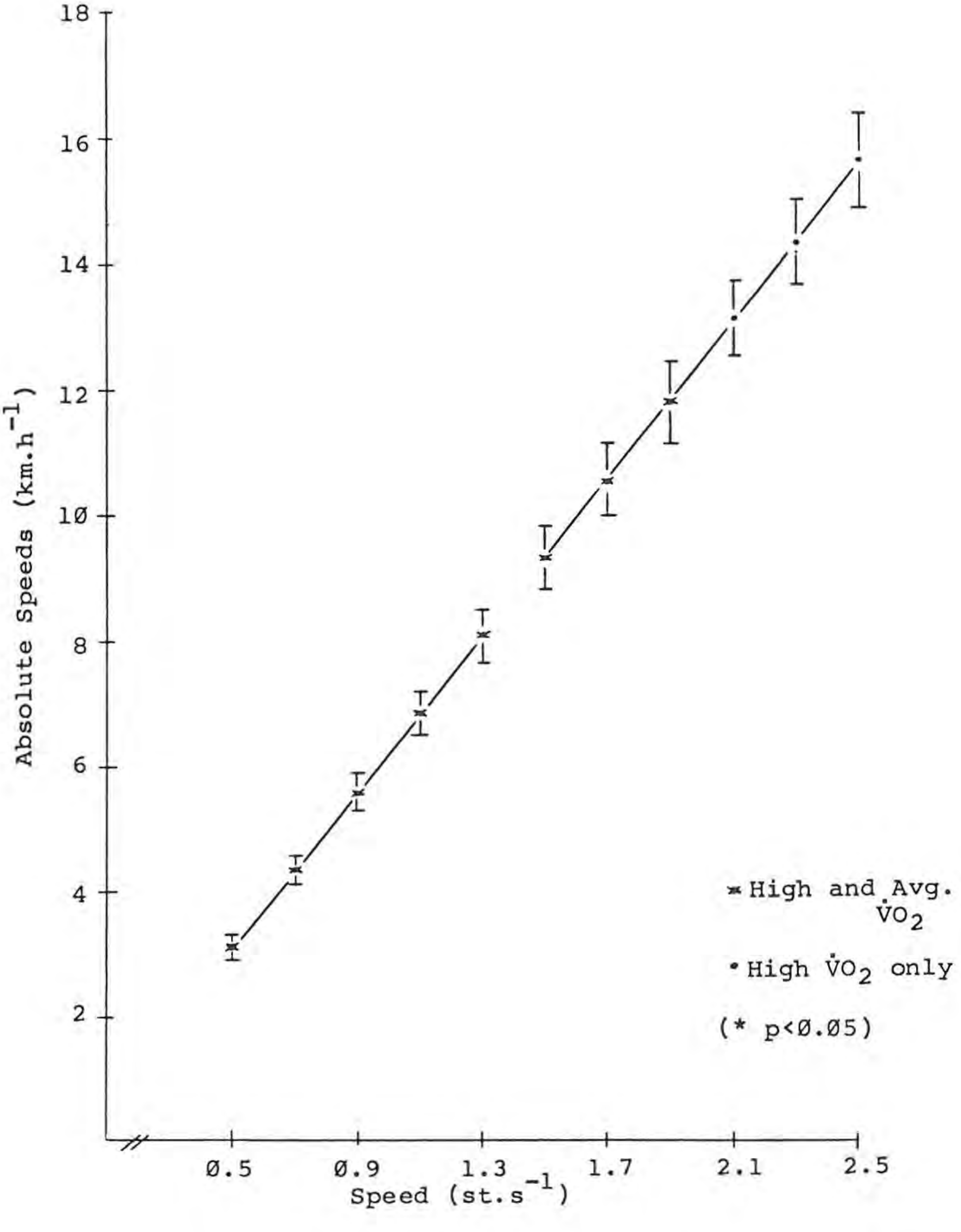


Figure 26 Absolute speeds at the relative speeds used in this study - high and average $\dot{V}O_2$ groups compared.

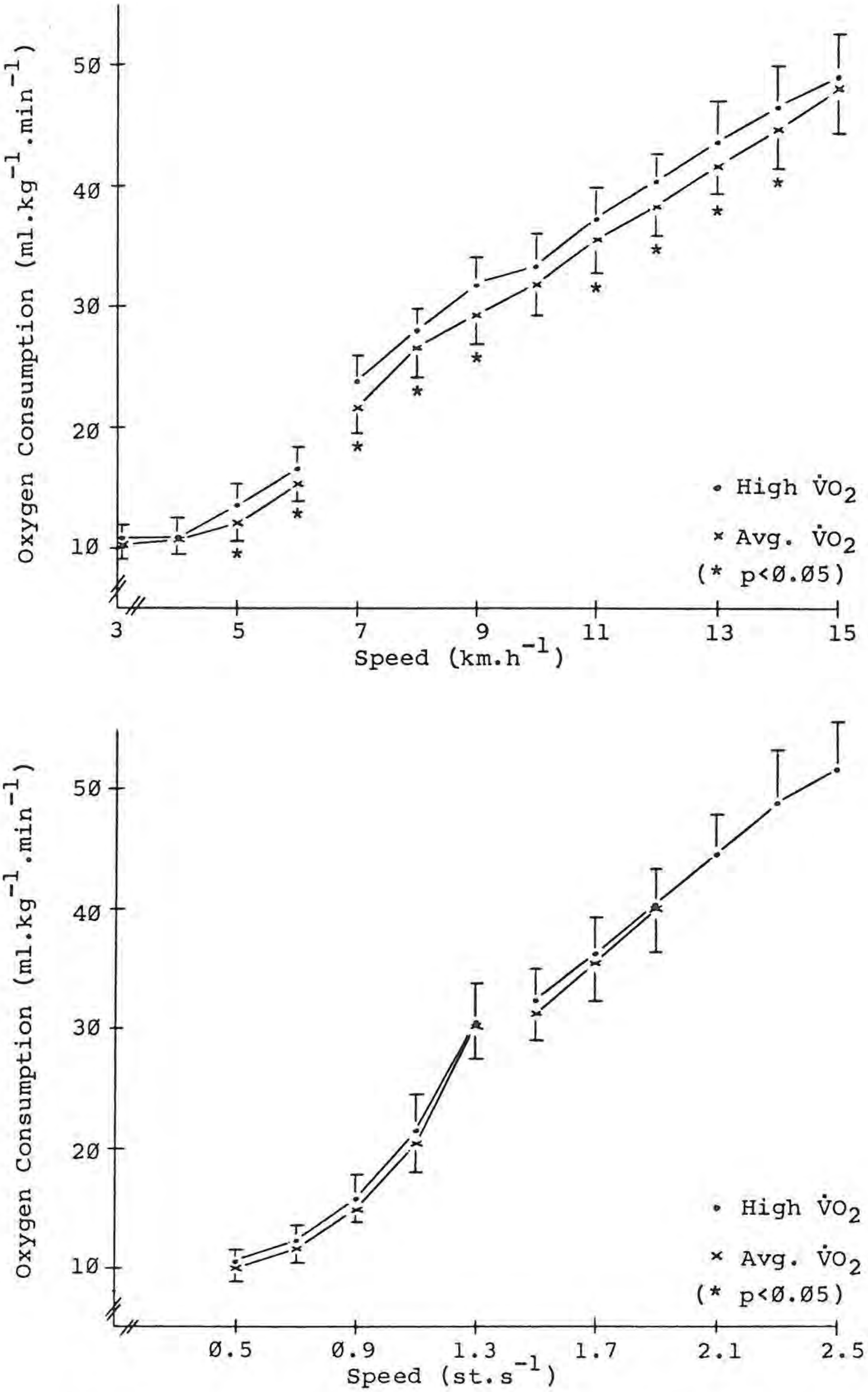


Figure 27 Oxygen consumption versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.

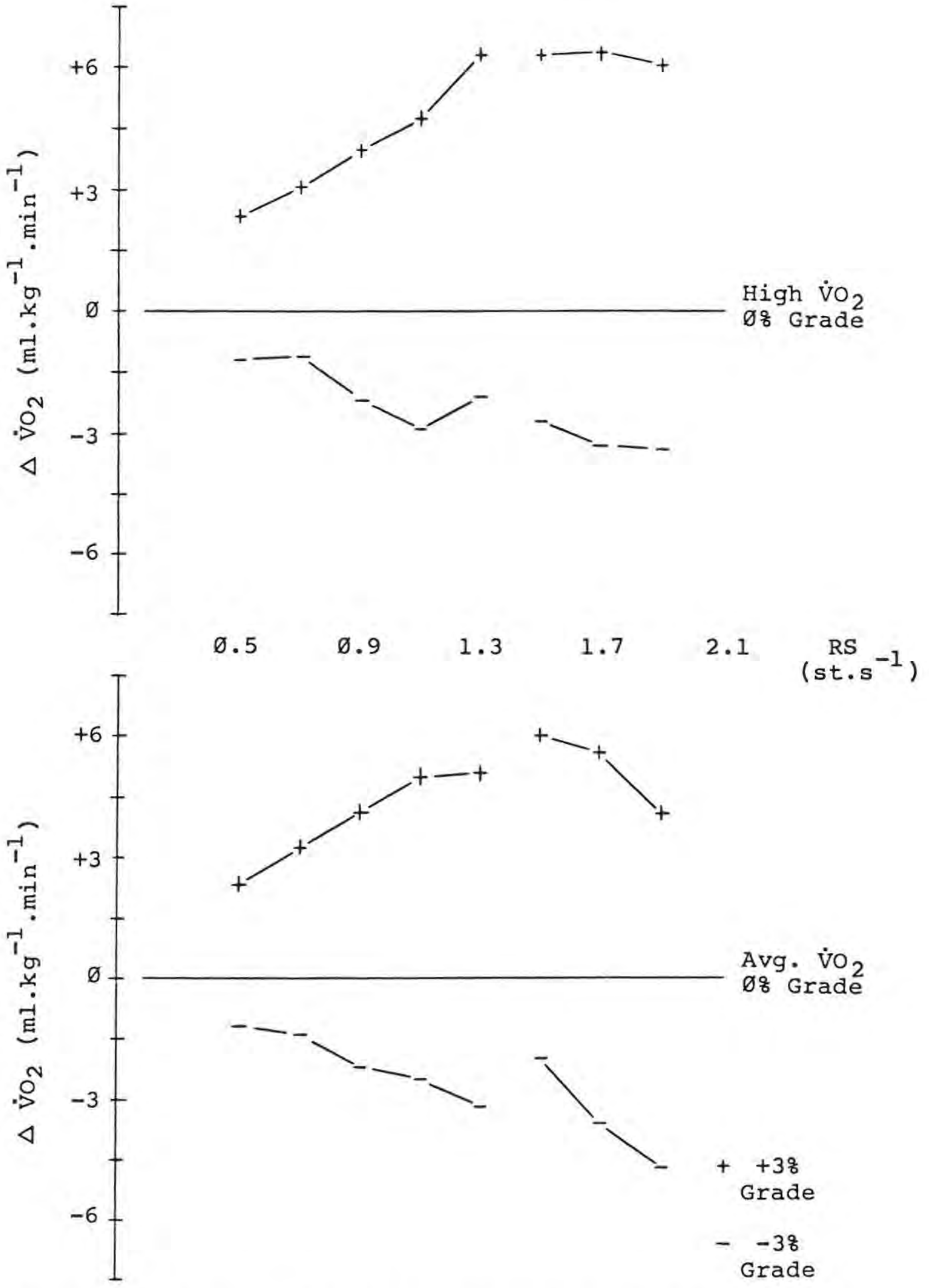


Figure 28 Change in oxygen consumption during grade walking and running at relative speeds in subjects with high and average $\dot{V}O_2$. Data points plotted are differentials from the oxygen consumption observed at 0% grade for that velocity.

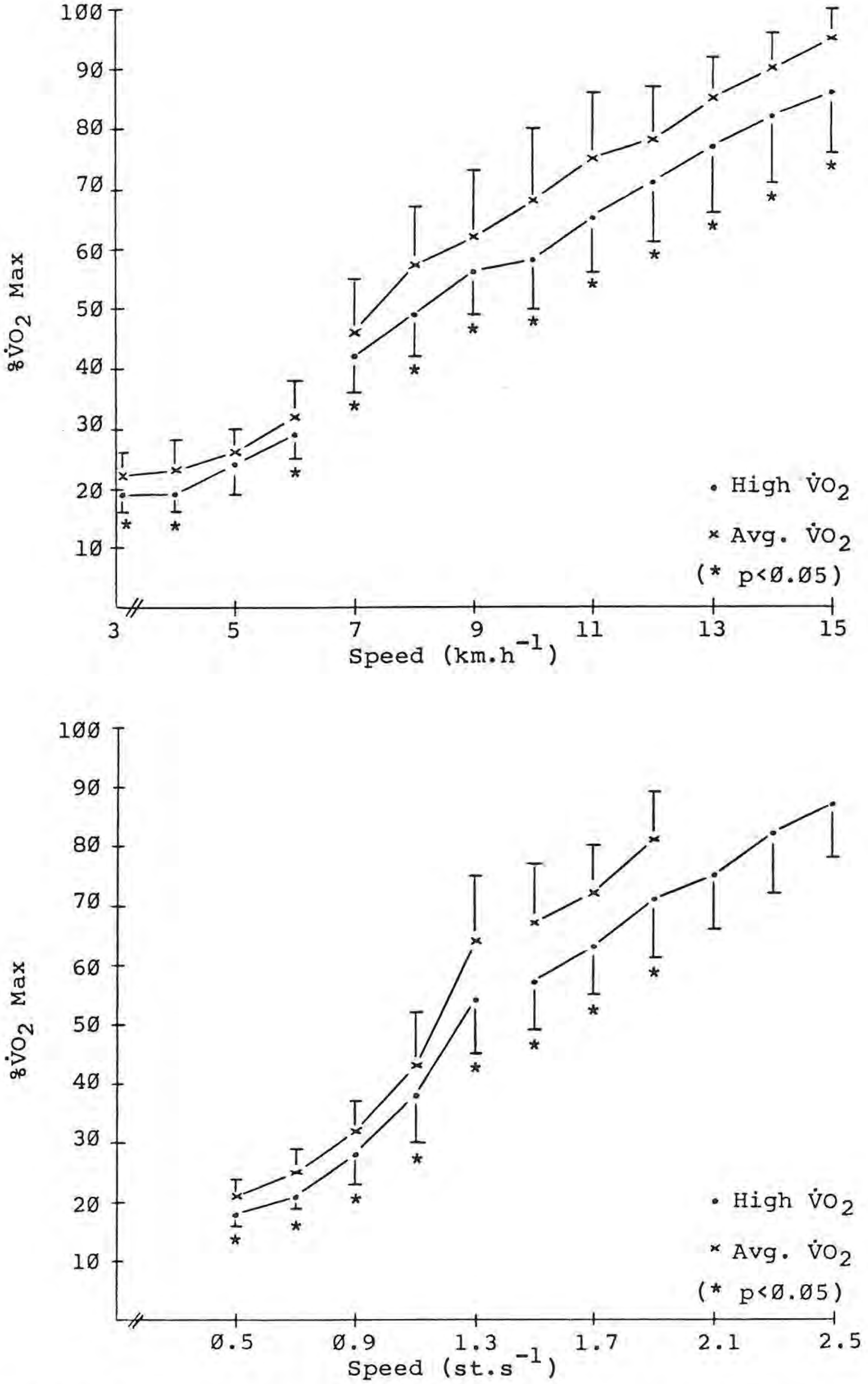


Figure 29 Percent of maximal oxygen consumption versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.

When the stride length (Figure 31, page 193) and cadence (Figure 35, page 197) data were examined, it was clear that the high $\dot{V}O_2$ max group employed a longer stride length and a lower cadence to achieve velocity especially at higher speeds ($p<0.05$). This finding, when viewed in the light of a higher oxygen consumption at the same absolute velocities in the high $\dot{V}O_2$ max group would seem to support the contention, expressed earlier, that longer freely-chosen stride length is more costly of energy (Figure 30, page 192). Burke and Berger (1976) suggested that the increased energy cost associated with over-striding was due to greater hip rotation, an increase in the amount of shoulder movement and a greater vertical displacement of the centre of mass of the body. A lower step length/cadence ratio (Figure 37, page 199) seems to be related to the lower oxygen consumption response. When stride length was expressed in terms relative to stature (Figure 33, page 195) and leg length (Figure 34, page 196), the high and average $\dot{V}O_2$ max groups were essentially the same. The only differences which occurred were at higher velocities, where members of the high $\dot{V}O_2$ max group were "striding-out" relatively more than the average $\dot{V}O_2$ max group ($p<0.05$).

The decreased economy of running with a longer than optimal stride length has been attributed to the increase in vertical oscillation of the centre of gravity of the body (Hogberg 1952a). Nelson and Gregor (1976) found that over a four year training period improvements in performance were paralleled by decreases in stride length. Another possible explanation for the economy of higher cadence gait was provided by Clarke et al (1983). They found that shock absorption (shank deceleration) was reduced by 5 to 10% when cadence was increased by 8 to 11%.

The data in the present study revealed that the average $\dot{V}O_2$ max group had a slightly lower leg length to stature ratio compared with the high $\dot{V}O_2$ max group (insignificantly so). Although Cavanagh and Williams (1982) have indicated that stride length and leg length are unrelated, it is possible that those with shorter legs relative to stature may take shorter strides.

Leg muscle mass is proportional to leg length (Ross and Marfell-Jones 1982). Thus, another consequence of the subjects in the high $\dot{V}O_2$ max group having relatively longer legs would be that a greater percentage of their muscle mass would be located in the lower limbs. This relatively greater active muscle mass involved in locomotion may have contributed to the finding that the high $\dot{V}O_2$ max group consumed more oxygen during locomotion than the average group (Figure 30, page 192).

Examination of the economy and efficiency data (Figures 41, 42, 43 and 44, pages 203 to 206) revealed that the high $\dot{V}O_2$ max group was lower in both economy and efficiency than the average group when evaluated at absolute speeds ($p<0.05$). Weltman and Katch (1976) reported slightly higher efficiency values for a high $\dot{V}O_2$ max group on a bicycle

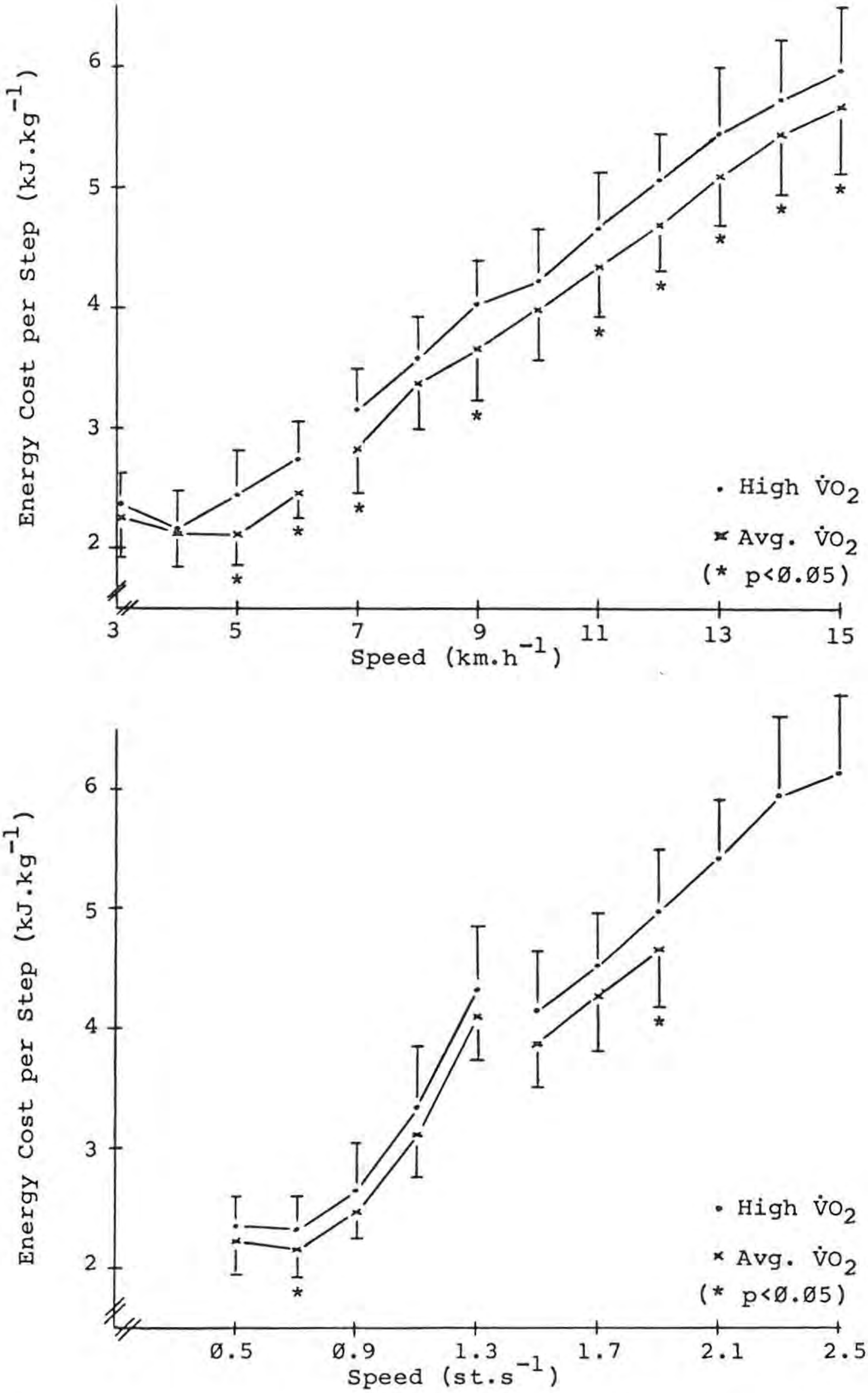
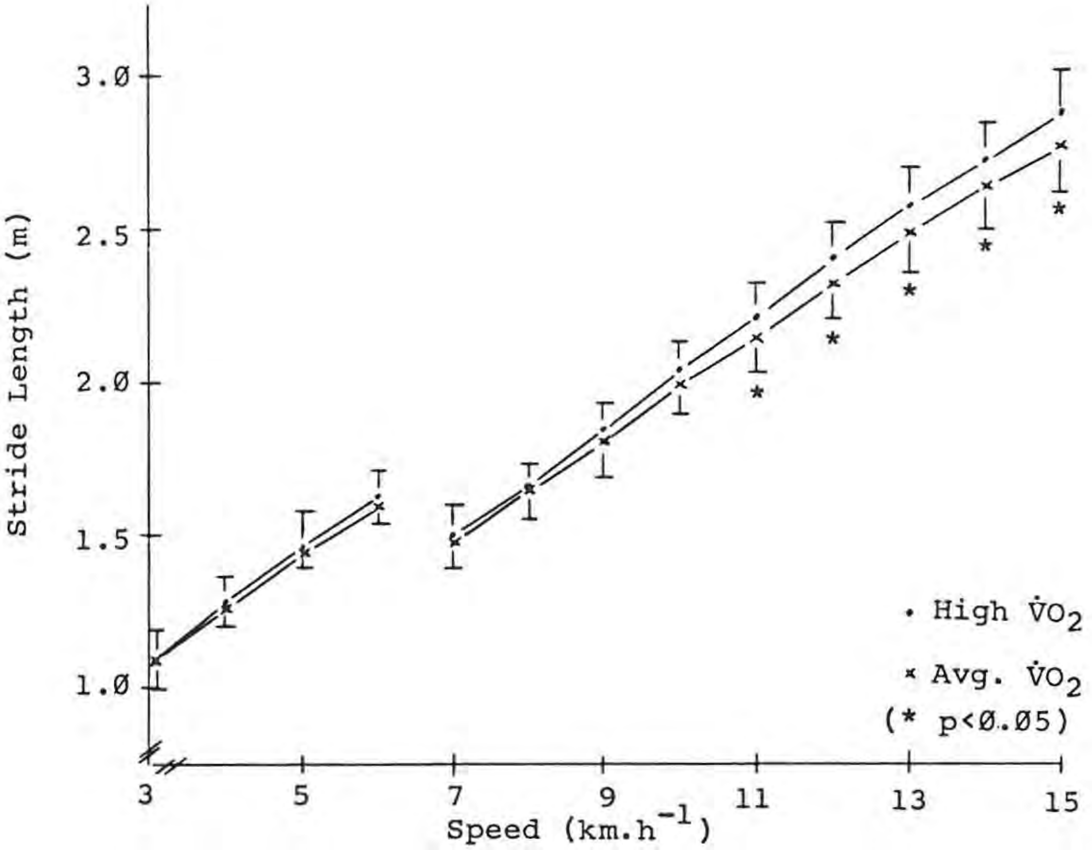


Figure 30 Energy cost per step versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.



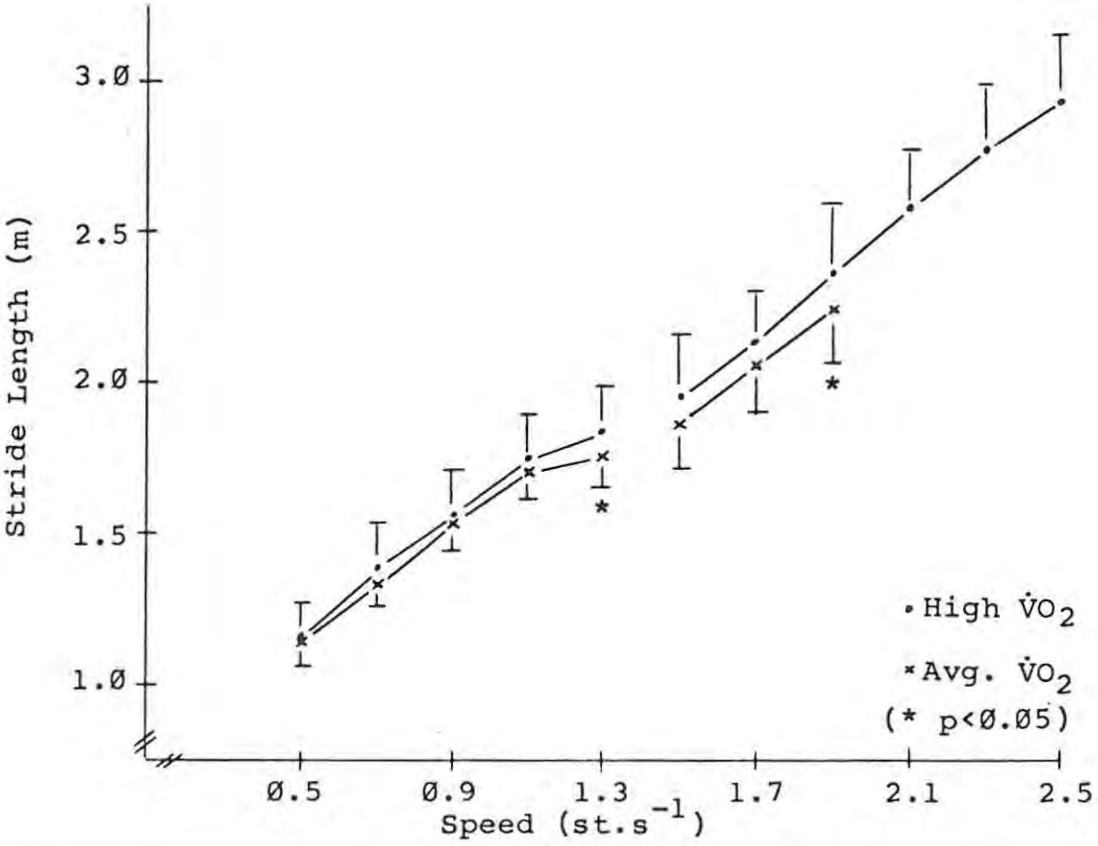


Figure 31 Stride length versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.

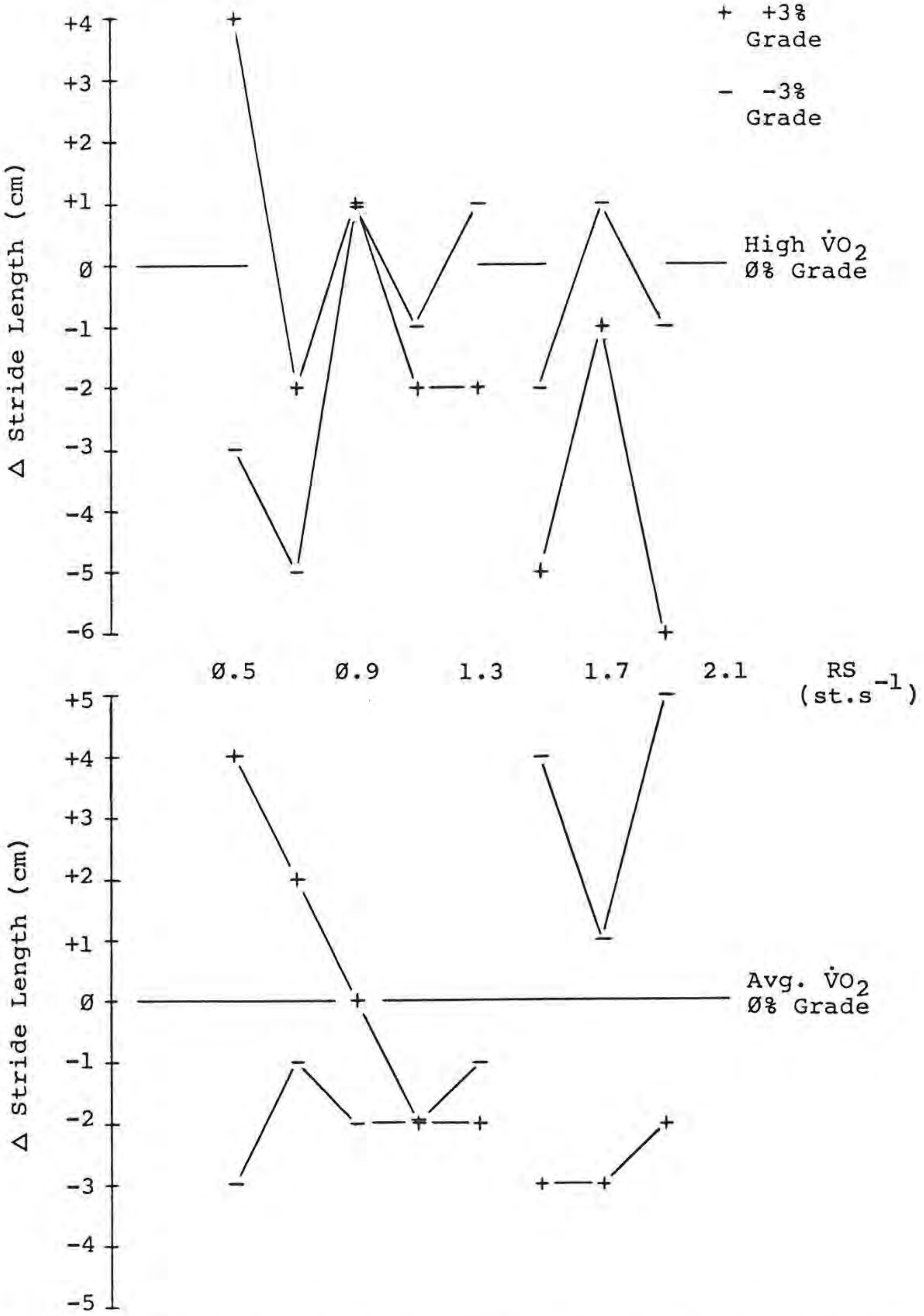


Figure 32 Change in stride length during grade walking and running at relative speeds in subjects with high and average $\dot{V}O_2$. Data points plotted are differentials from the stride length observed at 0% grade for that velocity.

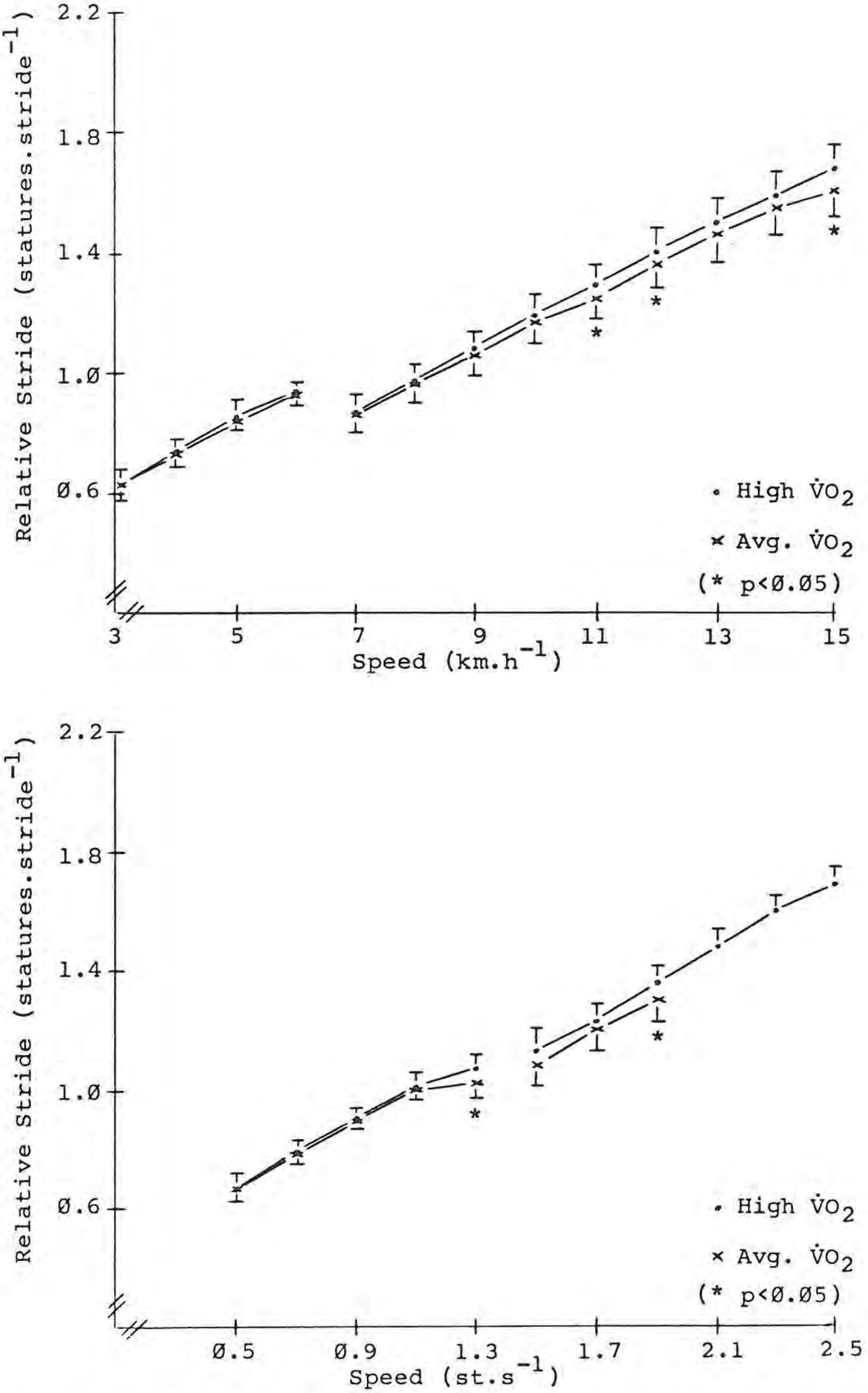


Figure 33 Relative stride (statures per stride) versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.

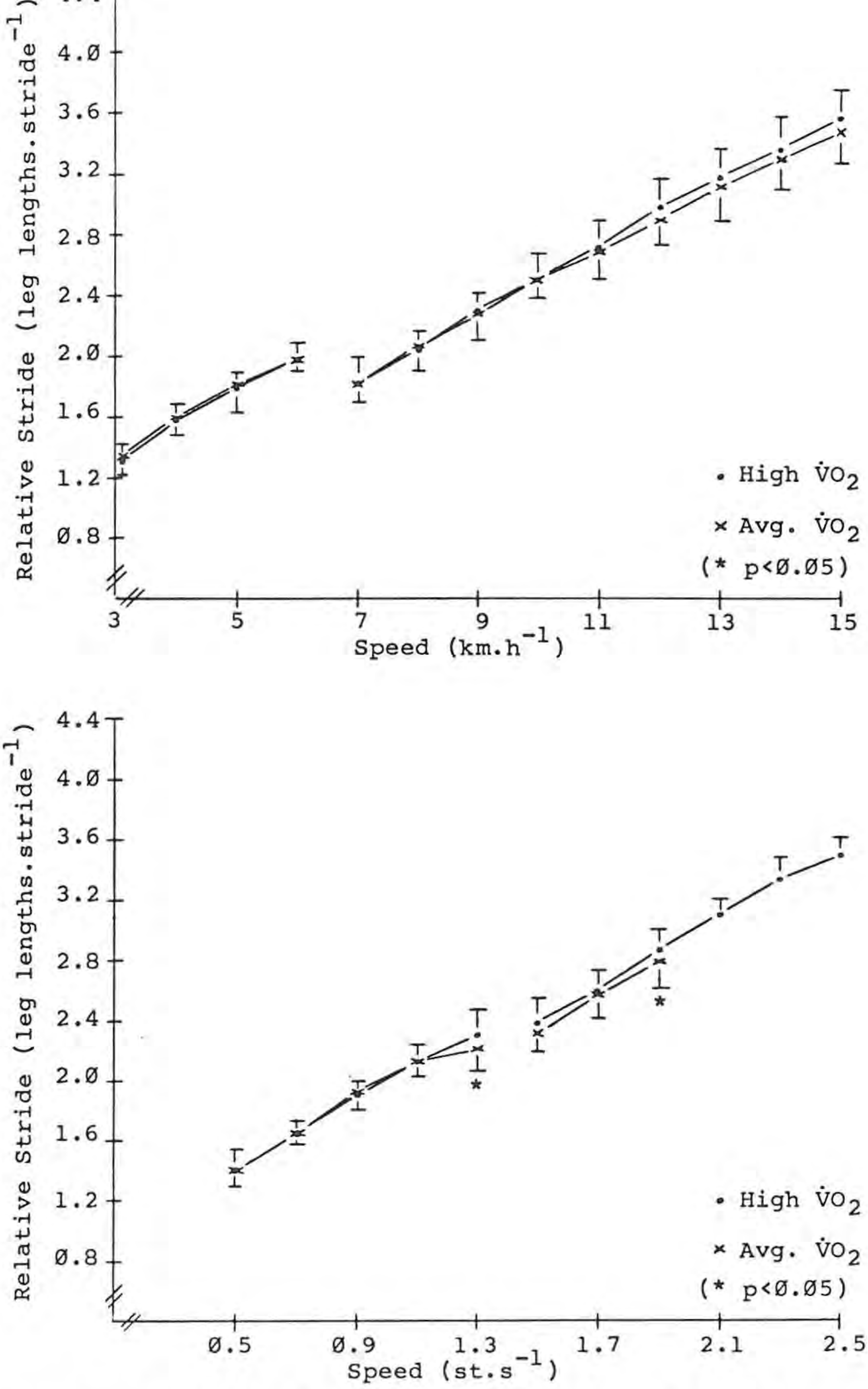
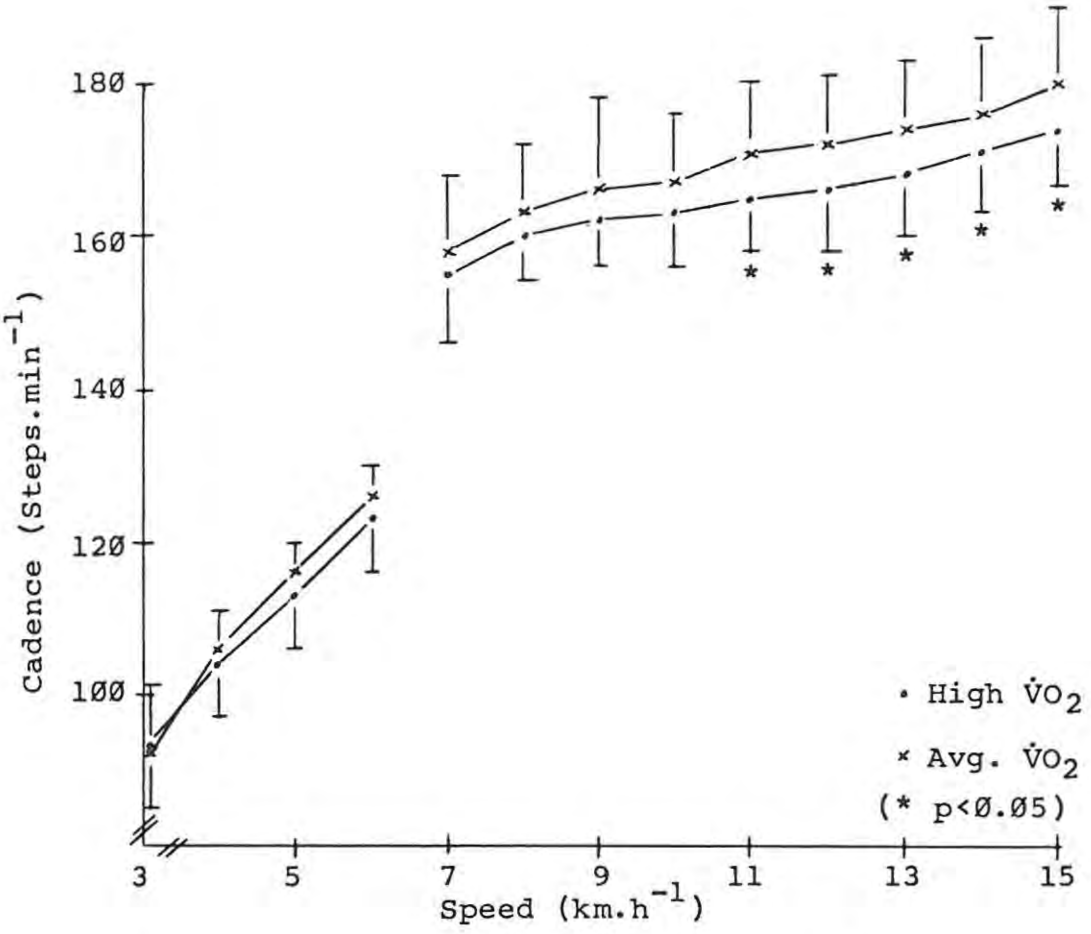


Figure 34 Relative stride (leg lengths per stride) versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.



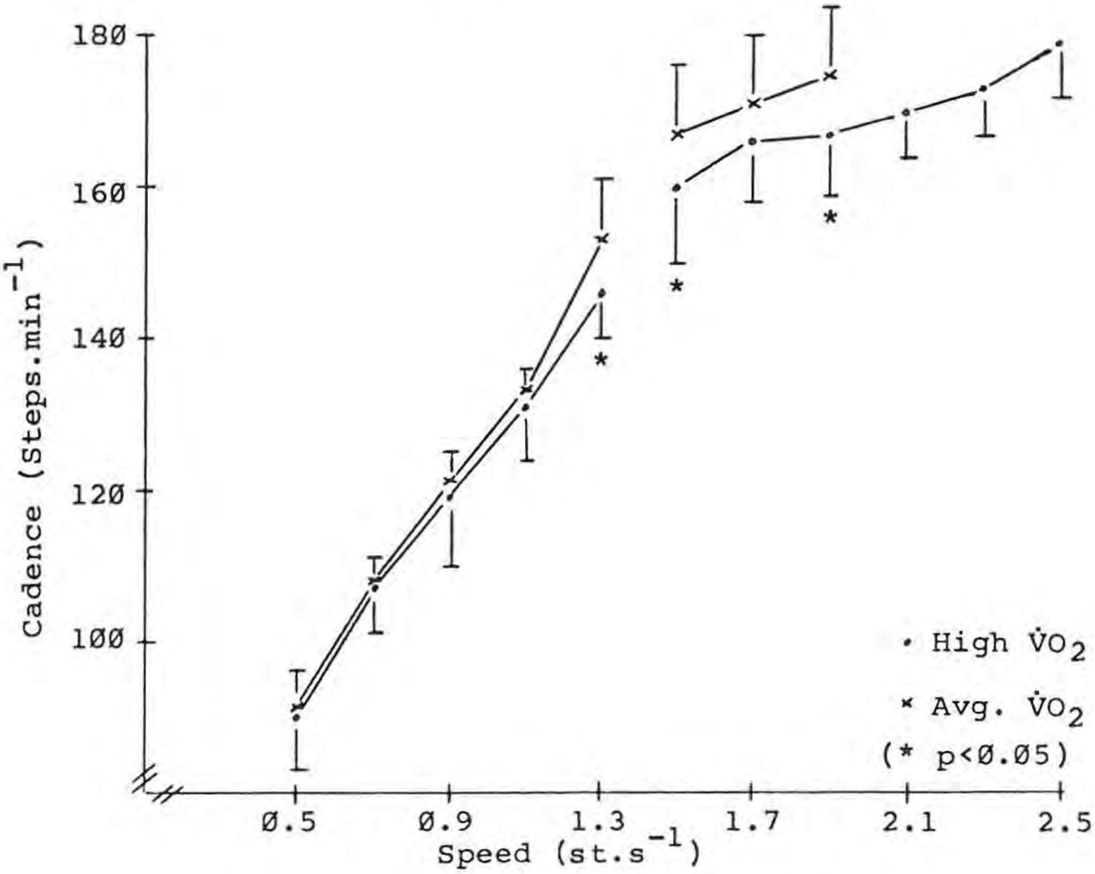


Figure 35 Cadence versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.

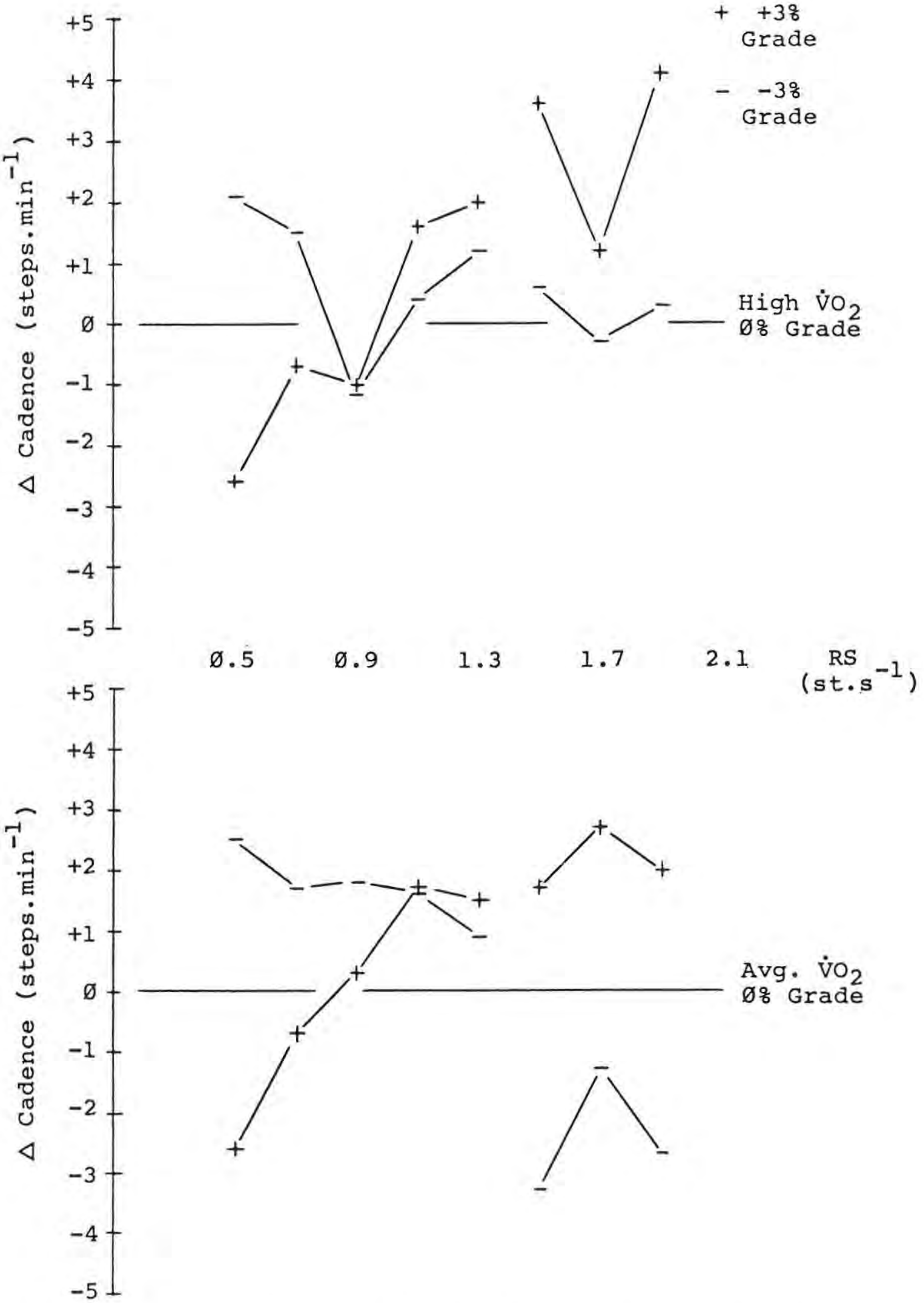


Figure 36 Change in cadence during grade walking and running at relative speeds in subjects with high and average $\dot{V}O_2$. Data points plotted are differentials from the cadence observed at 0% grade for that velocity.

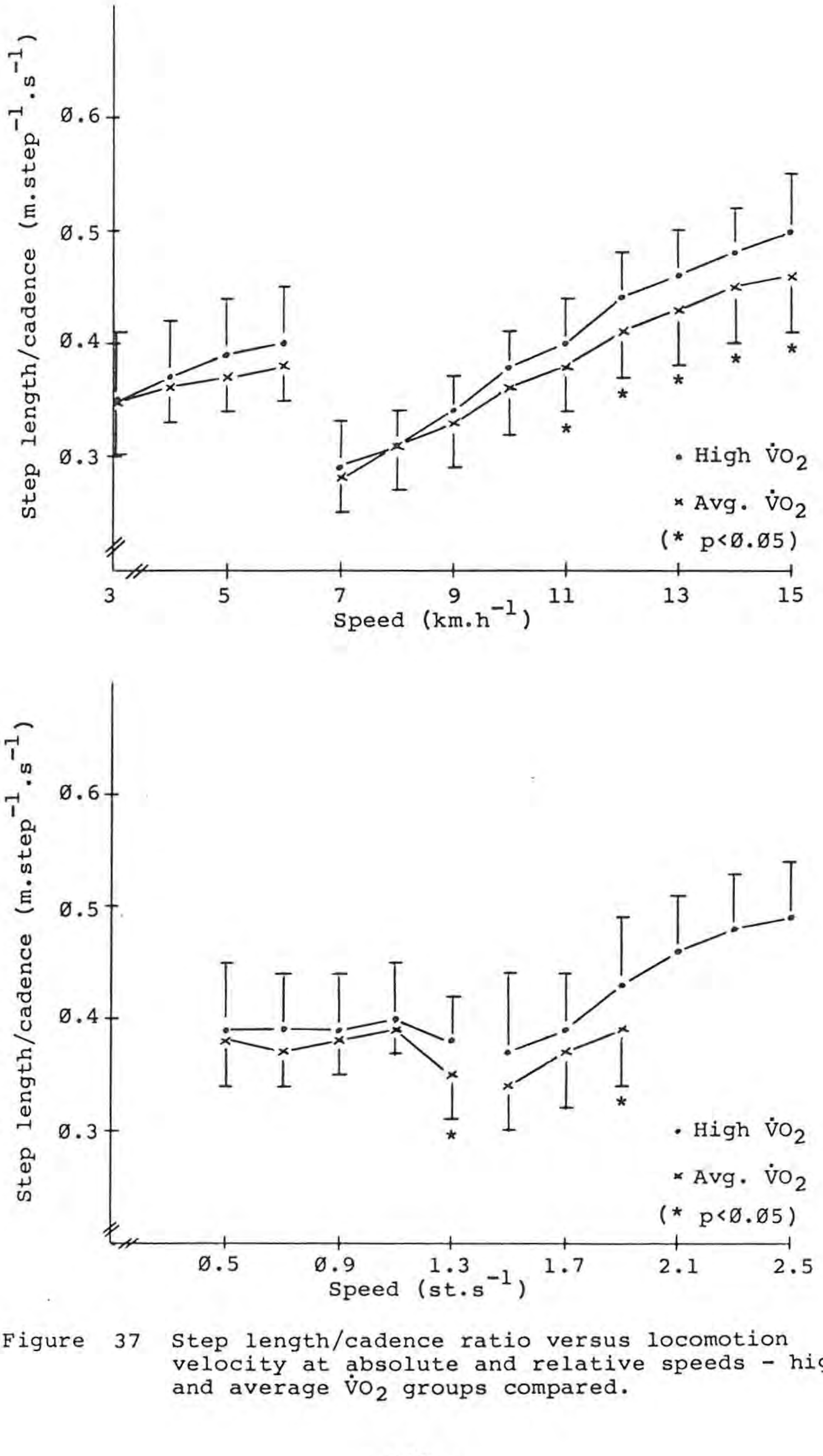


Figure 37 Step length/cadence ratio versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.

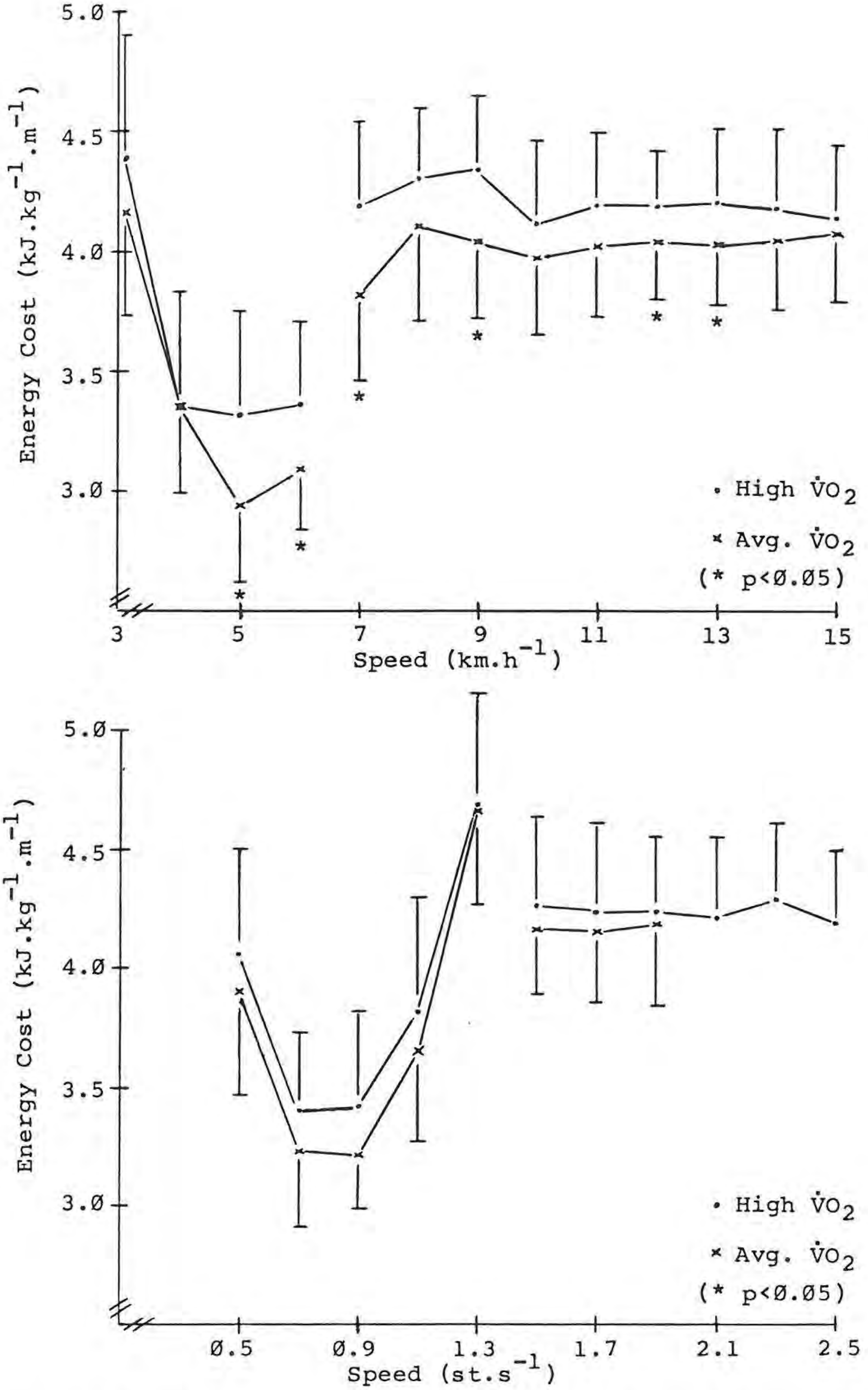


Figure 38 Energy cost per unit distance versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.

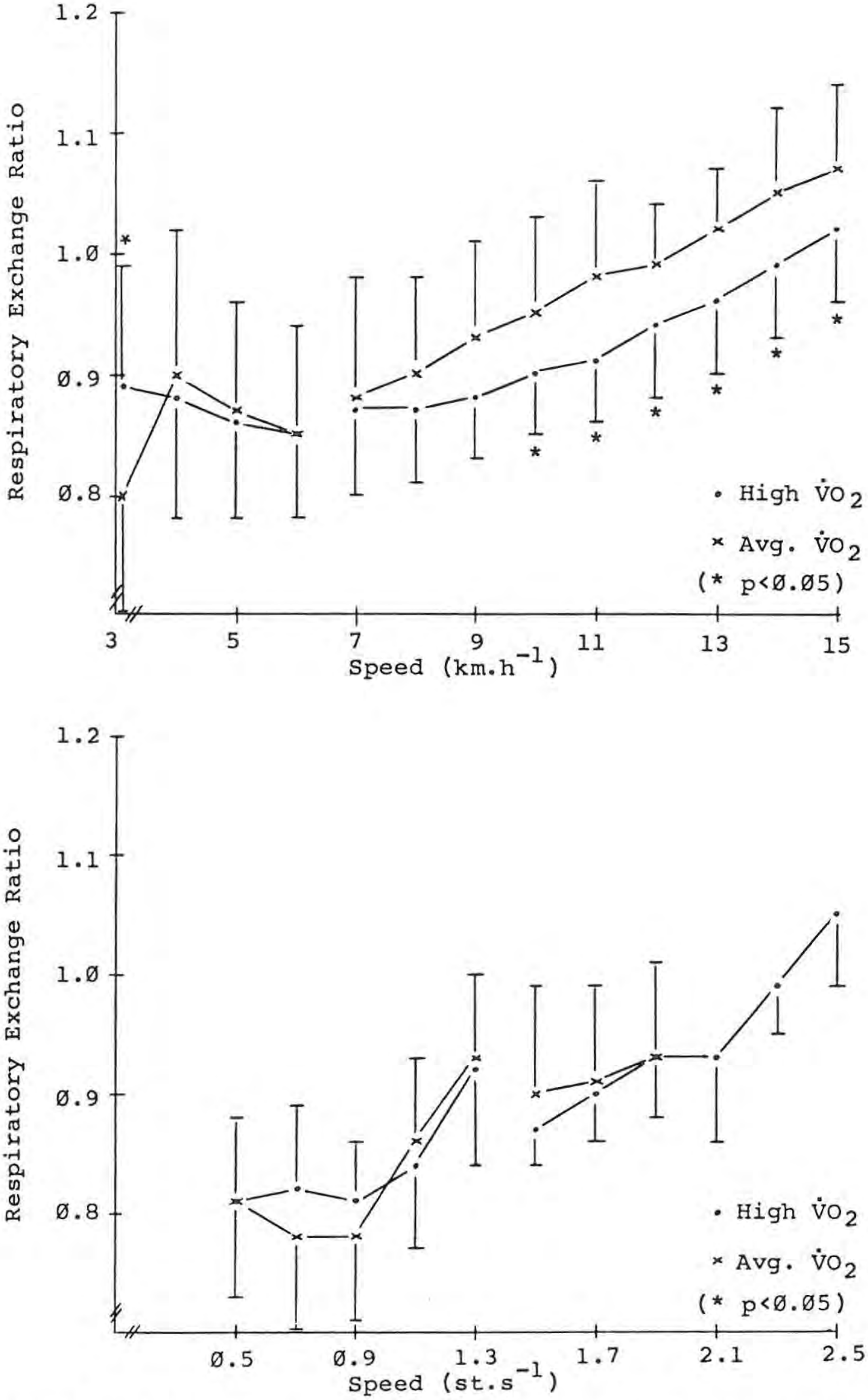
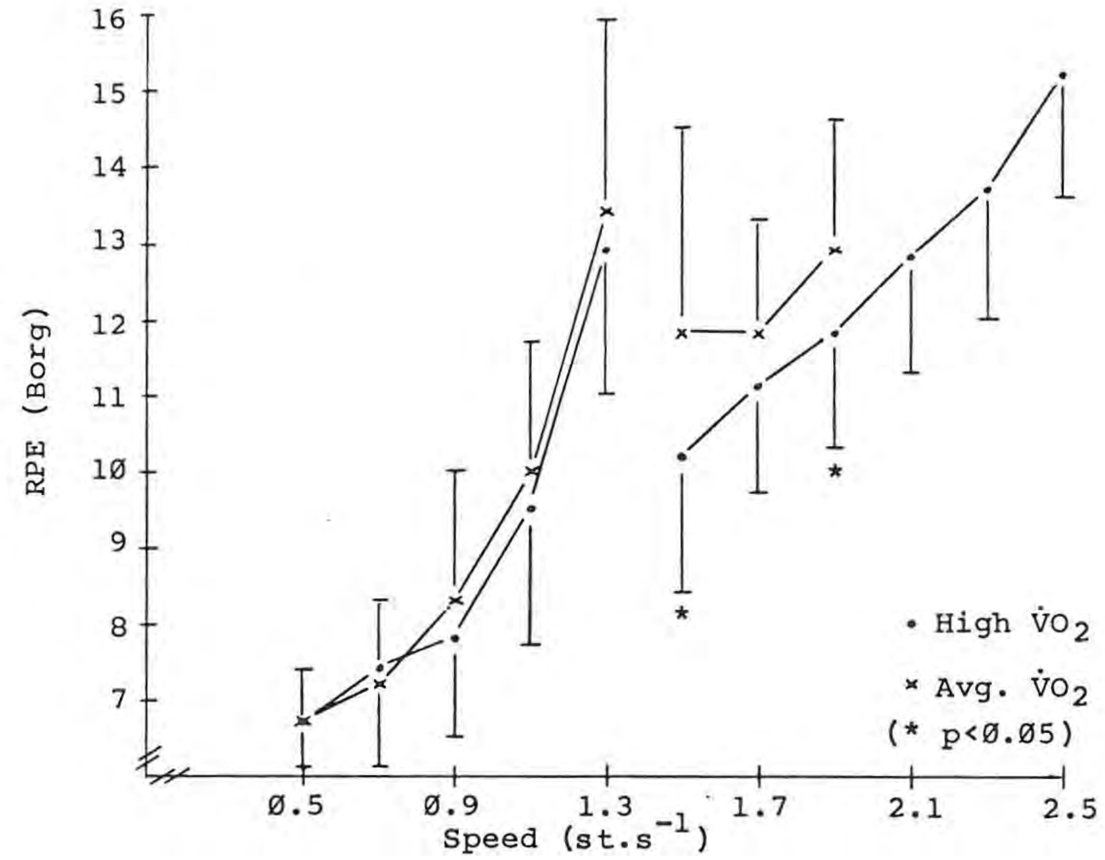


Figure 39 Respiratory exchange ratio versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.



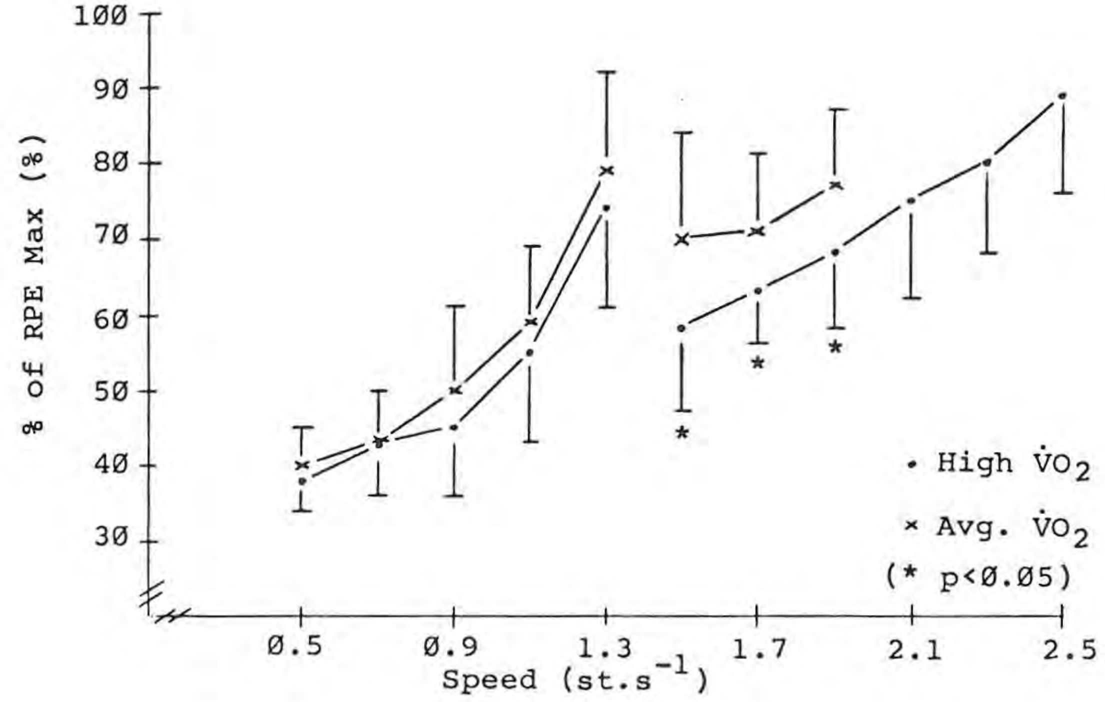
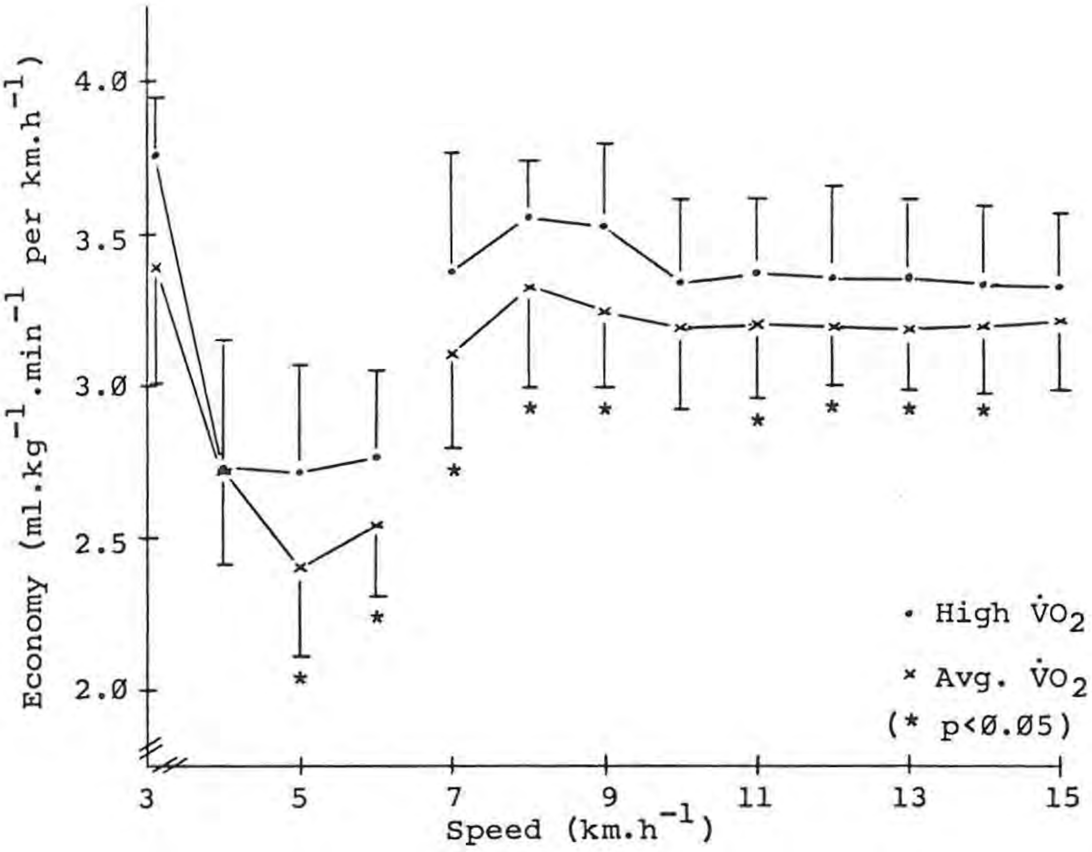


Figure 40 Ratings of perceived exertion versus locomotion velocity at relative speeds - high and average $\dot{V}O_2$ groups compared.



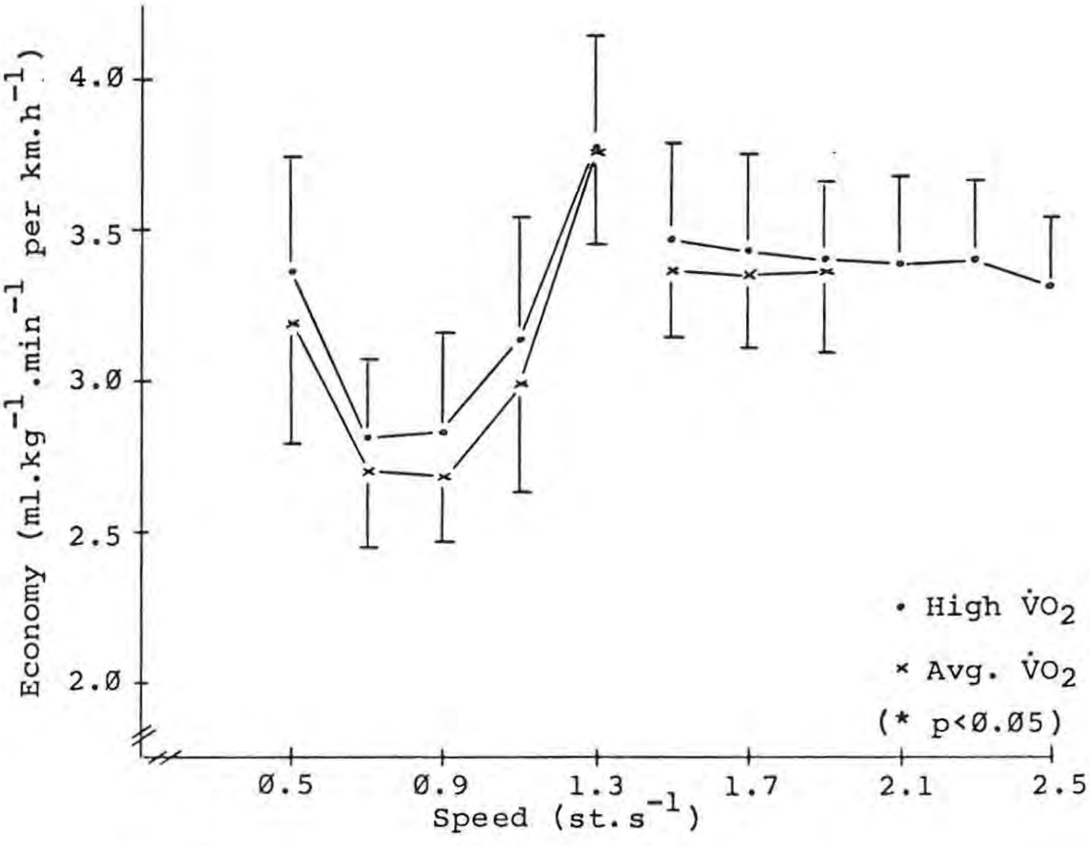
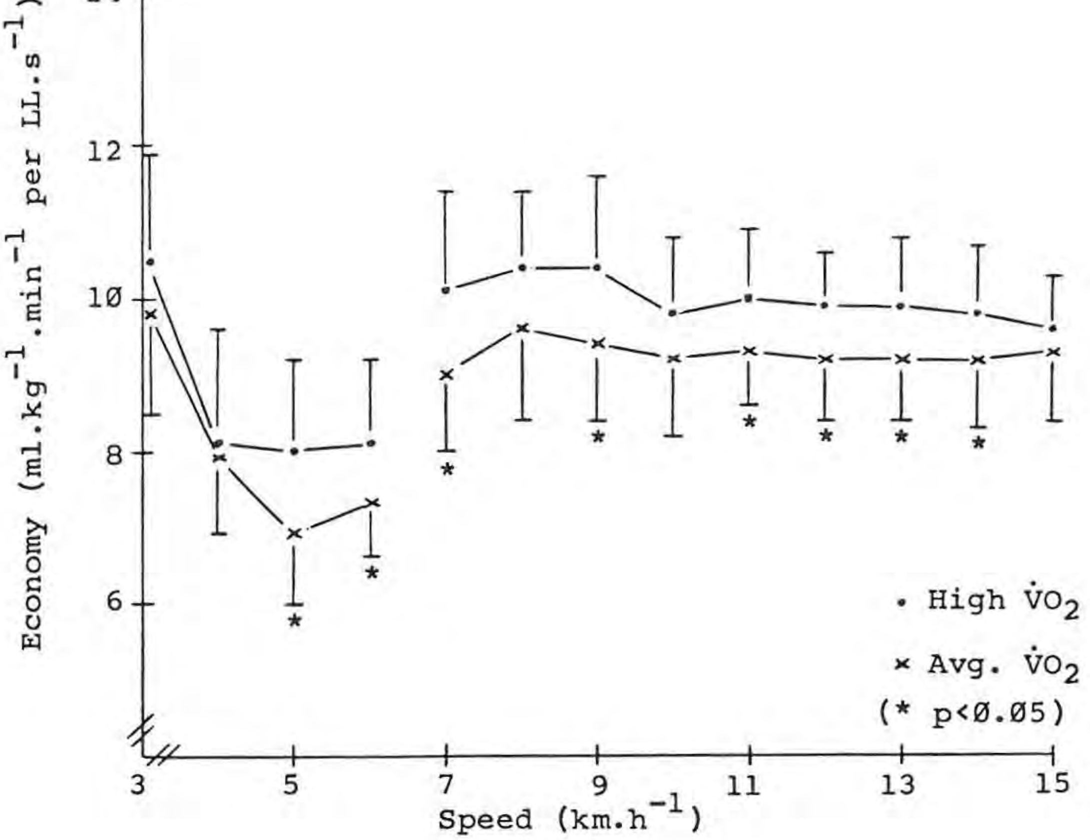


Figure 41 Economy ($\dot{V}O_2$ per km.h$^{-1}$) versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.



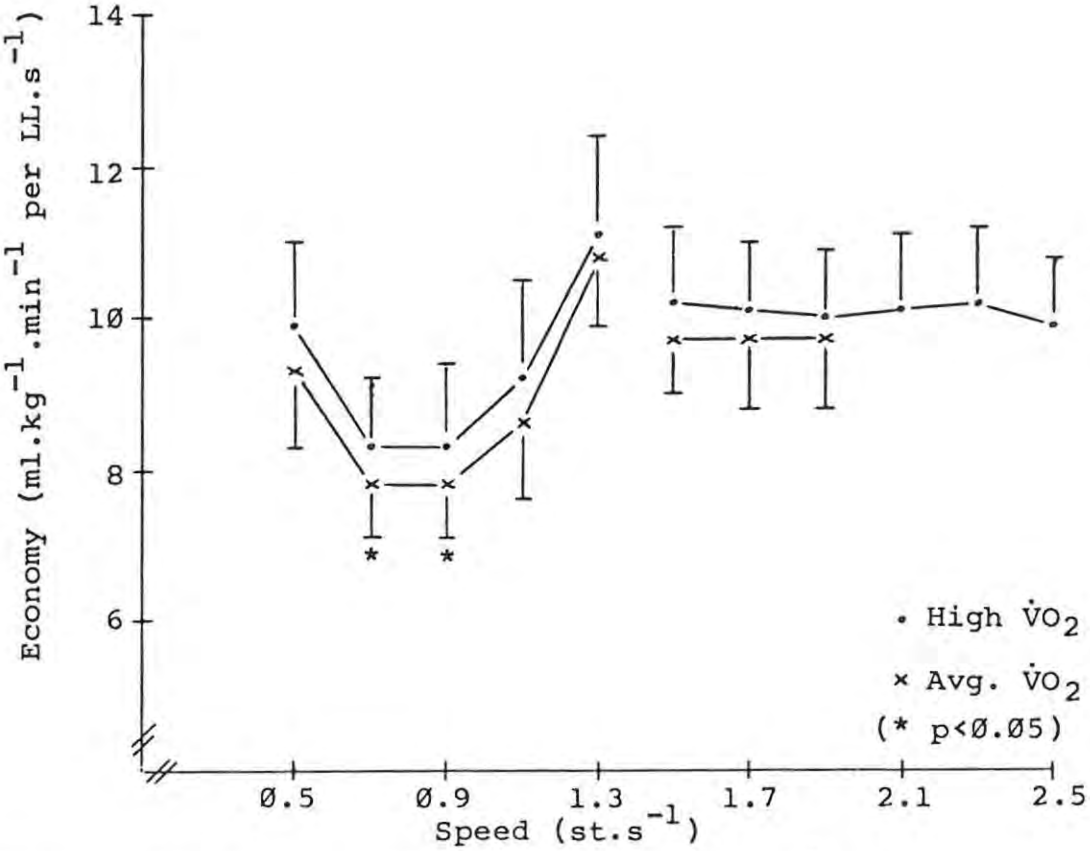
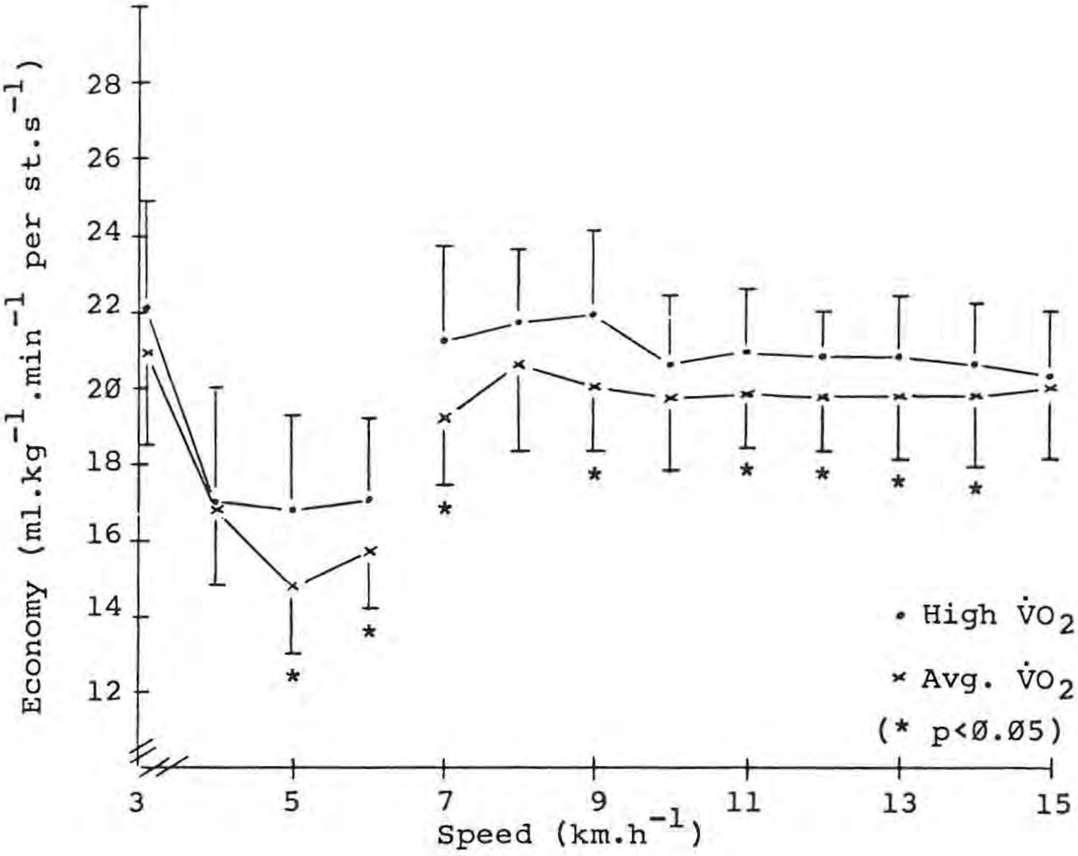


Figure 42 Economy ($\dot{V}O_2$ per leg length.s$^{-1}$) versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.



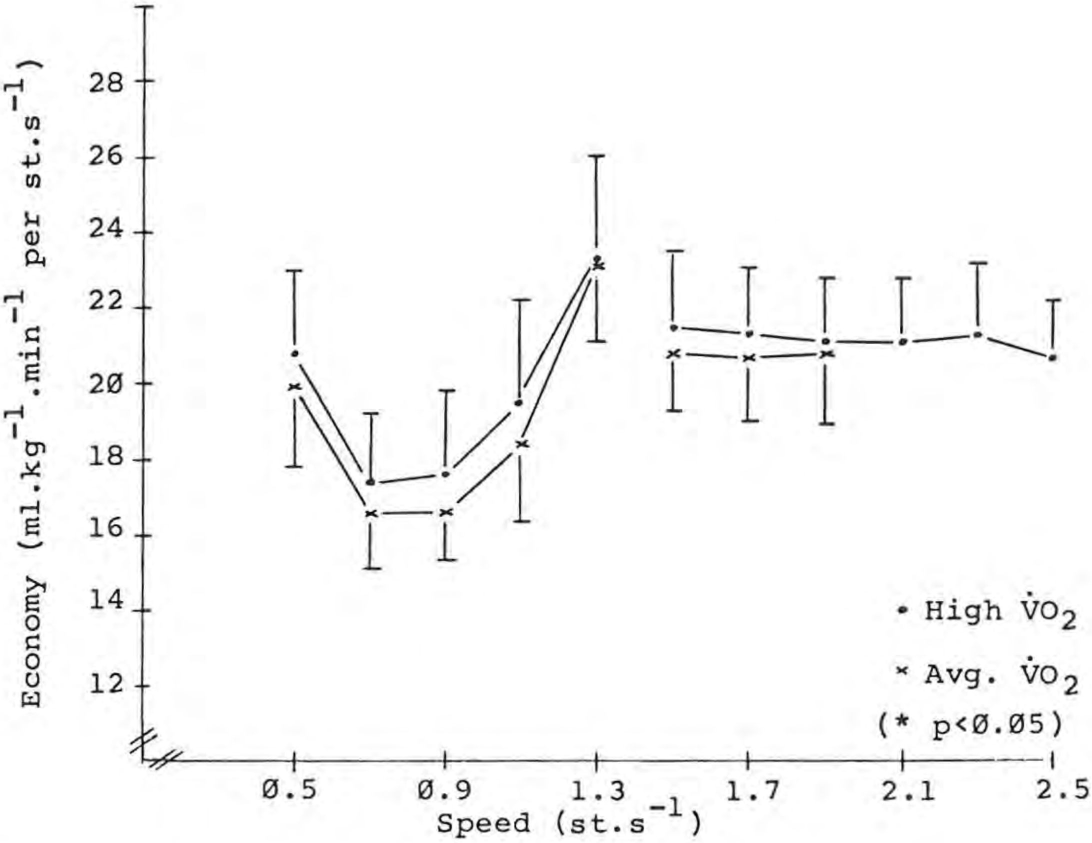


Figure 43 Economy ($\dot{V}O_2$ per st.s$^{-1}$) versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.

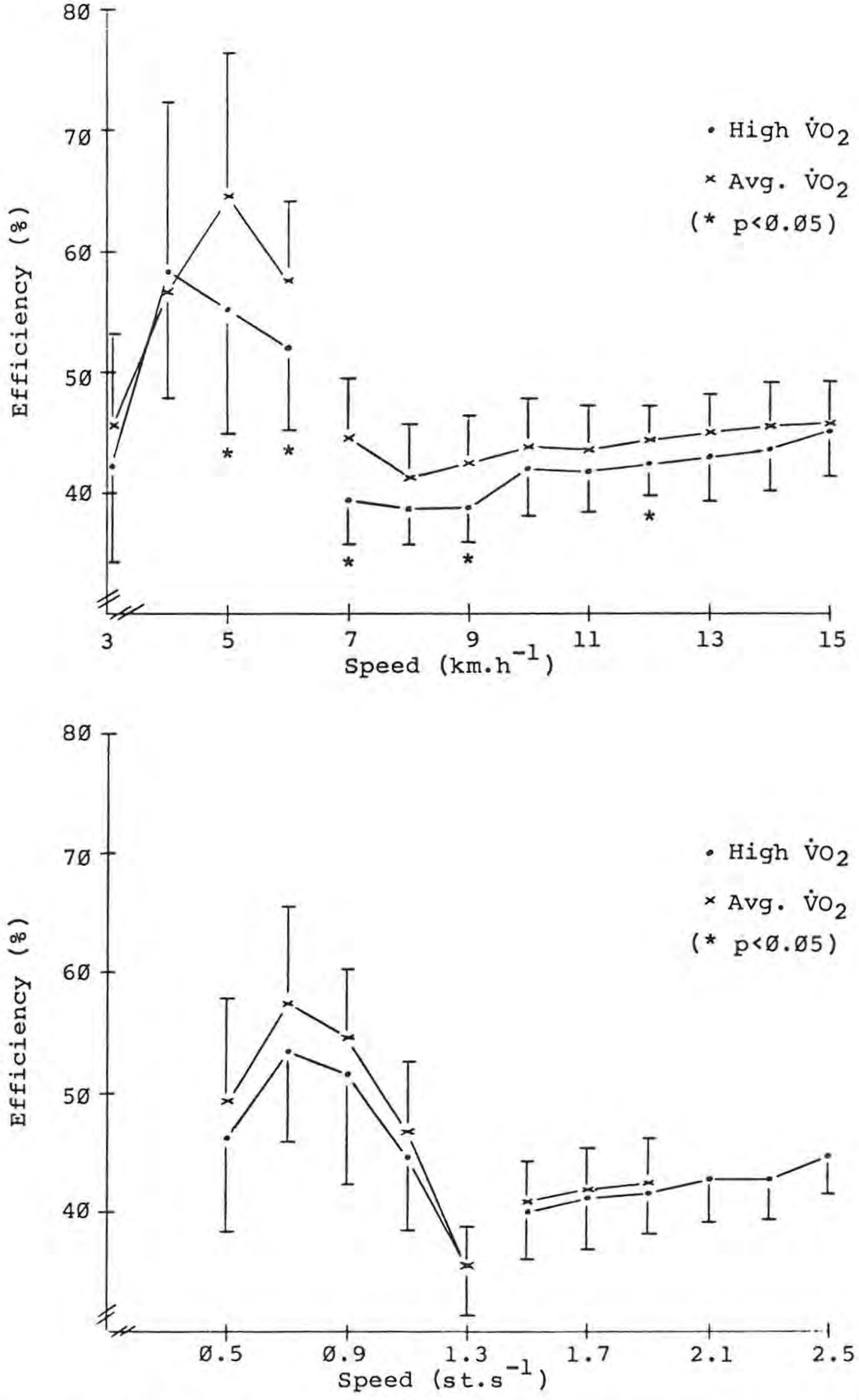


Figure 44 Estimated efficiency versus locomotion velocity at absolute and relative speeds - high and average $\dot{V}O_2$ groups compared.

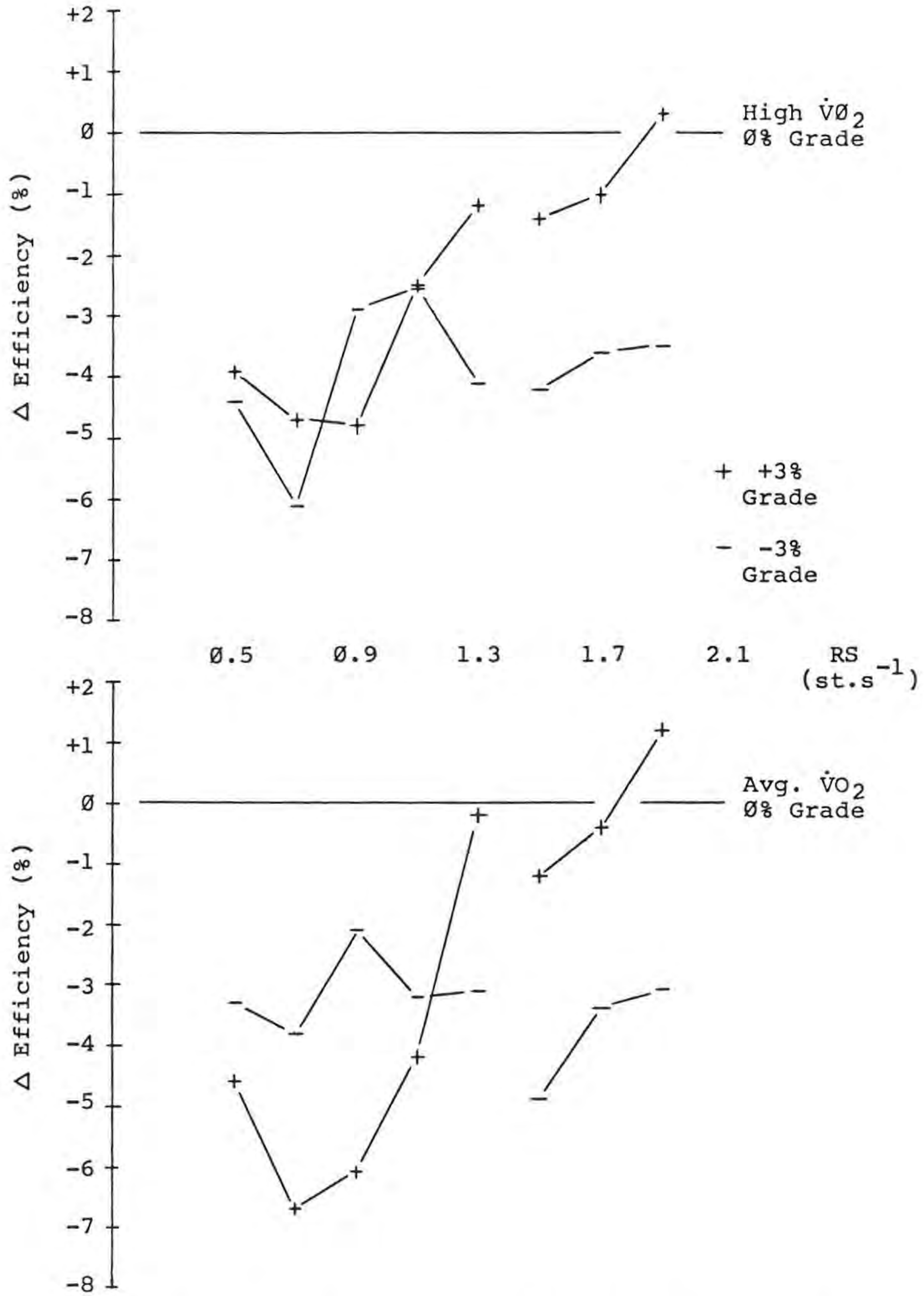


Figure 45 Change in efficiency during grade walking and running at relative speeds in subjects with high and average $\dot{V}O_2$. Data points plotted are differentials from the efficiency observed at 0% grade for that velocity.

ergometer task when compared with an average $\dot{V}O_2$ max group. This was the case despite approximately equal submaximal oxygen consumptions. Mayhew (1977), on the other hand, found that amongst a group of trained runners, those with the higher $\dot{V}O_2$ max were less efficient.

The two $\dot{V}O_2$ max groups had similar locomotion economy and efficiency during tests at various relative speeds. The oxygen consumption, economy and efficiency data taken together imply that the use of relative speed may even out differences between mixed groups of subjects of approximately equal average stature, but moderate variation in stature. In other words, individual differences, within these groups, in oxygen consumption per unit of velocity may be minimized through setting velocity relative to stature.

## THE COMPLEXITY OF LOCOMOTION

The central focus of this dissertation is the simple act of moving from place to place - human upright bipedal locomotion. Locomotion is described as a "simple act" purely because most people, having learned to walk and run, relegate the motor programmes involved to lower levels of consciousness as they go about their daily tasks. Human locomotion, however, is far from simple, with a myriad of factors of a biochemical, biomechanical, psychological and physiological nature interacting constantly to produce action (Williams 1985). What makes locomotor actions efficient and/or economical has been the subject of scrutiny for a number of years (Hill 1922, Ogasawara 1934, Cavanagh and Kram 1985a). It is unfortunate that the topic has not often been approached in a multidisciplinary fashion. The result has been that "scientists in each of the subdisciplines have traditionally ascribed the reasons for variation in 'efficiency' to another subdiscipline" (Cavanagh and Kram 1985a).

The present study attempted to integrate overt mechanical features of locomotion with the perception of exertion, the physiological responses and the resultant economy and efficiency while standardizing the velocity of locomotion for a significant measure of morphology - stature. It is deemed appropriate, at this point, without a reiteration of the entire review of literature, to relate the major trends in this study to selected key findings. Furthermore, a brief summary of important factors related to economy and efficiency is indicated as the plethora of information on this topic defies easy synthesis.

Males and females in this study did not differ in stride length, cadence, oxygen consumption, economy or efficiency in response to progressive increases in absolute velocity. This was surprising as a number of studies have indicated that females generally move with a smaller stride length and higher cadence than men at the same velocity (Booyens and Keatinge 1957, Falls and Humphrey 1976). The women in the present study were found to have a "masculine" leg length/stature ratio even though absolute leg length was within the normal female range (Ross and Marfell-Jones 1982). The present female subjects were comparable to sportswomen in this regard (Hebbelinck et al 1981). As it has been reported (Nunneley 1978, Pate and Kriska 1984) that the 'average' young adult, Western World female is more sedentary than her male counterpart, the relatively vigorous nature of the experimental protocol used in the present study may have encouraged an atypically active group of females to volunteer for this study. All of these factors may have contributed to the lack of difference between males and females at absolute speeds.

At speeds set relative to stature males demonstrated a higher oxygen consumption response coupled with a greater stride length. The men, being taller, were moving at higher velocities. The differences in velocity, oxygen consumption and stride length between males and females were essentially the same (6%) implying that relative speed did not factor out individual differences between the sexes.

The comparison of high $\dot{V}O_2$ max subjects to those of average $\dot{V}O_2$ max revealed that the "high" subjects had a greater stride length and submaximal oxygen consumption response to the absolute speed test which led to reduced economy. This is consistent with Mayhew's (1977) findings and supports his suggestion that those with a higher maximal oxygen consumption can afford to be less economical as they have greater aerobic reserve. When "high" and "average" groups were compared at relative speeds these differences in stride length and oxygen consumption largely disappeared. This would tend to support the suggestion (Grieve and Gear 1966) that the use of relative speed minimizes inter-subject variability; the finding that the coefficient of variation in economy was the same whether absolute or relative speed was employed notwithstanding. That male-female grouping comparisons do not support this trend may be a function of other structural differences previously alluded to, such as percentage body fat and the equivalence of $\dot{V}O_2$ (per kg LBM) at relative speeds, femoral convergence, or differential distribution of body mass on the limbs (Cavanagh and Kram 1985b).

Many investigators have referred to the "optimal phenomena" in evaluations of the energy cost of locomotion identifying that at specific, individually-determined combinations of cadence and stride length economy is maximized (Cavanagh and Williams 1982). Most of this work, however, has involved experimental manipulation of cadence at specific velocities. Cavanagh et al (1977) simply measured stride length in 'elite' and 'good' runners, and Pollock (1977) measured their submaximal $\dot{V}O_2$. They found that the 'good' runners had a longer stride length, and a higher submaximal oxygen consumption response. In an indirect fashion, as in the present study, the implication was that a longer stride length, despite it being 'freely chosen', was less economical. The present findings of higher stride length associated with lower economy, and slight negative correlations between cadence and $\dot{V}O_2$ would support this view.

It is Daniels' opinion (Daniels 1985) that the term efficiency should not be used to relate the energy demands of running to the velocity of running, as horizontal movement is the result of only part of the work being done by the body during movement from one place to another. It is for this reason that he feels running economy is a term more applicable to the relationship between running velocity and energy expenditure. While correct in an absolute sense, this approach leads to semantic and logical difficulties. Consider the situation of two runners equal in economy, one of whom performs more work in the vertical oscillations of the centre of gravity and limb rotation during running. This runner would be more efficient even though the extra work performed did not contribute to the prime task of locomotion - that of moving the body mass from place to place. Economy and efficiency should, in logic, provide the same assessment of locomotor capability. Perhaps the solution to this dilemma would be to calculate the efficiency of locomotion using only the work done to provide kinetic energy (and change in potential energy if on a grade) in the numerator. In this fashion, the work of alternately raising and lowering the centre of mass, and of rotating limbs, would be removed from the numerator of the efficiency calculation but not the denominator. This work is considered irrelevant to locomotion's prime function in that it is entirely possible to perform more work in raising and lowering the centre of gravity, and in limb rotation, without affecting locomotion velocity. The energy cost of such actions, however, must be taken into account if one is to have a valid assessment of the effectiveness of performance. Both efficiency and economy of locomotion should be equally reflective of locomotor effectiveness.

Efficiency and economy are influenced by a great number of factors. "Baseline subtractions" in the denominator of the efficiency calculation, performed in attempts to relate the changes in mechanical energy to the associated changes in metabolism, do not have universal support. While the work done by the centre of mass has been used a great deal in the past as a measure of total body energy output, this method has been criticized. More recent investigations have relied on the segmental analysis approach in which the "internal" work performed to change the energy levels of the limb segments has been included. While, in logic, the segmental approach is inherently more valid, it is complicated by the fact that there are a number of computational schemes which can be employed to sum the energy changes from the segments. Winter's (1979a) approach enjoys the greatest support and accounts for transfer of energy both within- and between-segments.

Assumptions regarding the relative contributions of positive and negative work, the amount and nature of between- and within-segment energy transfer, the storage of elastic energy during eccentric loading and the influence of muscle and joint frictional characteristics influence the calculation of power output (Williams and Cavanagh 1983). Muscle dynamics, especially the length-tension and force-velocity relationships (Hill 1922), and muscle fibre composition influence performance.

While various equations exist to predict oxygen uptake from movement velocity (Van der Walt and Wyndham 1973), reliance on these values disguises the considerable inter-subject variation in economy. It has been suggested that variations in economy are a function of age, temperature, fatigue, aerobic-anaerobic metabolism interaction, stride length and training (Daniels 1985). Variability between individuals of the same body size in the distance of the insertions of key muscles from joint centres, the relative distribution of body mass on limb segments and aspects of muscle architecture such as fibre orientation or length could also influence economy (Cavanagh and Kram 1985b). Footwear and the energy stored in, and returned from, the running surface have been implicated in economy (Williams 1985).

To conclude this discussion, the following quotation makes it abundantly clear that the multi-disciplinary nature of the problem of reconcilling locomotor power output, efficiency and economy demands the balanced holistic approach of a human movement specialist.

> "A better understanding of the complex interactions involved in measuring mechanical power and efficiency might best be obtained using a multidisciplinary approach. Biomechanists often devote a great deal of time and energy to precise collection and intricate manipulation of kinematic and kinetic data to yield a sophisticated model for the measure of mechanical power. Once the complicated mechanical measures are obtained, it is usually assumed that a simple

measure of oxygen consumption is all that is necessary to delineate the associated metabolic energy expenditure. Physiologists, on the other hand, argue the finer points of the energetics of metabolism and arrive at sophisticated models to account for the subtle interactions of aerobic and anaerobic metabolism under different conditions. Once these interactions are quantified, they typically assume that a simple mechanical measure, such as the external work done on a cycle ergometer, is all that is necessary to quantify the mechanical power generated. Both groups tend to underestimate the complexity of the problem when it is approached from the other discipline. A concerted effort should be made by biomechanists and physiologists to work more closely together in order to more completely explore the fundamental relationships between movement and associated energy costs."

(Williams 1985)

# CHAPTER V

## SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A number of investigators have evaluated the relationship between locomotor velocity and energy expenditure in Man. One consistent finding has been the substantial variability between individuals in this relationship. Some reports have implicated linear dimensions of body morphology as being a contributing factor. None, however, has standardized locomotor velocity for a significant aspect of morphology in an attempt to probe the etiology of this variability in Man. Taking a multi-disciplinary, integrated approach, this study explored variability in human locomotor economy and efficiency in subjects moving at velocities set relative to body stature.

### HYPOTHESES

It was hypothesized that:

1) The economy of locomotion is a linear function of relative speed ($st.s^{-1}$).

2) The inter-subject variability in oxygen consumption at absolute and relative velocities is equal.

3) The economy of locomotion in males and females is equal.

4) The economy of locomotion in those with high and those with average maximal aerobic capacity is equal.

## SUMMARY OF PROCEDURES

In order to facilitate reliable and rapid data collection in this study an on-line, computer-aided data acquisition system was developed. Standard laboratory oxygen and carbon dioxide analysers, drawing air continuously from an expired air mixing chamber, along with an inspired volumeter were interfaced with a micro-computer. By means of continuous sampling, and appropriate time-unit based software, the system enabled the collection of metabolic and respiratory data in response to locomotor effort on a motorized treadmill. Precise control, and display, of treadmill velocity was facilitated through the on-line computer. Necessities regarding the quantity and consistency of data collected, the sequencing of samples and the precise speed control made the on-line system indispensable to the present protocol.

Data collected using the on-line system was validated, both for steady-state and unsteady-state response, against the standard technique of Douglas bag collections. Ten well-trained long distance runners were tested on two occasions, a week apart, in random order. One test was conducted using the bag system and the other with the on-line system. Each time, the subject ran for 5 min at 8 $km.h^{-1}$, followed by 1 $km.h^{-1}$ increases per min until 17 $km.h^{-1}$, followed by 2.5% grade increases per min until exhaustion. Oxygen consumption was measured and compared at various submaximal velocities, and at maximum effort.

The results obtained using the on-line computer-aided data acquisition system were comparable to those obtained by standard Douglas bag methods. The overall mean difference between the two systems in $\dot{V}O_2$ was only 1.2%. The on-line system was found to be reliable for assessment of both sub-maximal and maximal exercise responses (Figures 2 to 4, pages 107 to 109).

Male (n = 2) and female (n = 2) subjects participated in a pilot testing protocol designed to evaluate the reliability of procedures used in this study. Foot length, stature, body mass, sitting height and four skinfold fat measurements were obtained on five occasions. The subjects performed eight treadmill walks and runs: at relative speeds of 0.5, 1.1, 1.5 and 1.9 $st.s^{-1}$ on 0% and +3% grade. The on-line system was used to evaluate respiratory and metabolic response, and the subjects were brought to within 10 bpm of initial rest heart rate between each effort. Each session was 4 min in duration with three 30 s samples of $\dot{V}O_2$ taken between 2.5 min and 4 min. All eight conditions were completed in one test period. This entire procedure was repeated and the two sessions compared to assess the reliability of the protocol. Before each exercise session treadmill speed was set to that subject's relative speed, and any alteration after the subject was on the treadmill was noted.

The test - re-test reproducibility of the data collection procedures was apparent from the statistical analyses performed on pilot test results. It was found that pre-set treadmill speed was reduced by the action of the subject walking or running ($p<0.05$). Accordingly, speed was adjusted, during the experiment, after the subject was on the treadmill. There were no differences between the $\dot{V}O_2$'s obtained from 2.5 - 3 min, 3 - 3.5 min or 3.5 - 4 min, indicating that a 1 min sample from min 3 - 4 was being collected with the subject in a stable steady-state. The reliability of the protocol was confirmed by the finding that the $\dot{V}O_2$ response to the eight conditions of the first pilot test was the same as that for the second. Anthropometric measures were equally reliably obtained.

Young male and female subjects (n = 42) volunteered to participate in this study. The subject groupings were: male, high $\dot{V}O_2$ max (n = 11); male, average $\dot{V}O_2$ max (n = 10); female, high $\dot{V}O_2$ max (n = 10); and female, average $\dot{V}O_2$ max (n = 11). Each subject was habituated to treadmill walking and running by exposure, in 5 min segments, to a selection of experimental conditions chosen to allow the subject to experience each relative speed and grade. This 45 min of practice was distributed across three 15 min periods on different days. Subjects wore the mouthpiece and experienced the procedures involved in gas analysis during the last half of these sessions. Anthropometric data were collected on each subject during the habituation process. Stature, sitting height, foot length, body mass, and four measures of skinfold thickness - tricep, bicep, subscapular and supra-iliac were obtained using standard techniques.

Following initial habituation, the subject participated in a test of maximal oxygen consumption. This involved 1 $km.h^{-1}$ per min increases in walking speed from 3 to 6 $km.h^{-1}$ inclusive, and 1 $km.h^{-1}$ per min increases in running speed from 7 to 17 $km.h^{-1}$ or until exhaustion. If the subject had not achieved $\dot{V}O_2$ max by the time he had completed a minute at 17 $km.h^{-1}$, the grade was raised by +1% per min until the end of the test. Samples for oxygen consumption were obtained for 25 s out of each 30 s. Cadence was counted visually for 30 s at each velocity. The Borg RPE scale was applied at the end of the test to ascertain the subject's maximum rating of perceived exertion.

The subject was then asked to return to the laboratory on four more occasions. On each occasion he/she was asked to walk or run at 6 of the 24 relative speed ($st.s^{-1}$) conditions. The conditions were: walks at 0.5, 0.7, 0.9, 1.1 and 1.3 $st.s^{-1}$ and runs at 1.5, 1.7 and 1.9 $st.s^{-1}$ at each of +3%, 0% and -3% grade. The order of presentation of these conditions was randomly determined, first a walk then a run. Selected high aerobic capacity subjects were asked to run at three additional higher velocities - 2.1, 2.3 and 2.5 st.$s^{-1}$ at 0% grade.

Resting heart rate was obtained 5 to 10 minutes after the subject's arrival. For each condition the treadmill speed was adjusted to the correct stature-related value after the subject had initiated treadmill locomotion. The subject walked or ran for 4 min. He went onto the mouthpiece at 2 min, and a 60 s expired air sample was analysed using the on-line system starting at min 3. Cadence was measured by visual count for 30 s between min 3 and 4. RPE was obtained during the same period. After the computer had printed out the results, the subject was asked to rest quietly until heart rate had dropped to within 10 bpm of initial rate before initiating the next condition.

Statistical analysis of these data was performed as follows: Student's related "t" test to evaluate the validity of the on-line system in comparison with the Douglas bag approach; Student's related "t" test to assess the reliability of data collected during pilot testing; regression analysis of the $\dot{V}O_2$ - velocity relationship at both absolute and relative speeds; repeated measures ANOVA to assess the variability in economy at absolute and relative velocities; and two-factor ANOVA applied to the male, female - high, average $\dot{V}O_2$ max group data to assess sexual dimorphism and/or aerobic capacity effects on efficiency and economy at absolute and relative speeds.

## SUMMARY OF RESULTS

The males were, as expected, larger in most body dimensions compared with the females ($p<0.05$). The females exhibited greater %fat ($p<0.05$). Males and females did not differ in the ratio of leg length to stature. The males had a greater $\dot{V}O_2$ max ($ml.kg^{-1}.min^{-1}$) than the females ($p<0.05$), and experienced ventilatory threshold at a higher absolute velocity ($p<0.05$). The ventilatory threshold (%$\dot{V}O_2$ max) of males and females was similar and relatively low (63 - 65%). Maximum ratings of perceived exertion were the same ($\overline{X} = 17.2$) in males and females (Table II, page 130).

The relationship between oxygen consumption and relative speed ($st.s^{-1}$), while walking, was exponential in nature (Figure 6 and Table III, pages 135 and 137). The following equation represents the average response of all four subject groups:

$$\dot{V}O_2\ (ml.kg^{-1}.min^{-1}) = 4.747 * e^{(1.371*RS)}$$

While running, this relationship differed for male and female subjects.

Males:

$$\dot{V}O_2\ (ml.kg^{-1}.min^{-1}) = -0.876 + 22.095 * RS(st.s^{-1})$$

Females:

$$\dot{V}O_2\ (ml.kg^{-1}.min^{-1}) = 4.363 + 17.879 * RS(st.s^{-1})$$

Even though the coefficients of determination were very similar for all four equation forms (Table IV, page 139), i.e. linear, logarithmic, exponential and power, the average $\dot{V}O_2$ max groups exhibited exponential best fits to the running oxygen consumption - relative speed relationship while the high $\dot{V}O_2$ max groups exhibited linear or nearly linear, logarithmic best fit (Figure 29, page 189). Thus, the high $\dot{V}O_2$ max subjects could be said to be more uniform in their running economy compared with subjects of lower aerobic capacity.

The coefficients of variation (CV) in economy per unit of absolute speed ($km.h^{-1}$) (9.01%) (Figure 21, page 168) and per unit of relative speed ($st.s^{-1}$) (9.08%) (Figure 23, page 170) did not differ. However, the CV of economy of relative speed (leg $length.s^{-1}$) (9.91%) (Figure 22, page 169) was significantly higher ($p<0.05$) than these. The disparity between the coefficients of variation of both stature and leg length, and CV's for stride length, cadence and economy support the finding that relative speed did not reduce inter-subject variability in economy (Table V, page 144).

Males and females did not differ in their oxygen consumption, cadence, stride length, energy cost per step, energy cost per unit distance, RPE, economy or efficiency responses at absolute walking and running velocities (Figures 6, 10, 11, 15, 18, 20, 21, 24 pages 135, 149, 150, 154, 162, 166, 168, 171). Females, however, were working at a higher $\%\dot{V}O_2$ max, higher $\dot{V}O_2$ per kg lean body mass, and higher relative stride at absolute speed than the males ($p<0.05$) (Figures 8, 9, 13, 14, pages 147, 148, 152, 153).

At relative speeds ($st.s^{-1}$) some of these similarities disappeared. When considered in relative speed terms males had higher ($p<0.05$) $\dot{V}O_2$ per kg of body mass, stride length, and energy cost per step than females (Figures 6, 10, 11, pages 135, 149, 150). Males and females exhibited equal $\dot{V}O_2$ per kg LBM, relative stride, cadence, energy cost per metre, RPE, and efficiency at the same relative speeds (Figures 9, 13, 14, 15, 18, 20, 24, pages 148, 152 to 154, 162, 166, 171). Even though working at a lower absolute oxygen consumption, the females were working relatively harder (in $\%\dot{V}O_2$ max) than the males (Figure 8, page 147). The females were more economical than the males ($p<0.05$) when considered in relative speed terms (Figures 22, 23, pages 169 and 170).

Males and females reacted to locomotion on uphill (+3%) and downhill (-3%) grades in exactly the same fashion. During walking, the $\dot{V}O_2$ of uphill locomotion was 1.4 times that for downhill locomotion. During running this differential was 1.28. Relative to the $\dot{V}O_2$ at 0% grade, the $\dot{V}O_2$ at +3% grade increased by approximately twice the $\dot{V}O_2$ decrease at -3% grade (Figure 7, page 136). The efficiency of both uphill and downhill walking was less than that at 0% grade, as was the efficiency of downhill running ($p<0.05$). The efficiency of uphill running was found to be equal to that of level running (Figure 25, page 172). These efficiency results are probably suspect given some of the contentious assumptions inherent in the efficiency calculation.

Stride length and cadence patterns for uphill and downhill locomotion were altered by gradient conditions. As speed increased stride length at +3% grade decreased, and cadence increased, relative to locomotor patterns at 0% grade (Figures 12, 16, pages 151 and 155). These effects were significant at running velocities ($p<0.05$). The opposite pattern was observed for downhill locomotion - stride length increased and cadence decreased with increases in speed. Stride length and cadence at moderate walking (0.9 $st.s^{-1}$) and running (1.7 $st.s^{-1}$) velocities were very similar to the patterns observed at 0% grade.

On measures made, the high and average $\dot{V}O_2$ max groups were very similar anthropometrically - differing only in %fat and body mass (average group higher) ($p<0.05$) (Table VII, page 185). While the high $\dot{V}O_2$ max group had a significantly higher ($p<0.05$) maximal aerobic capacity, both groups were equal in ventilatory threshold.

The high $\dot{V}O_2$ max group demonstrated higher submaximal oxygen consumption compared with the average $\dot{V}O_2$ max group at absolute speeds but not at relative speeds (despite closely similar average stature) (Figure 27, page 187). The average $\dot{V}O_2$ max group was working relatively harder under all conditions (%$\dot{V}O_2$ max) ($p<0.05$) (Figure 29, page 189). This finding was confirmed by the respiratory exchange ratio (Figure 39, page 201) and RPE data

(Figure 40, page 202), especially at higher running velocities. The high $\dot{V}O_2$ max group employed a greater stride length and lower cadence to achieve velocity ($p<0.05$) (Figures 31, 35, pages 193 and 197). However, with the exception of some of the higher velocities, the groups used the same relative stride during locomotion (Figures 33, 34, pages 195 and 196). When compared at absolute speeds, the economy and efficiency of the high $\dot{V}O_2$ max group was below the average group ($p<0.05$). However, at relative speeds the two groups exhibited the same economy and efficiency (Figures 41 to 44, pages 203 to 206).

It was observed that there was a tendency for stride length increases, at any given velocity, to be associated with increases in oxygen consumption. The trend towards an inverse relationship between cadence and $\dot{V}O_2$ at specific velocities supported this observation (Table VI, page 159).

Economy and efficiency at walking velocities were found to be greater than for running velocities. There was a distinct maximum in economy and efficiency of walking that occurred between 0.7 and 0.9 $st.s^{-1}$ with both higher and lower velocities eliciting lower economy and efficiency responses. During running, however, economy and efficiency remained relatively unchanged with changes in velocity (Figures 21 to 24, pages 168 to 171).

## CONCLUSIONS

Based on the findings of this study, the following conclusions were drawn:

1. The first hypothesis was rejected for walking velocities but retained for running. The economy of walking is an exponential function of relative speed ($st.s^{-1}$). The economy of running is a linear function of relative speed.

2. The second hypothesis was retained. The setting of speed relative to stature does not alter the inter-subject variability in oxygen consumption compared to locomotion at absolute speeds. Group data (with similar mean stature), however, show a tendency towards minimization of variability at relative locomotor speeds.

3. The third hypothesis was rejected. Females are more economical at speeds set relative to their stature than are males.

4. Hypothesis four was retained. Those with high, and those with average maximal aerobic capacity do not differ in economy while walking and running at speeds set relative to stature.

5. The economy of walking, which exhibits an optimal point near "preferred speed" (as determined in the literature), is greater than the economy of running.

6. Stride length and oxygen consumption appear to be directly related, albeit tenuously. Increases in stride length during locomotion at any velocity (especially during running) are associated with increases in oxygen consumption.

7. The use of speed set relative to stature is indicated in locomotion studies for which comparisons are to be made between individuals with substantially different quantities of metabolically active tissue relative to total body mass.

8. There is considerable lack of uniformity, and disagreement amongst experts, regarding the applicability of various assumptions to the calculation of locomotor efficiency. This lack of concensus applies equally to the assessment of power output and the measurement of energy expenditure.

9. Following validation of the on-line computer-assisted data acquisition system specifically developed to facilitate this study, it was concluded that the system, and the protocol employed, provided for valid, reliable measurements of locomotor economy.

## RECOMMENDATIONS

The following recommendations for future study merit consideration:

1. Studies of the efficiency and/or economy of locomotion should be performed in a multi-disciplinary, holistic fashion. A unifocal approach tends to obfuscate, rather than add clarity to our understanding of this complex area of study.

2. The universality of the equation proposed by Heglund *et al* (1982) for prediction of locomotor power output from speed and body mass should be evaluated. In particular, estimates of power output using this prediction equation should be compared with power output measurements using the summation of segmental energies approach and the "realistic assumptions" regarding energy storage, energy transfer and positive/negative work relationships alluded to by Williams and Cavanagh (1983).

3. The relationship between freely-chosen stride length and the ratio of leg length to stature should be explored. Data in the present study show a tendency towards the existence of a direct relationship.

4. The direct relationship between freely-chosen stride length and oxygen consumption at any velocity seen in this study should be further evaluated.

5. The max test protocol, and the economy/efficiency data generated, could be used to predict endurance potential. A subject displaying a high $\dot{V}O_2$ max and ventilatory threshold combined with elevated economy and efficiency, and naturally chosen, lower than average stride length at any given velocity, might well prove to be a formidable competitor in endurance activities.

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# APPENDIX 1

## ON-LINE DATA-ACQUISITION SYSTEM EQUATIONS

With the advent of powerful, dedicated micro-computers, it has been possible to take the open-circuit method of metabolic assessment (Consolazio _et al_ 1963) a substantial step forward in speed and convenience. The marriage of the on-line inspired volumeter, expired air mixing chamber and electronic gas analysers (Graham _et al_ 1980) with a micro-computer enables rapid, continuous analysis of respiratory gas exchange. Furthermore, immediate computation of subject responses is possible, with printed output appearing during the experimental period. The computer programme developed for the present study was designed to calculate oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (R), ventilatory equivalents for oxygen (V.E. for $O_2$) and carbon dioxide (V.E. for $CO_2$), oxygen pulse ($O_2$ Pulse) (Consolazio _et al_ 1963), and an estimate of cardiac output ($\dot{Q}$) and stroke volume (S.V.) (Faulkner _et al_ 1977).

The following equations form the computational package used in the on-line computer-aided data acquisition system.

1) Partial Pressure of Water Vapour ($PH_2O$) (mmHg):

$PH_2O$ = EXP(2.303*(8.10765-(1750.286/(235+T))))

Where T = gas temperature (degrees C)

2) Correction factor to reduce ambient conditions to standard temperature and pressure, dry (STPD):

$\text{STPD FACTOR} = (273/(273+T))*((PB-(FRH*PH_2O))/760)$

Where PB = barometric pressure (mm Hg)
FRH = fractional relative humidity of inspired air

3) Correction of Inspired ambient volume ($\dot{V}I$) for sample duration and STPD:

$\dot{V}ISTPD(l.min^{-1}) = \dot{V}I(l)*\text{STPD FACTOR}*(60/\text{Time})$

Where Time = sample duration (s)

4) Fractional nitrogen inspired ($FIN_2$) and expired ($FEN_2$):

$FIN_2 = 1-(FIO_2+FICO_2)$

$FEN_2 = 1-(FEO_2+FECO_2)$

5) Oxygen Consumption ($\dot{V}O_2$):

$\dot{V}O_2(l.min^{-1}) = \dot{V}ISTPD*(FIO_2-((FIN_2/FEN_2)*FEO_2))$

6) Carbon Dioxide Production ($\dot{V}CO_2$):

$\dot{V}CO_2(l.min^{-1}) = \dot{V}ISTPD*(((FIN_2/FEN_2)*FECO_2)-FICO_2)$

7) Respiratory exchange ratio (R):

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

8) Oxygen consumption per kilogram of body mass ($\dot{V}O_2$):

$\dot{V}O_2(ml.kg^{-1}.min^{-1}) = (1000*\dot{V}O_2(l.min^{-1}))/\text{Body mass (kg)}$

9) Breathing frequency (f):

$f(br.min^{-1}) = f(br)*(60/\text{sample duration(s)})$

10) Average tidal volume ($\overline{V}t$):

$\overline{V}t(l.br^{-1}) = \dot{V}ISTPD(l.min^{-1})/f(br.min^{-1})$

11) Ventilatory Equivalent (V.E.) for oxygen:

V.E. for $O_2$ = $(\dot{V}ISTPD(l.min^{-1})/\dot{V}O_2(l.min^{-1}))/10$
$(l.100mlO_2^{-1})$

12) Ventilatory Equivalent (V.E.) for carbon dioxide:

V.E. for $CO_2$ = $(\dot{V}ISTPD(l.min^{-1})/\dot{V}CO_2(l.min^{-1}))/10$
$(l.100mlCO_2^{-1})$

13) Oxygen pulse ($O_2$ Pulse):

$O_2$ Pulse = $(1000*\dot{V}O_2(l.min^{-1}))$/heart rate$(b.min^{-1})$
$(mlO_2.bt^{-1})$

14) Estimated cardiac output ($\dot{Q}$):

$\dot{Q}(l.min^{-1})=(ZZ+(5.2*\dot{V}O_2(ml.kg^{-1}.min^{-1})))*(BM/1000)$

Where ZZ = 66 if male subject
ZZ = 75 if female subject
BM = Body mass (kg)

15) Stroke volume (S.V.):

S.V.$(ml.bt^{-1})$ = $(1000*\dot{Q}(l.min^{-1}))$/heart rate $(b.min^{-1})$

# APPENDIX 2

## ON-LINE DATA-ACQUISITION SYSTEM SOFTWARE

The software for this system was developed by the author with some guidance from a computer programmer. The basic programme involved the following steps. All variables are initialized and the dimensions of the data arrays are set (at 50 samples). Subject and experimental conditions are then input, followed by the loading of the computer's internal clock for monitoring of sample initiation and duration, and total elapsed time. Automatic sequencing information (on a 10 min repeating cycle) is then input. Once the experiment begins, the computer automatically samples according to this sequence, unless you interrupt the flow to collect data on an irregular basis by keyboard input. The sample duration is completely selectable, however, present applications tend towards 25 s samples every 30 s for continuous sampling ("CONT30"), and 60 s samples for the discontinuous method ("AUTO" and "MANUAL").

Each sample, regardless of the duration or sequencing, is taken as follows. An initial volumeter reading is taken of the gasmeter output through a 16 bit, cascade incremental counter integral of the computer (with 0.1 l accuracy). The oxygen, carbon dioxide, gas temperature and heart rate readings (from the A-to-D converter) are accumulated sequentially for the sample duration. Twice during each sweep of the A-to-D converter, a check is made to determine whether a new breath has started and, if so, the ventilatory frequency counter is incremented. At the end of the sample time, the final volumeter reading is taken. In addition to the immediate feedback on the display screen, the following data are printed after every sample: experiment elapsed time, sample duration, $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$), $\dot{V}O_2$ ($l.min^{-1}$), $\dot{V}CO_2$ ($l.min^{-1}$), respiratory exchange ratio, minute volume inspired, heart rate, ventilatory equivalent for $O_2$ and $CO_2$, oxygen pulse, ventilatory frequency, tidal volume, estimates of cardiac output and stroke volume, and percent of maximal oxygen uptake (Consolazio _et al_ 1963, Faulkner _et al_ 1977). In addition, the gas fractions of $O_2$ and $CO_2$, gas temperature, partial pressure of water vapour and appropriate STPD factor are recorded for each sample.

Programme listings for "AUTO", "MANUAL" AND "CONT30" appear on the following pages. The programming language is BASIC.

```
80 REM "AUTO"
90 REM ON-LINE PHYSIOLOGICAL DATA COLLECTION
100 REM REGULAR SAMPLING INTERVALS - AUTOMATIC
110 POKE HEX("20"),HEX("7E"):REM - CHANGE MEMEND
125 DIM A(21),SD(100),FI(3),CL$(100)
150 DATA 0.2093,0.0004,0.7903
160 DATA 0.9876
170 FOR I=1 TO 3:READ FI(I):NEXT I
180 READ VF
190 EXEC,"GET TIMER":REM - LOAD TIMING ROUTINE
200 POKE HEX("24"),HEX("7F"):POKE HEX("25"),HEX("00")
210 PRINT"THIS IS A PROGRAM TO ENABLE YOU TO COLLECT PHYSIOLOGICAL DATA"
220 PRINT"ON-LINE.  YOU WILL BE ASKED TO ENTER CERTAIN INFORMATION."
230 PRINT"THE COMPUTER WILL ASK YOU TO ENTER FIRST AND LAST SAMPLE TIMES"
235 PRINT"AS WELL AS THE REPEATING SAMPLING SEQUENCE YOU WANT FOR EACH 10 MINUTE
S"
240 PRINT" ":PRINT" "
245 PRINT"YOU MUST LEAVE AT LEAST 5 SECONDS BETWEEN THE END OF ONE SAMPLE"
247 PRINT"AND THE BEGINNING OF THE NEXT FOR PRINTER OUTPUT."
250 PRINT" ":PRINT" "
260 PRINT:PRINT"PLEASE ENTER THE FOLLOWING INFORMATION:-"
270 INPUT"SUBJECT NAME: ",NM$
280 INPUT"SUBJECT SEX(M/F): ",SX$
285 IF SX$<>"M" AND SX$<>"F" GOTO 280
290 INPUT"SUBJECT MASS(KG): ",WT
295 IF WT<20 GOTO 290
296 IF WT>120 GOTO 290
300 INPUT"SUBJECT AGE(YRS): ",AG
304 PRINT"NOW ENTER THE MAXIMUM OXYGEN UPTAKE OF YOUR SUBJECT (ENTER 0 IF UNKNOW
N)-"
305 INPUT"SUBJECT MAX VO2 (ML/KG/MIN): ";MV
310 INPUT"EXPERIMENT: ",E$
320 INPUT"CONDITION: ",C$
330 INPUT"DATE: ",DA$
340 INPUT"TIME OF DAY: ",TI$
350 INPUT"BAROMETRIC PRESSURE(MM HG): ",BP
355 IF BP<670 GOTO 350
356 IF BP>760 GOTO 350
360 INPUT"RELATIVE HUMIDITY(%): ",RH
365 IF RH<0 GOTO 360
366 IF RH>100 GOTO 360
370 DEF FNR1(X)=INT(10*X+0.5)/10
380 DEF FNR2(X)=INT(100*X+0.5)/100
390 DEF FNR3(X)=INT(1000*X+0.5)/1000
395 DEF FNR4(X)=INT(10000*X+0.5)/10000
400 FH=RH/100
410 K=0:G=0:O1=0:O3=0
420 REM - SET UP TO READ INSPIRED VOLUME (16 BIT NUMBER ON PORT 0)
430 POKE HEX("8001"),0:POKE HEX("8000"),0:POKE HEX("8001"),4
440 POKE HEX("8003"),0:POKE HEX("8002"),0:POKE HEX("8003"),4
450 REM - SET UP A/D (CHANNELS 0-3)
460 POKE 32777,0:POKE 32776,0:POKE 32777,4
470 POKE 32779,0:POKE 32778,0:POKE 32779,4
480 POKE 32799,0:POKE 32798,255:POKE 32799,4
490 OPEN"0.PRINT.SYS" AS 0
500 PRINT #0, TAB(20);"ON-LINE PHYSIOLOGICAL DATA"
510 PRINT #0, TAB(20);"=========================="
520 PRINT #0, " "
560 PRINT #0, "EXPERIMENT: ";E$
570 PRINT #0, "CONDITION: ";C$
580 PRINT #0, " "
590 PRINT #0,"SUBJECT NAME: ";NM$;"  (";SX$;")";TAB(50);"AGE: ";AG;TAB(65);"MASS
 (KG): ";WT
595 PRINT #0, " "
597 IF MV=0 GOTO 600
598 PRINT #0,"MAXIMAL OXYGEN UPTAKE (ML/KG/MIN): ";MV
599 PRINT #0,""
600 PRINT #0,"DATE: ";DA$;TAB(50);"TIME OF DAY: ";TI$
605 PRINT #0, " "
610 PRINT #0,"BAROMETRIC PRESSURE (MM HG): ";BP;TAB(50);"RELATIVE HUMIDITY (%):
";RH
```

```
620 PRINT #0, " "
630 PRINT #0, "THE COLUMN HEADED 'TIME' SHOWS THE ELAPSED TIME FROM THE START ";
640 PRINT #0, "OF THE EXPERIMENT TO THE START OF THE CURRENT SAMPLE PERIOD."
650 PRINT #0, "THE NUMBER IN BRACKETS IS THE SAMPLE DURATION IN SECONDS."
660 PRINT #0, " ":PRINT #0, " "
665 PRINT #0, "-------------------------------------------------------------";
666 PRINT #0, "-------------------------------------------------------------"
670 PRINT #0, "NO     TIME       R VO2   VO2  VCO2   R   VI(STPD) HR    F   TEM
P  FEO2   FECO2";
680 PRINT #0, "  VE-02 VE-CO2   Q    SV   O2 PU   VT    SPEED"
690 PRINT #0, "                ML/KG   L/M   L/M        L/M    B/M  BR/M";
700 PRINT #0, TAB(84);"L/100ML    L/M  ML/B  ML/B   L/BR   KM/HR"
710 PRINT #0, "-------------------------------------------------------------";
712 PRINT #0, "-------------------------------------------------------------"
725 PRINT:PRINT"WHEN WOULD YOU LIKE TO OBTAIN YOUR FIRST SAMPLE?"
727 PRINT:INPUT" WHAT MINUTE: ",M
729 PRINT:INPUT"WHAT SECONDS: ",S
731 FS=(60*M)+S
735 PRINT:PRINT"WHEN WOULD YOU LIKE TO OBTAIN YOUR LAST SAMPLE?"
736 PRINT:PRINT"IF UNKNOWN - ESTIMATE AS LONGER THAN EXPECTED DURATION OF TEST"
737 PRINT:INPUT"   WHAT HOUR: ",HH
738 PRINT:INPUT" WHAT MINUTE: ",M
739 PRINT:INPUT"WHAT SECONDS: ",S
741 LS=(3600*HH)+(60*M)+S
743 IF LS<FS THEN GOTO 725
745 PRINT:INPUT"ENTER SAMPLE DURATION IN SECONDS: ",SD(K+1)
750 PRINT:INPUT"HOW MANY SAMPLES PER 10 MINUTES: ",H
755 IF H<=20 THEN GOTO 770
760 PRINT:PRINT"SORRY - MAXIMUM NUMBER OF SAMPLES IS 20, PLEASE RE-ENTER"
765 GOTO 750
770 FOR G=1 TO H
775 PRINT:PRINT"TIME OF SAMPLE ";G:INPUT" - MINUTE(S): ",M:INPUT" - SECONDS: ",S
780 A(G)=(60*M)+S
785 NEXT G
787 G=1:J=0
788 IF G=H THEN A(G+1)=A(1)+ 600
789 D=A(G):E=SD(K+1):J=A(G+1)
790 IF J=0 THEN GOTO 801
791 IF D+E>J-5 THEN GOTO 797
793 IF G=H GOTO 801
795 G=G+1
796 GOTO 789
797 PRINT:PRINT"SORRY - YOU MUST LEAVE AT LEAST 5 SECONDS BETWEEN SAMPLES FOR OU
TPUT"
799 PRINT:PRINT"PLEASE RE-ENTER SAMPLING SEQUENCE":GOTO 745
801 G=1
802 D=A(G):E=SD(K+1)
803 IF FS+E>D-5 AND FS+E<=D THEN GOTO 811
805 IF G=H THEN GOTO 816
807 G=G+1
809 GOTO 802
811 PRINT:PRINT"SORRY - FIRST SAMPLE ENDS WITHIN 5 SECONDS OF THE START OF SAMPL
E ";G
815 PRINT:PRINT"PLEASE RE-ENTER SAMPLING SEQUENCE":GOTO 725
816 PRINT:INPUT "CHECK TREADMILL SPEED (Y/N)",TS$
818 IF TS$="Y" THEN GOSUB 4000
820 PRINT:PRINT:INPUT"PRESS S, THEN PRESS RETURN TO START THE EXPERIMENT",B$
825 IF B$<>"S" GOTO 820
830 X=USR(X):REM - START THE CLOCK
840 GOSUB 3700
845 GOSUB 3400
850 IF U>=FS-1 GOTO 960
855 IF U>=(T3+1) THEN GOTO 840
860 GOTO 845
865 SD(K+1)=SD(K)
866 IF H=1 GOTO 903
867 IF K>1 GOTO 877
868 G=1
870 D=A(G):L=SD(K)
871 IF D>(FS+L+4)THEN GOTO 905
872 G=G+1
```

```
873 IF H=2 THEN GOTO 905
874 IF G<>H THEN GOTO 870
875 G=0
877 G=G+1
878 IF G<>(H+1) THEN GOTO 905
880 FOR G=1 TO H
885 A(G)=A(G)+600
900 NEXT G
903 G=1
904 IF H=1 THEN A(G)=A(G)+600
905 GOSUB 3700
910 GOSUB 3400
915 IF U>=LS-1 THEN GOTO 960
920 IF U>=A(G)-1 THEN GOTO 960
925 IF U>=(T3+1) THEN GOTO 905
930 GOTO 910
960 K=K+1:REM - INITIALIZE
965 N=0:OT=0:TC=0:TH=0:TT=0:BB=500:CC=600:F=0:DD=0:EE=0:GG=0
966 HH=0:SP=0
970 REM START SAMPLE TIMER
980 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
990 T1=10*VAL(S1$)+VAL(S2$)
1000 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
1010 T2=10*VAL(S1$)+VAL(S2$)
1020 IF T1<>T2 GOTO 1040
1030 GOTO 1000
1040 V1=(PEEK(HEX("8002"))*256+PEEK(HEX("8000")))/10
1050 PRINT:PRINT"############"
1060 REM - READ THE CLOCK
1070 H1$=CHR$(PEEK(HEX("7F93"))):H2$=CHR$(PEEK(HEX("7F94")))
1080 M1$=CHR$(PEEK(HEX("7F95"))):M2$=CHR$(PEEK(HEX("7F96")))
1090 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
1100 CL$=H1$+H2$+":"+M1$+M2$+":"+S1$+S2$
1110 REM - DETERMINE SAMPLE END
1120 FT=3600*(10*VAL(H1$)+VAL(H2$))+60*(10*VAL(M1$)+VAL(M2$))+10*VAL(S1$)+VAL(S2
$)
1125 FT=FT+SD(K)
1140 POKE 32798,0
1160 GOSUB 3000
1165 IF CK>(FT-1) GOTO 1370
1170 O2=(PEEK(32778)*256+PEEK(32776))/100
1175 N=N+1
1180 OT=OT+O2
1200 POKE 32798,1
1210 GOSUB 3000
1215 IF CK>(FT-1) GOTO 1370
1220 CO=(PEEK(32778)*256+PEEK(32776))/100
1225 DD=DD+1
1230 TC=TC+CO
1240 GOSUB 3200
1260 POKE 32798,2
1270 GOSUB 3000
1275 IF CK>(FT-1) GOTO 1370
1280 HR=((PEEK(32778)*256+PEEK(32776))/10)+10
1285 EE=EE+1
1290 TH=TH+HR
1300 IF GG<20 GOTO 1328
1305 IF (GG-20)=HH GOTO 1328
1310 POKE 32798,4
1311 GOSUB 3200
1312 GOSUB 3000
1314 IF CK>(FT-1) GOTO 1370
1316 S=((PEEK(32778)*256+PEEK(32776))*0.0054226)-0.05997
1318 HH=HH+1
1320 SP=SP+S
1322 GOTO 1140
1328 POKE 32798,3
1330 GOSUB 3000
1332 GOSUB 3200
1335 IF CK>(FT-1) GOTO 1370
1340 T=(PEEK(32778)*256+PEEK(32776)-2731)/10
```

```
1345 GG=GG+1
1350 TT=TT+T
1360 GOTO 1140
1370 V2=(PEEK(HEX("8002"))*256+PEEK(HEX("8000")))/10
1380 IF V2<V1 THEN V2=V2+409.5
1390 IV=(V2-V1)*VF
1400 O=OT/N:C=TC/DD:HR=TH/EE:T=TT/GG
1405 SP=SP/HH
1410 O=O/100:C=C/100
1420 PW=EXP(2.303*(8.10765-(1750.286/(235+T))))
1430 SF=(273/(273+T))*((BP-(FH*PW))/760)
1440 N=1-(O+C)
1450 VS=IV*SF*(60/SD(K))
1460 VO=VS*(FI(1)-((FI(3)/N)*O))
1470 VC=VS*(((FI(3)/N)*C)-FI(2))
1480 R=VC/VO
1490 RV=VO*1000/WT
1493 IF MV=0 GOTO 1500
1495 PV=(RV/MV)*100
1500 F=F*60/SD(K)
1510 TV= VS/F
1520 PRINT:PRINT"SAMPLE ";K;" -    REL VO2=";FNR1(RV);"    R=";FNR2(R);"    SPEED
(KM/H)=";FNR2(SP)
1525 IF MV=0 GOTO 1530
1527 PRINT:PRINT"PERCENT OF MAX VO2=";FNR1(PV)
1530 PRINT:PRINT"SAMPLE ";K;"   LAST DVO2=";INT((O1-O3)*1000);"   THIS DVO2=";IN
T((VO-O1)*1000)
1560 PRINT:ZZ=66:IF SX$="F" THEN ZZ=75
1570 I=K
1580 EO=(VS/VO)/10
1590 EC=(VS/VC)/10
1595 IF HR = 0 GOTO 1610
1600 OP=VO*1000/HR
1610 RV=VO*1000/WT
1620 Q=ZZ+(5.2*RV)
1630 Q=Q*WT/1000
1640 IF HR=0 GOTO 1670
1650 SV=(Q*1000)/HR
1660 PRINT #0," "
1670 PRINT #0, I;TAB(3);CL$;"(";SD(I);")";TAB(18);FNR1(RV);TAB(25);FNR2(VO);TAB(
31);FNR2(VC);TAB(37);FNR2(R);
1680 PRINT #0, TAB(43);FNR2(VS);TAB(51);INT(HR);TAB(57);INT(F);
1685 PRINT #0, TAB(61);FNR1(T);TAB(66);FNR4(O);TAB(74);FNR4(C);
1690 PRINT #0, TAB(82);FNR2(EO);TAB(88);FNR2(EC);TAB(95);FNR1(Q);
1695 PRINT #0, TAB(101);INT(SV);TAB(106);FNR2(OP);TAB(113);FNR2(TV);
1700 PRINT #0, TAB(120);FNR2(SP)
1710 IF MV=0 GOTO 1740
1715 PRINT #0, ""
1720 PRINT #0, TAB(3);"%VO2 MAX= ";FNR1(PV)
1725 O3=O1:O1=VO
1740 IF U>=LS-1 THEN GOTO 1750
1742 PRINT
1745 GOTO 865
1750 POKE HEX("8013"),0:POKE HEX("8012"),HEX("80"):REM - STOP CLOCK
1760 END
3000 M1$=CHR$(PEEK(HEX("7F95"))):M2$=CHR$(PEEK(HEX("7F96")))
3005 H1$=CHR$(PEEK(HEX("7F93"))):H2$=CHR$(PEEK(HEX("7F94")))
3010 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
3020 CK=3600*(10*VAL(H1$)+VAL(H2$))+60*(10*VAL(M1$)+VAL(M2$))+10*VAL(S1$)+VAL(S2
$)
3040 RETURN
3200 AA=(PEEK(HEX("8002"))*256+PEEK(HEX("8000")))/10
3210 IF BB=CC AND AA<>BB THEN F=F+1
3220 CC=BB:BB=AA
3230 RETURN
3400 H1$=CHR$(PEEK(HEX("7F93"))):H2$=CHR$(PEEK(HEX("7F94")))
3410 M1$=CHR$(PEEK(HEX("7F95"))):M2$=CHR$(PEEK(HEX("7F96")))
3420 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
3430 U=3600*(10*VAL(H1$)+VAL(H2$))+60*(10*VAL(M1$)+VAL(M2$))+10*VAL(S1$)+VAL(S2$
)
```

```
3432 CK$=H1$+H2$+":"+M1$+M2$+":"+S1$+S2$
3434 SP=0
3436 POKE 32798,4
3438 FOR KK=1 TO 15:NEXT KK
3440 FOR PP=1 TO 10
3442 S=((PEEK(32778)*256+PEEK(32776))*0.0054226)-0.05997
3444 SP=SP+S
3446 NEXT PP
3448 SP=SP/10
3450 IF U/5<>INT(U/5) THEN GOTO 3454
3452 IF U/5=INT(U/5) THEN GOTO 3456
3454 IF U>=(T3+1) THEN PRINT CK$,
3455 GOTO 3460
3456 IF U>=(T3+1) THEN PRINT SP,
3460 RETURN
3700 H1$=CHR$(PEEK(HEX("7F93"))):H2$=CHR$(PEEK(HEX("7F94")))
3710 M1$=CHR$(PEEK(HEX("7F95"))):M2$=CHR$(PEEK(HEX("7F96")))
3720 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
3730 T3=3600*(10*VAL(H1$)+VAL(H2$))+60*(10*VAL(M1$)+VAL(M2$))+10*VAL(S1$)+VAL(S2
$)
3740 RETURN
4000 FOR MM=1 TO 10:REM SPEED CHECK SUBROUTINE
4010 PP=0:SP=0
4020 POKE 32798,4
4030 FOR KK=1 TO 15:NEXT KK
4040 S=((PEEK(32778)*256+PEEK(32776))*0.0054226)-0.05997
4050 PP=PP+1
4060 SP=SP+S
4070 IF PP<16 GOTO 4020
4080 SP=SP/PP
4090 PRINT "SPEED(KM/H)= ";SP
4100 NEXT MM
4110 SP=0
4120 RETURN
```

```
80 REM "MANUAL"
90 REM ON-LINE PHYSIOLOGICAL DATA COLLECTION
100 REM IRREGULAR SAMPLING INTERVALS - MANUAL
110 POKE HEX("20"),HEX("7E"):REM - CHANGE MEMEND
120 DIM CL$(50),O(50),C(50),HR(50),T(50),IV(50),PW(50),SF(50)
125 DIM A(21), PV(50)
130 DIM N(50),VS(50),VO(50),R(50),EO(50),EC(50),OP(50),FI(3)
140 DIM SD(50),SV(50),RV(50),Q(50),VC(50),F(50),TV(50)
145 DIM SP(50)
150 DATA 0.2093,0.0004,0.7903
160 DATA 0.9876
170 FOR I=1 TO 3:READ FI(I):NEXT I
180 READ VF
190 EXEC,"GET TIMER":REM - LOAD TIMING ROUTINE
200 POKE HEX("24"),HEX("7F"):POKE HEX("25"),HEX("00")
210 PRINT"THIS IS A PROGRAM TO ENABLE YOU TO COLLECT PHYSIOLOGICAL DATA"
220 PRINT"ON-LINE.  YOU WILL BE ASKED TO ENTER CERTAIN INFORMATION."
230 PRINT"THE COMPUTER WILL THEN WAIT FOR YOU TO PRESS A CERTAIN KEY"
240 PRINT"BEFORE SAMPLING FOR A GIVEN PERIOD. THIS PROCESS MAY BE REPEATED"
250 PRINT"UNTIL THE EXPERIMENT IS TERMINATED BY PRESSING ANOTHER KEY."
260 PRINT:PRINT"PLEASE ENTER THE FOLLOWING INFORMATION:-"
270 INPUT"SUBJECT NAME: ",NM$
280 INPUT"SUBJECT SEX(M/F): ",SX$
285 IF SX$<>"M" AND SX$<>"F" GOTO 280
290 INPUT"SUBJECT MASS(KG): ",WT
295 IF WT<20 GOTO 290
296 IF WT>120 GOTO 290
300 INPUT"SUBJECT AGE(YRS): ",AG
304 PRINT"NOW ENTER THE MAXIMUM OXYGEN UPTAKE OF YOUR SUBJECT (ENTER 0 IF UNKNOW
N)-"
305 INPUT"SUBJECT MAX VO2 (ML/KG/MIN): ";MV
310 INPUT"EXPERIMENT: ",E$
320 INPUT"CONDITION: ",C$
330 INPUT"DATE: ",DA$
340 INPUT"TIME OF DAY: ",TI$
350 INPUT"BAROMETRIC PRESSURE(MM HG): ",BP
355 IF BP<670 GOTO 350
356 IF BP>760 GOTO 350
360 INPUT"RELATIVE HUMIDITY(%): ",RH
365 IF RH<0 GOTO 360
366 IF RH>100 GOTO 360
370 DEF FNR1(X)=INT(10*X+0.5)/10
380 DEF FNR2(X)=INT(100*X+0.5)/100
390 DEF FNR3(X)=INT(1000*X+0.5)/1000
395 DEF FNR4(X)=INT(10000*X+0.5)/10000
400 FH=RH/100
410 K=0
420 REM - SET UP TO READ INSPIRED VOLUME (16 BIT NUMBER ON PORT 0)
430 POKE HEX("8001"),0:POKE HEX("8000"),0:POKE HEX("8001"),4
440 POKE HEX("8003"),0:POKE HEX("8002"),0:POKE HEX("8003"),4
450 REM - SET UP A/D (CHANNELS 0-3)
460 POKE 32777,0:POKE 32776,0:POKE 32777,4
470 POKE 32779,0:POKE 32778,0:POKE 32779,4
480 POKE 32799,0:POKE 32798,255:POKE 32799,4
490 OPEN"0.PRINT.SYS" AS 0
500 PRINT #0, TAB(20);"ON-LINE PHYSIOLOGICAL DATA"
510 PRINT #0, TAB(20);"=========================="
520 PRINT #0, " "
560 PRINT #0, "EXPERIMENT: ";E$
570 PRINT #0, "CONDITION: ";C$
580 PRINT #0, " "
590 PRINT #0, "SUBJECT NAME: ";NM$;"  (";SX$;")";TAB(50);"AGE: ";AG;TAB(65);"MAS
S (KG): ";WT
595 PRINT #0, " "
597 IF MV=0 GOTO 600
598 PRINT #0,"MAXIMAL OXYGEN UPTAKE (ML/KG/MIN): ";MV
599 PRINT #0,""
600 PRINT #0, "DATE: ";DA$;TAB(50);"TIME OF DAY: ";TI$
605 PRINT #0, " "
610 PRINT #0, "BAROMETRIC PRESSURE (MM HG): ";BP;TAB(50);"RELATIVE HUMIDITY (%):
 ";RH
```

```
620 PRINT #0, " "
630 PRINT #0, "THE COLUMN HEADED 'TIME' SHOWS THE ELAPSED TIME FROM THE START"
640 PRINT #0, "OF THE EXPERIMENT TO THE START OF THE CURRENT SAMPLE PERIOD."
650 PRINT #0, "THE NUMBER IN BRACKETS IS THE SAMPLE DURATION IN SECONDS."
660 PRINT #0,  " ":PRINT #0, " "
665 PRINT #0, "---------------------------------------------------------------";
666 PRINT #0, "---------------------------------------------------------------"
670 PRINT #0, "NO      TIME       R VO2   VO2  VCO2   R   VI(STPD) HR    F   TEM
P  FEO2   FECO2";
680 PRINT #0, "  VE-O2 VE-CO2   Q    SV   O2 PU   VT    SPEED"
690 PRINT #0, "                   ML/KG   L/M   L/M         L/M    B/M  BR/M";
700 PRINT #0, TAB(84);"L/100ML     L/M  ML/B  ML/B   L/BR   KM/HR"
710 PRINT #0, "---------------------------------------------------------------";
712 PRINT #0, "---------------------------------------------------------------"
850 PRINT:PRINT:INPUT"PRESS S, THEN PRESS RETURN TO START THE EXPERIMENT",B$
860 IF B$<>"S" GOTO 850
870 X=USR(X):REM - START THE CLOCK AND INITIALIZE
880 N=0:OT=0:TC=0:TH=0:TT=0:BB=500:CC=600:F(K+1)=0
890 DD=0:EE=0:GG=0:HH=0:SP=0
900 PRINT:INPUT"ENTER NEW SAMPLE DURATION?(Y/N) ",AN$
910 IF AN$="N" THEN SD(K+1)=SD(K):GOTO 925
920 PRINT:INPUT"ENTER DURATION IN SECONDS: ",SD(K+1)
925 PRINT:INPUT"CHECK TREADMILL SPEED?(Y/N) ",TS$
926 IF TS$="Y" THEN GOSUB 3500
930 PRINT:INPUT"TO SAMPLE: PRESS S (RETURN) ",K$
940 IF K$<>"S" AND K$<>"T" GOTO 930
950 IF K$="T" GOTO 1750
960 K=K+1
970 REM START SAMPLE TIMER
980 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
990 T1=10*VAL(S1$)+VAL(S2$)
1000 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
1010 T2=10*VAL(S1$)+VAL(S2$)
1020 IF T1<>T2 GOTO 1040
1030 GOTO 1000
1040 V1=(PEEK(HEX("8002"))*256+PEEK(HEX("8000")))/10
1050 PRINT"############"
1060 REM - READ THE CLOCK
1070 H1$=CHR$(PEEK(HEX("7F93"))):H2$=CHR$(PEEK(HEX("7F94")))
1080 M1$=CHR$(PEEK(HEX("7F95"))):M2$=CHR$(PEEK(HEX("7F96")))
1090 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
1100 CL$(K)=H1$+H2$+":"+M1$+M2$+":"+S1$+S2$
1110 REM - DETERMINE SAMPLE END
1120 FT=3600*(10*VAL(H1$)+VAL(H2$))+60*(10*VAL(M1$)+VAL(M2$))+10*VAL(S1$)+VAL(S2
$)
1125 FT=FT+SD(K)
1140 POKE 32798,0
1160 GOSUB 3000
1165 IF CK>(FT-1) GOTO 1370
1170 O2=(PEEK(32778)*256+PEEK(32776))/100
1175 N=N+1
1180 OT=OT+O2
1200 POKE 32798,1
1210 GOSUB 3000
1215 IF CK>(FT-1) GOTO 1370
1220 CO=(PEEK(32778)*256+PEEK(32776))/100
1225 DD=DD+1
1230 TC=TC+CO
1240 GOSUB 3200
1260 POKE 32798,2
1270 GOSUB 3000
1275 IF CK>(FT-1) GOTO 1370
1280 HR=((PEEK(32778)*256+PEEK(32776))/10)+10
1285 EE=EE+1
1290 TH=TH+HR
1300 IF GG<20 GOTO 1328
1305 IF (GG-20)=HH GOTO 1328
1310 POKE 32798,4
1311 GOSUB 3200
1312 GOSUB 3000
1314 IF CK>(FT-1) GOTO 1370
```

```
1316 S=((PEEK(32778)*256+PEEK(32776))*0.0054226)-0.05997
1318 HH=HH+1
1320 SP=SP+S
1322 GOTO 1140
1328 POKE 32798,3
1330 GOSUB 3000
1332 GOSUB 3200
1335 IF CK>(FT-1) GOTO 1370
1340 T=(PEEK(32778)*256+PEEK(32776)-2731)/10
1345 GG=GG+1
1350 TT=TT+T
1360 GOTO 1140
1370 V2=(PEEK(HEX("8002"))*256+PEEK(HEX("8000")))/10
1380 IF V2<V1 THEN V2=V2+409.5
1390 IV(K)=(V2-V1)*VF
1400 O(K)=OT/N:C(K)=TC/DD:HR(K)=TH/EE:T(K)=TT/GG
1405 SP(K)=SP/HH
1410 O(K)=O(K)/100:C(K)=C(K)/100
1420 PW(K)=EXP(2.303*(8.10765-(1750.286/(235+T(K)))))
1430 SF(K)=(273/(273+T(K)))*((BP-(FH*PW(K)))/760)
1440 N(K)=1-(O(K)+C(K))
1450 VS(K)=IV(K)*SF(K)*(60/SD(K))
1460 VO(K)=VS(K)*(FI(1)-((FI(3)/N(K))*O(K)))
1470 VC(K)=VS(K)*(((FI(3)/N(K))*C(K))-FI(2))
1480 R(K)=VC(K)/VO(K)
1490 RV(K)=VO(K)*1000/WT
1493 IF MV=0 GOTO 1500
1495 PV(K)=(RV(K)/MV)*100
1500 F(K)=F(K)*60/SD(K)
1510 TV(K)= VS(K)/F(K)
1520 PRINT:PRINT"SAMPLE ";K;" -    REL VO2=";FNR1(RV(K));"     R=";FNR2(R(K));"
 SPEED(KM/H)=";FNR2(SP(K))
1525 IF MV=0 GOTO 1530
1527 PRINT:PRINT"PERCENT OF MAX VO2=";FNR1(PV(K))
1530 IF K<3 GOTO 1560
1540 PRINT:PRINT"SAMPLE ";K;"  LAST DVO2=";INT((VO(K-1)-VO(K-2))*1000);"  THIS D
VO2=";INT((VO(K)-VO(K-1))*1000)
1560 ZZ=66:IF SX$="F" THEN ZZ=75
1570 I=K
1580 EO(I)=(VS(I)/VO(I))/10
1590 EC(I)=(VS(I)/VC(I))/10
1595 IF HR(I) = 0 GOTO 1610
1600 OP(I)=VO(I)*1000/HR(I)
1610 RV(I)=VO(I)*1000/WT
1620 Q(I)=ZZ+(5.2*RV(I))
1630 Q(I)=Q(I)*WT/1000
1640 IF HR(I)=0 GOTO 1670
1650 SV(I)=(Q(I)*1000)/HR(I)
1660 PRINT #0," "
1670 PRINT #0, I;TAB(3);CL$(I);"(";SD(I);")";TAB(18);FNR1(RV(I));TAB(25);FNR2(VO
(I));TAB(31);FNR2(VC(I));TAB(37);FNR2(R(I));
1680 PRINT #0, TAB(43);FNR2(VS(I));TAB(51);INT(HR(I));TAB(57);INT(F(I));
1685 PRINT #0, TAB(61);FNR1(T(I));TAB(66);FNR4(O(I));TAB(74);FNR4(C(I));
1690 PRINT #0, TAB(82);FNR2(EO(I));TAB(88);FNR2(EC(I));TAB(95);FNR1(Q(I));
1695 PRINT #0, TAB(101);INT(SV(I));TAB(106);FNR2(OP(I));TAB(113);FNR2(TV(I));
1700 PRINT #0, TAB(120);FNR2(SP(I))
1710 IF MV=0 GOTO 1740
1715 PRINT #0, ""
1720 PRINT #0, TAB(3);"%VO2 MAX= ";FNR1(PV(I))
1740 GOTO 880
1750 POKE HEX("8013"),0:POKE HEX("8012"),HEX("80"):REM - STOP CLOCK
1760 END
3000 M1$=CHR$(PEEK(HEX("7F95"))):M2$=CHR$(PEEK(HEX("7F96")))
3005 H1$=CHR$(PEEK(HEX("7F93"))):H2$=CHR$(PEEK(HEX("7F94")))
3010 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
3020 CK=3600*(10*VAL(H1$)+VAL(H2$))+60*(10*VAL(M1$)+VAL(M2$))+10*VAL(S1$)+VAL(S2
$)
```

```
3040 RETURN
3200 AA=(PEEK(HEX("8002"))*256+PEEK(HEX("8000")))/10
3210 IF BB=CC AND AA<>BB THEN F(K)=F(K)+1
3220 CC=BB:BB=AA
3230 RETURN
3500 FOR MM=1 TO 10: REM SPEED CHECK SUBROUTINE
3510 PP=0:SP=0
3520 POKE 32798,4
3530 FOR KK=1 TO 15:NEXT KK
3540 S=((PEEK(32778)*256+PEEK(32776))*0.0054226)-0.05997
3550 PP=PP+1
3560 SP=SP+S
3570 IF PP<16 GOTO 3520
3580 SP=SP/PP
3590 PRINT"SPEED(KM/H)= ";SP
3600 NEXT MM
3610 SP=0
3620 RETURN
```

```
80 REM "CONT30"
90 REM ON-LINE PHYSIOLOGICAL DATA COLLECTION
95 REM CONTINUOUS AUTOMATIC SAMPLES EVERY 30 SECONDS WITH SAMPLE DURATION 25 SEC
ONDS
100 REM FIRST SAMPLE STARTS AT 0 MIN 30 SECONDS - LAST SAMPLE IS AT 25 MINUTES
110 POKE HEX("20"),HEX("7E"):REM - CHANGE MEMEND
120 DIM CL$(50),O(50),C(50),HR(50),T(50),IV(50),PW(50),SF(50)
125 DIM A(21),PV(50)
130 DIM N(50),VS(50),VO(50),R(50),EO(50),EC(50),OP(50),FI(3)
140 DIM SD(50),SV(50),RV(50),Q(50),VC(50),F(50),TV(50)
145 DIM SP(50)
150 DATA 0.2093,0.0004,0.7903
160 DATA 0.9876
170 FOR I=1 TO 3:READ FI(I):NEXT I
180 READ VF
190 EXEC,"GET TIMER":REM - LOAD TIMING ROUTINE
200 POKE HEX("24"),HEX("7F"):POKE HEX("25"),HEX("00")
210 PRINT"THIS IS A PROGRAM TO ENABLE YOU TO COLLECT PHYSIOLOGICAL DATA"
220 PRINT"ON-LINE.  YOU WILL BE ASKED TO ENTER CERTAIN INFORMATION."
230 PRINT"THE COMPUTER WILL ASK YOU TO ENTER FIRST AND LAST SAMPLE TIMES"
235 PRINT"AS WELL AS THE REPEATING SAMPLING SEQUENCE YOU WANT FOR EACH 10 MINUTE
S"
240 PRINT" ":PRINT" "
245 PRINT"YOU MUST LEAVE AT LEAST 5 SECONDS BETWEEN THE END OF ONE SAMPLE"
247 PRINT"AND THE BEGINNING OF THE NEXT FOR PRINTER OUTPUT."
250 PRINT" ":PRINT" "
260 PRINT:PRINT"PLEASE ENTER THE FOLLOWING INFORMATION:-"
270 INPUT"SUBJECT NAME: ",NM$
280 INPUT"SUBJECT SEX(M/F): ",SX$
285 IF SX$<>"M" AND SX$<>"F" GOTO 280
290 INPUT"SUBJECT MASS(KG): ",WT
295 IF WT<20 GOTO 290
296 IF WT>120 GOTO 290
300 INPUT"SUBJECT AGE(YRS): ",AG
304 PRINT"NOW ENTER THE MAXIMAL OXYGEN UPTAKE OF YOUR SUBJECT (ENTER 0 IF UNKNOW
N)-"
305 INPUT"SUBJECT MAX VO2 (ML/KG/MIN): ";MV
310 INPUT"EXPERIMENT: ",E$
320 INPUT"CONDITION: ",C$
330 INPUT"DATE: ",DA$
340 INPUT"TIME OF DAY: ",TI$
350 INPUT"BAROMETRIC PRESSURE(MM HG): ",BP
355 IF BP<670 GOTO 350
356 IF BP>760 GOTO 350
360 INPUT"RELATIVE HUMIDITY(%): ",RH
365 IF RH<0 GOTO 360
366 IF RH>100 GOTO 360
370 DEF FNR1(X)=INT(10*X+0.5)/10
380 DEF FNR2(X)=INT(100*X+0.5)/100
390 DEF FNR3(X)=INT(1000*X+0.5)/1000
395 DEF FNR4(X)=INT(10000*X+0.5)/10000
400 FH=RH/100
410 K=0:G=0
420 REM - SET UP TO READ INSPIRED VOLUME (16 BIT NUMBER ON PORT 0)
430 POKE HEX("8001"),0:POKE HEX("8000"),0:POKE HEX("8001"),4
440 POKE HEX("8003"),0:POKE HEX("8002"),0:POKE HEX("8003"),4
450 REM - SET UP A/D (CHANNELS 0-3)
460 POKE 32777,0:POKE 32776,0:POKE 32777,4
470 POKE 32779,0:POKE 32778,0:POKE 32779,4
480 POKE 32799,0:POKE 32798,255:POKE 32799,4
490 OPEN"0.PRINT.SYS" AS 0
500 PRINT #0, TAB(20);"ON-LINE PHYSIOLOGICAL DATA"
510 PRINT #0, TAB(20);"=========================="
520 PRINT #0, " "
560 PRINT #0, "EXPERIMENT: ";E$
570 PRINT #0, "CONDITION: ";C$
580 PRINT #0, " "
590 PRINT #0,"SUBJECT NAME: ";NM$;"  (";SX$;")";TAB(50);"AGE: ";AG;TAB(65);"MASS
 (KG): ";WT
```

```
595 PRINT #0, " "
597 IF MV=0 GOTO 600
598 PRINT #0, "MAXIMAL OXYGEN UPTAKE (ML/KG/MIN): ";MV
599 PRINT #0,""
600 PRINT #0,"DATE: ";DA$;TAB(50);"TIME OF DAY: ";TI$
605 PRINT #0, " "
610 PRINT #0,"BAROMETRIC PRESSURE (MM HG): ";BP;TAB(50);"RELATIVE HUMIDITY (%):
";RH
620 PRINT #0, " "
630 PRINT #0, "THE COLUMN HEADED 'TIME' SHOWS THE ELAPSED TIME FROM THE START ";
640 PRINT #0, "OF THE EXPERIMENT TO THE START OF THE CURRENT SAMPLE PERIOD."
650 PRINT #0, "THE NUMBER IN BRACKETS IS THE SAMPLE DURATION IN SECONDS."
660 PRINT #0, " ":PRINT #0, " "
665 PRINT #0, "---------------------------------------------------------------";
666 PRINT #0, "---------------------------------------------------------------"
670 PRINT #0, "NO      TIME       R VO2   VO2  VCO2   R   VI(STPD) HR    F   TEM
P  FEO2   FECO2";
680 PRINT #0, "  VE-O2 VE-CO2   Q    SV   O2 PU   VT    SPEED"
690 PRINT #0, "                   ML/KG   L/M   L/M         L/M    B/M  BR/M";
700 PRINT #0,TAB(84);"L/100ML     L/M  ML/B  ML/B   L/BR   KM/HR"
710 PRINT #0, "---------------------------------------------------------------";
712 PRINT #0, "---------------------------------------------------------------"
731 FS=30
741 LS=1500
745 SD(K+1)=25
750 H=20
760 A(0)=0
770 FOR G=1 TO H
775 A(G)=A(G-1)+30
785 NEXT G
820 PRINT:PRINT:INPUT"PRESS S, THEN PRESS RETURN TO START THE EXPERIMENT",B$
825 IF B$<>"S" GOTO 820
830 X=USR(X):REM - START THE CLOCK
840 GOSUB 3700
845 GOSUB 3400
850 IF U>=FS-1 GOTO 960
855 IF U>=(T3+1) THEN GOTO 840
860 GOTO 845
865 SD(K+1)=SD(K)
866 IF K>1 GOTO 877
868 G=1
870 D=A(G):L=SD(K)
871 IF D>(FS+L+4)THEN GOTO 905
872 G=G+1
874 IF G<>H THEN GOTO 870
875 G=0
877 G=G+1
878 IF G<>(H+1) THEN GOTO 905
880 FOR G=1 TO H
885 A(G)=A(G)+600
900 NEXT G
903 G=1
905 GOSUB 3700
910 GOSUB 3400
915 IF U>=LS-1 THEN GOTO 960
920 IF U>=A(G)-1 THEN GOTO 960
925 IF U>=(T3+1) THEN GOTO 905
930 GOTO 910
960 K=K+1:REM - INITIALIZE
965 N=0:OT=0:TC=0:TH=0:TT=0:BB=500:CC=600:F(K+1)=0:DD=0:EE=0:GG=0
966 HH=0:SP=0
970 REM START SAMPLE TIMER
980 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
990 T1=10*VAL(S1$)+VAL(S2$)
1000 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
1010 T2=10*VAL(S1$)+VAL(S2$)
1020 IF T1<>T2 GOTO 1040
1030 GOTO 1000
1040 V1=(PEEK(HEX("8002"))*256+PEEK(HEX("8000")))/10
1050 PRINT:PRINT"############"
```

```
1060 REM - READ THE CLOCK
1070 H1$=CHR$(PEEK(HEX("7F93"))):H2$=CHR$(PEEK(HEX("7F94")))
1080 M1$=CHR$(PEEK(HEX("7F95"))):M2$=CHR$(PEEK(HEX("7F96")))
1090 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
1100 CL$(K)=H1$+H2$+":"+M1$+M2$+":"+S1$+S2$
1110 REM - DETERMINE SAMPLE END
1120 FT=60*(10*VAL(M1$)+VAL(M2$))+10*VAL(S1$)+VAL(S2$)+SD(K)
1140 POKE 32798,0
1160 GOSUB 3000
1165 IF CK>(FT-1) GOTO 1370
1170 O2=(PEEK(32778)*256+PEEK(32776))/100
1175 N=N+1
1180 OT=OT+O2
1200 POKE 32798,1
1210 GOSUB 3000
1215 IF CK>(FT-1) GOTO 1370
1220 CO=(PEEK(32778)*256+PEEK(32776))/100
1225 DD=DD+1
1230 TC=TC+CO
1240 GOSUB 3200
1260 POKE 32798,2
1270 GOSUB 3000
1275 IF CK>(FT-1) GOTO 1370
1280 HR=((PEEK(32778)*256+PEEK(32776))/10)+10
1285 EE=EE+1
1290 TH=TH+HR
1300 IF GG<20 GOTO 1328
1305 IF (GG-20)=HH GOTO 1328
1310 POKE 32798,4
1311 GOSUB 3200
1312 GOSUB 3000
1314 IF CK>(FT-1) GOTO 1370
1316 S=((PEEK(32778)*256+PEEK(32776))*0.0054226)-0.05997
1318 HH=HH+1
1320 SP=SP+S
1322 GOTO 1140
1328 POKE 32798,3
1330 GOSUB 3000
1332 GOSUB 3200
1335 IF CK>(FT-1) GOTO 1370
1340 T=(PEEK(32778)*256+PEEK(32776)-2731)/10
1345 GG=GG+1
1350 TT=TT+T
1360 GOTO 1140
1370 V2=(PEEK(HEX("8002"))*256+PEEK(HEX("8000")))/10
1380 IF V2<V1 THEN V2=V2+409.5
1390 IV(K)=(V2-V1)*VF
1400 O(K)=OT/N:C(K)=TC/DD:HR(K)=TH/EE:T(K)=TT/GG
1405 SP(K)=SP/HH
1410 O(K)=O(K)/100:C(K)=C(K)/100
1420 PW(K)=EXP(2.303*(8.10765-(1750.286/(235+T(K)))))
1430 SF(K)=(273/(273+T(K)))*((BP-(FH*PW(K)))/760)
1440 N(K)=1-(O(K)+C(K))
1450 VS(K)=IV(K)*SF(K)*(60/SD(K))
1460 VO(K)=VS(K)*(FI(1)-((FI(3)/N(K))*O(K)))
1470 VC(K)=VS(K)*(((FI(3)/N(K))*C(K))-FI(2))
1480 R(K)=VC(K)/VO(K)
1490 RV(K)=VO(K)*1000/WT
1493 IF MV=0 GOTO 1500
1495 PV(K)=(RV(K)/MV)*100
1500 F(K)=F(K)*60/SD(K)
1510 TV(K)= VS(K)/F(K)
1520 PRINT:PRINT"SAMPLE ";K;" -    REL VO2=";FNR1(RV(K));"      R=";FNR2(R(K));"
 SPEED(KM/H)=";FNR2(SP(K))
1530 IF K<3 GOTO 1560
1540 PRINT:PRINT"%MAX VO2=";FNR1(PV(K));"     LAST DVO2=";INT((VO(K-1)-VO(K-2))*1
000);"     THIS DVO2=";INT((VO(K)-VO(K-1))*1000)
1560 PRINT:ZZ=66:IF SX$="F" THEN ZZ=75
1570 I=K
1580 EO(I)=(VS(I)/VO(I))/10
1590 EC(I)=(VS(I)/VC(I))/10
```

```
1595 IF HR(I) = 0 GOTO 1610
1600 OP(I)=VO(I)*1000/HR(I)
1610 RV(I)=VO(I)*1000/WT
1620 Q(I)=ZZ+(5.2*RV(I))
1630 Q(I)=Q(I)*WT/1000
1640 IF HR(I)=0 GOTO 1670
1650 SV(I)=(Q(I)*1000)/HR(I)
1660 PRINT #0," "
1670 PRINT #0, I;TAB(3);CL$(I);"(";SD(I);")";TAB(18);FNR1(RV(I));TAB(25);FNR2(VO
(I));TAB(31);FNR2(VC(I));TAB(37);FNR2(R(I));
1680 PRINT #0, TAB(43);FNR2(VS(I));TAB(51);INT(HR(I));TAB(57);INT(F(I));
1685 PRINT #0, TAB(61);FNR1(T(I));TAB(66);FNR4(O(I));TAB(74);FNR4(C(I));
1690 PRINT #0, TAB(82);FNR2(EO(I));TAB(88);FNR2(EC(I));TAB(95);FNR1(Q(I));
1695 PRINT #0, TAB(101);INT(SV(I));TAB(106);FNR2(OP(I));TAB(113);FNR2(TV(I));
1700 PRINT #0, TAB(120);FNR2(SP(I))
1740 IF U>=LS-1 THEN GOTO 1750
1745 GOTO 865
1750 POKE HEX("8013"),0:POKE HEX("8012"),HEX("80"):REM - STOP CLOCK
1760 END
3000 M1$=CHR$(PEEK(HEX("7F95"))):M2$=CHR$(PEEK(HEX("7F96")))
3010 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
3020 CK=60*(10*VAL(M1$)+VAL(M2$))+10*VAL(S1$)+VAL(S2$)
3040 RETURN
3200 AA=(PEEK(HEX("8002"))*256+PEEK(HEX("8000")))/10
3210 IF BB=CC AND AA<>BB THEN F(K)=F(K)+1
3220 CC=BB:BB=AA
3230 RETURN
3400 H1$=CHR$(PEEK(HEX("7F93"))):H2$=CHR$(PEEK(HEX("7F94")))
3410 M1$=CHR$(PEEK(HEX("7F95"))):M2$=CHR$(PEEK(HEX("7F96")))
3420 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
3430 U=3600*(10*VAL(H1$)+VAL(H2$))+60*(10*VAL(M1$)+VAL(M2$))+10*VAL(S1$)+VAL(S2$
)
3440 CK$=H1$+H2$+":"+M1$+M2$+":"+S1$+S2$
3450 IF U>=(T3+1) THEN PRINT CK$,
3460 RETURN
3700 H1$=CHR$(PEEK(HEX("7F93"))):H2$=CHR$(PEEK(HEX("7F94")))
3710 M1$=CHR$(PEEK(HEX("7F95"))):M2$=CHR$(PEEK(HEX("7F96")))
3720 S1$=CHR$(PEEK(HEX("7F97"))):S2$=CHR$(PEEK(HEX("7F98")))
3730 T3=3600*(10*VAL(H1$)+VAL(H2$))+60*(10*VAL(M1$)+VAL(M2$))+10*VAL(S1$)+VAL(S2
$)
3740 RETURN
```

# APPENDIX 3

## PRE-TEST INFORMATION TO SUBJECTS

# WORK PHYSIOLOGY LABORATORY

## PRE-TEST QUESTIONNAIRE

Experiment________________________________________

Name:________________________ Subject number:________

Date:___/___/___ Time of Day:___________

1) Hours of sleep last night?:________________________

2) Do you feel well rested? YES NO

3) Any illnesses or injuries during the past two weeks?

   YES NO __________________________________

4) Time of last meal?___________ Normal, Big, Small?

5) Are you on any medication? YES NO ___________

6) Have you had anything to eat, drink or smoke during the last hour? YES NO ________________________

7) Is there any reason why you should not participate in this test? YES NO ________________________

Signature of Subject____________________

Signature of Investigator________________

## RHODES UNIVERSITY

## DEPARTMENT OF HUMAN MOVEMENT STUDIES AND PHYSICAL EDUCATION

## SUBJECT CONSENT FORM

I, ________________________________ having been fully informed of the nature of the research entitled Economy and Efficiency of Locomotion do hereby give my consent to act as a subject in the above-named research.

### PROCEDURES, RISKS AND BENEFITS

You will be asked to habituate to treadmill walking and running in 3 sessions of 15 minutes practice. This will be followed by a test of maximal work capacity involving a progressively increasing speed run on the treadmill while we continuously measure oxygen consumption via inspired and expired air analysis. On each of four other days you will be asked to walk or run slowly, moderately or quickly at 0, +3 and -3 percent grade. These 24 conditions will be randomly assigned six per test day. Each condition will last 4 minutes with a short rest in between. Again oxygen consumption will be measured. Before one of the habituation sessions we will measure your height, sitting height, foot length, body mass and four skinfolds.

The risks you may encounter during this experiment are similar to those experienced during light to heavy exercise. We will have a safety person on hand at all times to protect your interests.

The benefits you will accrue will include personal information on your maximal exercise capability ($\dot{V}O_2$ max), the speed at which you personally are most economical, an estimate of your percent body fat, your lean body mass and ideal body mass. Furthermore, you will be providing a valuable service to the advancement of our knowledge in this area of human performance.

I am fully aware of the procedures involved as well as the potential risks and benefits attendant to my participation as explained to me verbally and in writing. In agreeing to participate in this research, I waive any legal recourse against the researchers or Rhodes University, from any and all claims resulting from personal injuries sustained. This waiver shall be binding upon my heirs and personal representatives. I realize that it is necessary for me to promptly report to the researcher any signs or symptoms indicating any abnormality or distress.

I am aware that I may withdraw my consent and withdraw from participation in the research at any time. I am aware that my anonymity will be protected at all times, and agree that the information collected may be used and published for statistical or scientific purposes.

I have read the foregoing and I understand it. Any questions which may have occurred to me have been answered to my satisfaction.

Subject (or legal representative)

(PRINT NAME) (SIGNATURE) (DATE)

**********************************************************

Person Administering Informed Consent

(PRINT NAME) (SIGNATURE) (DATE)

**********************************************************

Witness

(PRINT NAME) (SIGNATURE) (DATE)

**********************************************************

Project Supervisor

(PRINT NAME) (SIGNATURE) (DATE)

**********************************************************

The following instruction was read to each subject prior to their test of maximal oxygen uptake. They were reminded of it's content before each walk/run session:

> "We want you to estimate how hard you feel the work is: that is we want you to rate the degree of perceived exertion you feel. By perceived exertion we mean the total amount of exertion and physical fatigue, combining all sensations and feelings of physical stress, effort and fatigue. Don't concern yourself with any one factor such as leg discomfort or shortness of breath, but try to concentrate on your total inner feeling of exertion. Try to estimate as honestly and objectively as possible. Don't underestimate the degree of exertion you feel, but don't overestimate it either. Just try to estimate as accurately as possible. When you are asked to rate your work, you should do so by giving the numerical value on the scale in front of you which indicates your evaluation of your perceived exertion at that moment. A rating of 6 corresponds with feelings of exertion while standing quietly on the treadmill. A rating of 20 reflects maximal exertion."
>
> (Mihevic 1983)

# RATING OF PERCEIVED EXERTION

Subjects were asked to rate their perceptions of exertion numerically on the following scale.

## THE BORG RPE SCALE

6

7 - very, very light

8

9 - very light

10

11 - fairly light

12

13 - somewhat hard

14

15 - hard

16

17 - very hard

18

19 - very, very hard

20

## APPENDIX 4

## TREADMILL SPEED RELATIONSHIPS

Relative speed is expressed as the fraction of stature (m) covered overground during locomotion per second. Thus:

(1) Velocity ($m.s^{-1}$) = Relative Speed x Stature (m)

(2) Velocity ($m.min^{-1}$) = Velocity ($m.s^{-1}$) x 60

(3) Velocity ($km.h^{-1}$) = Velocity ($m.s^{-1}$) x 3.6

By direct measurement on the treadmill used in this study:

1 belt count = 1.27 m

Thus:

Counts per 30s = (Velocity ($m.s^{-1}$) x 30s)/1.27

or, with substitution from equation (1) and simplifying:

Counts per 30s = Stature (m) x (Relative Speed x 23.622)

The following tables were developed, based on these relationships, to facilitate setting the correct velocity for subjects with statures between 150 cm and 200 cm.

Table VIII Absolute velocities (m.s$^{-1}$) at walking relative speeds for individuals of different stature

| Stature | Velocity (m.s$^{-1}$) at Walking Relative Speeds | | | | |
|---|---|---|---|---|---|
| (cm) | 0.5 | 0.7 | 0.9 | 1.1 | 1.3 |
| 150 | 0.75 | 1.05 | 1.35 | 1.65 | 1.95 |
| 151 | 0.76 | 1.06 | 1.36 | 1.66 | 1.96 |
| 152 | 0.76 | 1.06 | 1.37 | 1.67 | 1.98 |
| 153 | 0.77 | 1.07 | 1.38 | 1.68 | 1.99 |
| 154 | 0.77 | 1.08 | 1.39 | 1.69 | 2.00 |
| 155 | 0.78 | 1.09 | 1.40 | 1.71 | 2.02 |
| 156 | 0.78 | 1.09 | 1.40 | 1.72 | 2.03 |
| 157 | 0.79 | 1.10 | 1.41 | 1.73 | 2.04 |
| 158 | 0.79 | 1.11 | 1.42 | 1.74 | 2.05 |
| 159 | 0.80 | 1.11 | 1.43 | 1.75 | 2.07 |
| 160 | 0.80 | 1.12 | 1.44 | 1.76 | 2.08 |
| 161 | 0.81 | 1.13 | 1.45 | 1.77 | 2.09 |
| 162 | 0.81 | 1.13 | 1.46 | 1.78 | 2.11 |
| 163 | 0.82 | 1.14 | 1.47 | 1.79 | 2.12 |
| 164 | 0.82 | 1.15 | 1.48 | 1.80 | 2.13 |
| 165 | 0.83 | 1.16 | 1.49 | 1.82 | 2.15 |
| 166 | 0.83 | 1.16 | 1.49 | 1.83 | 2.16 |
| 167 | 0.84 | 1.17 | 1.50 | 1.84 | 2.17 |
| 168 | 0.84 | 1.18 | 1.51 | 1.85 | 2.18 |
| 169 | 0.85 | 1.18 | 1.52 | 1.86 | 2.20 |
| 170 | 0.85 | 1.19 | 1.53 | 1.87 | 2.21 |
| 171 | 0.86 | 1.20 | 1.54 | 1.88 | 2.22 |
| 172 | 0.86 | 1.20 | 1.55 | 1.89 | 2.24 |
| 173 | 0.87 | 1.21 | 1.56 | 1.90 | 2.25 |
| 174 | 0.87 | 1.22 | 1.57 | 1.91 | 2.26 |
| 175 | 0.88 | 1.23 | 1.58 | 1.93 | 2.28 |
| 176 | 0.88 | 1.23 | 1.58 | 1.94 | 2.29 |
| 177 | 0.89 | 1.24 | 1.59 | 1.95 | 2.30 |
| 178 | 0.89 | 1.25 | 1.60 | 1.96 | 2.31 |
| 179 | 0.90 | 1.25 | 1.61 | 1.97 | 2.33 |
| 180 | 0.90 | 1.26 | 1.62 | 1.98 | 2.34 |
| 181 | 0.91 | 1.27 | 1.63 | 1.99 | 2.35 |
| 182 | 0.91 | 1.27 | 1.64 | 2.00 | 2.37 |
| 183 | 0.92 | 1.28 | 1.65 | 2.01 | 2.38 |
| 184 | 0.92 | 1.29 | 1.66 | 2.02 | 2.39 |
| 185 | 0.93 | 1.30 | 1.67 | 2.04 | 2.41 |
| 186 | 0.93 | 1.30 | 1.67 | 2.05 | 2.42 |
| 187 | 0.94 | 1.31 | 1.68 | 2.06 | 2.43 |
| 188 | 0.94 | 1.32 | 1.69 | 2.07 | 2.44 |
| 189 | 0.95 | 1.32 | 1.70 | 2.08 | 2.46 |
| 190 | 0.95 | 1.33 | 1.71 | 2.09 | 2.47 |
| 191 | 0.96 | 1.34 | 1.72 | 2.10 | 2.48 |
| 192 | 0.96 | 1.34 | 1.73 | 2.11 | 2.50 |
| 193 | 0.97 | 1.35 | 1.74 | 2.12 | 2.51 |
| 194 | 0.97 | 1.36 | 1.75 | 2.13 | 2.52 |
| 195 | 0.98 | 1.37 | 1.76 | 2.15 | 2.54 |
| 196 | 0.98 | 1.37 | 1.76 | 2.16 | 2.55 |
| 197 | 0.99 | 1.38 | 1.77 | 2.17 | 2.56 |
| 198 | 0.99 | 1.39 | 1.78 | 2.18 | 2.57 |
| 199 | 1.00 | 1.39 | 1.79 | 2.19 | 2.59 |
| 200 | 1.00 | 1.40 | 1.80 | 2.20 | 2.60 |

Table IX Absolute velocities ($m.s^{-1}$) at running relative speeds for individuals of different stature

| Stature | Velocity ($m.s^{-1}$) at Running Relative Speeds | | | | | |
|---|---|---|---|---|---|---|
| (cm) | 1.5 | 1.7 | 1.9 | 2.1 | 2.3 | 2.5 |
| 150 | 2.25 | 2.55 | 2.85 | 3.15 | 3.45 | 3.75 |
| 151 | 2.27 | 2.57 | 2.87 | 3.17 | 3.47 | 3.78 |
| 152 | 2.28 | 2.58 | 2.89 | 3.19 | 3.50 | 3.80 |
| 153 | 2.30 | 2.60 | 2.91 | 3.21 | 3.52 | 3.83 |
| 154 | 2.31 | 2.62 | 2.93 | 3.23 | 3.54 | 3.85 |
| 155 | 2.33 | 2.64 | 2.95 | 3.26 | 3.57 | 3.88 |
| 156 | 2.34 | 2.65 | 2.96 | 3.28 | 3.59 | 3.90 |
| 157 | 2.36 | 2.67 | 2.98 | 3.30 | 3.61 | 3.93 |
| 158 | 2.37 | 2.69 | 3.00 | 3.32 | 3.63 | 3.95 |
| 159 | 2.39 | 2.70 | 3.02 | 3.34 | 3.66 | 3.98 |
| 160 | 2.40 | 2.72 | 3.04 | 3.36 | 3.68 | 4.00 |
| 161 | 2.42 | 2.74 | 3.06 | 3.38 | 3.70 | 4.03 |
| 162 | 2.43 | 2.75 | 3.08 | 3.40 | 3.73 | 4.05 |
| 163 | 2.45 | 2.77 | 3.10 | 3.42 | 3.75 | 4.08 |
| 164 | 2.46 | 2.79 | 3.12 | 3.44 | 3.77 | 4.10 |
| 165 | 2.48 | 2.81 | 3.14 | 3.47 | 3.80 | 4.13 |
| 166 | 2.49 | 2.82 | 3.15 | 3.49 | 3.82 | 4.15 |
| 167 | 2.51 | 2.84 | 3.17 | 3.51 | 3.84 | 4.18 |
| 168 | 2.52 | 2.86 | 3.19 | 3.53 | 3.86 | 4.20 |
| 169 | 2.54 | 2.87 | 3.21 | 3.55 | 3.89 | 4.23 |
| 170 | 2.55 | 2.89 | 3.23 | 3.57 | 3.91 | 4.25 |
| 171 | 2.57 | 2.91 | 3.25 | 3.59 | 3.93 | 4.28 |
| 172 | 2.58 | 2.92 | 3.27 | 3.61 | 3.96 | 4.30 |
| 173 | 2.60 | 2.94 | 3.29 | 3.63 | 3.98 | 4.33 |
| 174 | 2.61 | 2.96 | 3.31 | 3.65 | 4.00 | 4.35 |
| 175 | 2.63 | 2.98 | 3.33 | 3.68 | 4.03 | 4.38 |
| 176 | 2.64 | 2.99 | 3.34 | 3.70 | 4.05 | 4.40 |
| 177 | 2.66 | 3.01 | 3.36 | 3.72 | 4.07 | 4.43 |
| 178 | 2.67 | 3.03 | 3.38 | 3.74 | 4.09 | 4.45 |
| 179 | 2.69 | 3.04 | 3.40 | 3.76 | 4.12 | 4.48 |
| 180 | 2.70 | 3.06 | 3.42 | 3.78 | 4.14 | 4.50 |
| 181 | 2.72 | 3.08 | 3.44 | 3.80 | 4.16 | 4.53 |
| 182 | 2.73 | 3.09 | 3.46 | 3.82 | 4.19 | 4.55 |
| 183 | 2.75 | 3.11 | 3.48 | 3.84 | 4.21 | 4.58 |
| 184 | 2.76 | 3.13 | 3.50 | 3.86 | 4.23 | 4.60 |
| 185 | 2.78 | 3.15 | 3.52 | 3.89 | 4.26 | 4.63 |
| 186 | 2.79 | 3.16 | 3.53 | 3.91 | 4.28 | 4.65 |
| 187 | 2.81 | 3.18 | 3.55 | 3.93 | 4.30 | 4.68 |
| 188 | 2.82 | 3.20 | 3.57 | 3.95 | 4.32 | 4.70 |
| 189 | 2.85 | 3.21 | 3.59 | 3.97 | 4.35 | 4.73 |
| 190 | 2.85 | 3.23 | 3,61 | 3.99 | 4.37 | 4.75 |
| 191 | 2.87 | 3.25 | 3.63 | 4.01 | 4.39 | 4.78 |
| 192 | 2.58 | 3.26 | 3.65 | 4.03 | 4.42 | 4.80 |
| 193 | 2.90 | 3.28 | 3.67 | 4.05 | 4.44 | 4.83 |
| 194 | 2.91 | 3.30 | 3.69 | 4.07 | 4.46 | 4.85 |
| 195 | 2.93 | 3.32 | 3.71 | 4.10 | 4.49 | 4.88 |
| 196 | 2.94 | 3.33 | 3.72 | 4.12 | 4.51 | 4.90 |
| 197 | 2.96 | 3.35 | 3.74 | 4.14 | 4.53 | 4.93 |
| 198 | 2.97 | 3.37 | 3.76 | 4.16 | 4.55 | 4.95 |
| 199 | 2.99 | 3.38 | 3.78 | 4.18 | 4.58 | 4.98 |
| 200 | 3.00 | 3.40 | 3.80 | 4.20 | 4.60 | 5.00 |

Table X Absolute velocities (km.h$^{-1}$) at walking relative speeds for individuals of different stature

| Stature (cm) | Velocity (km.h$^{-1}$) at Walking Relative Speeds | | | | |
|---|---|---|---|---|---|
| | 0.5 | 0.7 | 0.9 | 1.1 | 1.3 |
| 150 | 2.70 | 3.78 | 4.86 | 5.94 | 7.02 |
| 151 | 2.72 | 3.81 | 4.89 | 5.98 | 7.07 |
| 152 | 2.74 | 3.83 | 4.92 | 6.02 | 7.11 |
| 153 | 2.75 | 3.86 | 4.96 | 6.06 | 7.16 |
| 154 | 2.77 | 3.88 | 4.99 | 6.10 | 7.21 |
| 155 | 2.79 | 3.91 | 5.02 | 6.14 | 7.25 |
| 156 | 2.81 | 3.93 | 5.05 | 6.18 | 7.30 |
| 157 | 2.83 | 3.96 | 5.09 | 6.22 | 7.35 |
| 158 | 2.84 | 3.98 | 5.12 | 6.26 | 7.39 |
| 159 | 2.86 | 4.01 | 5.15 | 6.30 | 7.44 |
| 160 | 2.88 | 4.03 | 5.18 | 6.34 | 7.49 |
| 161 | 2.90 | 4.06 | 5.22 | 6.38 | 7.53 |
| 162 | 2.92 | 4.08 | 5.25 | 6.42 | 7.58 |
| 163 | 2.93 | 4.11 | 5.28 | 6.45 | 7.63 |
| 164 | 2.95 | 4.13 | 5.31 | 6.49 | 7.68 |
| 165 | 2.97 | 4.16 | 5.35 | 6.53 | 7.72 |
| 166 | 2.99 | 4.18 | 5.38 | 6.57 | 7.77 |
| 167 | 3.01 | 4.21 | 5.41 | 6.61 | 7.82 |
| 168 | 3.02 | 4.23 | 5.44 | 6.65 | 7.86 |
| 169 | 3.04 | 4.26 | 5.48 | 6.69 | 7.91 |
| 170 | 3.06 | 4.28 | 5.51 | 6.73 | 7.96 |
| 171 | 3.08 | 4.31 | 5.54 | 6.77 | 8.00 |
| 172 | 3.10 | 4.33 | 5.57 | 6.81 | 8.05 |
| 173 | 3.11 | 4.36 | 5.61 | 6.85 | 8.10 |
| 174 | 3.13 | 4.38 | 5.64 | 6.89 | 8.14 |
| 175 | 3.15 | 4.41 | 5.67 | 6.93 | 8.19 |
| 176 | 3.17 | 4.44 | 5.70 | 6.97 | 8.24 |
| 177 | 3.19 | 4.46 | 5.73 | 7.01 | 8.28 |
| 178 | 3.20 | 4.49 | 5.77 | 7.05 | 8.33 |
| 179 | 3.22 | 4.51 | 5.80 | 7.09 | 8.38 |
| 180 | 3.24 | 4.54 | 5.83 | 7.13 | 8.42 |
| 181 | 3.26 | 4.56 | 5.86 | 7.17 | 8.47 |
| 182 | 3.28 | 4.59 | 5.90 | 7.21 | 8.52 |
| 183 | 3.29 | 4.61 | 5.93 | 7.25 | 8.56 |
| 184 | 3.31 | 4.64 | 5.96 | 7.29 | 8.61 |
| 185 | 3.33 | 4.66 | 5.99 | 7.33 | 8.66 |
| 186 | 3.35 | 4.69 | 6.03 | 7.37 | 8.70 |
| 187 | 3.37 | 4.71 | 6.06 | 7.41 | 8.75 |
| 188 | 3.38 | 4.74 | 6.09 | 7.44 | 8.80 |
| 189 | 3.40 | 4.76 | 6.12 | 7.48 | 8.85 |
| 190 | 3.42 | 4.79 | 6.16 | 7.52 | 8.89 |
| 191 | 3.44 | 4.81 | 6.19 | 7.56 | 8.94 |
| 192 | 3.46 | 4.84 | 6.22 | 7.60 | 8.99 |
| 193 | 3.47 | 4.86 | 6.25 | 7.64 | 9.03 |
| 194 | 3.49 | 4.89 | 6.29 | 7.68 | 9.08 |
| 195 | 3.51 | 4.91 | 6.32 | 7.72 | 9.13 |
| 196 | 3.53 | 4.94 | 6.35 | 7.76 | 9.17 |
| 197 | 3.55 | 4.96 | 6.38 | 7.80 | 9.22 |
| 198 | 3.56 | 4.99 | 6.42 | 7.84 | 9.27 |
| 199 | 3.58 | 5.01 | 6.45 | 7.88 | 9.31 |
| 200 | 3.60 | 5.04 | 6.48 | 7.92 | 9.36 |

Table XI Absolute velocities (km.h$^{-1}$) at running relative speeds for individuals of different stature

| Stature (cm) | Velocity (km.h$^{-1}$) at Running Relative Speeds | | | | | |
|---|---|---|---|---|---|---|
| | 1.5 | 1.7 | 1.9 | 2.1 | 2.3 | 2.5 |
| 150 | 8.10 | 9.18 | 10.26 | 11.34 | 12.42 | 13.50 |
| 151 | 8.15 | 9.24 | 10.33 | 11.41 | 12.50 | 13.59 |
| 152 | 8.21 | 9.30 | 10.40 | 11.49 | 12.59 | 13.68 |
| 153 | 8.26 | 9.36 | 10.47 | 11.57 | 12.67 | 13.77 |
| 154 | 8.32 | 9.42 | 10.53 | 11.64 | 12.75 | 13.86 |
| 155 | 8.37 | 9.49 | 10.60 | 11.72 | 12.83 | 13.95 |
| 156 | 8.42 | 9.55 | 10.67 | 11.79 | 12.92 | 14.04 |
| 157 | 8.48 | 9.61 | 10.74 | 11.87 | 13.00 | 14.13 |
| 158 | 8.52 | 9.67 | 10.81 | 11.94 | 13.08 | 14.22 |
| 159 | 8.59 | 9.73 | 10.88 | 12.02 | 13.17 | 14.31 |
| 160 | 8.64 | 9.79 | 10.94 | 12.10 | 13.25 | 14.40 |
| 161 | 8.69 | 9.85 | 11.01 | 12.17 | 13.33 | 14.49 |
| 162 | 8.75 | 9.91 | 11.08 | 12.25 | 13.41 | 14.58 |
| 163 | 8.80 | 9.98 | 11.15 | 12.32 | 13.50 | 14.67 |
| 164 | 8.86 | 10.04 | 11.22 | 12.40 | 13.58 | 14.76 |
| 165 | 8.91 | 10.10 | 11.29 | 12.47 | 13.66 | 14.85 |
| 166 | 8.96 | 10.16 | 11.35 | 12.55 | 13.74 | 14.94 |
| 167 | 9.02 | 10.22 | 11.42 | 12.63 | 13.83 | 15.03 |
| 168 | 9.07 | 10.28 | 11.49 | 12.70 | 13.91 | 15.12 |
| 169 | 9.13 | 10.34 | 11.56 | 12.78 | 13.99 | 15.21 |
| 170 | 9.18 | 10.40 | 11.63 | 12.85 | 14.08 | 15.30 |
| 171 | 9.23 | 10.47 | 11.70 | 12.93 | 14.16 | 15.39 |
| 172 | 9.29 | 10.53 | 11.76 | 13.00 | 14.24 | 15.48 |
| 173 | 9.34 | 10.59 | 11.83 | 13.08 | 14.32 | 15.57 |
| 174 | 9.40 | 10.65 | 11.90 | 13.15 | 14.41 | 15.66 |
| 175 | 9.45 | 10.71 | 11.97 | 13.23 | 14.49 | 15.75 |
| 176 | 9.50 | 10.77 | 12.04 | 13.31 | 14.57 | 15.84 |
| 177 | 9.56 | 10.83 | 12.11 | 13.38 | 14.66 | 15.93 |
| 178 | 9.61 | 10.89 | 12.18 | 13.46 | 14.74 | 16.02 |
| 179 | 9.67 | 10.95 | 12.24 | 13.53 | 14.82 | 16.11 |
| 180 | 9.72 | 11.02 | 12.31 | 13.61 | 14.90 | 16.20 |
| 181 | 9.77 | 11.08 | 12.38 | 13.68 | 14.99 | 16.29 |
| 182 | 9.83 | 11.14 | 12.45 | 13.76 | 15.07 | 16.38 |
| 183 | 9.88 | 11.20 | 12.52 | 13.83 | 15.15 | 16.47 |
| 184 | 9.94 | 11.26 | 12.59 | 13.91 | 15.24 | 16.56 |
| 185 | 9.99 | 11.32 | 12.65 | 13.99 | 15.32 | 16.65 |
| 186 | 10.04 | 11.38 | 12.72 | 14.06 | 15.40 | 16.74 |
| 187 | 10.10 | 11.44 | 12.79 | 14.14 | 15.48 | 16.83 |
| 188 | 10.15 | 11.51 | 12.86 | 14.21 | 15.57 | 16.92 |
| 189 | 10.21 | 11.57 | 12.93 | 14.29 | 15.65 | 17.01 |
| 190 | 10.26 | 11.63 | 13.00 | 14.36 | 15.73 | 17.10 |
| 191 | 10.31 | 11.69 | 13.06 | 14.44 | 15.81 | 17.19 |
| 192 | 10.37 | 11.75 | 13.13 | 14.52 | 15.90 | 17.28 |
| 193 | 10.42 | 11.81 | 13.20 | 14.59 | 15.98 | 17.37 |
| 194 | 10.48 | 11.87 | 13.27 | 14.67 | 16.06 | 17.46 |
| 195 | 10.53 | 11.93 | 13.34 | 14.74 | 16.15 | 17.55 |
| 196 | 10.58 | 12.00 | 13.41 | 14.82 | 16.23 | 17.64 |
| 197 | 10.64 | 12.06 | 13.47 | 14.89 | 16.31 | 17.73 |
| 198 | 10.69 | 12.12 | 13.54 | 14.97 | 16.39 | 17.82 |
| 199 | 10.75 | 12.18 | 13.61 | 15.04 | 16.48 | 17.91 |
| 200 | 10.80 | 12.24 | 13.68 | 15.12 | 16.56 | 18.00 |

Table XII Number of treadmill belt counts in 30s to achieve walking relative speeds (st.$s^{-1}$) for individuals of different stature

| Stature | Counts per 30s at Walking Relative Speeds | | | | |
|---|---|---|---|---|---|
| (cm) | 0.5 | 0.7 | 0.9 | 1.1 | 1.3 |
| 150 | 17.7 | 24.8 | 31.9 | 39.0 | 46.1 |
| 151 | 17.8 | 25.0 | 32.1 | 39.2 | 46.4 |
| 152 | 18.0 | 25.1 | 32.3 | 39.5 | 46.7 |
| 153 | 18.1 | 25.3 | 32.5 | 39.8 | 47.0 |
| 154 | 18.2 | 25.5 | 32.7 | 40.0 | 47.3 |
| 155 | 18.3 | 25.6 | 33.0 | 40.3 | 47.6 |
| 156 | 18.4 | 25.8 | 33.2 | 40.5 | 47.9 |
| 157 | 18.5 | 26.0 | 33.4 | 40.8 | 48.2 |
| 158 | 18.7 | 26.1 | 33.6 | 41.1 | 48.5 |
| 159 | 18.8 | 26.3 | 33.8 | 41.3 | 48.8 |
| 160 | 18.9 | 26.5 | 34.0 | 41.6 | 49.1 |
| 161 | 19.0 | 26.6 | 34.2 | 41.8 | 49.4 |
| 162 | 19.1 | 26.8 | 34.4 | 42.1 | 49.7 |
| 163 | 19.3 | 27.0 | 34.7 | 42.4 | 50.1 |
| 164 | 19.4 | 27.1 | 34.9 | 42.6 | 50.4 |
| 165 | 19.5 | 27.3 | 35.1 | 42.9 | 50.7 |
| 166 | 19.6 | 27.4 | 35.3 | 43.1 | 51.0 |
| 167 | 19.7 | 27.6 | 35.5 | 43.4 | 51.3 |
| 168 | 19.8 | 27.8 | 35.7 | 43.7 | 51.6 |
| 169 | 20.0 | 27.9 | 35.9 | 43.9 | 51,9 |
| 170 | 20.1 | 28.1 | 36.1 | 44.2 | 52.2 |
| 171 | 20.2 | 28.3 | 36.4 | 44.4 | 52.5 |
| 172 | 20.3 | 28.4 | 36.6 | 44.7 | 52.8 |
| 173 | 20.4 | 28.6 | 36.8 | 45.0 | 53.1 |
| 174 | 20.6 | 28.8 | 37.0 | 45.2 | 53.4 |
| 175 | 20.7 | 28.9 | 37.2 | 45.5 | 53.7 |
| 176 | 20.8 | 29.1 | 37.4 | 45.7 | 54.1 |
| 177 | 20.9 | 29.3 | 37.6 | 46.0 | 54.4 |
| 178 | 21.0 | 29.4 | 37.8 | 46.3 | 54.7 |
| 179 | 21.1 | 29.6 | 38.1 | 46.5 | 55.0 |
| 180 | 21.3 | 29.8 | 38.3 | 46.8 | 55.3 |
| 181 | 21.4 | 29.9 | 38.5 | 47.0 | 55.6 |
| 182 | 21.5 | 30.1 | 38.7 | 47.3 | 55.9 |
| 183 | 21.6 | 30.3 | 38.9 | 47.6 | 56.2 |
| 184 | 21.7 | 30.4 | 39.1 | 47.8 | 56.5 |
| 185 | 21.9 | 30.6 | 39.3 | 48.1 | 56.8 |
| 186 | 22.0 | 30.8 | 39.5 | 48.3 | 57.1 |
| 187 | 22.1 | 30.9 | 39.8 | 48.6 | 57.4 |
| 188 | 22.2 | 31.1 | 40.0 | 48.9 | 57.7 |
| 189 | 22.3 | 31.3 | 40.2 | 49.1 | 58.0 |
| 190 | 22.4 | 31.4 | 40.4 | 49.4 | 58.3 |
| 191 | 22.6 | 31.6 | 40.6 | 49.6 | 58.7 |
| 192 | 22.7 | 31.7 | 40.8 | 49.9 | 59.0 |
| 193 | 22.8 | 31.9 | 41.0 | 50.1 | 59.3 |
| 194 | 22.9 | 32.1 | 41.2 | 50.4 | 59.6 |
| 195 | 23.0 | 32.2 | 41.5 | 50.7 | 59.9 |
| 196 | 23.1 | 32.4 | 41.7 | 50.9 | 60.2 |
| 197 | 23.3 | 32.6 | 41.9 | 51.2 | 60.5 |
| 198 | 23.4 | 32.7 | 42.1 | 51.4 | 60.8 |
| 199 | 23.5 | 32.9 | 42.3 | 51.7 | 61.1 |
| 200 | 23.6 | 33.1 | 42.5 | 52.0 | 61.4 |

Table XIII Number of treadmill belt counts in 30s to achieve running relative speeds (st.s$^{-1}$) for individuals of different stature

| Stature | Counts per 30s at Running Relative Speeds | | | | | |
|---|---|---|---|---|---|---|
| (cm) | 1.5 | 1.7 | 1.9 | 2.1 | 2.3 | 2.5 |
| 150 | 53.1 | 60.2 | 67.3 | 74.4 | 81.5 | 88.6 |
| 151 | 53.5 | 60.6 | 67.8 | 74.9 | 82.0 | 89.2 |
| 152 | 53.9 | 61.0 | 68.2 | 75.4 | 82.6 | 89.8 |
| 153 | 54.2 | 61.4 | 68.7 | 75.9 | 83.1 | 90.4 |
| 154 | 54.6 | 61.8 | 69.1 | 76.4 | 83.7 | 90.9 |
| 155 | 54.9 | 62.2 | 69.6 | 76.9 | 84.2 | 91.5 |
| 156 | 55.3 | 62.6 | 70.0 | 77.4 | 84.8 | 92.1 |
| 157 | 55.6 | 63.0 | 70.5 | 77.9 | 85.3 | 92.7 |
| 158 | 56.0 | 63.4 | 70.9 | 78.4 | 85.8 | 93.3 |
| 159 | 56.3 | 63.9 | 71.4 | 78.9 | 86.4 | 93.9 |
| 160 | 56.7 | 64.3 | 71.8 | 79.4 | 86.9 | 94.5 |
| 161 | 57.0 | 64.7 | 72.3 | 79.9 | 87.5 | 95.1 |
| 162 | 57.4 | 65.1 | 72.7 | 80.4 | 88.0 | 95.7 |
| 163 | 57.8 | 65.5 | 73.2 | 80.9 | 88.6 | 96.3 |
| 164 | 58.1 | 65.9 | 73.6 | 81.4 | 89.1 | 96.9 |
| 165 | 58.5 | 66.3 | 74.1 | 81.9 | 89.6 | 97.4 |
| 166 | 58.8 | 66.7 | 74.5 | 82.4 | 90.2 | 98.0 |
| 167 | 59.2 | 67.1 | 75.0 | 82.8 | 90.7 | 98.6 |
| 168 | 59.5 | 67.5 | 75.4 | 83.3 | 91.3 | 99.2 |
| 169 | 59.9 | 67.9 | 75.9 | 83.8 | 91.8 | 99.8 |
| 170 | 60.2 | 68.3 | 76.3 | 84.3 | 92.4 | 100.4 |
| 171 | 60.6 | 68.7 | 76.7 | 84.8 | 92.9 | 101.0 |
| 172 | 60.9 | 69.1 | 77.2 | 85.3 | 93.4 | 101.6 |
| 173 | 61.3 | 69.5 | 77.6 | 85.8 | 94.0 | 102.2 |
| 174 | 61.7 | 69.9 | 78.1 | 86.3 | 94.5 | 102.8 |
| 175 | 62.0 | 70.3 | 78.5 | 86.8 | 95.1 | 103.3 |
| 176 | 62.4 | 70.7 | 79.0 | 87.3 | 95.6 | 103.9 |
| 177 | 62.7 | 71.1 | 79.4 | 87.8 | 96.2 | 104.5 |
| 178 | 63.1 | 71.5 | 79.9 | 88.3 | 96.7 | 105.1 |
| 179 | 63.4 | 71.9 | 80.3 | 88.8 | 97.3 | 105.7 |
| 180 | 63.8 | 72.3 | 80.8 | 89.3 | 97.8 | 106.3 |
| 181 | 64.1 | 72.7 | 81.2 | 89.8 | 98.3 | 106.9 |
| 182 | 64.5 | 73.1 | 81.7 | 90.3 | 98.9 | 107.5 |
| 183 | 64.8 | 73.5 | 82.1 | 90.8 | 99.4 | 108.1 |
| 184 | 65.2 | 73.9 | 82.6 | 91.3 | 100.0 | 108.7 |
| 185 | 65.6 | 74.3 | 83.0 | 91.8 | 100.5 | 109.3 |
| 186 | 65.9 | 74.7 | 83.5 | 92.3 | 101.1 | 109.8 |
| 187 | 66.3 | 75.1 | 83.9 | 92.8 | 101.6 | 110.4 |
| 188 | 66.6 | 75.5 | 84.4 | 93.3 | 102.1 | 111.0 |
| 189 | 67.0 | 75.9 | 84.8 | 93.8 | 102.7 | 111.6 |
| 190 | 67.3 | 76.3 | 85.3 | 94.3 | 103.2 | 112.2 |
| 191 | 67.7 | 76.7 | 85.7 | 94.7 | 103.8 | 112.8 |
| 192 | 68.0 | 77.1 | 86.2 | 95.2 | 104.3 | 113.4 |
| 193 | 68.4 | 77.5 | 86.2 | 95.7 | 104.9 | 114.0 |
| 194 | 68.7 | 77.9 | 87.1 | 96.2 | 105.4 | 114.6 |
| 195 | 69.1 | 78.3 | 87.5 | 96.7 | 105.9 | 115.2 |
| 196 | 69.4 | 78.7 | 88.0 | 97.2 | 106.5 | 115.7 |
| 197 | 69.8 | 79.1 | 88.4 | 97.7 | 107.0 | 116.3 |
| 198 | 70.2 | 79.5 | 88.9 | 98.2 | 107.6 | 116.9 |
| 199 | 70.5 | 79.9 | 89.3 | 98.7 | 108.1 | 117.5 |
| 200 | 70.9 | 80.3 | 89.8 | 99.2 | 108.7 | 118.1 |

Table XIV Treadmill velocity calibration information for absolute speeds

| Speed km/h | Speed m/min | Speed m/s | Counts in 30s | Speed km/h | Speed m/min | Speed m/s | Counts in 30s |
|---|---|---|---|---|---|---|---|
| 3.0 | 50.0 | 0.83 | 19.7 | 13.0 | 216.7 | 3.61 | 85.3 |
| 3.2 | 53.3 | 0.89 | 21.0 | 13.2 | 220.0 | 3.67 | 86.6 |
| 3.4 | 56.7 | 0.94 | 22.3 | 13.4 | 223.3 | 3.72 | 87.9 |
| 3.6 | 60.0 | 1.00 | 23.6 | 13.6 | 226.7 | 3.78 | 89.2 |
| 3.8 | 63.3 | 1.06 | 24.9 | 13.8 | 230.0 | 3.83 | 90.6 |
| 4.0 | 66.7 | 1.11 | 26.3 | 14.0 | 233.3 | 3.89 | 91.9 |
| 4.2 | 70.0 | 1.17 | 27.6 | 14.2 | 236.7 | 3.94 | 93.2 |
| 4.4 | 73.3 | 1.22 | 28.9 | 14.4 | 240.0 | 4.00 | 94.5 |
| 4.6 | 76.7 | 1.28 | 30.2 | 14.6 | 243.3 | 4.06 | 95.8 |
| 4.8 | 80.0 | 1.33 | 31.5 | 14.8 | 246.7 | 4.11 | 97.1 |
| 5.0 | 83.3 | 1.39 | 32.8 | 15.0 | 250.0 | 4.17 | 98.4 |
| 5.2 | 86.7 | 1.44 | 34.1 | 15.2 | 253.3 | 4.22 | 99.7 |
| 5.4 | 90.0 | 1.50 | 35.4 | 15.4 | 256.7 | 4.28 | 101.1 |
| 5.6 | 93.3 | 1.56 | 36.8 | 15.6 | 260.0 | 4.33 | 102.4 |
| 5.8 | 96.7 | 1.61 | 38.1 | 15.8 | 263.3 | 4.39 | 103.7 |
| 6.0 | 100.0 | 1.67 | 39.4 | 16.0 | 266.7 | 4.44 | 105.0 |
| 6.2 | 103.3 | 1.72 | 40.7 | 16.2 | 270.0 | 4.50 | 106.3 |
| 6.4 | 106.7 | 1.78 | 42.0 | 16.4 | 273.3 | 4.56 | 107.6 |
| 6.6 | 110.0 | 1.83 | 43.3 | 16.6 | 276.6 | 4.61 | 108.9 |
| 6.8 | 113.3 | 1.89 | 44.6 | 16.8 | 280.0 | 4.67 | 110.2 |
| 7.0 | 116.7 | 1.94 | 45.9 | 17.0 | 283.3 | 4.72 | 111.6 |
| 7.2 | 120.0 | 2.00 | 47.2 | 17.2 | 286.7 | 4.78 | 112.9 |
| 7.4 | 123.3 | 2.06 | 48.6 | 17.4 | 290.0 | 4.83 | 114.2 |
| 7.6 | 126.7 | 2.11 | 49.9 | 17.6 | 293.3 | 4.89 | 115.5 |
| 7.8 | 130.0 | 2.17 | 51.2 | 17.8 | 296.7 | 4.94 | 116.8 |
| 8.0 | 133.3 | 2.22 | 52.5 | 18.0 | 300.0 | 5.00 | 118.1 |
| 8.2 | 136.7 | 2.28 | 53.8 | 18.2 | 303.3 | 5.06 | 119.4 |
| 8.4 | 140.0 | 2.33 | 55.1 | 18.4 | 306.7 | 5.11 | 120.7 |
| 8.6 | 143.3 | 2.39 | 56.4 | 18.6 | 310.0 | 5.17 | 122.1 |
| 8.8 | 146.7 | 2.44 | 57.7 | 18.8 | 313.3 | 5.22 | 123.4 |
| 9.0 | 150.0 | 2.50 | 59.1 | 19.0 | 316.7 | 5.28 | 124.7 |
| 9.2 | 153.3 | 2.56 | 60.4 | 19.2 | 320.0 | 5.33 | 126.0 |
| 9.4 | 156.7 | 2.61 | 61.7 | 19.4 | 323.3 | 5.39 | 127.3 |
| 9.6 | 160.0 | 2.67 | 63.0 | 19.6 | 326.7 | 5.44 | 128.6 |
| 9.8 | 163.3 | 2.72 | 64.3 | 19.8 | 330.0 | 5.50 | 129.9 |
| 10.0 | 166.7 | 2.78 | 65.6 | 20.0 | 333.3 | 5.56 | 131.2 |
| 10.2 | 170.0 | 2.83 | 66.9 | 20.2 | 336.7 | 5.61 | 132.6 |
| 10.4 | 173.3 | 2.89 | 68.2 | 20.4 | 340.0 | 5.67 | 133.9 |
| 10.6 | 176.7 | 2.94 | 69.6 | 20.6 | 343.3 | 5.72 | 135.2 |
| 10.8 | 180.0 | 3.00 | 70.9 | 20.8 | 346.7 | 5.78 | 136.5 |
| 11.0 | 183.3 | 3.06 | 72.2 | 21.0 | 350.0 | 5.83 | 137.8 |
| 11.2 | 186.7 | 3.11 | 73.5 | 21.2 | 353.3 | 5.89 | 139.1 |
| 11.4 | 190.0 | 3.17 | 74.8 | 21.4 | 356.7 | 5.94 | 140.4 |
| 11.6 | 193.3 | 3.22 | 76.1 | 21.6 | 360.0 | 6.00 | 141.7 |
| 11.8 | 196.7 | 3.28 | 77.4 | 21.8 | 363.3 | 6.06 | 143.0 |
| 12.0 | 200.0 | 3.33 | 78.7 | 22.0 | 366.7 | 6.11 | 144.4 |
| 12.2 | 203.3 | 3.39 | 80.1 | 22.2 | 370.0 | 6.17 | 145.7 |
| 12.4 | 206.7 | 3.44 | 81.4 | 22.4 | 373.3 | 6.22 | 147.0 |
| 12.6 | 210.0 | 3.50 | 82.7 | 22.6 | 376.7 | 6.28 | 148.3 |
| 12.8 | 213.3 | 3.56 | 84.0 | 22.8 | 380.0 | 6.33 | 149.6 |

# APPENDIX 5

## DATA RECORDING SHEETS

# ECONOMY AND EFFICIENCY OF LOCOMOTION

## PILOT TESTING DATA SHEET

NAME: ____________________ DATE: ___/___/___

Sex: M F

### Treadmill Velocity

| RS | Grade | Pre-set Counts.$30s^{-1}$ | Actual counts.$30s^{-1}$ |
|---|---|---|---|
| 0.5 | 0 | ______ | ______ |
| 1.1 | 0 | ______ | ______ |
| 1.5 | 0 | ______ | ______ |
| 1.9 | 0 | ______ | ______ |
| 0.5 | +3 | ______ | ______ |
| 1.1 | +3 | ______ | ______ |
| 1.5 | +3 | ______ | ______ |
| 1.9 | +3 | ______ | ______ |

### Anthropometry

| | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 |
|---|---|---|---|---|---|
| Stature (cm) | ______ | ______ | ______ | ______ | ______ |
| Sitting Height (cm) | ______ | ______ | ______ | ______ | ______ |
| Body Mass (kg) | ______ | ______ | ______ | ______ | ______ |
| Foot Length (cm) | ______ | ______ | ______ | ______ | ______ |
| Skinfold Bicep (mm) | ______ | ______ | ______ | ______ | ______ |
| Skinfold Subscapular (mm) | ______ | ______ | ______ | ______ | ______ |
| Skinfold Tricep (mm) | ______ | ______ | ______ | ______ | ______ |
| Skinfold Supra-iliac (mm) | ______ | ______ | ______ | ______ | ______ |

# ECONOMY AND EFFICIENCY OF LOCOMOTION

## WALK/RUN PILOT TESTING DATA SHEET

NAME: ________________________ DATE ____/____/____

Sex: M F

Test: 1 2

Rest Heart Rate __________ b.min$^{-1}$

Criterion Heart Rate _____ b.min$^{-1}$

Test Condition

| | RS/Grade | Oxygen Consumption (ml.kg$^{-1}$.min$^{-1}$) | | | Pre-Heart Rate |
|---|---|---|---|---|---|
| | | 2.5-3 | 3-3.5 | 3.5-4.0 | (b.min$^{-1}$) |
| 1. | ____/____ | _____ | _____ | _______ | _________ |
| 2. | ____/____ | _____ | _____ | _______ | _________ |
| 3. | ____/____ | _____ | _____ | _______ | _________ |
| 4. | ____/____ | _____ | _____ | _______ | _________ |
| 5. | ____/____ | _____ | _____ | _______ | _________ |
| 6. | ____/____ | _____ | _____ | _______ | _________ |
| 7. | ____/____ | _____ | _____ | _______ | _________ |
| 8. | ____/____ | _____ | _____ | _______ | _________ |

## ECONOMY AND EFFICIENCY OF LOCOMOTION

## HABITUATION DATA COLLECTION SHEET

NAME: ____________________ SUBJECT NUMBER: ______

SEX: M F BIRTHDATE: ___/___/___ AGE: ____ YRS.

LOCAL ADDRESS ____________________ PHONE __________
____________________
____________________

HOME ADDRESS ____________________ PHONE __________
____________________
____________________

HABITUATION 1 DATE ___/___/___ TIME OF DAY _____

____ Informed consent
____ Stature (cm) . . . . . . . . . . . . . . . . . ____.__
____ Demonstrate treadmill technique
____ Subject practice on and off treadmill at 0.5 RS
____ 5 min. 0.5 rel. speed 0% grade walk
____ 5 min. 1.7 rel. speed 0% grade run
____ 5 min. 1.3 rel. speed +3% grade walk

HABITUATION 2 DATE ___/___/___ TIME OF DAY _____

____ Stature (cm) . . . . . . . . . . . . . . . . . ____.__
____ Sitting height (cm) . . . . . . . . . . . . . ____.__
____ Body mass (kg) . . . . . . . . . . . . . . . . ____.__
____ Foot length (cm) . . . . . . . . . . . . . . . ____.__
____ Skinfold Bicep (mm) . . . . . . . . . . . . . ____.__
____ Skinfold Subscapular (mm) . . . . . . . . . . ____.__
____ Skinfold Tricep (mm) . . . . . . . . . . . . . ____.__
____ Skinfold Supra-iliac (mm) . . . . . . . . . . ____.__
____ Mouthpiece instruction
____ 5 min. 1.1 rel. speed 0% grade walk
____ on mouthpiece min. 3-5 for next two conditions
____ 5 min. 0.7 rel. speed +3% grade walk
____ 5 min. 1.7 rel. speed -3% grade run

HABITUATION 3 DATE ___/___/___ TIME OF DAY _____

____ On mouthpiece min. 3-5 for all conditions
____ 5 min. 0.9 rel. speed -3% grade walk
____ 5 min. 1.9 rel. speed +3% grade run
____ 5 min. 1.5 rel. speed -3% grade run

# ECONOMY AND EFFICIENCY OF LOCOMOTION

## MAX TEST DATA COLLECTION SHEET

NAME: ______________________ SUBJECT NUMBER: _______

DATE: ____/____/____ TIME OF DAY: __________

Body mass ________.____ kg

Barometric Pressure _____ mm Hg Relative Humidity _____%

Check

- ____ Administer pre-test questionnaire
- ____ Load "Cont30"
- ____ Enter estimated max (Men 50, Women 43)
- ____ Set treadmill 0% grade, 3 $km.h^{-1}$ (20 counts/30 s)
- ____ Start clock and computer together

| Time (min) | Speed ($km.h^{-1}$) | Cadence ($steps.min^{-1}$) | Time (min) | Speed ($km.h^{-1}$) | Cadence ($steps.min^{-1}$) |
|---|---|---|---|---|---|
| 0 | WALK 3 | | 10 | 13 | |
| 1 | 4 | | 11 | 14 | |
| 2 | 5 | | 12 | 15 | |
| 3 | 6 | | 13 | 16 | |
| 4 | RUN 7 | | 14 | 17 | |
| 5 | "AUTO" 8 | | 15 | "MAN" 1% | |
| 6 | 9 | | 16 | 2% | |
| 7 | 10 | | 17 | 3% | |
| 8 | 11 | | 18 | 4% | |
| 9 | 12 | | 19 | 5% | |

MAX RPE ________ MAX $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$) __________

Circle aerobic capacity group: HIGH LOW

Comments: ______________________________________________

# ECONOMY AND EFFICIENCY OF LOCOMOTION

## WALK/RUN DATA COLLECTION SHEET

NAME: ______________________ SUBJECT NUMBER: ______

DATE: ___/___/___ TIME OF DAY: _________

Body mass ______.____ kg Stature _______.____ cm

Barometric Pressure _____ mm Hg Relative Humidity ____%

Walk/run session 1 2 3 4

Check

____ Administer pre-test questionnaire
____ Load "Manual"
____ Resting heart rate (b.min$^{-1}$) . . . . . . . . ________
____ Set treadmill speed and grade
____ Subject starts walk/run
____ Start clock and computer together
____ Subject on mouthpiece at 2 minutes
____ Start 1 minute computer sample at 3 minutes
____ Subject off treadmill at 4 minutes
____ Subject recovers until heart rate < (rest + 10 beats)
____ Repeat for each condition

| | RS/grade | Counts/30s | km.h$^{-1}$ | RPE | Cadence | Pre-HR |
|---|---|---|---|---|---|---|
| 1. | / | | | | | |
| 2. | / | | | | | |
| 3. | / | | | | | |
| 4. | / | | | | | |
| 5. | / | | | | | |
| 6. | / | | | | | |

# ECONOMY AND EFFICIENCY OF LOCOMOTION

## SUBJECT DATA CHECK LIST

NAME: ____________________ SUBJECT NUMBER: ______

LOCAL ____________________ PHONE __________
ADDRESS ____________________
____________________

HOME ____________________ PHONE __________
ADDRESS ____________________
____________________

Check when Completed:

____ Habituation 1 Date ___/___/___
  ____ Informed Consent

____ Habituation 2 Date ___/___/___
  ____ Stature ____.____ cm ____ Mass ____.____ kg
  ____ Skinfolds
  ____ Data calculated and tabulated

____ Habituation 3 Date ___/___/___

____ Max Test Date ___/___/___
  ____ $\dot{V}O_2$max ________ ml.kg$^{-1}$.min$^{-1}$
  ____ Group Selection High Low
  ____ Data calculated and tabulated

____ Walk/Run 1 Date ___/___/___
  ____ 6 conditions ___/___ ___/___ ___/___
  ___/___ ___/___ ___/___
  ____ Data calculated and tabulated

____ Walk/Run 2 Date ___/___/___
  ____ 6 conditions ___/___ ___/___ ___/___
  ___/___ ___/___ ___/___
  ____ Data calculated and tabulated

____ Walk/Run 3 Date ___/___/___
  ____ 6 conditions ___/___ ___/___ ___/___
  ___/___ ___/___ ___/___
  ____ Data calculated and tabulated

____ Walk/Run 4 Date ___/___/___
  ____ 6 conditions ___/___ ___/___ ___/___
  ___/___ ___/___ ___/___
  ____ Data calculated and tabulated

____ Derived variables calculated and tabulated

____ Subject Information Sheet completed

____ Subject sent Information Sheet and thank you letter

____ Subject sent summary of study

# APPENDIX 6

## EQUATIONS AND RELATIONSHIPS USED FOR COMPUTED DATA

1) Percent Fat

-for young males

$\text{Body density}=1.1613-(0.0632 * \text{LOG SUM of 4 skinfolds})$

-for young females

$\text{Body density}=1.1599-(0.0717 * \text{LOG SUM of 4 skinfolds})$

$\%\text{Fat} = ((4.95/\text{body density}) - 4.5) * 100$

2) $\text{Lean body mass} = \text{body mass} - (\text{body mass} * (\%\text{fat}/100))$

(kg) (kg) (kg)

3) $\text{Ideal body mass} = \text{lean body mass}/(1-(\text{Ideal }\%\text{fat}/100))$

(kg) (kg)

where Ideal %fat = 20% for females

= 12% for males

4) $\text{BSA} = (\text{body mass}^{0.425}) * (\text{stature}^{0.725}) * 0.007184$

($m^2$) (kg) (cm)

5) Leg length = stature - sitting height

(cm) (cm) (cm)

6) Stride length = 2 * (velocity/cadence)

(m) (m.min$^{-1}$) (steps.min$^{-1}$)

7) Step length/cadence = (stride length * 30)/cadence

(m.step$^{-1}$.s$^{-1}$) (m) (steps.min$^{-1}$)

8) Relative stride = stride length/stature

(st.stride$^{-1}$) (m) (m)

9) Relative stride = stride length/leg length

(LL.stride$^{-1}$) (m) (m)

10) Relative speed = velocity/stature

(st.s$^{-1}$) (m.s$^{-1}$) (m)

11) Relative Speed = velocity/leg length

(LL.s$^{-1}$) (m.s$^{-1}$) (m)

12) Relative Speed = velocity/foot length

(FL.s$^{-1}$) (m.s$^{-1}$) (m)

13) Gross energy cost = $\dot{V}O_2$ * EE

(kJ.min$^{-1}$) (l.min$^{-1}$) (kJ.l$^{-1}$)

Where:

EE = 19.616 + (((R - 0.707)/0.293) * 1.511)

(kJ.l$^{-1}$)

and

R = respiratory exchange ratio

14) Net energy cost = gross energy cost - rest energy cost
(kJ.min$^{-1}$) (kJ.min$^{-1}$) (kJ.min$^{-1}$)

15) Energy cost/step = ((EC/body mass)/cadence)*1000
(J.kg$^{-1}$.step$^{-1}$) (kJ.min$^{-1}$) (kg) (steps.min$^{-1}$)

16) $\dot{V}O_2$ per LBM = $\dot{V}O_2$/lean body mass
(ml.$^{-1}$kg$^{-1}$.min$^{-1}$) (ml.min$^{-1}$) (kg)

17) Energy cost/metre = (EC/body mass)/velocity
(J.kg$^{-1}$.m$^{-1}$) (J.min$^{-1}$) (kg) (m.min$^{-1}$)

18) <u>Economy</u>

$\dot{V}O_2$ per absolute speed = $\dot{V}O_2$/velocity
(ml.kg$^{-1}$.min$^{-1}$ per km.h$^{-1}$) (km.h$^{-1}$)

$\dot{V}O_2$ per relative speed = $\dot{V}O_2$/RS
(ml.kg$^{-1}$.min$^{-1}$ per st.s$^{-1}$) (st.s$^{-1}$)

$\dot{V}O_2$ per relative speed (LL) = $\dot{V}O_2$/RS(LL)
(ml.kg$^{-1}$.min$^{-1}$ per LL.s$^{-1}$) (LL.s$^{-1}$)

19) Power Output (Heglund *et al* 1982)

$$\text{Power} = (((0.478*v^{1.53})+(0.685*v)+0.072)*\text{BM}+\text{Grade work}$$

(W) (kg) (W)

Where:

v = velocity ($m.s^{-1}$)

$$\text{Grade work} = (\text{body mass} * 9.8) * (\text{grade fraction}) * v$$

(W) (kg)

20) Efficiency

$$\text{Net efficiency} = ((\text{power} * 0.06)/\text{net energy cost}) * 100$$

(%) (W) ($kJ.min^{-1}$)

Note: See attached computer programme which calculates these data.

```
]LIST

100  REM  EANDE
110  REM  CALCULATES A NUMBER OF VARIABLES
120  REM   RELATED TO EFFICIENCY AND ECONOMY OF LOCOMOTION
130  HOME
140  DEF  FN R0(X) =  INT (X + 0.5)
150  DEF  FN R1(X) =  INT (10 * X + 0.5) / 10
160  DEF  FN R2(X) =  INT (100 * X + 0.5) / 100
170  DEF  FN R3(X) =  INT (1000 * X + 0.5) / 1000
180 D$ =  CHR$ (4)
190 W$ = ""
200  PRINT : INPUT "SUBJECT NAME? ";NAME$
300  PRINT : INPUT "CALCULATE ANTHROPOMETRIC RESULTS (Y/N)? ";A$
310  IF A$ = "Y" THEN  GOSUB 3000
320  PRINT : INPUT "CALCULATE MAX TEST DATA (Y/N)? ";B$
330  IF B$ = "Y" THEN  GOSUB 4000
340  PRINT : INPUT "CALCULATE WALK/RUN TEST DATA (Y/N)? ";C$
350  IF C$ = "Y" THEN  GOSUB 4500
380  PRINT : INPUT "CALCULATE MORE DATA FOR THIS SUBJECT (Y/N)? ";F$
390  IF F$ = "Y" THEN  GOTO 300
395  CLEAR
400  PRINT : INPUT "CALCULATE RESULTS FOR ANOTHER SUBJECT (Y/N)? ";G$
410  IF G$ = "Y" THEN  GOTO 130
420  HOME
430  PRINT "THANK YOU AND CHEERS!"
440  END
3000  REM  ANTHROPOMETRY SUBROUTINE
3010  HOME
3020  PRINT "INPUT THE FOLLOWING DATA:"
3030  PRINT : INPUT "STATURE (CM)? ";ST
3040  PRINT : INPUT "SITTING HEIGHT (CM)? ";SH
3050  PRINT : INPUT "BODY MASS (KG)? ";BM
3060  PRINT : INPUT "FOOT LENGTH (CM)? ";FL
3070  PRINT : INPUT "BICEP SKINFOLD (MM)? ";BS
3080  PRINT : INPUT "SUBSCAPULAR SKINFOLD (MM)? ";SS
3090  PRINT : INPUT "TRICEP SKINFOLD (MM)? ";TS
3100  PRINT : INPUT "SUPRAILIAC SKINFOLD (MM)? ";SI
3110  PRINT : INPUT "SUBJECT AGE (YEARS)? ";AGE
3120 SK = ( LOG (TS + BS + SS + SI)) / 2.3025851
3130  PRINT : INPUT "SUBJECT SEX (M/F)? ";SE$
3140  IF SE$ <  > "M" AND SE$ <  > "F" THEN  GOTO 3130
3150  IF SE$ = "F" GOTO 3230
3160  IF AGE =  < 16 THEN D = 1.1533 - (0.0643 * SK)
3170  IF AGE > 16 AND AGE =  < 19 THEN D = 1.162 - (0.063 * SK)
3180  IF AGE > 19 AND AGE =  < 29 THEN D = 1.1613 - (0.0632 * SK)
3190  IF AGE > 29 AND AGE =  < 39 THEN D = 1.1422 - (0.0544 * SK)
3200  IF AGE > 39 AND AGE =  < 49 THEN D = 1.162 - (0.07 * SK)
3210  IF AGE > 50 THEN D = 1.1715 - (0.0779 * SK)
3220  GOTO 3290
3230  IF AGE =  < 16 THEN D = 1.1369 - (0.0598 * SK)
3240  IF AGE > 16 AND AGE =  < 19 THEN D = 1.1549 - (0.0678 * SK)
3250  IF AGE > 19 AND AGE =  < 29 THEN D = 1.1599 - (0.0717 * SK)
3260  IF AGE > 29 AND AGE =  < 39 THEN D = 1.1423 - (0.0632 * SK)
3270  IF AGE > 39 AND AGE =  < 49 THEN D = 1.1333 - (0.0612 * SK)
3280  IF AGE > 50 THEN D = 1.1339 - (0.0645 * SK)
3290 PF = ((4.95 / D) - 4.5)
3295 BL = BM * PF
3300 LBM = BM - BL
3310  IF SE$ = "F" THEN DF = 20
3320  IF SE$ = "M" THEN DF = 12
3330 IBM = (BM - BL) / (1 - (DF / 100))
3340 SA = (BM ^ 0.425) * (ST ^ 0.725) * 0.007184
3350 LL = ST - SH
3360 LS = (LL / ST) * 100
```

```
3360 LS = (LL / ST) * 100
3370 FR = (FL / LL) * 100
3380  PRINT D$;"PR#1"
3390  PRINT : PRINT "ANTHROPOMETRY FOR: ";NAME$
3400  PRINT : PRINT "PERCENT FAT= "; FN R1(PF * 100)
3410  PRINT : PRINT "LEAN BODY MASS (KG)= "; FN R1(LBM)
3420  PRINT : PRINT "IDEAL BODY MASS (KG)= "; FN R1(IBM - 1);" TO "; FN R1(IBM +
 1)
3430  PRINT : PRINT "BODY SURFACE AREA (SQ.M.)= "; FN R2(SA)
3440  PRINT : PRINT "LEG LENGTH (CM)= "; FN R1(LL)
3450  PRINT : PRINT "LEG LENGTH AS % OF STATURE = "; FN R1(LS)
3460  PRINT : PRINT "FOOT LENGTH AS % OF LEG LENGTH = "; FN R1(FR)
3465  PRINT : PRINT
3470  PRINT D$;"PR#0"
3480  HOME
3490  RETURN
4000  REM  MAX TEST SUBROUTINE
4010  REM  MAX 3 KM/H START AND UP BY
4020  REM  1 KM/H PER MIN TO 17 KM/H
4030  REM  THEN UP BY 1% EACH MINUTE
4040  PRINT : PRINT "INPUT THE FOLLOWING INFORMATION:"
4045  PRINT : INPUT "SUBJECT BODY MASS (KG)? ";BM
4050  PRINT : INPUT "ACTUAL SPEED - THIS SAMPLE (KM/H)? ";SP
4055  IF SP < 16.5 THEN GD = 0
4060  IF SP >  = 16.5 THEN  PRINT : INPUT "GRADE FOR THIS SAMPLE (%)? ";GD
4070  PRINT D$;"PR#1"
4080  PRINT : PRINT "MAX TEST RESULTS FOR: ";NAME$
4090  PRINT : PRINT "AT A SPEED OF "; FN R0(SP);" KM/H"
4095  PRINT : PRINT "AND A GRADE OF "; FN R0(GD);" PERCENT"
4100  PRINT D$;"PR#0"
4110  GOSUB 6000
4120  PRINT : PRINT : PRINT : INPUT "ANOTHER MAX TEST SAMPLE FOR THIS SUBJECT (Y
/N)? ";H$
4125  IF H$ = "Y" THEN  GOTO 4050
4130  IF H$ <  > "N" GOTO 4120
4140  HOME
4150  RETURN
4500  REM  WALK/RUN TEST SUBROUTINE
4505  PRINT : INPUT "THIS SUBJECT'S MAX RPE IS? ";MR
4510  PRINT : PRINT "INPUT THE FOLLOWING INFORMATION:"
4520  PRINT : INPUT "ACTUAL SPEED FOR THIS SAMPLE (KM/H)? ";SP
4530  PRINT : INPUT "RELATIVE SPEED FOR THIS SAMPLE? ";RS
4540  PRINT : INPUT "GRADE FOR THIS SAMPLE (%)? ";GD
4545  PRINT : INPUT "SUBJECT BODY MASS (KG)? ";BM
4550  PRINT D$;"PR#1"
4560  PRINT : PRINT "WALK/RUN TEST RESULTS FOR: ";NAME$
4570  PRINT : PRINT "AT A RELATIVE SPEED OF ";RS
4580  PRINT : PRINT "AND A GRADE (%) OF ";GD
4590  PRINT D$;"PR#0"
4600  GOSUB 6000
4605 PR = (RPE / MR) * 100
4610  PRINT D$;"PR#1"
4620  PRINT "PERCENT OF MAX RPE = "; FN R0(PR)
4625  PRINT : PRINT
4630  PRINT D$;"PR#0"
4640  PRINT : PRINT : PRINT : INPUT "ANOTHER WALK/RUN SAMPLE FOR THIS SUBJECT (Y
/N)? ";I$
4650  IF I$ = "Y" THEN  GOTO 4510
4660  IF I$ <  > "N" THEN  GOTO 4640
4670  HOME
4680  RETURN
6000  REM  CALCULATION SUBROUTINE FOR
6010  REM  ECONOMY AND EFFICIENCY
6020  PRINT : PRINT : PRINT : PRINT "HAVE YOU JUST FINISHED ANTHROPOMETRIC"
6030  PRINT : INPUT "ANALYSIS FOR THIS SUBJECT (Y/N)? ";J$
6040  IF J$ = "Y" THEN  GOTO 6100
```

```
6050  IF J$ <  > "N" THEN  GOTO 6030
6060  PRINT : INPUT "SUBJECT LEG LENGTH (CM)? ";LL
6070  PRINT : INPUT "SUBJECT FOOT LENGTH (CM)? ";FL
6080  PRINT : INPUT "SUBJECT LEAN BODY MASS (KG)? ";LBM
6090  PRINT : INPUT "SUBJECT BODY SURFACE AREA (MXM)? ";SA
6095  PRINT : INPUT "SUBJECT STATURE (CM)? ";ST
6100  PRINT : PRINT "INPUT THE FOLLOWING DATA:"
6120  PRINT : INPUT "CADENCE (STEPS/MIN)? ";CA
6130  IF MR = 0 THEN  GOTO 6150
6140  PRINT : INPUT "RPE SCALE SCORE? ";RPE
6150  PRINT : INPUT "VO2 (L/MIN)? ";VO2
6160  PRINT : INPUT "RESP. EXCH. RATIO (R)? ";R
6170  IF R > 1 THEN R = 1
6180  IF R < 0.707 THEN R = 0.707
6190 EE = 19.616 + (((R - 0.707) / 0.293) * 1.511)
6200 EC = VO2 * EE
6210 CS = ((EC / BM) / CA) * 1000
6220 VLBM = (VO2 / LBM) * 1000
6230 VBSA = (VO2 * 1000) / SA
6240 VM = SP / 0.06
6250 CM = ((EC / BM) / VM) * 1000
6260 E1 = ((VO2 * 1000) / BM) / SP
6270 SL = 2 * (VM / CA)
6280 SDT = 120 / CA
6290 SC = (SL * 30) / CA
6300 RL = (VM / 60) / (LL / 100)
6310 RF = (VM / 60) / (FL / 100)
6320 RS = (SP / 3.6) / (ST / 100)
6325 E2 = ((VO2 * 1000) / BM) / RL
6330 E3 = ((VO2 * 1000) / BM) / RS
6400 GW = (BM * 9.8) * (GD / 100) * (SP / 3.6)
6410 V = SP / 3.6
6420 P1 = (((0.478 * V ^ 1.53) + (0.685 * V) + 0.072) * BM) + GW
6430 P2 = (1.09 * BM * V) + GW
6440 P3 = (BM * (0.0362787 * SP ^ 2)) + GW
6445 NC = EC - ((BM * 0.0035) * EE)
6450 P4 = (((CA / 60) * (BM * 9.8) * V) * (0.136 + (0.066 * V))) + GW
6455 N1E = ((P1 * 0.06) / NC) * 100
6460 P5 = ((0.714 * ((BM / 2) * V ^ 2)) + 500) + GW
6470 N2E = ((P2 * 0.06) / NC) * 100
6480 N3E = ((P3 * 0.06) / NC) * 100
6490 N4E = ((P4 * 0.06) / NC) * 100
6500 N5E = ((P5 * 0.06) / NC) * 100
6600  REM  OUTPUT OF E AND E DATA
6610  PRINT D$;"PR#1"
6620  PRINT : PRINT : PRINT "GAIT CHARACTERISTICS:"
6630  PRINT : PRINT "STRIDE LENGTH (M) = "; FN R2(SL)
6640  PRINT "STRIDE TIME (S) = "; FN R2(SDT)
6650  PRINT "STEP LENGTH/CADENCE RATIO (M/ST/S) = "; FN R2(SC)
6660  PRINT "ACTUAL RELATIVE SPEED (ST/S) = "; FN R2(RS)
6670  PRINT "REL. SP. (LEG LENGTHS/S) = "; FN R2(RL)
6680  PRINT "REL. SP. (FOOT LENGTHS/S) = "; FN R2(RF)
6690  PRINT : PRINT : PRINT : PRINT "ENERGY COST DATA:"
6700  PRINT : PRINT "GROSS ENERGY COST (KJ/MIN) = "; FN R2(EC)
6710  PRINT "NET ENERGY COST (KJ/MIN) = "; FN R2(NC)
6720  PRINT "ENERGY COST PER STEP(J/KG) = "; FN R2(CS)
6730  PRINT "VO2 PER LBM (ML/KG) = "; FN R2(VLBM)
6740  PRINT "VO2 PER LBM (ML/MIN/SQ.M.) = "; FN R2(VBSA)
6750  PRINT "ENERGY COST PER DISTANCE (J/KG/M) = "; FN R2(CM)
6760  PRINT : PRINT : PRINT : PRINT "LOCOMOTION ECONOMY:"
6770  PRINT : PRINT "VO2 PER ABS. SPEED (ML/KG PER KM/H) = "; FN R2(E1)
6780  PRINT "VO2 PER REL. SPEED (ML/KG PER LL/S) = "; FN R2(E2)
6790  PRINT "VO2 PER REL. SPEED (ML/KG PER ST/S) = "; FN R2(E3)
6800  PRINT : PRINT : PRINT : PRINT "POWER OUTPUT AND NET EFFICIENCY:"
6805  PRINT : PRINT "WHOLE BODY"
6810  PRINT : PRINT "HEGLUND P1 (W) = "; FN R1(P1);"     E1 (%) = "; FN R1(N1E)
6820  PRINT : PRINT "WINTER P2 (W) = "; FN R1(P2);"     E2 (%) = "; FN R1(N2E)
6825  PRINT : PRINT "HORIZONTAL WORK ONLY"
6830  PRINT : PRINT "CAVAGNA, S, M P3 (W) = "; FN R1(P3);"     E3 (%) = "; FN P1
(N3E)
6840  PRINT : PRINT "CAVAGNA, M P4 (W) = "; FN R1(P4);"     E4 (%) = "; FN R1(N4
E)
6855  PRINT : PRINT
6900  PRINT D$;"PR#0"
6910  RETURN
```

# APPENDIX 7

## SUMMARY OF DATA

The following tables contain the mean responses of subject groups to the max test (absolute speed) and the walk/run tests (relative speeds). Data collected at uphill and downhill grades are summarized in the latter part of this Appendix.

Table XV Statistical summary of general information for male subjects

| | General Information | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Age (y) | 21.0 | 1.8 | 22.5 | 4.2 |
| Stature (cm) | 178.7 | 8.3 | 175.8 | 6.7 |
| Sitting Height (cm) | 93.3 | 3.6 | 94.3 | 3.0 |
| Body Mass (kg) | 68.85 | 5.07 | 73.75 | 7.22 |
| Foot Length (cm) | 26.1 | 1.4 | 26.0 | 1.3 |
| %Fat | 13.5 | 2.3 | 17.1 | 3.2 |
| Lean Body Mass (kg) | 59.54 | 4.52 | 61.14 | 6.62 |
| Ideal Body Mass (kg) | 67.47 | 4.95 | 69.40 | 7.72 |
| Body Surface Area ($m^2$) | 1.86 | 0.11 | 1.90 | 0.12 |
| Leg Length (cm) | 85.5 | 5.5 | 81.5 | 5.3 |
| Leg Length/Stature (%) | 47.8 | 1.3 | 46.3 | 1.7 |
| Foot Length/Leg Length (%) | 30.5 | 1.3 | 31.9 | 1.6 |
| Max RPE | 17.6 | 1.5 | 16.8 | 1.6 |
| Max $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$) | 61.67 | 3.74 | 53.26 | 3.17 |
| V.T. (%Max $\dot{V}O_2$) | 64.2 | 7.2 | 65.4 | 9.6 |
| V.T. ($ml.kg^{-1}.min^{-1}$) | 39.65 | 5.42 | 34.90 | 6.01 |
| V.T. Velocity ($km.h^{-1}$) | 12.27 | 2.20 | 10.70 | 2.11 |

Table XVI Statistical summary of general information for female subjects

|  | General Information |  |  |  |
|---|---|---|---|---|
|  | High $\dot{V}O_2$ |  | Average $\dot{V}O_2$ |  |
|  | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Age (y) | 20.6 | 1.1 | 21.6 | 2.9 |
| Stature (cm) | 165.9 | 4.5 | 168.0 | 5.2 |
| Sitting Height (cm) | 87.6 | 3.5 | 88.7 | 2.6 |
| Body Mass (kg) | 58.22 | 6.91 | 62.33 | 7.20 |
| Foot Length (cm) | 23.7 | 0.9 | 24.1 | 1.2 |
| %Fat | 21.8 | 4.2 | 25.4 | 3.1 |
| Lean Body Mass (kg) | 45.32 | 3.84 | 46.45 | 5.26 |
| Ideal Body Mass (kg) | 56.66 | 4.81 | 58.08 | 5.67 |
| Body Surface Area ($m^2$) | 1.64 | 0.10 | 1.71 | 0.11 |
| Leg Length (cm) | 78.3 | 2.4 | 79.3 | 2.9 |
| Leg Length/Stature (%) | 47.2 | 1.2 | 47.2 | 0.6 |
| Foot Length/Leg Length (%) | 30.1 | 1.6 | 30.4 | 1.4 |
| Max RPE | 17.5 | 1.5 | 17.1 | 1.0 |
| Max $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$) | 52.95 | 5.29 | 42.95 | 4.65 |
| V.T. (%Max $\dot{V}O_2$) | 63.0 | 6.3 | 62.8 | 9.9 |
| V.T. ($ml.kg^{-1}.min^{-1}$) | 33.44 | 5.19 | 27.12 | 5.62 |
| V.T. Velocity ($km.h^{-1}$) | 9.30 | 1.89 | 8.55 | 1.75 |

Table XVII Statistical summary of absolute speed at various velocities for male and female subjects

| Speed | Absolute Speed (km.$h^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Male | | | | |
| Relative (st.$s^{-1}$) | | | | |
| 0.5 | 3.22 | .15 | 3.17 | .12 |
| 0.7 | 4.50 | .21 | 4.43 | .18 |
| 0.9 | 5.78 | .27 | 5.70 | .22 |
| 1.1 | 7.08 | .32 | 6.97 | .27 |
| 1.3 | 8.36 | .40 | 8.23 | .32 |
| 1.5 | 9.65 | .46 | 9.49 | .37 |
| 1.7 | 10.94 | .52 | 10.76 | .43 |
| 1.9 | 12.21 | .58 | 12.02 | .46 |
| 2.1 | 13.55 | .38 | | |
| 2.3 | 14.82 | .41 | | |
| 2.5 | 16.15 | .51 | | |
| Female | | | | |
| Relative (st.$s^{-1}$) | | | | |
| 0.5 | 2.99 | .08 | 3.03 | .10 |
| 0.7 | 4.19 | .10 | 4.23 | .14 |
| 0.9 | 5.38 | .14 | 5.45 | .17 |
| 1.1 | 6.58 | .18 | 6.65 | .20 |
| 1.3 | 7.76 | .21 | 7.87 | .24 |
| 1.5 | 8.95 | .24 | 9.08 | .28 |
| 1.7 | 10.16 | .27 | 10.25 | .37 |
| 1.9 | 11.35 | .31 | 11.48 | .39 |
| 2.1 | 12.55 | .22 | | |
| 2.3 | 13.69 | .24 | | |
| 2.5 | 14.94 | .27 | | |

Table XVIII  Statistical summary of stride length at various velocities for male subjects

| Speed | Stride Length (m) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute (km.h$^{-1}$) | | | | |
| 3 | 1.09 | .07 | 1.10 | .09 |
| 4 | 1.31 | .07 | 1.26 | .06 |
| 5 | 1.52 | .08 | 1.45 | .06 |
| 6 | 1.66 | .09 | 1.60 | .06 |
| 7 | 1.49 | .10 | 1.46 | .08 |
| 8 | 1.67 | .06 | 1.62 | .10 |
| 9 | 1.85 | .08 | 1.79 | .13 |
| 10 | 2.05 | .08 | 1.99 | .11 |
| 11 | 2.25 | .09 | 2.14 | .12 |
| 12 | 2.45 | .10 | 2.34 | .13 |
| 13 | 2.61 | .11 | 2.52 | .13 |
| 14 | 2.78 | .11 | 2.69 | .14 |
| 15 | 2.95 | .13 | 2.80 | .17 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | 1.20 | .09 | 1.15 | .06 |
| 0.7 | 1.42 | .11 | 1.36 | .06 |
| 0.9 | 1.64 | .13 | 1.58 | .09 |
| 1.1 | 1.81 | .12 | 1.76 | .09 |
| 1.3 | 1.91 | .12 | 1.81 | .10 |
| 1.5 | 2.05 | .23 | 1.87 | .17 |
| 1.7 | 2.21 | .16 | 2.09 | .18 |
| 1.9 | 2.49 | .19 | 2.29 | .20 |
| 2.1 | 2.71 | .12 | | |
| 2.3 | 2.91 | .13 | | |
| 2.5 | 3.09 | .10 | | |

Table XIX Statistical summary of stride length at various velocities for female subjects

| Speed | Stride Length (m) |  |  |  |
|---|---|---|---|---|
|  | High $\dot{V}O_2$ |  | Average $\dot{V}O_2$ |  |
|  | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute ($km.h^{-1}$) |  |  |  |  |
| 3 | 1.07 | .11 | 1.06 | .08 |
| 4 | 1.25 | .10 | 1.26 | .07 |
| 5 | 1.40 | .14 | 1.44 | .05 |
| 6 | 1.59 | .09 | 1.60 | .06 |
| 7 | 1.52 | .10 | 1.49 | .10 |
| 8 | 1.67 | .08 | 1.67 | .09 |
| 9 | 1.85 | .08 | 1.84 | .11 |
| 10 | 2.04 | .10 | 2.01 | .10 |
| 11 | 2.20 | .13 | 2.16 | .11 |
| 12 | 2.39 | .13 | 2.32 | .13 |
| 13 | 2.56 | .13 | 2.49 | .14 |
| 14 | 2.69 | .13 | 2.60 | .15 |
| 15 | 2.84 | .11 | 2.75 | .09 |
| Relative ($st.s^{-1}$) |  |  |  |  |
| 0.5 | 1.12 | .12 | 1.14 | .09 |
| 0.7 | 1.35 | .16 | 1.31 | .08 |
| 0.9 | 1.47 | .11 | 1.50 | .08 |
| 1.1 | 1.68 | .13 | 1.68 | .08 |
| 1.3 | 1.78 | .12 | 1.71 | .10 |
| 1.5 | 1.85 | .12 | 1.85 | .12 |
| 1.7 | 2.04 | .14 | 2.03 | .15 |
| 1.9 | 2.22 | .15 | 2.17 | .11 |
| 2.1 | 2.39 | .09 |  |  |
| 2.3 | 2.58 | .10 |  |  |
| 2.5 | 2.69 | .07 |  |  |

Table XX Statistical summary of relative stride ($\text{statures.stride}^{-1}$) at various velocities for male subjects

| Speed | Relative Stride ($\text{statures.stride}^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute ($\text{km.h}^{-1}$) | | | | |
| 3 | .61 | .03 | .62 | .05 |
| 4 | .73 | .02 | .72 | .03 |
| 5 | .85 | .03 | .83 | .02 |
| 6 | .93 | .02 | .91 | .03 |
| 7 | .83 | .05 | .83 | .03 |
| 8 | .93 | .04 | .92 | .03 |
| 9 | 1.04 | .05 | 1.02 | .04 |
| 10 | 1.15 | .06 | 1.13 | .04 |
| 11 | 1.26 | .06 | 1.22 | .05 |
| 12 | 1.37 | .07 | 1.33 | .06 |
| 13 | 1.46 | .07 | 1.43 | .08 |
| 14 | 1.56 | .08 | 1.53 | .09 |
| 15 | 1.65 | .09 | 1.59 | .09 |
| Relative ($\text{st.s}^{-1}$) | | | | |
| 0.5 | .67 | .03 | .65 | .03 |
| 0.7 | .79 | .03 | .77 | .02 |
| 0.9 | .91 | .03 | .90 | .02 |
| 1.1 | 1.01 | .03 | 1.00 | .04 |
| 1.3 | 1.07 | .04 | 1.03 | .06 |
| 1.5 | 1.14 | .10 | 1.06 | .07 |
| 1.7 | 1.24 | .06 | 1.19 | .07 |
| 1.9 | 1.39 | .07 | 1.30 | .08 |
| 2.1 | 1.51 | .06 | | |
| 2.3 | 1.62 | .05 | | |
| 2.5 | 1.73 | .04 | | |

Table XXI Statistical summary of relative stride ($statures.stride^{-1}$) at various velocities for female subjects

| Speed | Relative Stride ($statures.stride^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute ($km.h^{-1}$) | | | | |
| 3 | .64 | .06 | .63 | .05 |
| 4 | .75 | .05 | .75 | .05 |
| 5 | .85 | .08 | .86 | .03 |
| 6 | .96 | .03 | .95 | .03 |
| 7 | .91 | .05 | .89 | .06 |
| 8 | 1.01 | .05 | 1.00 | .05 |
| 9 | 1.12 | .04 | 1.10 | .08 |
| 10 | 1.23 | .05 | 1.20 | .07 |
| 11 | 1.33 | .06 | 1.28 | .07 |
| 12 | 1.44 | .06 | 1.39 | .08 |
| 13 | 1.55 | .07 | 1.48 | .09 |
| 14 | 1.62 | .06 | 1.57 | .10 |
| 15 | 1.71 | .07 | 1.65 | .07 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | .68 | .06 | .68 | .05 |
| 0.7 | .78 | .05 | .78 | .03 |
| 0.9 | .88 | .05 | .89 | .03 |
| 1.1 | 1.01 | .07 | 1.00 | .02 |
| 1.3 | 1.07 | .06 | 1.02 | .05 |
| 1.5 | 1.11 | .05 | 1.10 | .06 |
| 1.7 | 1.23 | .06 | 1.21 | .07 |
| 1.9 | 1.33 | .06 | 1.30 | .06 |
| 2.1 | 1.45 | .02 | | |
| 2.3 | 1.56 | .04 | | |
| 2.5 | 1.63 | .03 | | |

Table XXII Statistical summary of relative stride (leg lengths.stride$^{-1}$) at various velocities for male subjects

| Speed | Relative Stride (leg lengths.stride$^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute (km.h$^{-1}$) | | | | |
| 3 | 1.28 | .06 | 1.35 | .09 |
| 4 | 1.53 | .06 | 1.55 | .10 |
| 5 | 1.78 | .07 | 1.79 | .08 |
| 6 | 1.95 | .08 | 1.96 | .10 |
| 7 | 1.75 | .12 | 1.80 | .08 |
| 8 | 1.95 | .11 | 1.99 | .08 |
| 9 | 2.17 | .13 | 2.19 | .09 |
| 10 | 2.41 | .16 | 2.44 | .09 |
| 11 | 2.64 | .16 | 2.61 | .10 |
| 12 | 2.87 | .19 | 2.88 | .16 |
| 13 | 3.06 | .19 | 3.10 | .22 |
| 14 | 3.27 | .20 | 3.30 | .24 |
| 15 | 3.46 | .23 | 3.44 | .22 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | 1.41 | .08 | 1.41 | .08 |
| 0.7 | 1.66 | .07 | 1.67 | .08 |
| 0.9 | 1.92 | .05 | 1.94 | .08 |
| 1.1 | 2.12 | .06 | 2.16 | .13 |
| 1.3 | 2.23 | .08 | 2.22 | .13 |
| 1.5 | 2.39 | .20 | 2.29 | .12 |
| 1.7 | 2.59 | .12 | 2.56 | .14 |
| 1.9 | 2.91 | .13 | 2.81 | .14 |
| 2.1 | 3.13 | .15 | | |
| 2.3 | 3.36 | .12 | | |
| 2.5 | 3.57 | .11 | | |

Table XXIII Statistical summary of relative stride ($\text{leg lengths.stride}^{-1}$) at various velocities for female subjects

| Speed | Relative Stride ($\text{leg lengths.stride}^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute ($km.h^{-1}$) | | | | |
| 3 | 1.37 | .14 | 1.34 | .10 |
| 4 | 1.59 | .12 | 1.59 | .09 |
| 5 | 1.79 | .18 | 1.81 | .06 |
| 6 | 2.03 | .10 | 2.01 | .07 |
| 7 | 1.94 | .13 | 1.88 | .14 |
| 8 | 2.14 | .12 | 2.11 | .11 |
| 9 | 2.37 | .12 | 2.32 | .16 |
| 10 | 2.60 | .14 | 2.54 | .14 |
| 11 | 2.81 | .17 | 2.72 | .15 |
| 12 | 3.05 | .16 | 2.94 | .18 |
| 13 | 3.28 | .18 | 3.15 | .20 |
| 14 | 3.43 | .18 | 3.33 | .20 |
| 15 | 3.63 | .17 | 3.52 | .15 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | 1.43 | .15 | 1.43 | .10 |
| 0.7 | 1.66 | .12 | 1.65 | .07 |
| 0.9 | 1.88 | .13 | 1.89 | .06 |
| 1.1 | 2.15 | .15 | 2.11 | .05 |
| 1.3 | 2.36 | .26 | 2.16 | .10 |
| 1.5 | 2.36 | .14 | 2.34 | .13 |
| 1.7 | 2.61 | .16 | 2.57 | .15 |
| 1.9 | 2.83 | .15 | 2.75 | .14 |
| 2.1 | 3.04 | .10 | | |
| 2.3 | 3.28 | .16 | | |
| 2.5 | 3.43 | .12 | | |

Table XXIV Statistical summary of step length/cadence at various velocities for male subjects

| Speed | Step Length/Cadence ($m.step^{-1}.s^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\bar{X}$ | SD | $\bar{X}$ | SD |
| Absolute ($km.h^{-1}$) | | | | |
| 3 | .36 | .05 | .36 | .06 |
| 4 | .38 | .03 | .36 | .03 |
| 5 | .41 | .04 | .38 | .03 |
| 6 | .42 | .05 | .38 | .03 |
| 7 | .29 | .04 | .28 | .03 |
| 8 | .31 | .02 | .30 | .04 |
| 9 | .34 | .03 | .32 | .05 |
| 10 | .38 | .03 | .36 | .04 |
| 11 | .41 | .03 | .38 | .04 |
| 12 | .45 | .03 | .41 | .04 |
| 13 | .47 | .04 | .44 | .04 |
| 14 | .50 | .04 | .46 | .05 |
| 15 | .52 | .05 | .47 | .06 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | .40 | .05 | .38 | .03 |
| 0.7 | .41 | .04 | .38 | .02 |
| 0.9 | .42 | .05 | .39 | .03 |
| 1.1 | .42 | .04 | .39 | .02 |
| 1.3 | .39 | .04 | .36 | .04 |
| 1.5 | .39 | .08 | .33 | .05 |
| 1.7 | .40 | .05 | .37 | .05 |
| 1.9 | .46 | .06 | .39 | .06 |
| 2.1 | .49 | .04 | | |
| 2.3 | .51 | .04 | | |
| 2.5 | .53 | .03 | | |

Table XXV Statistical summary of step length/cadence at various velocities for female subjects

| Speed | Step Length/Cadence (m.step$^{-1}$.s$^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute (km.h$^{-1}$) | | | | |
| 3 | .35 | .07 | .34 | .05 |
| 4 | .35 | .06 | .36 | .04 |
| 5 | .37 | .05 | .37 | .02 |
| 6 | .38 | .05 | .38 | .03 |
| 7 | .30 | .04 | .29 | .04 |
| 8 | .32 | .03 | .31 | .03 |
| 9 | .34 | .03 | .34 | .04 |
| 10 | .38 | .04 | .36 | .04 |
| 11 | .40 | .04 | .38 | .04 |
| 12 | .43 | .04 | .40 | .04 |
| 13 | .46 | .05 | .43 | .05 |
| 14 | .46 | .04 | .43 | .05 |
| 15 | .48 | .04 | .45 | .03 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | .38 | .08 | .39 | .05 |
| 0.7 | .37 | .06 | .36 | .04 |
| 0.9 | .36 | .05 | .37 | .03 |
| 1.1 | .39 | .05 | .38 | .03 |
| 1.3 | .37 | .04 | .34 | .03 |
| 1.5 | .34 | .04 | .34 | .04 |
| 1.7 | .37 | .05 | .36 | .05 |
| 1.9 | .39 | .04 | .38 | .03 |
| 2.1 | .36 | .02 | | |
| 2.3 | .43 | .03 | | |
| 2.5 | .44 | .02 | | |

Table XXVI Statistical summary of cadence at various velocities for male subjects

| Speed | Cadence (steps.min$^{-1}$) High $\dot{V}O_2$ $\bar{X}$ | High $\dot{V}O_2$ SD | Average $\dot{V}O_2$ $\bar{X}$ | Average $\dot{V}O_2$ SD |
|---|---|---|---|---|
| Absolute (km.h$^{-1}$) | | | | |
| 3 | 92.5 | 6.4 | 91.9 | 6.8 |
| 4 | 101.6 | 4.8 | 105.4 | 4.8 |
| 5 | 110.2 | 5.8 | 114.7 | 4.3 |
| 6 | 120.5 | 6.3 | 125.2 | 4.3 |
| 7 | 156.4 | 10.2 | 159.8 | 9.0 |
| 8 | 160.4 | 5.7 | 165.5 | 11.0 |
| 9 | 162.6 | 6.6 | 169.0 | 12.8 |
| 10 | 162.4 | 6.6 | 168.0 | 9.0 |
| 11 | 163.6 | 6.5 | 171.4 | 9.5 |
| 12 | 164.0 | 6.6 | 171.4 | 8.9 |
| 13 | 166.2 | 6.8 | 173.0 | 8.8 |
| 14 | 167.5 | 6.4 | 174.6 | 9.8 |
| 15 | 171.0 | 6.1 | 179.6 | 11.2 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | 89.7 | 4.3 | 91.9 | 3.9 |
| 0.7 | 105.8 | 4.5 | 108.7 | 2.7 |
| 0.9 | 115.6 | 9.4 | 120.4 | 3.4 |
| 1.1 | 130.3 | 3.6 | 133.8 | 3.0 |
| 1.3 | 146.4 | 5.1 | 152.3 | 8.1 |
| 1.5 | 158.1 | 12.2 | 169.9 | 10.1 |
| 1.7 | 165.1 | 7.5 | 172.4 | 9.6 |
| 1.9 | 163.9 | 8.5 | 175.7 | 10.7 |
| 2.1 | 167.1 | 6.4 | | |
| 2.3 | 170.0 | 5.1 | | |
| 2.5 | 173.9 | 4.2 | | |

Table XXVII Statistical summary of cadence at various velocities for female subjects

| Speed | Cadence (steps.min$^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute (km.h$^{-1}$) | | | | |
| 3 | 94.6 | 9.9 | 94.7 | 7.5 |
| 4 | 107.2 | 8.7 | 106.2 | 5.2 |
| 5 | 117.0 | 8.3 | 116.4 | 3.6 |
| 6 | 126.4 | 7.1 | 125.8 | 4.0 |
| 7 | 154.4 | 9.8 | 156.6 | 10.5 |
| 8 | 159.4 | 7.4 | 160.0 | 8.1 |
| 9 | 162.2 | 7.2 | 164.0 | 9.7 |
| 10 | 163.8 | 7.7 | 166.2 | 8.2 |
| 11 | 166.4 | 7.4 | 171.5 | 8.1 |
| 12 | 168.2 | 8.8 | 173.1 | 9.2 |
| 13 | 169.8 | 8.0 | 174.9 | 10.0 |
| 14 | 173.8 | 8.1 | 178.3 | 10.4 |
| 15 | 176.2 | 7.0 | 181.3 | 6.7 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | 89.8 | 8.2 | 89.2 | 5.8 |
| 0.7 | 108.0 | 7.3 | 107.3 | 3.5 |
| 0.9 | 122.5 | 6.6 | 121.6 | 4.1 |
| 1.1 | 131.2 | 8.6 | 132.4 | 3.1 |
| 1.3 | 146.3 | 8.1 | 153.6 | 7.8 |
| 1.5 | 161.8 | 6.8 | 163.9 | 8.6 |
| 1.7 | 166.2 | 7.6 | 168.6 | 9.2 |
| 1.9 | 171.2 | 7.1 | 174.0 | 6.7 |
| 2.1 | 174.8 | 3.6 | | |
| 2.3 | 177.4 | 5.2 | | |
| 2.5 | 185.0 | 3.2 | | |

Table XXVIII Statistical summary of relative $\dot{V}O_2$ (per kg) at various velocities for male subjects

| | Relative $\dot{V}O_2$ (ml.kg$^{-1}$.min$^{-1}$) | | | |
|---|---|---|---|---|
| Speed | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\bar{X}$ | SD | $\bar{X}$ | SD |
| Absolute (km.h$^{-1}$) | | | | |
| 3 | 11.08 | 1.15 | 10.03 | 1.03 |
| 4 | 11.29 | 1.85 | 10.98 | 1.25 |
| 5 | 13.25 | 1.95 | 11.99 | 1.33 |
| 6 | 16.73 | 2.06 | 15.03 | 1.57 |
| 7 | 23.89 | 2.52 | 21.31 | 1.77 |
| 8 | 27.40 | 2.03 | 27.02 | 2.43 |
| 9 | 31.86 | 2.80 | 29.66 | 1.47 |
| 10 | 32.35 | 2.67 | 31.81 | 2.75 |
| 11 | 36.50 | 3.07 | 35.91 | 2.36 |
| 12 | 39.16 | 1.43 | 38.89 | 2.20 |
| 13 | 42.81 | 3.86 | 42.48 | 2.55 |
| 14 | 45.41 | 3.25 | 46.36 | 2.37 |
| 15 | 48.30 | 3.82 | 49.71 | 3.18 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | 10.71 | 1.21 | 10.39 | 1.07 |
| 0.7 | 12.72 | 1.32 | 11.94 | 1.03 |
| 0.9 | 16.49 | 1.59 | 15.21 | 1.12 |
| 1.1 | 21.79 | 2.81 | 20.80 | 2.32 |
| 1.3 | 31.37 | 3.53 | 31.16 | 3.46 |
| 1.5 | 32.81 | 2.47 | 31.91 | 2.44 |
| 1.7 | 37.06 | 2.73 | 36.38 | 3.13 |
| 1.9 | 40.90 | 2.78 | 42.12 | 2.69 |
| 2.1 | 45.20 | 3.49 | | |
| 2.3 | 50.36 | 4.35 | | |
| 2.5 | 53.66 | 3.07 | | |

Table XXIX Statistical summary of relative $\dot{V}O_2$ (per kg) at various velocities for female subjects

| Speed | Relative $\dot{V}O_2$ (ml.kg$^{-1}$.min$^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute (km.h$^{-1}$) | | | | |
| 3 | 10.21 | 1.09 | 10.25 | 1.23 |
| 4 | 10.38 | 1.32 | 10.71 | 1.20 |
| 5 | 13.83 | 1.57 | 11.96 | 1.54 |
| 6 | 16.45 | 1.39 | 15.38 | 1.17 |
| 7 | 23.85 | 1.57 | 22.02 | 2.46 |
| 8 | 28.67 | 1.42 | 26.25 | 2.76 |
| 9 | 31.62 | 1.70 | 28.83 | 2.90 |
| 10 | 34.13 | 2.66 | 31.82 | 2.54 |
| 11 | 37.79 | 2.40 | 34.87 | 2.76 |
| 12 | 41.63 | 2.42 | 37.41 | 2.27 |
| 13 | 44.57 | 2.41 | 40.19 | 2.42 |
| 14 | 47.53 | 3.48 | 42.33 | 2.52 |
| 15 | 49.83 | 3.59 | 45.07 | 2.50 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | 10.16 | 1.00 | 9.60 | .91 |
| 0.7 | 11.65 | 0.98 | 11.21 | 1.16 |
| 0.9 | 15.09 | 2.17 | 14.66 | 1.15 |
| 1.1 | 21.04 | 3.34 | 19.78 | 2.19 |
| 1.3 | 29.42 | 2.90 | 29.35 | 1.63 |
| 1.5 | 31.66 | 3.08 | 30.56 | 1.90 |
| 1.7 | 35.17 | 3.29 | 33.99 | 2.14 |
| 1.9 | 39.33 | 3.45 | 37.69 | 3.11 |
| 2.1 | 43.28 | 3.64 | | |
| 2.3 | 46.76 | 3.58 | | |
| 2.5 | 48.88 | 3.34 | | |

Table XXX Statistical summary of respiratory exchange ratio at various velocities for male subjects

| Speed | Respiratory Exchange Ratio | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute ($km.h^{-1}$) | | | | |
| 3 | .91 | .08 | .74 | .10 |
| 4 | .90 | .09 | .94 | .12 |
| 5 | .89 | .07 | .89 | .08 |
| 6 | .86 | .06 | .87 | .06 |
| 7 | .86 | .07 | .88 | .09 |
| 8 | .86 | .05 | .89 | .06 |
| 9 | .88 | .05 | .92 | .06 |
| 10 | .89 | .04 | .93 | .05 |
| 11 | .90 | .05 | .96 | .05 |
| 12 | .93 | .05 | .97 | .04 |
| 13 | .95 | .04 | 1.00 | .03 |
| 14 | .97 | .04 | 1.02 | .04 |
| 15 | 1.00 | .05 | 1.05 | .05 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | .84 | .07 | .81 | .08 |
| 0.7 | .84 | .06 | .80 | .06 |
| 0.9 | .82 | .04 | .81 | .06 |
| 1.1 | .84 | .05 | .84 | .06 |
| 1.3 | .91 | .07 | .92 | .04 |
| 1.5 | .88 | .03 | .88 | .06 |
| 1.7 | .88 | .03 | .91 | .09 |
| 1.9 | .92 | .04 | .92 | .06 |
| 2.1 | .93 | .02 | | |
| 2.3 | .98 | .03 | | |
| 2.5 | 1.05 | .07 | | |

Table XXXI Statistical summary of respiratory exchange ratio at various velocities for female subjects

| Speed | Respiratory Exchange Ratio | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute ($km.h^{-1}$) | | | | |
| 3 | .87 | .12 | .85 | .12 |
| 4 | .86 | .10 | .87 | .13 |
| 5 | .84 | .09 | .86 | .11 |
| 6 | .83 | .08 | .84 | .10 |
| 7 | .87 | .07 | .88 | .11 |
| 8 | .88 | .06 | .92 | .10 |
| 9 | .89 | .06 | .94 | .10 |
| 10 | .91 | .06 | .97 | .11 |
| 11 | .92 | .06 | 1.00 | .10 |
| 12 | .95 | .07 | 1.00 | .06 |
| 13 | .98 | .07 | 1.04 | .06 |
| 14 | 1.01 | .06 | 1.08 | .08 |
| 15 | 1.04 | .06 | 1.11 | .09 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | .78 | .06 | .81 | .09 |
| 0.7 | .79 | .07 | .77 | .07 |
| 0.9 | .80 | .05 | .75 | .06 |
| 1.1 | .83 | .08 | .88 | .08 |
| 1.3 | .94 | .09 | .93 | .08 |
| 1.5 | .87 | .04 | .92 | .11 |
| 1.7 | .91 | .05 | .91 | .06 |
| 1.9 | .94 | .07 | .95 | .10 |
| 2.1 | .94 | .12 | | |
| 2.3 | .99 | .04 | | |
| 2.5 | 1.05 | .06 | | |

Table XXXII Statistical summary of $\%\dot{V}O_2$ max at various velocities for male subjects

| Speed | $\%\dot{V}O_2$ Max | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute ($km.h^{-1}$) | | | | |
| 3 | 18.0 | 1.6 | 18.8 | 1.7 |
| 4 | 18.3 | 2.9 | 20.6 | 2.0 |
| 5 | 21.5 | 2.9 | 22.6 | 2.7 |
| 6 | 26.9 | 3.2 | 28.3 | 2.8 |
| 7 | 38.9 | 5.3 | 40.1 | 3.1 |
| 8 | 44.5 | 4.1 | 50.8 | 4.3 |
| 9 | 51.9 | 5.8 | 55.8 | 3.3 |
| 10 | 52.6 | 4.8 | 60.0 | 6.7 |
| 11 | 59.3 | 5.3 | 67.6 | 4.5 |
| 12 | 63.7 | 4.4 | 73.2 | 5.8 |
| 13 | 69.6 | 7.2 | 79.9 | 5.1 |
| 14 | 73.9 | 7.1 | 87.2 | 4.0 |
| 15 | 78.6 | 7.6 | 93.5 | 5.3 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | 17.4 | 2.3 | 19.6 | 2.5 |
| 0.7 | 20.7 | 2.2 | 22.5 | 2.5 |
| 0.9 | 26.8 | 3.1 | 28.7 | 2.7 |
| 1.1 | 35.5 | 5.5 | 39.3 | 5.9 |
| 1.3 | 51.1 | 6.9 | 58.9 | 8.7 |
| 1.5 | 53.4 | 5.2 | 60.2 | 6.4 |
| 1.7 | 60.4 | 6.6 | 68.5 | 7.1 |
| 1.9 | 66.7 | 7.3 | 77.4 | 7.0 |
| 2.1 | 72.4 | 8.4 | | |
| 2.3 | 80.8 | 10.8 | | |
| 2.5 | 85.9 | 8.3 | | |

Table XXXIII Statistical summary of %$\dot{V}O_2$ max at various velocities for female subjects

| Speed | %$\dot{V}O_2$ Max | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute (km.h$^{-1}$) | | | | |
| 3 | 19.5 | 2.9 | 24.5 | 4.5 |
| 4 | 19.8 | 3.2 | 25.4 | 5.0 |
| 5 | 26.5 | 4.5 | 28.2 | 4.9 |
| 6 | 31.3 | 4.1 | 36.2 | 4.3 |
| 7 | 45.4 | 4.7 | 51.9 | 8.8 |
| 8 | 54.6 | 5.5 | 62.1 | 11.2 |
| 9 | 60.1 | 5.5 | 68.0 | 11.5 |
| 10 | 64.9 | 7.2 | 75.0 | 11.0 |
| 11 | 71.9 | 7.5 | 82.0 | 9.7 |
| 12 | 79.1 | 7.0 | 83.7 | 7.4 |
| 13 | 84.8 | 8.2 | 89.8 | 6.0 |
| 14 | 90.3 | 8.0 | 93.7 | 5.2 |
| 15 | 94.5 | 6.3 | 98.4 | 2.2 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | 19.4 | 2.8 | 22.6 | 3.1 |
| 0.7 | 22.2 | 3.1 | 26.4 | 4.3 |
| 0.9 | 28.8 | 5.4 | 34.5 | 4.7 |
| 1.1 | 40.3 | 8.6 | 47.0 | 10.2 |
| 1.3 | 56.2 | 8.9 | 69.4 | 10.6 |
| 1.5 | 60.4 | 8.7 | 72.2 | 10.7 |
| 1.7 | 66.8 | 9.7 | 76.0 | 6.7 |
| 1.9 | 74.9 | 10.0 | 84.3 | 7.9 |
| 2.1 | 77.4 | 9.0 | | |
| 2.3 | 83.8 | 10.7 | | |
| 2.5 | 87.6 | 9.3 | | |

Table XXXIV Statistical summary of energy cost per step at various velocities for male subjects

| Speed | Energy Cost per Step (kJ.kg$^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute (km.h$^{-1}$) | | | | |
| 3 | 2.49 | .28 | 2.27 | .30 |
| 4 | 2.29 | .37 | 2.16 | .27 |
| 5 | 2.47 | .38 | 2.15 | .28 |
| 6 | 2.81 | .34 | 2.46 | .28 |
| 7 | 3.12 | .43 | 2.74 | .30 |
| 8 | 3.49 | .33 | 3.37 | .41 |
| 9 | 4.02 | .41 | 3.65 | .35 |
| 10 | 4.11 | .44 | 3.95 | .44 |
| 11 | 4.61 | .49 | 4.39 | .36 |
| 12 | 4.96 | .26 | 4.77 | .37 |
| 13 | 5.38 | .64 | 5.18 | .46 |
| 14 | 5.69 | .52 | 5.62 | .45 |
| 15 | 5.98 | .62 | 5.88 | .56 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | 2.42 | .26 | 2.28 | .29 |
| 0.7 | 2.45 | .30 | 2.21 | .21 |
| 0.9 | 2.82 | .28 | 2.55 | .22 |
| 1.1 | 3.41 | .49 | 3.15 | .34 |
| 1.3 | 4.44 | .51 | 4.23 | .40 |
| 1.5 | 4.28 | .54 | 3.87 | .37 |
| 1.7 | 4.61 | .38 | 4.36 | .50 |
| 1.9 | 5.18 | .43 | 4.86 | .50 |
| 2.1 | 5.63 | .52 | | |
| 2.3 | 6.24 | .67 | | |
| 2.5 | 6.52 | .48 | | |

Table XXXV Statistical summary of energy cost per step at various velocities for female subjects

| Speed | Energy Cost per Step ($kJ.kg^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute ($km.h^{-1}$) | | | | |
| 3 | 2.21 | .18 | 2.22 | .32 |
| 4 | 1.97 | .21 | 2.06 | .28 |
| 5 | 2.42 | .38 | 2.09 | .25 |
| 6 | 2.65 | .27 | 2.47 | .17 |
| 7 | 3.17 | .26 | 2.89 | .43 |
| 8 | 3.70 | .31 | 3.39 | .40 |
| 9 | 4.02 | .32 | 3.66 | .52 |
| 10 | 4.32 | .44 | 4.00 | .43 |
| 11 | 4.69 | .46 | 4.27 | .46 |
| 12 | 5.17 | .44 | 4.60 | .42 |
| 13 | 5.50 | .43 | 4.99 | .33 |
| 14 | 5.76 | .50 | 5.17 | .43 |
| 15 | 5.97 | .41 | 5.31 | .32 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | 2.27 | .24 | 2.18 | .30 |
| 0.7 | 2.17 | .17 | 2.10 | .23 |
| 0.9 | 2.48 | .41 | 2.39 | .22 |
| 1.1 | 3.26 | .58 | 3.07 | .37 |
| 1.3 | 4.20 | .57 | 3.97 | .32 |
| 1.5 | 4.01 | .47 | 3.86 | .37 |
| 1.7 | 4.39 | .51 | 4.19 | .44 |
| 1.9 | 4.78 | .52 | 4.47 | .41 |
| 2.1 | 5.12 | .28 | | |
| 2.3 | 5.54 | .41 | | |
| 2.5 | 5.58 | .40 | | |

Table XXXVI Statistical summary of relative $\dot{V}O_2$ (per kg LBM) at various velocities for male subjects

| | Relative $\dot{V}O_2$ (ml.kg$^{-1}$LBM.min$^{-1}$) | | | |
|---|---|---|---|---|
| Speed | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\bar{X}$ | SD | $\bar{X}$ | SD |
| Absolute (km.h$^{-1}$) | | | | |
| 3 | 12.90 | 1.58 | 12.10 | 1.02 |
| 4 | 13.10 | 2.07 | 13.28 | 1.38 |
| 5 | 15.35 | 2.43 | 14.44 | 1.47 |
| 6 | 19.20 | 2.38 | 18.13 | 1.51 |
| 7 | 27.69 | 3.02 | 25.68 | 1.82 |
| 8 | 31.79 | 2.20 | 32.78 | 2.27 |
| 9 | 36.95 | 3.19 | 35.77 | 1.65 |
| 10 | 37.52 | 2.80 | 38.38 | 3.45 |
| 11 | 42.35 | 3.52 | 43.32 | 3.33 |
| 12 | 45.45 | 2.44 | 46.91 | 2.84 |
| 13 | 49.63 | 4.46 | 51.18 | 2.16 |
| 14 | 52.65 | 3.63 | 55.91 | 2.07 |
| 15 | 56.02 | 4.44 | 59.93 | 2.79 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | 12.36 | 1.56 | 12.52 | 1.30 |
| 0.7 | 14.70 | 1.67 | 14.47 | 1.37 |
| 0.9 | 19.03 | 1.98 | 18.44 | 1.48 |
| 1.1 | 25.20 | 3.27 | 25.20 | 3.08 |
| 1.3 | 36.31 | 4.04 | 37.60 | 4.67 |
| 1.5 | 37.88 | 2.68 | 38.52 | 2.97 |
| 1.7 | 42.96 | 3.27 | 43.91 | 3.65 |
| 1.9 | 47.26 | 2.80 | 49.58 | 3.51 |
| 2.1 | 51.81 | 3.53 | | |
| 2.3 | 57.58 | 4.04 | | |
| 2.5 | 61.30 | 2.80 | | |

Table XXXVII Statistical summary of relative $\dot{V}O_2$ (per kg LBM) at various velocities for female subjects

| Speed | Relative $\dot{V}O_2$ (ml.kg$^{-1}$LBM.min$^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute (km.h$^{-1}$) | | | | |
| 3 | 13.17 | 1.68 | 13.81 | 1.37 |
| 4 | 13.32 | 1.76 | 14.42 | 1.62 |
| 5 | 17.81 | 2.54 | 16.12 | 2.00 |
| 6 | 21.19 | 2.20 | 20.66 | 1.25 |
| 7 | 29.66 | 2.50 | 29.73 | 3.90 |
| 8 | 36.81 | 2.45 | 35.35 | 3.90 |
| 9 | 40.61 | 2.91 | 38.81 | 3.89 |
| 10 | 43.89 | 4.61 | 42.85 | 3.58 |
| 11 | 48.56 | 3.88 | 46.89 | 3.42 |
| 12 | 53.43 | 3.55 | 50.33 | 3.33 |
| 13 | 57.24 | 4.12 | 53.80 | 3.53 |
| 14 | 61.09 | 5.35 | 57.06 | 3.99 |
| 15 | 63.93 | 4.68 | 61.69 | 3.53 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | 13.06 | 1.42 | 13.05 | 1.43 |
| 0.7 | 14.99 | 1.37 | 15.33 | 1.36 |
| 0.9 | 19.36 | 2.93 | 19.89 | 1.36 |
| 1.1 | 27.00 | 4.69 | 26.90 | 3.31 |
| 1.3 | 37.86 | 4.18 | 39.83 | 2.14 |
| 1.5 | 40.59 | 4.19 | 41.52 | 2.48 |
| 1.7 | 45.23 | 4.47 | 45.64 | 2.04 |
| 1.9 | 50.47 | 5.19 | 50.74 | 3.84 |
| 2.1 | 55.04 | 5.76 | | |
| 2.3 | 59.51 | 5.71 | | |
| 2.5 | 62.35 | 5.52 | | |

Table XXXVIII Statistical summary of $\dot{V}O_2$ (per $m^2$ BSA) at various velocities for male subjects

| Speed | $\dot{V}O_2$ (ml.min$^{-1}$ per m$^2$ of BSA) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute (km.h$^{-1}$) | | | | |
| 3 | 412 | 52 | 389 | 39 |
| 4 | 415 | 66 | 426 | 46 |
| 5 | 489 | 72 | 465 | 57 |
| 6 | 612 | 69 | 583 | 55 |
| 7 | 883 | 92 | 826 | 66 |
| 8 | 1014 | 69 | 1048 | 82 |
| 9 | 1170 | 105 | 1151 | 60 |
| 10 | 1198 | 95 | 1233 | 98 |
| 11 | 1351 | 110 | 1391 | 79 |
| 12 | 1451 | 74 | 1507 | 67 |
| 13 | 1584 | 139 | 1646 | 88 |
| 14 | 1681 | 127 | 1799 | 95 |
| 15 | 1788 | 145 | 1929 | 135 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | 394 | 43 | 407 | 45 |
| 0.7 | 469 | 48 | 465 | 37 |
| 0.9 | 607 | 52 | 592 | 42 |
| 1.1 | 803 | 91 | 808 | 89 |
| 1.3 | 1158 | 114 | 1209 | 147 |
| 1.5 | 1209 | 75 | 1238 | 85 |
| 1.7 | 1371 | 96 | 1412 | 114 |
| 1.9 | 1509 | 93 | 1596 | 131 |
| 2.1 | 1662 | 92 | | |
| 2.3 | 1849 | 139 | | |
| 2.5 | 1967 | 72 | | |

Table XXXIX Statistical summary of $\dot{V}O_2$ (per $m^2$ BSA) at various velocities for female subjects

| | $\dot{V}O_2$ (ml.min$^{-1}$ per $m^2$ of BSA) | | | |
|---|---|---|---|---|
| Speed | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute (km.h$^{-1}$) | | | | |
| 3 | 362 | 43 | 374 | 32 |
| 4 | 366 | 44 | 390 | 38 |
| 5 | 492 | 79 | 437 | 52 |
| 6 | 583 | 59 | 560 | 40 |
| 7 | 846 | 90 | 804 | 88 |
| 8 | 1015 | 80 | 957 | 85 |
| 9 | 1120 | 93 | 1051 | 90 |
| 10 | 1209 | 124 | 1162 | 104 |
| 11 | 1339 | 116 | 1272 | 98 |
| 12 | 1472 | 102 | 1381 | 94 |
| 13 | 1577 | 110 | 1476 | 90 |
| 14 | 1683 | 141 | 1567 | 112 |
| 15 | 1761 | 123 | 1704 | 94 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | 360 | 38 | 354 | 36 |
| 0.7 | 413 | 41 | 415 | 29 |
| 0.9 | 534 | 85 | 541 | 53 |
| 1.1 | 746 | 148 | 729 | 97 |
| 1.3 | 1045 | 133 | 1081 | 75 |
| 1.5 | 1119 | 124 | 1127 | 74 |
| 1.7 | 1247 | 135 | 1253 | 74 |
| 1.9 | 1389 | 129 | 1394 | 125 |
| 2.1 | 1527 | 157 | | |
| 2.3 | 1651 | 163 | | |
| 2.5 | 1730 | 149 | | |

Table XL Statistical summary of energy cost per metre at various velocities for male subjects

| Speed | Energy Cost per Metre ($kJ.kg^{-1}.m^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute ($km.h^{-1}$) | | | | |
| 3 | 4.57 | .50 | 4.14 | .40 |
| 4 | 3.50 | .52 | 3.42 | .37 |
| 5 | 3.26 | .49 | 2.96 | .31 |
| 6 | 3.38 | .41 | 3.09 | .32 |
| 7 | 4.18 | .41 | 3.74 | .32 |
| 8 | 4.19 | .30 | 4.17 | .38 |
| 9 | 4.34 | .37 | 4.09 | .20 |
| 10 | 3.99 | .32 | 3.97 | .35 |
| 11 | 4.09 | .33 | 4.09 | .26 |
| 12 | 4.05 | .14 | 4.07 | .22 |
| 13 | 4.11 | .37 | 4.12 | .24 |
| 14 | 4.08 | .31 | 4.19 | .22 |
| 15 | 4.05 | .32 | 4.20 | .27 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | 4.04 | .48 | 3.96 | .41 |
| 0.7 | 3.44 | .34 | 3.26 | .33 |
| 0.9 | 3.45 | .32 | 3.23 | .26 |
| 1.1 | 3.76 | .44 | 3.64 | .39 |
| 1.3 | 4.66 | .57 | 4.71 | .51 |
| 1.5 | 4.18 | .33 | 4.15 | .28 |
| 1.7 | 4.18 | .38 | 4.18 | .34 |
| 1.9 | 4.17 | .24 | 4.25 | .34 |
| 2.1 | 4.16 | .33 | | |
| 2.3 | 4.28 | .32 | | |
| 2.5 | 4.21 | .26 | | |

Table XLI Statistical summary of energy cost per metre at various velocities for female subjects

| Speed | Energy Cost per Metre ($kJ.kg^{-1}.m^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\bar{X}$ | SD | $\bar{X}$ | SD |
| Absolute ($km.h^{-1}$) | | | | |
| 3 | 4.18 | .49 | 4.17 | .47 |
| 4 | 3.19 | .40 | 3.28 | .35 |
| 5 | 3.38 | .37 | 2.92 | .34 |
| 6 | 3.34 | .29 | 3.10 | .21 |
| 7 | 4.18 | .30 | 3.87 | .39 |
| 8 | 4.41 | .24 | 4.05 | .40 |
| 9 | 4.34 | .22 | 3.97 | .39 |
| 10 | 4.24 | .34 | 3.97 | .30 |
| 11 | 4.27 | .27 | 3.96 | .31 |
| 12 | 4.32 | .26 | 3.98 | .24 |
| 13 | 4.29 | .23 | 3.92 | .22 |
| 14 | 4.29 | .33 | 3.86 | .24 |
| 15 | 4.21 | .30 | 3.86 | .19 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | 4.07 | .41 | 3.84 | .47 |
| 0.7 | 3.36 | .32 | 3.21 | .33 |
| 0.9 | 3.38 | .48 | 3.20 | .23 |
| 1.1 | 3.87 | .55 | 3.66 | .39 |
| 1.3 | 4.72 | .39 | 4.64 | .27 |
| 1.5 | 4.34 | .42 | 4.17 | .28 |
| 1.7 | 4.30 | .40 | 4.11 | .28 |
| 1.9 | 4.32 | .38 | 4.09 | .34 |
| 2.1 | 4.29 | .38 | | |
| 2.3 | 4.31 | .36 | | |
| 2.5 | 4.15 | .35 | | |

Table XLII Statistical summary of economy (per $km.h^{-1}$) at various velocities for male subjects

| Speed | Economy ($ml.kg^{-1}.min^{-1}$ per $km.h^{-1}$) High $\dot{V}O_2$ $\overline{X}$ | SD | Average $\dot{V}O_2$ $\overline{X}$ | SD |
|---|---|---|---|---|
| Absolute ($km.h^{-1}$) | | | | |
| 3 | 3.69 | .38 | 3.34 | .34 |
| 4 | 2.84 | .46 | 2.76 | .31 |
| 5 | 2.64 | .40 | 2.40 | .27 |
| 6 | 2.76 | .35 | 2.52 | .25 |
| 7 | 3.41 | .36 | 3.05 | .26 |
| 8 | 3.43 | .26 | 3.38 | .31 |
| 9 | 3.53 | .31 | 3.30 | .17 |
| 10 | 3.24 | .28 | 3.18 | .29 |
| 11 | 3.31 | .27 | 3.26 | .22 |
| 12 | 3.26 | .12 | 3.24 | .18 |
| 13 | 3.28 | .30 | 3.26 | .20 |
| 14 | 3.25 | .24 | 3.31 | .18 |
| 15 | 3.31 | .27 | 3.31 | .21 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | 3.32 | .41 | 3.18 | .44 |
| 0.7 | 2.83 | .28 | 2.73 | .24 |
| 0.9 | 2.85 | .28 | 2.68 | .22 |
| 1.1 | 3.08 | .34 | 2.99 | .32 |
| 1.3 | 3.76 | .42 | 3.79 | .42 |
| 1.5 | 3.40 | .27 | 3.37 | .24 |
| 1.7 | 3.39 | .31 | 3.38 | .28 |
| 1.9 | 3.35 | .19 | 3.42 | .26 |
| 2.1 | 3.33 | .25 | | |
| 2.3 | 3.40 | .25 | | |
| 2.5 | 3.34 | .21 | | |

Table XLIII Statistical summary of economy (per $km.h^{-1}$) at various velocities for female subjects

| Speed | Economy ($ml.kg^{-1}.min^{-1}$ per $km.h^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute ($km.h^{-1}$) | | | | |
| 3 | 3.41 | .36 | 3.42 | .41 |
| 4 | 2.61 | .34 | 2.69 | .32 |
| 5 | 2.78 | .33 | 2.39 | .32 |
| 6 | 2.75 | .24 | 2.55 | .21 |
| 7 | 3.31 | .44 | 3.15 | .35 |
| 8 | 3.59 | .18 | 3.27 | .36 |
| 9 | 3.51 | .19 | 3.19 | .32 |
| 10 | 3.42 | .27 | 3.18 | .25 |
| 11 | 3.44 | .22 | 3.15 | .25 |
| 12 | 3.46 | .20 | 3.14 | .20 |
| 13 | 3.42 | .19 | 3.10 | .18 |
| 14 | 3.41 | .25 | 3.05 | .19 |
| 15 | 3.33 | .24 | 3.04 | .15 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | 3.40 | .36 | 3.18 | .36 |
| 0.7 | 2.79 | .25 | 2.67 | .27 |
| 0.9 | 2.80 | .40 | 2.69 | .21 |
| 1.1 | 3.19 | .48 | 2.97 | .32 |
| 1.3 | 3.79 | .33 | 3.73 | .19 |
| 1.5 | 3.54 | .35 | 3.37 | .22 |
| 1.7 | 3.47 | .34 | 3.32 | .21 |
| 1.9 | 3.46 | .31 | 3.28 | .28 |
| 2.1 | 3.45 | .35 | | |
| 2.3 | 3.41 | .30 | | |
| 2.5 | 3.28 | .27 | | |

Table XLIV Statistical summary of economy (per leg length.$s^{-1}$) at various velocities for male subjects

| Speed | Economy ($ml.kg^{-1}.min^{-1}$ per $LL.s^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute ($km.h^{-1}$) | | | | |
| 3 | 11.32 | 1.18 | 9.81 | 1.32 |
| 4 | 8.76 | 1.72 | 8.08 | 0.92 |
| 5 | 8.14 | 1.42 | 7.07 | 0.98 |
| 6 | 8.49 | 1.20 | 7.38 | 0.90 |
| 7 | 10.53 | 1.56 | 8.96 | 1.13 |
| 8 | 10.57 | 1.28 | 9.95 | 1.35 |
| 9 | 10.89 | 1.41 | 9.67 | 0.91 |
| 10 | 9.98 | 1.15 | 9.36 | 1.16 |
| 11 | 10.20 | 1.11 | 9.56 | 0.63 |
| 12 | 10.02 | 0.70 | 9.50 | 0.85 |
| 13 | 10.11 | 1.07 | 9.57 | 0.99 |
| 14 | 10.00 | 0.96 | 9.71 | 0.88 |
| 15 | 9.90 | 1.01 | 9.73 | 0.99 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | 10.18 | 1.16 | 9.60 | 1.08 |
| 0.7 | 8.69 | 0.93 | 7.90 | 0.67 |
| 0.9 | 8.76 | 0.94 | 7.83 | 0.62 |
| 1.1 | 9.49 | 1.28 | 8.76 | 1.06 |
| 1.3 | 11.55 | 1.43 | 10.89 | 1.07 |
| 1.5 | 10.47 | 0.97 | 9.88 | 0.92 |
| 1.7 | 10.41 | 0.80 | 9.92 | 1.04 |
| 1.9 | 10.30 | 0.85 | 10.02 | 0.84 |
| 2.1 | 10.41 | 0.97 | | |
| 2.3 | 10.61 | 1.04 | | |
| 2.5 | 10.38 | 0.70 | | |

Table XLV Statistical summary of economy (per leg length.$s^{-1}$) at various velocities for female subjects

| Speed | Economy ($ml.kg^{-1}.min^{-1}$ per LL.$s^{-1}$) High $\dot{V}O_2$ $\overline{X}$ | SD | Average $\dot{V}O_2$ $\overline{X}$ | SD |
|---|---|---|---|---|
| Absolute ($km.h^{-1}$) | | | | |
| 3 | 9.59 | 0.90 | 9.77 | 1.29 |
| 4 | 7.34 | 0.94 | 7.67 | 1.00 |
| 5 | 7.82 | 0.91 | 6.82 | 0.93 |
| 6 | 7.75 | 0.66 | 7.29 | 0.63 |
| 7 | 9.61 | 0.74 | 8.99 | 0.86 |
| 8 | 10.11 | 0.66 | 9.34 | 1.02 |
| 9 | 9.90 | 0.71 | 9.11 | 0.92 |
| 10 | 9.63 | 0.78 | 9.07 | 0.79 |
| 11 | 9.68 | 0.72 | 8.98 | 0.68 |
| 12 | 9.75 | 0.67 | 9.82 | 0.64 |
| 13 | 9.64 | 0.61 | 8.81 | 0.46 |
| 14 | 9.60 | 0.82 | 8.60 | 0.49 |
| 15 | 9.37 | 0.77 | 8.57 | 0.38 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | 9.56 | 0.93 | 9.04 | 0.84 |
| 0.7 | 7.84 | 0.59 | 7.60 | 0.70 |
| 0.9 | 7.89 | 1.06 | 7.68 | 0.65 |
| 1.1 | 8.98 | 1.28 | 8.49 | 1.05 |
| 1.3 | 10.68 | 0.96 | 10.65 | 0.68 |
| 1.5 | 9.97 | 0.95 | 9.62 | 0.65 |
| 1.7 | 9.76 | 0.89 | 9.42 | 0.64 |
| 1.9 | 9.75 | 0.80 | 9.34 | 0.85 |
| 2.1 | 9.77 | 0.89 | | |
| 2.3 | 9.66 | 0.77 | | |
| 2.5 | 9.28 | 0.72 | | |

Table XLVI Statistical summary of economy (per st.s$^{-1}$) at various velocities for male subjects

| Speed | Economy (ml.kg$^{-1}$.min$^{-1}$ per st.s$^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\bar{X}$ | SD | $\bar{X}$ | SD |
| Absolute (km.h$^{-1}$) | | | | |
| 3 | 23.70 | 2.54 | 21.14 | 2.31 |
| 4 | 18.29 | 3.29 | 17.40 | 1.77 |
| 5 | 17.02 | 2.84 | 15.22 | 1.85 |
| 6 | 17.75 | 2.33 | 15.90 | 1.69 |
| 7 | 22.01 | 3.02 | 19.30 | 1.98 |
| 8 | 22.08 | 2.30 | 21.43 | 2.31 |
| 9 | 22.76 | 2.55 | 20.85 | 1.36 |
| 10 | 20.85 | 2.06 | 20.16 | 2.08 |
| 11 | 21.32 | 1.97 | 20.63 | 1.05 |
| 12 | 20.95 | 1.16 | 20.48 | 1.33 |
| 13 | 21.13 | 1.99 | 20.63 | 1.59 |
| 14 | 20.91 | 1.66 | 20.87 | 1.41 |
| 15 | 20.70 | 1.86 | 20.97 | 1.53 |
| Relative (st.s$^{-1}$) | | | | |
| 0.5 | 21.31 | 2.42 | 20.72 | 2.18 |
| 0.7 | 18.18 | 1.89 | 17.02 | 1.42 |
| 0.9 | 18.32 | 1.76 | 16.91 | 1.23 |
| 1.1 | 19.84 | 2.55 | 18.84 | 2.10 |
| 1.3 | 24.15 | 2.72 | 23.95 | 2.70 |
| 1.5 | 21.88 | 1.65 | 21.31 | 1.62 |
| 1.7 | 21.79 | 1.59 | 21.39 | 1.83 |
| 1.9 | 21.54 | 1.45 | 21.63 | 1.59 |
| 2.1 | 21.51 | 1.70 | | |
| 2.3 | 21.93 | 1.92 | | |
| 2.5 | 21.48 | 1.20 | | |

Table XLVII   Statistical summary of economy (per st.$s^{-1}$) at various velocities for female subjects

| Speed | Economy (ml.$kg^{-1}$.$min^{-1}$ per st.$s^{-1}$) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute (km.$h^{-1}$) | | | | |
| 3 | 20.32 | 1.85 | 20.70 | 2.63 |
| 4 | 15.55 | 1.97 | 16.24 | 2.07 |
| 5 | 16.60 | 2.07 | 14.45 | 1.89 |
| 6 | 16.43 | 1.51 | 15.44 | 1.27 |
| 7 | 20.37 | 1.40 | 19.04 | 1.73 |
| 8 | 21.32 | 1.31 | 19.77 | 2.02 |
| 9 | 20.98 | 1.32 | 19.30 | 1.81 |
| 10 | 20.40 | 1.53 | 19.19 | 1.49 |
| 11 | 20.50 | 1.30 | 19.03 | 1.35 |
| 12 | 20.66 | 1.25 | 18.92 | 1.22 |
| 13 | 20.41 | 1.05 | 18.68 | 0.89 |
| 14 | 20.33 | 1.55 | 18.28 | 0.96 |
| 15 | 19.84 | 1.41 | 18.27 | 0.79 |
| Relative (st.$s^{-1}$) | | | | |
| 0.5 | 20.26 | 1.96 | 19.16 | 1.80 |
| 0.7 | 16.62 | 1.33 | 16.11 | 1.46 |
| 0.9 | 16.74 | 2.41 | 16.27 | 1.31 |
| 1.1 | 19.06 | 2.93 | 17.98 | 2.01 |
| 1.3 | 22.65 | 2.26 | 22.56 | 1.26 |
| 1.5 | 21.13 | 2.04 | 20.37 | 1.25 |
| 1.7 | 20.69 | 1.93 | 19.98 | 1.22 |
| 1.9 | 20.67 | 1.82 | 19.80 | 1.64 |
| 2.1 | 20.52 | 1.72 | | |
| 2.3 | 20.31 | 1.52 | | |
| 2.5 | 19.49 | 1.31 | | |

Table XLVIII Statistical summary of efficiency at various velocities for male subjects

| Speed | Efficiency (%) | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute ($km.h^{-1}$) | | | | |
| 3 | 39.4 | 6.4 | 45.8 | 8.3 |
| 4 | 54.4 | 12.2 | 55.0 | 8.3 |
| 5 | 57.3 | 11.8 | 64.1 | 12.3 |
| 6 | 52.1 | 8.1 | 58.2 | 8.2 |
| 7 | 39.2 | 4.2 | 45.3 | 4.4 |
| 8 | 39.8 | 3.3 | 40.3 | 4.1 |
| 9 | 38.9 | 3.6 | 41.4 | 2.3 |
| 10 | 43.3 | 3.8 | 43.8 | 4.4 |
| 11 | 42.9 | 4.1 | 42.8 | 3.0 |
| 12 | 43.7 | 1.7 | 43.7 | 2.6 |
| 13 | 44.1 | 4.5 | 43.9 | 2.9 |
| 14 | 44.9 | 3.7 | 43.7 | 2.5 |
| 15 | 46.1 | 4.1 | 44.3 | 3.0 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | 46.1 | 8.5 | 47.4 | 8.6 |
| 0.7 | 52.3 | 8.0 | 56.3 | 7.7 |
| 0.9 | 50.2 | 6.4 | 54.4 | 6.0 |
| 1.1 | 45.3 | 6.0 | 47.0 | 6.6 |
| 1.3 | 35.9 | 5.0 | 35.4 | 4.3 |
| 1.5 | 40.9 | 3.5 | 41.1 | 3.3 |
| 1.7 | 41.9 | 4.2 | 41.7 | 3.6 |
| 1.9 | 42.7 | 2.8 | 41.7 | 3.4 |
| 2.1 | 43.8 | 3.8 | | |
| 2.3 | 43.3 | 3.6 | | |
| 2.5 | 44.8 | 3.0 | | |

Table XLIX Statistical summary of efficiency at various velocities for female subjects

| | Efficiency (%) | | | |
|---|---|---|---|---|
| Speed | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Absolute ($km.h^{-1}$) | | | | |
| 3 | 45.1 | 8.5 | 45.0 | 7.5 |
| 4 | 62.1 | 15.8 | 58.2 | 9.6 |
| 5 | 52.8 | 7.9 | 65.1 | 11.6 |
| 6 | 52.0 | 5.7 | 57.1 | 4.9 |
| 7 | 39.5 | 3.4 | 43.7 | 5.4 |
| 8 | 37.5 | 2.3 | 41.8 | 5.1 |
| 9 | 38.8 | 2.3 | 43.3 | 4.9 |
| 10 | 40.6 | 4.0 | 43.7 | 3.8 |
| 11 | 40.8 | 2.8 | 44.5 | 3.9 |
| 12 | 40.9 | 2.4 | 45.1 | 3.1 |
| 13 | 41.9 | 2.4 | 46.3 | 3.0 |
| 14 | 42.6 | 3.7 | 47.8 | 3.4 |
| 15 | 44.2 | 3.2 | 48.4 | 2.7 |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | 46.1 | 7.3 | 50.9 | 9.0 |
| 0.7 | 54.6 | 7.3 | 58.3 | 8.5 |
| 0.9 | 53.0 | 11.7 | 55.0 | 5.3 |
| 1.1 | 43.9 | 6.5 | 46.7 | 5.5 |
| 1.3 | 34.8 | 3.1 | 35.4 | 2.5 |
| 1.5 | 39.0 | 4.4 | 40.7 | 3.4 |
| 1.7 | 40.2 | 4.4 | 42.0 | 3.5 |
| 1.9 | 40.6 | 4.3 | 43.1 | 4.0 |
| 2.1 | 41.7 | 4.0 | | |
| 2.3 | 42.3 | 3.7 | | |
| 2.5 | 44.9 | 4.0 | | |

Table L Statistical summary of RPE at 0% grade at various velocities for male and female subjects

| Speed | RPE at 0% Grade | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Male | | | | |
| Relative (st.$s^{-1}$) | | | | |
| 0.5 | 6.8 | 0.6 | 6.9 | 0.9 |
| 0.7 | 7.6 | 1.2 | 7.6 | 1.2 |
| 0.9 | 8.2 | 1.4 | 8.5 | 1.4 |
| 1.1 | 9.9 | 1.6 | 10.3 | 1.2 |
| 1.3 | 13.4 | 1.6 | 13.0 | 1.3 |
| 1.5 | 10.3 | 1.6 | 11.3 | 1.0 |
| 1.7 | 11.1 | 1.5 | 11.9 | 1.0 |
| 1.9 | 11.6 | 1.2 | 12.8 | 0.8 |
| 2.1 | 12.6 | 1.0 | | |
| 2.3 | 13.3 | 1.3 | | |
| 2.5 | 14.6 | 1.5 | | |
| Female | | | | |
| Relative (st.$s^{-1}$) | | | | |
| 0.5 | 6.5 | 0.5 | 6.5 | 0.5 |
| 0.7 | 7.2 | 0.4 | 6.9 | 0.9 |
| 0.9 | 7.4 | 1.1 | 8.2 | 2.0 |
| 1.1 | 9.1 | 1.9 | 9.6 | 2.0 |
| 1.3 | 12.3 | 2.2 | 13.7 | 3.3 |
| 1.5 | 10.1 | 2.0 | 12.2 | 3.7 |
| 1.7 | 11.0 | 1.4 | 11.8 | 2.1 |
| 1.9 | 12.1 | 1.7 | 13.0 | 2.4 |
| 2.1 | 13.2 | 2.1 | | |
| 2.3 | 14.2 | 2.2 | | |
| 2.5 | 16.0 | 1.6 | | |

Table LI Statistical summary of % of max RPE at 0% grade at various velocities for male and female subjects

| Speed | % of Max RPE at 0% Grade | | | |
|---|---|---|---|---|
| | High $\dot{V}O_2$ | | Average $\dot{V}O_2$ | |
| | $\overline{X}$ | SD | $\overline{X}$ | SD |
| Male | | | | |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | 39.2 | 5.3 | 41.3 | 5.5 |
| 0.7 | 43.4 | 8.3 | 45.4 | 6.9 |
| 0.9 | 47.4 | 10.8 | 50.7 | 6.8 |
| 1.1 | 57.1 | 11.1 | 61.6 | 6.7 |
| 1.3 | 76.7 | 11.7 | 77.7 | 8.6 |
| 1.5 | 58.3 | 10.5 | 68.3 | 7.0 |
| 1.7 | 63.6 | 8.4 | 71.6 | 8.6 |
| 1.9 | 66.2 | 8.8 | 76.7 | 7.0 |
| 2.1 | 71.3 | 11.1 | | |
| 2.3 | 74.7 | 7.9 | | |
| 2.5 | 82.0 | 9.4 | | |
| Female | | | | |
| Relative ($st.s^{-1}$) | | | | |
| 0.5 | 37.5 | 4.4 | 38.5 | 3.5 |
| 0.7 | 41.5 | 5.0 | 40.7 | 6.7 |
| 0.9 | 42.5 | 7.4 | 48.4 | 14.0 |
| 1.1 | 52.1 | 12.2 | 56.5 | 11.8 |
| 1.3 | 70.7 | 14.3 | 80.0 | 17.3 |
| 1.5 | 58.2 | 12.6 | 71.2 | 19.5 |
| 1.7 | 63.1 | 7.1 | 69.2 | 11.8 |
| 1.9 | 69.6 | 11.7 | 76.4 | 12.8 |
| 2.1 | 81.0 | 15.1 | | |
| 2.3 | 86.6 | 13.6 | | |
| 2.5 | 97.8 | 11.2 | | |

Table LII Responses of male and female subjects to grade (+3% and -3%) and level locomotion at various relative speeds

A - Oxygen Consumption (ml.kg$^{-1}$.min$^{-1}$)

| Subject/ Condition | | Relative Speed (st.s$^{-1}$) 0.5 | 0.7 | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 |
|---|---|---|---|---|---|---|---|---|---|
| Male | $\bar{X}$ | 12.9 | 15.7 | 20.1 | 26.7 | 37.5 | 38.6 | 43.3 | 47.7 |
| +3% | SD | .8 | 1.2 | 2.0 | 2.7 | 3.3 | 2.5 | 2.5 | 3.0 |
| Male | $\bar{X}$ | 10.6 | 12.4 | 15.9 | 21.3 | 31.3 | 32.4 | 36.7 | 41.5 |
| 0% | SD | 1.1 | 1.2 | 1.5 | 2.6 | 3.4 | 2.4 | 2.9 | 2.7 |
| Male | $\bar{X}$ | 9.4 | 10.9 | 13.7 | 18.9 | 28.7 | 30.0 | 33.5 | 37.0 |
| -3% | SD | 1.1 | 1.4 | 1.6 | 2.4 | 3.9 | 2.4 | 3.0 | 2.8 |
| Female | $\bar{X}$ | 12.1 | 14.4 | 18.7 | 24.7 | 34.5 | 37.3 | 40.1 | 42.5 |
| +3% | SD | 1.0 | 1.0 | 1.0 | 1.7 | 2.5 | 2.7 | 2.9 | 3.3 |
| Female | $\bar{X}$ | 9.9 | 11.4 | 14.9 | 20.4 | 29.4 | 31.1 | 34.6 | 38.6 |
| 0% | SD | 1.0 | 1.1 | 1.7 | 2.8 | 2.3 | 2.5 | 2.8 | 3.3 |
| Female | $\bar{X}$ | 8.7 | 10.4 | 12.6 | 17.4 | 26.5 | 28.9 | 31.1 | 35.1 |
| -3% | SD | 1.0 | 1.2 | 1.2 | 2.0 | 3.5 | 3.4 | 3.5 | 3.2 |

Analysis

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| M/F | | M>F | M>F | M>F | M>F | M>F | M>F | M>F | M>F |
| +3%/ 0% | p< | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| +3%/-3% | p< | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| 0%/-3% | p< | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |

Table LIII Responses of male and female subjects to grade (+3% and -3%) and level locomotion at various relative speeds

B - Stride Length (m)

| Subject/ | | | | Relative Speed ($st.s^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Condition | | 0.5 | 0.7 | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 |
| Male | $\bar{X}$ | 1.22 | 1.40 | 1.61 | 1.76 | 1.82 | 1.91 | 2.14 | 2.35 |
| +3% | SD | .08 | .08 | .11 | .11 | .12 | .17 | .18 | .17 |
| Male | $\bar{X}$ | 1.18 | 1.39 | 1.61 | 1.79 | 1.86 | 1.94 | 2.15 | 2.40 |
| 0% | SD | .08 | .09 | .11 | .11 | .12 | .16 | .18 | .22 |
| Male | $\bar{X}$ | 1.14 | 1.37 | 1.60 | 1.78 | 1.85 | 1.95 | 2.16 | 2.4 |
| -3% | SD | .09 | .10 | .11 | .12 | .13 | .18 | .18 | .16 |
| Female | $\bar{X}$ | 1.15 | 1.32 | 1.49 | 1.65 | 1.73 | 1.82 | 2.00 | 2.17 |
| +3% | SD | .10 | .08 | .10 | .09 | .09 | .13 | .13 | .13 |
| Female | $\bar{X}$ | 1.13 | 1.33 | 1.48 | 1.68 | 1.74 | 1.84 | 2.04 | 2.20 |
| 0% | SD | .10 | .12 | .09 | .11 | .11 | .12 | .14 | .13 |
| Female | $\bar{X}$ | 1.10 | 1.34 | 1.48 | 1.65 | 1.73 | 1.88 | 2.05 | 2.23 |
| -3% | SD | .09 | .08 | .10 | .10 | .14 | .11 | .15 | .12 |

<u>Analysis</u>

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| M/F | | – | M>F | M>F | M>F | M>F | – | M>F | M>F |
| +3%/ 0% | $p < 0.05$ | | – | – | 0.05 | – | 0.05 | 0.05 | – |
| +3%/-3% | $p < 0.05$ | | – | – | – | – | 0.05 | 0.05 | 0.05 |
| 0%/-3% | $p < 0.05$ | | – | – | – | – | – | – | 0.05 |

Table LIV Responses of male and female subjects to grade (+3% and -3%) and level locomotion at various relative speeds

C - Cadence (steps.min$^{-1}$)

| Subject/ | | Relative Speed (st.s$^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Condition | | 0.5 | 0.7 | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 |
| Male | $\overline{X}$ | 87.1 | 106.7 | 119.4 | 133.3 | 152.0 | 167.3 | 169.5 | 172.4 |
| +3% | SD | 4.1 | 3.3 | 4.0 | 4.5 | 7.1 | 10.5 | 9.8 | 8.5 |
| Male | $\overline{X}$ | 90.8 | 107.2 | 119.3 | 132.0 | 149.2 | 163.7 | 168.6 | 169.5 |
| 0% | SD | 4.2 | 3.9 | 3.8 | 3.7 | 7.2 | 12.5 | 9.2 | 11.2 |
| Male | $\overline{X}$ | 93.4 | 109.5 | 119.9 | 131.8 | 149.6 | 164.6 | 168.1 | 169.0 |
| -3% | SD | 4.4 | 4.3 | 4.1 | 4.3 | 8.1 | 10.4 | 10.1 | 7.8 |
| Female | $\overline{X}$ | 87.5 | 106.9 | 121.3 | 133.6 | 150.7 | 165.8 | 170.2 | 175.9 |
| +3% | SD | 6.7 | 5.4 | 6.1 | 4.4 | 6.8 | 8.7 | 8.3 | 8.5 |
| Female | $\overline{X}$ | 89.4 | 107.6 | 122.0 | 131.8 | 150.1 | 162.9 | 167.3 | 172.5 |
| 0% | SD | 6.9 | 5.5 | 5.3 | 6.2 | 8.6 | 7.7 | 8.3 | 6.9 |
| Female | $\overline{X}$ | 91.5 | 108.6 | 122.3 | 134.0 | 151.7 | 160.3 | 166.8 | 170.7 |
| -3% | SD | 6.5 | 7.3 | 7.2 | 5.8 | 11.5 | 7.2 | 9.6 | 6.9 |

Analysis

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| M/F | - | - | - | - | - | - | - | - |
| +3%/ 0% | $p < 0.05$ | - | - | 0.05 | - | 0.05 | 0.05 | - |
| +3%/-3% | $p < 0.05$ | 0.05 | - | - | - | 0.05 | 0.05 | 0.05 |
| 0%/-3% | $p < 0.05$ | - | - | - | - | - | - | 0.05 |

Table LV Responses of male and female subjects to grade (+3% and -3%) and level locomotion at various relative speeds

D - Efficiency (%)

| Subject/ | | Relative Speed ($st.s^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Condition | | 0.5 | 0.7 | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 |
| Male | $\overline{X}$ | 42.6 | 48.1 | 47.1 | 42.1 | 34.3 | 39.7 | 40.6 | 41.9 |
| +3% | SD | 3.8 | 4.8 | 4.9 | 4.0 | 3.0 | 2.5 | 2.7 | 2.9 |
| Male | $\overline{X}$ | 46.7 | 54.2 | 52.2 | 46.1 | 35.7 | 41.0 | 41.8 | 42.2 |
| 0% | SD | 8.4 | 7.9 | 6.4 | 6.2 | 4.6 | 3.3 | 3.8 | 3.1 |
| Male | $\overline{X}$ | 41.7 | 49.8 | 49.4 | 42.2 | 31.7 | 36.5 | 37.9 | 39.2 |
| -3% | SD | 6.8 | 8.4 | 7.3 | 5.9 | 4.4 | 3.4 | 3.7 | 3.6 |
| Female | $\overline{X}$ | 44.2 | 51.3 | 48.2 | 42.6 | 35.0 | 38.5 | 40.8 | 43.7 |
| +3% | SD | 5.4 | 5.9 | 3.5 | 3.0 | 2.5 | 3.2 | 3.3 | 3.8 |
| Female | $\overline{X}$ | 48.6 | 56.6 | 54.0 | 45.3 | 35.1 | 40.0 | 41.0 | 41.8 |
| 0% | SD | 8.4 | 8.0 | 8.7 | 6.0 | 2.8 | 4.1 | 4.0 | 4.2 |
| Female | $\overline{X}$ | 45.9 | 51.2 | 51.7 | 43.5 | 31.9 | 35.8 | 38.1 | 38.2 |
| -3% | SD | 9.9 | 10.3 | 6.5 | 6.1 | 4.3 | 5.2 | 5.1 | 4.1 |

### Analysis

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| M/F | | - | - | - | - | - | - | - | - |
| +3%/ 0% | $p<$ | 0.5 | 0.5 | 0.5 | - | - | - | - | - |
| +3%/-3% | $p<$ | - | - | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| 0%/-3% | $p<$ | 0.5 | 0.5 | - | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |

Table LVI Responses of subjects with high and average $\dot{V}O_2$ max to grade (+3% and -3%) and level locomotion at various relative speeds

A - Oxygen Consumption ($ml.kg^{-1}.min^{-1}$)

| Subject/ Condition | | Relative Speed ($st.s^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 0.5 | 0.7 | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 |
| High | $\bar{X}$ | 12.8 | 15.3 | 19.8 | 26.1 | 36.7 | 38.6 | 42.6 | 46.3 |
| +3% | SD | 0.8 | 1.5 | 1.9 | 3.0 | 3.5 | 2.3 | 2.9 | 4.4 |
| High | $\bar{X}$ | 10.5 | 12.2 | 15.8 | 21.4 | 30.4 | 32.3 | 36.2 | 40.2 |
| 0% | SD | 1.1 | 1.3 | 2.0 | 3.0 | 3.3 | 2.8 | 3.1 | 3.1 |
| High | $\bar{X}$ | 9.3 | 11.1 | 13.6 | 18.5 | 28.3 | 29.6 | 32.9 | 36.8 |
| -3% | SD | 1.1 | 1.4 | 1.6 | 2.7 | 4.4 | 2.7 | 3.8 | 3.1 |
| Avg | $\bar{X}$ | 12.3 | 14.8 | 19.0 | 25.3 | 35.3 | 37.2 | 40.9 | 44.1 |
| +3% | SD | 1.1 | 1.0 | 1.4 | 1.8 | 3.0 | 2.8 | 3.2 | 3.5 |
| Avg | $\bar{X}$ | 10.0 | 11.6 | 14.9 | 20.3 | 30.2 | 31.2 | 35.3 | 40.0 |
| 0% | SD | 1.0 | 1.1 | 1.1 | 2.3 | 2.8 | 2.2 | 2.9 | 3.6 |
| Avg | $\bar{X}$ | 8.8 | 10.2 | 12.7 | 17.8 | 27.0 | 29.2 | 31.7 | 35.3 |
| -3% | SD | 1.1 | 1.0 | 1.2 | 1.8 | 3.2 | 3.2 | 3.0 | 3.0 |

Analysis

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| High/Avg | H=A | H=A | H=A | H=A | H=A | H=A | H=A | H=A |
| +3%/ 0% | $p<$ 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| +3%/-3% | $p<$ 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| 0%/-3% | $p<$ 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |

Table LVII Responses of subjects with high and average $\dot{V}O_2$ max to grade (+3% and -3%) and level locomotion at various relative speeds

B - Stride Length (m)

| Subject/ | | Relative Speed ($st.s^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Condition | | 0.5 | 0.7 | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 |
| High | $\overline{X}$ | 1.20 | 1.37 | 1.57 | 1.73 | 1.82 | 1.90 | 2.12 | 2.30 |
| +3% | SD | .12 | .11 | .14 | .13 | .12 | .17 | .18 | .19 |
| High | $\overline{X}$ | 1.16 | 1.39 | 1.56 | 1.75 | 1.84 | 1.95 | 2.13 | 2.36 |
| 0% | SD | .11 | .14 | .15 | .14 | .14 | .21 | .17 | .22 |
| High | $\overline{X}$ | 1.13 | 1.34 | 1.57 | 1.74 | 1.85 | 1.93 | 2.14 | 2.35 |
| -3% | SD | .11 | .13 | .14 | .15 | .13 | .16 | .18 | .17 |
| Avg | $\overline{X}$ | 1.18 | 1.35 | 1.53 | 1.69 | 1.74 | 1.83 | 2.03 | 2.22 |
| +3% | SD | .08 | .07 | .09 | .09 | .08 | .13 | .15 | .15 |
| Avg | $\overline{X}$ | 1.14 | 1.33 | 1.53 | 1.71 | 1.76 | 1.86 | 2.06 | 2.24 |
| 0% | SD | .07 | .07 | .09 | .09 | .11 | .14 | .14 | .17 |
| Avg | $\overline{X}$ | 1.11 | 1.32 | 1.51 | 1.69 | 1.75 | 1.90 | 2.07 | 2.29 |
| -3% | SD | .07 | .08 | .09 | .09 | .11 | .14 | .16 | .16 |

Analysis

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| High/Avg | – | – | – | – | H>A | – | – | H>A |
| +3%/ 0% | $p< 0.05$ | – | – | 0.05 | – | 0.05 | 0.05 | – |
| +3%/-3% | $p< 0.05$ | – | – | – | – | 0.05 | 0.05 | 0.05 |
| 0%/-3% | $p< 0.05$ | – | – | – | – | – | – | 0.05 |

Table LVIII Responses of subjects with high and average $\dot{V}O_2$ max to grade (+3% and -3%) and level locomotion at various relative speeds

C - Cadence ($steps.min^{-1}$)

| Subject/ Condition | | Relative Speed ($st.s^{-1}$) 0.5 | 0.7 | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 |
|---|---|---|---|---|---|---|---|---|---|
| High | $\overline{X}$ | 87.2 | 106.2 | 119.3 | 132.3 | 148.3 | 164.4 | 166.8 | 171.5 |
| +3% | SD | 6.4 | 4.9 | 5.2 | 4.0 | 6.5 | 10.0 | 7.8 | 7.3 |
| High | $\overline{X}$ | 89.8 | 106.9 | 120.3 | 130.7 | 146.3 | 160.8 | 165.6 | 167.4 |
| 0% | SD | 6.3 | 5.9 | 5.7 | 6.3 | 6.6 | 7.4 | 7.4 | 8.5 |
| High | $\overline{X}$ | 91.9 | 108.4 | 119.2 | 131.1 | 147.5 | 161.4 | 165.3 | 167.7 |
| -3% | SD | 5.9 | 6.7 | 5.5 | 5.9 | 10.7 | 8.0 | 9.0 | 6.2 |
| Avg | $\overline{X}$ | 87.9 | 107.3 | 121.3 | 134.7 | 154.4 | 169.1 | 173.3 | 176.9 |
| +3% | SD | 4.5 | 3.9 | 5.0 | 4.6 | 5.9 | 8.8 | 9.2 | 9.1 |
| Avg | $\overline{X}$ | 90.5 | 108.0 | 121.0 | 133.0 | 152.9 | 167.4 | 170.6 | 174.9 |
| 0% | SD | 5.1 | 3.2 | 3.7 | 3.1 | 7.8 | 9.9 | 9.4 | 8.9 |
| Avg | $\overline{X}$ | 93.0 | 109.7 | 122.8 | 134.6 | 153.8 | 164.1 | 169.3 | 172.2 |
| -3% | SD | 5.2 | 5.2 | 6.0 | 3.5 | 8.1 | 10.0 | 10.4 | 7.9 |

Analysis

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| High/Avg | | – | – | – | H<A | H<A | – | – | H<A |
| +3%/ 0% | $p<$ | 0.05 | – | – | – | – | 0.05 | 0.05 | 0.05 |
| +3%/-3% | $p<$ | 0.05 | 0.05 | – | – | – | 0.05 | 0.05 | 0.05 |
| 0%/-3% | $p<$ | 0.05 | 0.05 | – | – | – | – | – | – |

Table LIX Responses of subjects with high and average $\dot{V}O_2$ max to grade (+3% and -3%) and level locomotion at various relative speeds

D - Efficiency (%)

| Subject/ Condition | | Relative Speed ($st.s^{-1}$) 0.5 | 0.7 | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 |
|---|---|---|---|---|---|---|---|---|---|
| High | $\overline{X}$ | 42.2 | 48.7 | 46.7 | 42.1 | 34.2 | 38.6 | 40.1 | 42.0 |
| +3% | SD | 3.5 | 6.7 | 4.3 | 3.8 | 2.9 | 2.9 | 2.9 | 3.5 |
| High | $\overline{X}$ | 46.1 | 53.4 | 51.5 | 44.6 | 35.4 | 40.0 | 41.1 | 41.7 |
| 0% | SD | 7.8 | 7.6 | 9.2 | 6.1 | 4.2 | 3.9 | 4.3 | 3.7 |
| High | $\overline{X}$ | 41.7 | 47.3 | 48.6 | 42.1 | 31.3 | 35.8 | 37.5 | 38.2 |
| -3% | SD | 6.9 | 8.2 | 6.2 | 6.8 | 4.5 | 4.1 | 4.9 | 3.9 |
| Avg | $\overline{X}$ | 44.6 | 50.7 | 48.6 | 42.6 | 35.2 | 39.7 | 41.4 | 43.6 |
| +3% | SD | 5.4 | 4.0 | 4.1 | 3.3 | 2.6 | 2.9 | 3.0 | 3.2 |
| Avg | $\overline{X}$ | 49.2 | 57.4 | 54.7 | 46.8 | 35.4 | 40.9 | 41.8 | 42.4 |
| 0% | SD | 8.7 | 8.0 | 5.5 | 5.9 | 3.4 | 3.3 | 3.5 | 3.7 |
| Avg | $\overline{X}$ | 45.9 | 53.6 | 52.6 | 43.6 | 32.3 | 36.0 | 38.4 | 39.3 |
| -3% | SD | 9.9 | 9.7 | 7.2 | 5.1 | 4.1 | 4.7 | 3.8 | 3.6 |

Analysis

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| High/Avg | | - | - | - | - | - | - | - | - |
| +3%/ 0% | p< | 0.05 | 0.05 | 0.05 | - | - | - | - | - |
| +3%/-3% | p< | - | - | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| 0%/-3% | p< | 0.05 | 0.05 | - | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |

# APPENDIX 8

## POST-TEST INFORMATION TO SUBJECTS

## ECONOMY AND EFFICIENCY OF LOCOMOTION

## INFORMATION TO SUBJECTS

________________________________, we have completed the
(Subject Name)
data collection phase of the locomotion study, and as a partial thank you for your involvement we can tell you the following things about you and your movement capability.

1) Stature _____._____ cm Body Mass _____._____ kg
-Your mass/stature ratio is:
above normal normal below normal

2) %Body Fat ______% Fat-free Body Mass ______ kg
Ideal Body Mass ________ kg
Body Surface Area ________ $m^2$
-Ideal body mass is based on having a desirable percent body fat (males 12%, females 20%)

3) Leg Length/Stature = ____________
Foot length/leg length = __________
-Your relative linear proportionality is:
normal, "leggy", "Big Foot"

4) Aerobic Fitness:
Maximum oxygen consumption __________ $ml.kg^{-1}.min^{-1}$

This means that you can increase your metabolic rate by ______ times over normal resting levels. The higher this value the greater will be the amount of endurance exercise you can perform without undue fatigue. Compared with normal values for young people your maximum is:
High Moderately High Medium Low

We have found that your ventilatory threshold during exercise was occurring at ______ percent of your maximum capacity. It has been found that the higher this value is, the greater effort you can expend during endurance exercise. Elite marathon runners have ventilatory threshold values between 80-85% while the averagely active young adult is usually around 65%.

5) Economy and Efficiency:

Your most economical movement velocities were:

| | $\text{km.h}^{-1}$ |
|---|---|
| Uphill (+3%) | __________ |
| Downhill (-3%) | __________ |
| Level (0%) | __________ |

At these three velocities your efficiency ratings were:

| | percent |
|---|---|
| Uphill (+3%) | __________ |
| Downhill (-3%) | __________ |
| Level (0%) | __________ |

An efficiency rating of 25% means that only 25% of the energy you burn up is being converted into useful work. Normal level walking efficiencies have been estimated to be between 50 and 60%.

Thank you very much for being a subject in our study. When the data are tabulated and analysed for all subjects we will sent you a summary of the results.

Should you have any questions about your own personal responses please do not hesitate to call us (3243) or visit the Department of Human Movement Studies for a chat.

Best wishes and thanks again.

Warmest regards,

Brian Goslin
Paul Candler
Andrew Bosch