ENERGETIC AND KINEMATIC RESPONSES TO MORPHOLOGY-NORMALISED SPEEDS OF WALKING AND RUNNING

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THESIS

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ABSTRACT

This study investigated the influence of human morphology upon selected physiological, biomechanical and psychological responses to horizontal locomotion. In so doing, it was possible to evaluate the effectiveness with which morphology-normalised speeds of walking and running reduced the between-subject variability that is inherent in human locomotor responses.

Twenty caucasian males were divided into two groups on the basis of stature - ten subjects in each of a "short" category (<170cm) and a "tall" category (>185cm). All subjects were habituated to treadmill locomotion prior to exposure to three walking treatments (0.83, 1.39 and 1.94m.s^{-1}) and three running treatments (2.50, 3.06 and 3.61m.s^{-1}). During each of these five-minute locomotor conditions, energetic ($\dot{V}O2$), kinematic (cadence and stride length) and psychophysical (central and local RPE) data were captured. From these data, lines of best fit were calculated for each subject, allowing for a prediction of the abovementioned locomotor variables from known absolute rates of progression. Using suitable regression equations, subject responses to morphology-normalised speeds of walking and running were effectively extrapolated.

When the rate of progression was expressed in absolute terms (m.s^{-1}), significant differences ($P < 0.05$) were found between the stature-related groups with respect to both energetic and kinematic locomotor responses. Such differences were successfully eliminated when use was made of locomotor speeds relativised on the basis of morphology.

This study concludes that the use of appropriately prescribed morphology-normalised rates of progression are effective in reducing the variability in locomotor responses between subjects differing significantly in stature.

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PREFACE

"It is commonly suggested that no two human bodies are exactly alike. To this statement it might be added that the ways in which two bodies may differ are endless. Our friends differ in appearance and in the way they behave. This variey is itself of some interest, but a more important problem is this: Do those who look most alike behave most alike?"

(Sheldon, 1940)

"The analysis of motor behaviour necessarily involves an investigation of the interactions of elements of an animal's morphology and utilised environment. After all, an animal's morphology conditions the types of behaviour it may express, and the types of environments in which it may live. At the same time, morphology tends to channel behaviour and the choice of environment into specific patterns. For example, given the characteristics of human lower-limb morphology, the possibilitis of efficient human quadrupedalism are obviously limited."

(Gomberg et al., 1979)

"Each organism tends to respond to any given stimulus in accordance with unique and personal constraints enforced upon it by factors such as morphological structure, movement history, genetic endowment and psychosocial background."

(Cavanagh and Kram, 1985a)

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CHAPTER ONE

THE PROBLEM

AN INTRODUCTION

Inherent movement is the prime sign of animal life (Basmajian 1967). It is this characteristic movement which distinguishes living organisms from non-living, inert matter. It follows that man, as an animal, must move. Even when he is not locomoting through his environment, he is nonetheless, via a process of manipulation, mobile. This is largely because man is the subject of locomotor, manipulative and communicative "imperatives" (Charteris et al. 1976), and as a consequence is in continual interaction with the environment in which he exists. It is via the vehicle of movement that man is able to communicate - to interact with and acquire knowledge about the external physical world. Thus, purposive movement is regulated not only by the state of the motile organism, but also by the state of the immediate environment. In this way premeditated movement provides the vital link in a complex system involving interaction between the physical world and the organism.

Man's movement patterns are very dependent upon his immediate environment, and he has no natural or habitual mode of moving - although he may have a preferred mode in a given environmental situation (Grieve 1968). There are consequently no fundamental patterns or stereotypes of movement in the human motoric repertoire. In fact, to suggest that such intrinsic motor patterns do exist is blatantly misleading, as no attempt is made therein to account for biological variability as the result of organism/environment interaction. Plants, animals and human beings respond to given stimuli according to their structure, but each structure can be and is modified by the environment in which it exists (Cooper et al. 1982). At birth the human organism is biologically "wired" for movement, but as growth and development ensue against a background of motive experience, appropriate neurologic control processes emerge allowing the organism to motorically adapt to an ever-changing and highly demanding environment. The past history of an organism limits and dictates future directions of structural and functional change (Liem & Wake 1985). In this way evolution acts by altering and optimising development. This is to say that man's movement patterns are to a certain extent prejudiced by a genetic (bipedal) history, but that sociocultural influences during the developing years tend to mould such evolutionary attributes. In other words, the adaptations of an organism within a given sociocultural context allow that organism to optimise its ability to survive and reproduce in a given environment (Liem & Wake 1985). This argument is succinctly expressed by Cooper and Glassow (1976) who suggest that: "...each species inherits a basic design that will be modified by its mode of maintaining life." Further corroboration is generated by Asmussen (1976) who proposes that: "...the organism is able to work out a programme for any intended movement on the basis of stored experiences in combination with the inherited patterns of reflex actions". Singer (1977) encapsulates the importance of both the genetic and learning experiences when he says: "...heredity sets the boundaries or the framework of the human system - yet there is always room for improvement which can be attained via interaction with the environment". Thus, in the final analysis, it must be stressed that all species evolve, and that such evolution endeavours to bring about an optimal condition that best allows the organism to manipulate its environment (Liem & Wake 1985).

Human movement is the target of numerous widely diverse attempts at definition. Russell (1965) suggests that movement is "a manifestation of life itself", an indirect reference to the fact that an organism can only continue its existence by moving in and interacting with its immediate environment. Other definitions have implied as much in more intricate and convoluted ways, but few encapsulate the notion that to live is to move quite as effectively. Charteris _et al_. (1976) propose a more functional interpretation by defining movement as "the temporal and spatial displacement of a body." Ultimately, however, biologic movement might best be described as the temporal and spatial interaction of an organism with an ever-changing physical and sociocultural environment. The dynamic characteristics of a given environment are of considerable significance, and adaptation of the organism is of critical importance, since the external physical world is always changing. Any given motive experience is the end-product of a unique but inevitable interaction between the organism and it's immediate environment.

The realisation of any preempted motor pattern is largely governed by the organism's ability to deal with three basic sources of variation, recognised by Higgins (1977) as environmental, biomechanical and morphological constraints. The environmental limitations to biologic movement embody the temporal and spatial configuration of events in the physical world external to the organism. Purposeful movement subsequently involves overcoming the external environmental forces acting upon the motive system. The biomechanical limitations to performance manifest themselves as those physical properties (such as inertia and gravity) which impinge upon the organisation of any movement. Purposeful movement thus necessitates the equilibration of the physical and mechanical forces disturbing organism homeostasis. Both environmental and biomechanical variability are ideally minimised in empirical studies of human movement, and it is the variability brought about by morphological constraints which demands the focus of attention for the purposes of this research.

These morphological constraints manifest themselves as variations between organisms by virtue of specific anatomical structure/function relationships (Higgins 1977). The physical size and shape of the motile organism will directly influence the nature of the movement expressed. Thus, the uniqueness of biological and motor responses from one performer to another is in part due to a morphological variability. When man walks or jumps or swims he does so in ways which are dictated by such physical attributes as body mass, leg length, bi-acromial diameter and bi-iliac diameter (to name but a few). As a consequence, morphologically alike organisms of different size tend to respond in dissimilar ways to any given movement task.

The two most fundamental forms of human locomotion are (bipedal) walking and running. As such, these locomotor modes constitute the most readily undertaken forms of modern day exercise (McArdle et al. 1986), and in fact represent the most characteristic and important activities of man for his relationship with the external world (Margaria 1976). It is not surprising therefore, that locomotor responses to walking and running have been the focus of much research initiated over the years. Man has shown an insatiable interest in the field of human movement. In fact, man-in-motion has been the subject of observation and recording (via mural paintings) since pre-historic times (Asmussen 1976), and it is a topic which even today continues to engender research. Movement responses (both metabolic and kinematic) with respect to locomotor speed expressed in **absolute** terms have been extensively researched by contemporary investigators (Margaria et al. 1963, Murray et al. 1964, Shephard 1969, Van der Walt & Wyndham 1973, Margaria 1976, Cavagna & Kaneko 1977, Dolgener 1982, Heglund et al. 1982, Mahler & Loke 1985, Sjodin & Svedenhag 1985, Goslin 1987). However, the same movement responses to locomotor speeds expressed in **relative** terms have been comparatively poorly investigated. It is hoped, therefore, that this research will contribute in some way to an understanding of the advantages and/or disadvantages associated with the relativisation of locomotor rates of progression with respect to the linear morphological dimensions of the motile subject.

THE CONCEPTUAL CHALLENGE

Scientific research necessitates the proposition of one or more hypotheses which must ultimately be subjected to rigorous testing before being rejected, or accepted as the most useful theories available at the present time (Best 1978). Like all scientists, therefore, the researcher of "man-in-motion" must, by definition, set out to refute previously formulated hypotheses by a process of empirical testing.

However, the systematic analysis of human movement should first incorporate a theoretical base and a carefully defined rationale out of which pertinent questions can be formulated (Higgins 1977). It is often difficult to recognise that empirical investigation involves definite conceptual considerations. It is nonetheless of paramount importance to acknowledge the interdependent relationship which exists between the empirical and the conceptual within any study of biologic movement. The former involves the collection of new data in order to test the research hypotheses generated for investigative purposes. The latter allows for consideration of the relevance of data one already has. A combination of both the empirical and the conceptual methods lends itself most appropriately to the provision of solutions to any problems encountered via investigative research.

The methodology of this study is firmly entrenched in the holistic approach to studying human movement as proposed by the "Centre-M" focus of Charteris et al. (1976). In terms of this kinetic model it is suggested that:

> "...human movement is incompletely and unsatisfactorily elucidated when studied, however meticulously, from the standpoint of only one of the physical, biological and social sciences." **(page 234)**.

The advantage of the "Centre-M" approach to study is further demonstrated by Shephard (1984), who maintains that, despite associated methodological drawbacks, a multi-disciplinary focus is necessary for solving the many problems facing modern research. In deference to the recommendations of these authors, this research has as its focus of attention, **"man-in-motion"**. By means of an holistic approach integrating energetic, kinematic and psychophysical parameters, it is hoped that this study will help elucidate the effects of morphological variability upon human responses to horizontal locomotion.

STATEMENT OF THE PROBLEM

There exists considerable research documentation pertinent to the effects of **absolute** speed conditions upon energetic locomotor responses (Ogasawara 1934, Bobbert 1960, Cotes & Meade 1960, Margaria et al. 1963, Menier & Pugh 1968, Knuttgen 1961, Van der Walt & Wyndham 1973, Margaria 1976, Winter 1982, Mahler & Loke 1985, Goslin 1987), biomechanical locomotor responses (Elftman 1939, Murray et al. 1964, Liberson 1965, Cavagna & Kaneko 1977, Pierrynowski et al. 1980, Heglund et al. 1982, Cavanagh & Kram 1985a, Daniels 1985) and psychophysical locomotor responses (Noble et al. 1973a, 1973b, Morgan 1973, Borg 1978, 1982, Pandolf 1978, 1982, Mihevic 1981, Rejeski 1981, Cafarelli 1982), yet very little research has concerned itself with the effects of morphology-normalised relative speeds upon the abovementioned locomotor parameters. Among these, some studies have established that use of speeds of locomotion relative to stature or lower-limb length are useful methods by which inter-individual biological variation with respect to certain measured parameters (predominantly energy expenditure) can be reduced (Grieve & Gear 1966, Alexander 1984, Williams 1987). However, the influence of other morphological characteristics upon the energetic, kinematic and psychophysical responses to human locomotion are only briefly researched. It remains arguable, therefore, as to whether a relativisation of walking and running speeds with respect to linear morphological measures such as leg length and bi-iliac diameter would be effective in reducing the inherent inter-individual variation in human locomotor responses.

The problems tackled in this research can be broadly outlined as follows:

1. To establish whether or not the energetic, kinematic and psychophysical responses to locomotor speeds expressed in absolute terms are significantly different with respect to morphologically similar subjects of unequal size.

2. To establish whether or not the energetic, kinematic and psychophysical responses to locomotor speeds expressed relative to selected physical characteristics are significantly different with respect to morphologically similar subjects of unequal size.

3. To determine which of ten methods of expressing speed (one absolute and nine relative speed expressions) is most effective in reducing the inter-individual variability with respect to energetic, kinematic and psychophysical locomotor responses.

RESEARCH HYPOTHESES

The following research hypotheses were developed for empirical investigation:

1. That there is no significant interactive effect between subject size and locomotor speed with respect to selected energetic, kinematic and psychophysical responses to walking or running gaits.

2. That morphologically similar subjects of unequal size respond (energetically, kinematically and psychophysically) in an identical fashion to walking or running at locomotor speeds expressed in absolute terms.

3. That morphologically similar subjects of unequal size respond (energetically, kinematically and psychophysically) in an identical fashion to walking or running speeds at locomotor expressed in relative terms.

STATISTICAL HYPOTHESES

The following statistical hypotheses have been derived for the purposes of this investigation:

1.

$$HO: \quad Usi \times Usp = 0$$

$$HA: \quad Usi \times Usp \neq 0$$

where **"Usi"** represents the effects of subject size upon the energetic, kinematic and psychophysical movement responses, and **"Usp"** represents the effects of locomotor speed upon the energetic, kinematic and psychophysical movement responses.

2.

$$HO: \quad Uat = Uas$$

$$HA: \quad Uat \neq Uas$$

where **"Uat"** represents the mean movement responses of selected energetic, kinematic and psychophysical parameters to locomotor speeds expressed in absolute terms for the "tall" subjects, and **"Uas"** represents the mean movement responses of selected energetic, kinematic and psychophysical parameters to locomotor speeds expressed in absolute terms for the "short" subjects.

3.

$$HO: \quad Urt = Urs$$

$$HA: \quad Urt \neq Urs$$

where **"Urt"** represents the mean movement responses of selected energetic, kinematic and psychophysical parameters to locomotor speeds expressed in relative terms for the "tall" subjects, and **"Urs"** represents the mean movement responses of selected energetic, kinematic and psychophysical parameters to locomotor speeds expressed in relative terms for the "short" subjects.

DELIMITATIONS

Twenty male caucasian students were selected to participate in this study. Selection of subjects was restricted to individuals falling within either one of two stature-specific categories - ten subjects shorter than 170cm and ten subjects taller than 185cm. Selection of subjects was further restricted to adult males of a healthy, sport-oriented background. The subjects used in this study can therefore be described as either "short" or "tall" adult males of a healthy, well-conditioned status.

The research protocol was delimited to an investigation of the energetic, kinematic and psychophysical responses of the human organism to bipedal locomotion on a motor-driven treadmill. The energetic analysis was restricted to the capture of oxygen consumption. Since only locomotor speeds of an aerobic nature were imposed, this simple measure of oxygen consumption was considered representative of the total energy expended by the subjects to complete the prescribed walking and running treatments. The biomechanical analysis was restricted to the capture of temporal and linear spatial kinematics, including measures of locomotor stride length and frequency. In view of the act that this investigation had as a focus of attention the effects of human morphology upon locomotor responses, it was felt that measures of the angular kinematics were of lesser relevance. Further, the lack of sophisticated technology rendered the accurate capture of such data impossible. Finally, the psychophysical analysis was delimited to a recording of local (muscle/joint) and central (cardiorespiratory) ratings of perceived locomotor exertion.

Subjects were required to visit the testing laboratory on each of two separate occasions. A first session was required to habituate subjects to treadmill locomotion (60-minutes discontinuous) and to measure and record anthropometric data. A second session was required for the capture of energetic, kinematic and psychophysical data during each of three five-minute walking conditions (0.83, 1.39 and $1.94 m.s^{-1}$) and three five-minute running conditions (2.50, 3.01 and $3.61 m.s^{-1}$). On the basis of the subjects' responses to these absolute locomotor treatments, extrapolations were made such that the same movement responses could be reported for a range of locomotor speeds expressed relative to any one of a number of morphological characteristics. In this way it was possible to ascertain whether or not the use of morphology-normalised speeds of walking or running are effective in reducing the variability in movement responses between subjects.

LIMITATIONS

There will always exist limitations in studies which make use of human subjects (Boring 1969), and such limitations will by definition impinge in some way upon the validity of the data collected. It is therefore of paramount importance for the researcher involved in empirical investigation to identify and control those factors which threaten to bias the validity and accuracy of any data captured. Bearing this in mind, the following factors were considered as limitations beyond the direct control of the investigator and recognised as impinging in some way upon the validity of the data reported in this study:

The number (20) of participants in the study constitutes a limitation as these subjects were not entirely representative of the general adult male population. For example, the choice of caucasian students from the Department of Human Movement Studies at Rhodes University must be considered a biased selection of subjects, since these individuals tend to be physically better conditioned than adult males generally. A more diverse range of fitness-levels in the subjects selected may have rendered the data captured more representative of the adult male population at large.

It was impossible to monitor the eating, sleeping and exercise habits of the subjects in the few hours preceeding data collection, and such factors may well have biased the results attained. With reference to pre-test ingestion of food, it is fairly well documented that the dynamic action of nutrient foodstuffs may influence considerably the physiological responses to a given exercise (Durnin & Namyslowski 1958, Consolazio _et al_. 1963, McDonald 1961). However, subjects were requested to refrain from eating and excessive activity 2-3 hours prior to testing.

Variability in subject motivation and/or mood-state must also be considered as impingements upon the validity of the data collected. Although such factors may not have affected the energetic locomotor responses, they may well have exerted considerable influence upon both the kinematic and pyschophysical variables. It is fairly well documented that subject mood will to some degree influence kinematic (foot-floor contact) responses to locomotor conditions (Sloman et al. 1982), as well as subjective ratings of perceived locomotor exertion (Carton & Rhodes 1985).

The personality traits of the subjects tested may also have biased the data collected. Inasmuch as that type-A personalities tend to return lower ratings of perceived exertion for a given work-load than do type-B personalities (Morgan 1973, Rejeski 1981, Carton & Rhodes 1985), the likely variation in the personality-type of the participants in this investigation must be reported as an uncontrolled variable.

Subjects were tested at different times during the day and were consequently exposed to varying environmental conditions. Even slight variations in ambient conditions during testing must be recognised as impinging to some degree upon the validity of the energetic and kinematic data captured (Durnin & Namyslowski 1958, Faria & Drummond 1982). Further, ratings of perceived exertion tend to fluctuate as the result of diurnal variations (Faria & Drummond 1982). Hence, the inconsistency in time of data collection must be considered a limitation. Having recognised this bias, however, it should be pointed out that all testing was undertaken in the Exercise Physiology laboratory of the Department of Human Movement Studies at Rhodes University, wherein ambient conditions tended to remain fairly stable with time. It was therefore considered unnecessary to specifically control the environmental conditions to which the subjects were exposed during testing.

All data were captured via indoor locomotion on a motor-driven treadmill. No field-testing was undertaken, and consequently any application of results attained from the study to outdoor overground locomotion must be of an extrapolative nature. Considering the effects of terrain (Soule & Goldman 1972) and wind-resistance (Costill & Fox 1969, Davies & Thompson 1979, Van Ingen Schenau 1980, Noakes 1986) on locomotor responses, the in-laboratory capture of data must be reported as a limitation.

CHAPTER TWO

A REVIEW OF THE RELATED LITERATURE

INTRODUCTION

Man has been referred to as a "featherless biped", and although he is not the only creature without feathers or a covering of body hair that uses its hindlimbs alone for moving about, there are certain aspects of human locomotion that are unique (Wolpoff 1980). Palaeontologic data suggests that bipedalism was a frequent means of locomoting in the australopithecine ancestors of man. In fact, evidence for the antiquity of human bipedality is offered by hominid footprints discovered in Pliocene strata at Laetoli which date back at least 3.7 million years (Johanson & Edey 1981, Charteris et al. 1982). However, there is much disagreement concerning how and why human ancestors adapted a bipedal mode of walking and running. Whether man's bipedality evolved for reasons of efficiency, or whether it simply freed his hands to facilitate a manipulation of his environment remains arguable.

It is clear that human bipedalism is not an adaptation to speed, since most quadrupedal animals of similar size can outrun a human - even a chimpanzee running bipedally is faster (Wolpoff 1980). Rodman and McHenry (1980) postulate, on the basis of extensive investigative research, that compared to quadrupedal mammals humans are inefficient when locomoting at high speeds. This finding augments that of Taylor et al. (1970), who suggest that bipedal locomotion at high speeds is twice as costly (per kilogram body mass per kilometer travelled) than is quadrupedal locomotion at similar speeds in mammals of the same size. Napier (1963) argues that the evolution of bipedality allowed man to cover great distances with a minimal expenditure of energy. Such locomotor efficiency, he says, was facilitated by a loping/striding gait made possible by specific morphological adaptations. However, Taylor and Rowntree (1973) dispute this contention on the basis of an investigation which suggests that for both chimpanzees and capuchin monkeys the energetic costs of travelling bipedally and quadrupedally are essentially the same. They conclude therefrom, that locomotor efficiency should not be used as a criterion on which to base arguments concerning the advantages and disadvantages of human bipedalism.

Many other factors, including the need for man to carry and to use tools, have been identified as likely selection pressures for man's adoption of an orthograde bipedal gait (Wolpoff 1980). However, it would appear that the discovery of new and more informative homonid fossils is essential to our total understanding of how and why the human species evolved from a four-legged to a two-legged mover. One proposition that is generally accepted on the basis of present day fossil evidence, is that certain morphological adaptations were pre-adaptive for man's bipedality, and that such adaptations continue even now to mould the human locomotor apparatus. Hence, any interpretation of man's bipedal history requires a complete understanding of the integrative roles played by structure and function. As expressed earlier, the behaviour patterns of any organism are dictated by the combined influences of morphological and environmental evolution. In other words, the behaviour of a particular animal must be seen in relation to its morphology and the environmental conditions in which it chooses to move. The analysis of any animal's positional or motor behaviour must therefore include an investigation of the interactive elements of that animal's morphology and utilised environment - that is to say the animal's motive experience must be seen with respect to the behaviour-morphology-environment interface (Gomberg et al. 1979).

The locomoting human organism has been the subject of investigation for thousands of years. In fact, the observation of human movement dates back to prehistoric times when man was the subject of numerous mural paintings (Asmussen 1976). Technological progression has allowed a more precise analysis of "man-in-motion" via the use of sophisticated film, video and computer equipment. Early studies tended to restrict themselves to independent interpretations of human movement from the point of view of only one of the physical, biological and social sciences. Contemporary research, however, adopts a more holistic approach entailing the capture and analysis of data with input from fields as seemingly diverse as physiology, kinetics, kinematics and psychosociology. In effect, the study of human performance has become a multidisciplinary venture with "movement" per se constituting the incontrovertible focus (Charteris et al. 1976).

PHYSIOLOGICAL RESPONSES TO LOCOMOTION

i) The Energetics of Muscular Contraction

Movement is energetically expensive. All forms of human activity are realised only via an increment in the energy expenditure of the muscle or muscle groups involved - this energetic increment being over and above that required for a basal existence. When a muscle is innervated it generates force via the contraction of its fibres. This generation of muscular force, which generally manifests itself in the form of movement, is characterised by an absorption of energy by the system. Simply put, this energy is extracted from the nutrients we ingest, transferred to the contractile elements of the skeletal musculature, converted from its chemical form into mechanical/kinetic energy to produce work (movement), before ultimately being dissipated from the body in the form of heat (Astrand & Rodahl 1977, Lamb 1984, McArdle et al. 1986). In short, the only way that an organism can move or realise work is to convert chemical (nutrient) energy into kinetic (movement) energy, or to store it as potential energy for later use (Heglund et al. 1982).

The metabolic process is not as simple as expressed above however, as the energy in food is not transferred directly to the muscle fibres for biologic work. Rather, it is harvested and chanelled through the the energy-rich compound adenosine triphosphate (ATP). The potential energy thus harnessed with the ATP molecule is readily utilised for all the energy requiring processes of the organism. Since ATP is stored in very low concentrations in human muscle (approximately 5 millimoles per kilogram of muscle), tightly controlled mechanisms must exist for the continual regeneration of ATP as muscular contraction proceeds (Green 1982). Thus, another important energy "reservoir" is stored in the muscle, namely creatine phosphate (CP), which is directly responsible for the resynthesis of expended ATP via the phosphorylation of adenosine diphosphate (ADP).

While the phosphagens of ATP and CP stored in the muscle constitute a readily available source of energy which can be released via non-oxidative (anaerobic) metabolism, skeletal muscle can generate or synthesise the ATP required for work of a longer duration via an oxidative (aerobic) phosphorylation of ADP (Astrand & Rodahl 1977, Lamb 1984, McArdle et al. 1986). The relative contributions of the various aerobic and anaerobic energy supplying pathways are dependent upon the intensity and duration of the activity. The energy for the muscular contraction characteristic of any given activity is generated via the interaction of three metabolic pathways:

The ATP-CP system fuels muscular activity for short duration (<10 seconds) and high intensity exercise. The energy is provided almost exclusively via the synthesis of the high energy phosphates ATP and CP stored in the muscle The breakdown and subsequent utilisation of this stored ATP and CP is not associated with an accumulation of lactic acid in the bloodstream, and is consequently termed the alactic anaerobic supply of energy. The continuation of activity fuelled by this "immediate" supply of energy is limited by the low concentrations of stored ATP and CP in the muscle (Green 1982).

Anaerobic glycolysis fuels muscle activity for moderate duration (10-120 seconds) and moderate intensity exercise. This supply of energy, alternatively referred to as the oxygen-independent glycolytic pathway, involves the regeneration of expended ATP stores via the non-oxidative metabolism of muscle glycogen and the subsequent phosphorylation of ADP. The continuation of activity fuelled via this "short-term" energy pathway is severely limited by an accumulation of lactic acid in the bloodstream, and for this reason the process of anaerobic glycolysis is considered the lactic anaerobic supply of energy (Green 1982).

Aerobic metabolism fuels muscle activity for long duration (>120 seconds) and low intensity exercise. This energy supply is characterised by the production of ATP via oxidative processes which involve the combustion (oxidation) of nutrient fuels in the muscle cell. In energetic terms there is no limit to the duration of activity fuelled via this "long-term" aerobic supply of energy - such limits are imposed by other factors including hypoglycaemia, electrolyte depletion, and muscle and joint fatigue etc. (Astrand & Rodahl 1977, de Vries 1980, Green 1982, Lamb 1984, McArdle et al. 1986).

The three energy pathways outlined above are not independent of one another - instead they are integrated and operate in concert such that the supply of energy to the working tissues is moderated to satisfy the immediate demands of the active musculature (Green 1982). All three systems operate concurrently, the contribution of each varying with respect to the relative intensity of the muscular activity. As exercise intensity increases, so more demand is placed upon the anaerobic supply of energy. During exercise of a low intensity (and also during rest), the necessary energy is delivered primarily via aerobic metabolism - but even under these conditions the contribution from anaerobic sources is not insignificant (Keul 1973, Astrand & Rodahl 1977, Green 1984, McArdle et al. 1986).

Even when resting, the human organism continues in its efforts to generate and transfer energy. This resting (basal) metabolism is necessary to support the vital functions of the body in its non-active state (McArdle et al. 1986), including an absorption of energy for the fuelling of respiration, circulation and ion transport (Cavanagh & Kram 1985a). In fact, research suggests that the energy demands of resting vertebrates are fairly substantial and easily measured (Bennett 1985). Basal metabolic rate (BMR) is correctly measured in an individual lying supine, and is generally associated with an energy cost of between $2.5ml.kg^{-1}.min^{-1}$ and $4.0ml.kg^{-1}.min^{-1}$. However, the metabolic cost of standing at rest is increased considerably due to the added energy required by the postural muscles. Standing basal energy costs appear to vary quite significantly between individuals, ranging from $5.0ml.kg^{-1}.min^{-1}$ (Morissey et al. 1985) to as much as $7.7ml.kg^{-1}.min^{-1}$ (Shephard 1969).

Muscular exercise has been aptly described (Margaria 1976) as an "amplifier" of the chemical and energetic metabolic processes of the human organism. This is to say that muscular contraction, and hence movement, is the ultimate product of metabolic activity, which is itself a direct consequence of the utilisation of fuel and oxygen by the (involved) muscle fibres (Sloan 1973, Noakes 1986). It follows that some definite relationship exists between the intensity of muscular exercise (biologic work) and metabolic activity.

An accepted physiological method of evaluating the energy expenditure of a given submaximal activity is to measure the aerobic requirements associated with that activity (McMiken & Daniels 1976, McArdle et al. 1986). The assumption here is that oxygen consumption during submaximal work of an aerobic nature represents exactly the energy requirements of that activity. In effect, this is a flawed contention, as total energy cost is reflected by the sum of both aerobic and anaerobic metabolism

(Daniels 1985). Accordingly, the oxygen consumption associated with any given task represents only a part, albeit a fairly substantial part, of the overall energy cost, as the input of energy from the anaerobic breakdown and resynthesis of ATP is ignored (Dolgener 1982). However, during submaximal aerobic activity, the energy supplied anaerobically constitutes only a minor fraction of the overall energy input, and for all intents and purposes this input can be considered negligible. Thus, the measure of oxygen uptake has been widely accepted as a convenient and accurate method of assessing metabolic cost, as long as the workload remains aerobic (Williams 1985).

The human body is a homeostatic organism. That is to say that it strives to maintain an equilibrium between its numerous systems and its immediate environment. The change from a state of rest to one of mobility involves changes in the activity of most systems of the body to adapt the organism to the new situation (Sloan 1973). When an individual begins work from rest and continues at a constant intensity, his cardiorespiratory systems increase their activity to meet the demands of the motile situation. Both heart-rate and oxygen consumption increase rapidly during the first few minutes before plateauing at a level sufficient to supply the necessary blood and oxygen required by the exercising tissues (Dill 1963, Martin 1974, Astrand & Rodahl 1977, Lamb 1984, McArdle et al. 1986). The point at which the heart-rate and oxygen consumption plateau is intensity dependent - the relationship between exercise intensity and energy cost being slightly curvilinear in nature (Gaesser & Brooks 1975). This plateau in circulorespiratory response is termed the "steady-state", and reflects a balance between aerobic energy supply and metabolic demand, which suggests that the various biological systems of the organism have found equilibrium with the new situation (Sloan 1973). Within the limits of this steady-state, oxygen consuming (aerobic) reactions supply practically all of the energy required to fuel the exercise, and any lactic acid that may be produced is effectively oxidised to resynthesise expended ATP stores or is reconverted into glucose (Astrand & Rodahl 1977, Lamb 1984, McArdle et al. 1986).

With incremental exercise, the increase in oxygen consumption proceeds in a slightly curvilinear fashion until it plateaus and reflects no further increase despite continued increments in workload. This level of energy expenditure is termed the maximal oxygen consumption ($\dot{V}O2$ max) and represents the organism's maximum capacity for the aerobic resynthesis of ATP (McArdle et al. 1986). Research suggests that below the level of maximum oxygen consumption, the curvilinear relationship between oxygen uptake and exercise intensity is reflected quantitatively by an approximate increase of 1.8ml of oxygen for each 9.804J increment in workload (Newton 1963, Lewis et al. 1982).

ii) The Energetics of Human Locomotion

Movement of the body is characteristic of all mammals. Such movement is expressed in a variety of ways, but locomotion represents the most common form of vertebrate activity and as such constitutes one of the more important vehicles for an organism's interaction with the external environment. As already discussed, all movement is energetically expensive, and the translocation of an animal's mass through space requires a considerable input of metabolic energy over and above basal requirements (Bennett 1985).

The magnitude of any locomotor metabolic input is a function of two interrelating variables: the mass of the moving body, and the rate at which that mass is moved. It is well established that body mass and the energy expended during physical work are linearly related, and that the expression of energy expenditure relative to body mass (ie. $ml.kg^{-1}$) effectively reduces the inter-individual variation in oxygen consumption (Miller & Blyth 1955, Durnin 1958, Ralston 1958, Bobbert 1960, Cotes & Meade 1960, Rasch & Pierson 1962, Wyndham et al. 1971, Van der Walt & Wyndham 1973, Margaria 1976, Mayhew et al. 1979). It is also well documented that energy expenditure is proportional to exercise intensity (Gaesser & Brooks 1975, Astrand & Rodahl 1977, Lamb 1984, McArdle et al. 1986). However, the nature of the relationship between exercise intensity (or speed) and energetic cost is not the same for all movement types and is very much activity dependent.

The rate of locomotor progression exerts a considerable influence upon the energetics of both walking and running, and comparatively small variations in movement speed elicit measurable differences in energy expenditure (Erickson et al. 1946). Each locomotory mode of a given organism, be it walking, running, swimming or flying, has its own p between energy cost and speed (Bennett 1985). It is widely that walking and running constitute the most readily means of locomotion in the human species, and that both (being related) involve the breakdown and resynthesis of ATP by the musculature and an associated consumption of oxygen. The exact nature of the locomotor/energy cost relationship is complex, however, as the body is continuously attempting to integrate the motion of its various segments and to control the activity of its muscles so as to minimise the energy expended at each step (Pierrynowski et al. 1980, Winter 1982). Very broadly speaking, the metabolic energy consumed aerobically by each gram of of a moving animal as it moves along the ground increases as a linear function of the speed of progression (Heglund et al. 1982). However, the nature of this energy cost/speed relationship is substantially different for walking and running locomotor gaits.

The relationship between mass-dependent energy cost and the rate of horizontal walking is generally reported to be curvilinear in nature for speeds up to about $2.22 m.s^{-1}$ (Passmore & Durnin 1955, Bobbert 1960, Grimby & Soderholm 1962, Margaria et al. 1963, Menier & Pugh 1968, Shephard 1969, Margaria 1976, McArdle et al. 1986, Noakes 1986, Williams 1987). This curvilinear relationship is revealed graphically as a positively sloped concave curve (see Figure 1), and suggests that as the speed of walking is incremented, the associated expenditure of energy increases disproportionately. Numerous authors (Bobbert 1960, Cotes & Meade 1960, Knuttgen 1961, Grimby & Soderholm 1962) have described this relationship further by suggesting that energy cost is linearly related to the square of walking speed.

An assumption that can be made from the premise that energy cost and walking speed are curvilinearly related is that there exists an optimal speed of walking at which the expenditure of energy is minimised. Any deviation in speed above or below this "optimum" tends to elicit a substantial increase in metabolic cost. The actual speed with which this energetic minimum corresponds has been the focus of much research, the result being a widespread difference of opinion. Table I reflects a summary of the findings of numerous research papers, and highlights the wide range of speeds reported as reflecting the most cost-efficient speed of walking. It is clear from Table I that no single speed of walking can

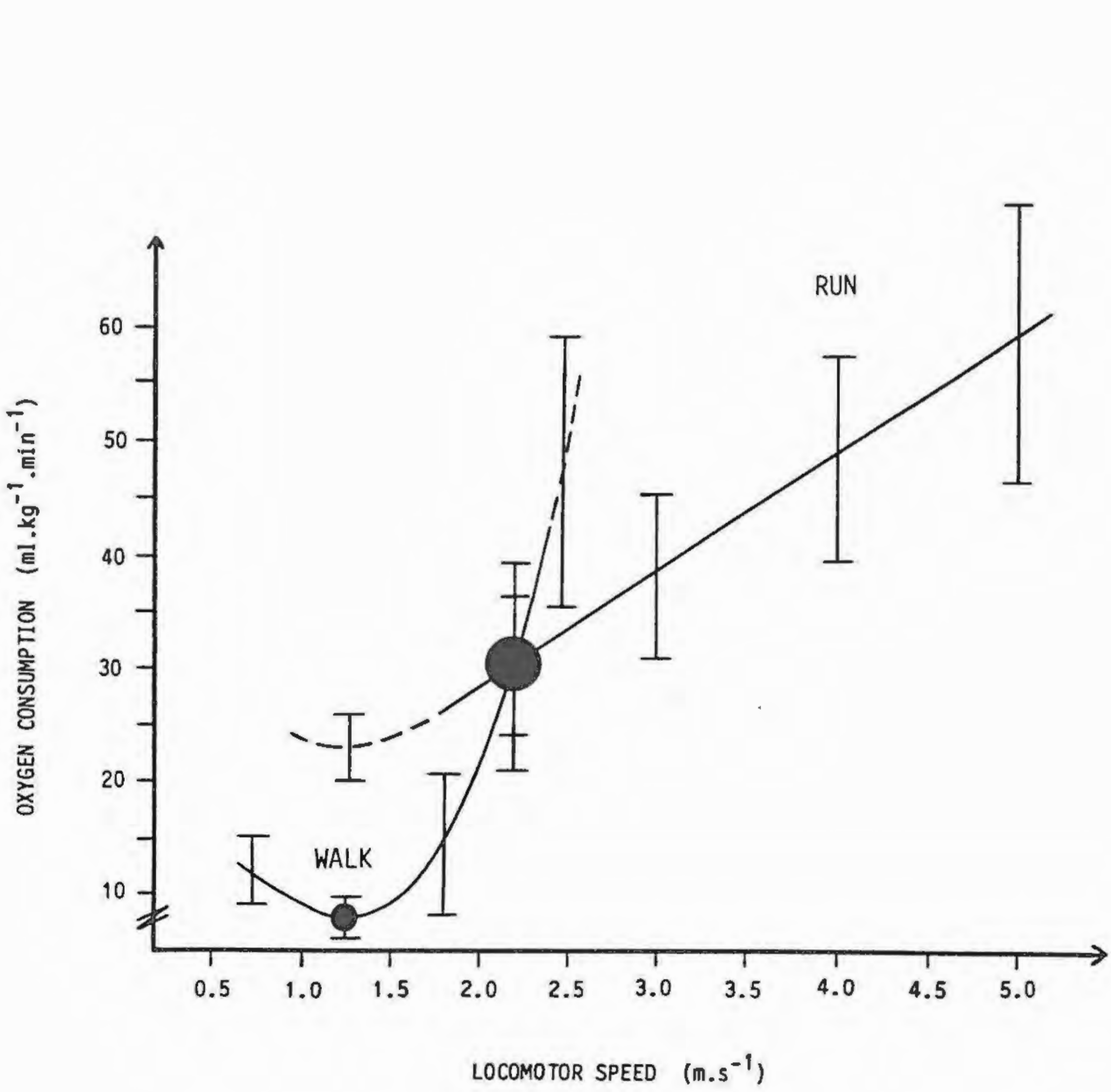


FIGURE 1: **the relationship between oxygen consumption and locomotor speed expressed in absolute terms.**

For all subjects oxygen consumption responds in a curvilinear fashion to increments in the speed of walking, and in a linear fashion to increments in the speed of running. However, for any given locomotor speed there exists considerable inter-individual variability in the oxygen consumed, with similarly shaped subjects of different size consuming differing volumes of oxygen per unit speed. Thus, locomotor oxygen consumption tends to differ quite obviously from one subject to another as the result of a morphological inequality. The smaller of the two shaded areas represents the most cost-efficient speed of walking, while the larger represents the walk/run interface. Both are influenced by subject morphology, and are consequently represented by a range of locomotor speeds (graph adapted from Williams, 1987).

TABLE I: a summary of the locomotor speeds described in the literature as constituting the most cost-efficient rate of walking.

SPEED		REFERENCE
m.s^{-1}	km.hr^{-1}	
1.00 - 1.67	3.60 - 6.00	McDonald 1961
1.06	3.80	Hettinger & Muller 1953
1.10	3.96	Cavagna *et al*. 1963
1.11	4.00	Margaria *et al*. 1963
1.11 - 1.39	4.00 - 5.00	Kamon & Belding 1971
1.13	4.05	Van der Walt & Wyndham 1973
1.22	4.39	Ralston & Lukin 1969
1.23	4.43	Ralston 1958
1.31	4.72	Zarrugh 1981, Goslin 1987
1.33	4.79	Zarrugh *et al*. 1974
1.36	4.90	Bhambhani & Singh 1985
1.37	4.93	Howley & Glover 1974
1.42	5.10	Bobbert 1960
1.51	5.40	Murray 1967

be considered as the least costly from an energetic point of view. Rather, a range of speeds exists within which walking is energetically optimised - the actual speed varying from subject to subject on the basis of an innate (morphological) variability. This is because every animal subconsciously adopts a fairly unique locomotor "style" which enables it to carry its own mass through space with a minimum expenditure of energy (Alexander 1980, Pierrynowski *et al*. 1980, Winter 1982).

Margaria et al. (1963) and Margaria (1976) suggest that the energetic cost associated with progression at the optimal walking speed is the equivalent of about 100 milliliters of oxygen (or 500 calories of energy) per kilogram body mass per kilometer travelled. In other words, the oxygen cost required to walk at the optimal speed is constant and a linear function of the distance covered. However, unlike in running, the metabolic cost of walking a given distance is very much speed dependent, and the expenditure of energy per kilogram of body mass per kilometer distance traversed increases at walking speeds above or below the optimum (Boje 1944).

The optimal rate of progression is generally very closely correlated with that speed freely and subconsciously chosen by the subject (Ralston 1958, Candler 1986). Although walking is basically a reflex action requiring no direct conscious control (Yamasaki & Sasaki 1982), subjects are able to self-regulate the walking action by manipulating certain "style" variables in order to minimise the associated energy cost (Cavanagh & Kram 1985b). The result of this self-regulation process is that the walking technique which subjects tend to freely adopt is very close to optimal across the entire range of locomotor speeds. These freely chosen speeds of progression range from about 1.0 to $2.0 m.s^{-1}$, and once again vary quite considerably between subjects by virtue of a morphological dissimilarity.

Regarding walking speeds in excess of about $2.22 m.s^{-1}$, it is fairly evident (see Figure 1) that a significant change is elicited in the energy cost/speed relationship earlier described. In fact, between about 2.22 and $4.20 m.s^{-1}$ the line relating energy expenditure and speed of walking becomes almost vertical, suggesting that at such speeds very slight increments in the rate of progression elicit disproportionately large increases in metabolic cost. Only in competition are walking speeds in excess of about $2.22 m.s^{-1}$ frequently encountered, and in such events these extreme speeds are realised at an enormous energetic cost. After all, the priority in competition walking is speed and not efficiency of movement. The average person is capable of walking at speeds up to about $2.5 m.s^{-1}$, yet competition walkers have evolved a technique of rolling the pelvis which allows them to reach speeds in excess of $4.0 m.s^{-1}$ and to average rates of progression of about $3.6 m.s^{-1}$ (Menier & Pugh 1968, McArdle et al. 1986).

is a locomotory mode that differs very significantly from that of , particularly with respect to mechanical and energetic rations. Early studies defined the relationship between energy expenditure and speed of running as curvilinear in nature (Sargent 1926, Ogasawara 1934, Boje 1944), but research since 1950 suggests that the energy cost of running increases as a linear function of speed, as long as the locomotion remains aerobic in nature (Margaria *et al*. 1963, Menier & Pugh 1968, Ribisl & Kachadorian 1969, Shephard 1969, Van der Walt & Wyndham 1973, McMiken & Daniels 1976, Astrand & Rodahl 1977, Bransford & Howley 1977, Davies & Thompson 1979, Mayhew *et al*. 1979, Conley & Krahenbuhl 1980, Dolgener 1982, Leger & Mercier 1984, Daniels 1985, Montoye *et al*. 1985, McArdle *et al*. 1986, Williams 1987). Generally speaking, as running speed increases from about 2.22 to 5.80$m.s^{-1}$, there is a proportional increase in the locomotor energy expenditure (see Figure 1).

The limit for purely aerobic running is set at a speed between about 5.5 and 5.8$m.s^{-1}$ (Menier & Pugh 1968, Cavagna & Kaneko 1977), although Mayhew *et al* (1979) put the figure as high as 6.7$m.s^{-1}$. It is clear, therefore, that the relationship between oxygen consumption (aerobic metabolism) and running speed is linear in nature as long as the rate of progression remains below about 6$m.s^{-1}$. However, the relationship between total energy expenditure (aerobic plus anaerobic metabolism) and rate of progression tends to be exponential in nature across the entire range of running speeds (Daniels 1985). This is because as running speed increases, the contribution to energy input from anaerobic sources becomes proportionately greater, and at very high running speeds (ie. sprinting) the aerobic supply of energy reaches a limit beyond which any further generation of energy must be attained via non-oxidative metabolism (McMiken & Daniels 1976).

The linearity of the (aerobic) energy cost/speed relationship in running suggests that the energy required to cover a given distance is constant and independent of speed (Margaria 1963, Margaria *et al*. 1963, Costill & Fox 1969, Van der Walt & Wyndham 1973, Howley & Glover 1974, Margaria 1976, McMiken & Daniels 1976, Cavagna & Kaneko 1977, Mayhew 1977, Fellingham *et al*. 1978, Cavanagh & Kram 1985b, Daniels 1985, McArdle *et al*. 1986). Further research (Margaria *et al*. 1963, Cavagna & Kaneko 1977, Cavanagh & Kram 1985b) has revealed that this constant locomotor energy cost is approximately 1kcal or 4.186kJ of energy (200ml oxygen) per kilogram body mass per kilometer travelled. Davies and Thompson (1979) report a similar locomotor caloric cost (for running) of approximately 0.95kcal.kg^{-1}.km^{-1}, while Mayhew (1977) and Howley and Glover (1974) propose costs of 0.97 and 0.98kcal.kg^{-1}.km^{-1} respectively. Finally, Mayhew et al. (1979) suggest that the cost of running a given distance is as high as 1.04kcal.kg^{-1}.km^{-1}. It would appear, therefore, that although the energetic cost of running a given distance is clearly independent of speed, it is very much subject-related and tends to vary form one individual to the next - possibly as the result of morphological variability. In other words, the energy required to run a given distance for any one individual is constant and independent of locomotor speed, but the actual caloric cost varies between subjects, tending to range from about 0.95 to 1.05kcal.kg^{-1}.km^{-1} depending upon the specific morphological characteristics of the runner.

The abovementioned inconsistencies aside, it is fairly apparent that the relationship between running speed and energy expenditure is highly predictable, and that as the rate of progression increases, the energy expenditure (oxygen consumption) rises proportionately. Costill and Fox (1969) quantify this predictability between running speed and energy cost by proposing a correlation coefficient relating the two parameters of between 0.95 and 0.98. This coefficient compares fairly favourably with the energy cost/running speed correlations reported by other researchers: 0.92 (Mayhew 1977); 0.91 (McMiken & Daniels 1976); and 0.86 (Conley & Krahenbuhl 1980).

Unlike in walking, there appears to be no running speed at which the energy expenditure is minimised. Rather, as can be inferred from the linear relationship expressed above, the expenditure of energy tends to decrease as the rate of progression is decremented. This appears to be the case as long as the running speed remains above about 2.22 - 2.50m.s^{-1}, below which speeds it becomes extremely difficult to execute the normal movements of a running gait, and walking becomes the less costly and freely chosen mode of progression. This said, however, some investigators have offered speeds of running at which they claim the human system is most efficient (ie. speeds at which the expenditure of energy is minimised). Bhambhani and Singh (1985) suggest a running speed of 2.58m.s^{-1}, a figure which compares favourably with the 3.06m.s^{-1}

reported by Mayhew (1977) and the 3.10m.s^{-1} proposed by Goslin (1987). Mayhew et al. (1979) describe a range of running speeds (between 3.00 and 3.17m.s^{-1}) within which the locomotor cost of running is optimised. However, it is the author's contention that these speeds in fact constitute the lower end of the running-speed continuum, and as such represent locomotor speeds below which walking becomes the most efficient means of progression rather than actual "optimal" speeds of running. However, Candler (1986) proposes that the locomotor interface occurs at a speed of about 2.22m.s^{-1}. It might be argued, therefore, that running speeds above this interface but below about 3.0m.s^{-1} are relatively inefficient - possibly because the rate of progression is too slow to allow for an effective input of energy via the elastic recoil of the locomotor musculature.

It is clear from the energy cost/speed relationship discussed thus far that there exists a range of speeds within which both walking and running are possible. It is generally, and correctly, understood that as a means of progression walking is suitable for lower speeds up to a certain limit, whereas running becomes the more suitable locomotor gait at higher speeds (Ogasawara 1934). The average man cannot walk at very high speeds, and nor can he execute the typical movement patterns of running at very low speeds. However, the actual speed at which subjects tend to adjust their locomotor gait from a walk to a run, or from a run to a walk, has engendered much research resulting in considerable controversy (Candler 1986).

Very generally speaking, individuals tend to walk at speeds below about 2.22m.s^{-1} and to run at speeds above this. There does exist, though, a walk/run interface within which both walking and running gaits are possible. This locomotor interface is reported by McArdle et al. (1986) as ranging from 1.90 to 2.50m.s^{-1}. However, research has for years endeavoured to identify a more specific interface speed. Shields (1982) for instance, suggests that the lines relating the energy expenditure to speed in walking and running intersect at 2.14m.s^{-1}. Similar findings are reported by Bobbert (1960) and Daniels (1985), who put the interface at a speed of 2.00m.s^{-1}. However, contemporary evidence points to a walk/run interface speed of about 2.22m.s^{-1} (see Figure 1), and strongly suggests that this figure may vary from subject to subject by virtue of a variability with respect to such morphological features as stature and lower-limb length (Menier & Pugh 1968, Leger & Mercier 1984, Candler 1986, McArdle et al. 1986, Goslin 1987).

If the locomotor speed is such that it permits both walking and running gaits, then from an energy cost point of view, running appears to be the least demanding (Ogasawara 1934). In fact, at speeds above the interface speed of $2.22 m.s^{-1}$, walking, although possible, becomes twice as costly as does running at the same speed (Menier & Pugh 1968, Candler 1986, McArdle et al. 1986). The reasons for this increased cost of walking above the locomotor interface are numerous, but the most important consideration would appear to be the greater musculature contracted during walking due to the excessive movement of the arms, hips and shoulders necessary to maintain the forward progression (Benedict & Murschhauser 1915, Ogasawara 1934, Hogberg 1952). Generally speaking, the self-selected running speed tends to be about 190% faster and about 48% more costly than that speed freely chosen when walking (Bhambhani & Singh 1985).

Many researchers, following their own investigations into the energetics of human locomotion, have described the relationship between energy cost and locomotor speed in terms of empirically derived regression equations. Such equations allow for the prediction of locomotor energy cost (oxygen consumption) from known absolute speeds of walking or running, and as such constitute very useful tools for the human movement specialist. However, there exists a great deal of variability between the many equations which exist for the prediction of locomotor energy cost, the result being an abundance of collectively useful but individually prejudiced equations. It is the author's opinion, therefore, that such equations tend to be inherently biased with respect to the particular characteristics of the specific subject sample tested. Unless these equations are defined with specific reference to the morphological characteristics of the subjects tested, they cannot have any universal relevence and become for all intents and purposes meaningless.

BIOMECHANICAL RESPONSES TO LOCOMOTION

i) Kinetic Considerations

The human gait has been described as an alternating loss and recovery of body equilibrium, and likened to a "series of catastrophes narrowly averted" (Steindler 1955). This is because human terrestrial locomotion is characterised by a perpetual vertical and horizontal displacement of the body emanating from a cyclic forward translation of the trunk over alternating bases of support (Murray 1967). In other words, human locomotion (both walking and running) is typified by a falling-forward of the body which is arrested by the displacement of a lower limb to a position ahead of the trunk so as to establish a solid foundation for continued support.

This is a very simplistic interpretation of what is, in effect, an extremely complex cycle of interrelated events. Locomotion is the end-product of an intricate muscular action coincident with a synchronised pattern of numerous joint movements (Wells 1971). Although locomotory propulsion is effected primarily by input from the lower limbs, the contributions made by the trunk and upper extremities are considerable. Accordingly, human locomotion should be interpreted as a movement pattern in which the reciprocal action of the extremities and trunk contribute to a maintenance of motile equilibrium as the organism continues its displacement over alternating bases of foot-floor support.

Human locomotion, like all organic movement, is energetically expensive. The locomotor action is made possible by the contraction of appropriate muscles, the energy for which is generated via substrate oxidation and glycolysis. This process involves an on-going conversion of nutrient energy into chemical (ATP) energy into kinetic energy. Thus, the motoric mechanism is fuelled by the continual conversion of energy from one form to another, and the transfer of energy both within and between body segments (Margaria et al. 1963, Pierrynowski et al. 1980, Frederick 1985). Once the locomotor musculature has initiated the appropriate motor response, the energy generated to effect motion is not totally expended. Although with every step during locomotion some of the energy generated via substrate glycolysis is absorbed by the active muscles, ligaments, articular surfaces and body fluids and is lost as useful input to the moving system in the form of heat, a large proportion of the energy is conserved by the motile organism and is reciprocally converted from one energy form (potential) to another (kinetic) (Margaria et al. 1963).

The total work done by an organism in motion is recognised as the sum of internal and external forces. Internal work describes those forces generated to move the body segments through the desired pattern to accomplish a given task, whereas external work refers to the mechanical forces generated by the body to overcome any resistance opposing the desired movement (Winter 1982, Goslin 1987). During horizontal progression, the internal work is realised by the contraction of the locomotor musculature and aided by the combined influence of inertia and gravity, and the only external forces to overcome are those imparted by air resistance and surface friction (Winter 1982). Elftman (1940) suggests that the motor-pattern typical of human locomotion is facilitated by a cooperative involvement of gravity, inertia, surface reaction and muscular contraction, and that any controlled movement is realised via an interaction of these elements as the body continues to move through space along a path of least resistance.

Independent and controlled locomotion requires of the lower extremities the ability to coordinate the integration of three prerequisite actions: i) support of the upright body, ii) the maintenance of balance in the upright position, and iii) the execution of a stepping-action to propel the body forward (Murray 1967). The support prerequisite during horizontal locomotion is facilitated by an alternating cycle of left and right foot-floor contacts. Balance is governed largely by transverse rotational displacements of the trunk coupled with sagittal extensor/flexor displacements of the extremities (Hinrichs et al. 1987). The propulsive component of the locomotor cycle is initiated by muscular contraction and sustained (partially) by an input from inertia and gravity. Locomotor propulsion can be very broadly divided into two vector forces - a forward motion and an upward motion. Forward propulsion is initiated primarily by contraction of the gastrocnemius and soleus muscles with a probable input from the quadriceps muscle (Basmajian 1967). This forward component serves to translate the body's centre of mass forward into a position over the supporting limb. The upward component is initiated largely via a contraction of the gluteal musculature and provides a sufficient foot-floor clearance as the swinging limb reverses from a backward to a forward direction in order to provide the next base of support in the gait cycle (Margaria 1976). Together, the forward and upward components of the locomotor cycle combine to facilitate the controlled and cyclic forward translation of the body through space.

The terrestrial locomotor gaits of all limbed animals are typified by alternating phases of support and swing. In order for any legged system to crawl, walk or run, each of its limbs must go through alternating periods when: i) it carries load and maintains contact with the locomotor surface, and ii) when it is unloaded and is free to move forward into a position which allows for the provision of a new base of support (Raibert & Sutherland 1983). The swing component of the gait is a low energy phase initiated by muscular contraction but sustained by a combined input from the properties of inertia and gravity. The support phase of the gait cycle constitutes the high energy component (Ralston & Lukin 1969), and is coincident with a more significant contractile activity of the locomotor musculature. The biomechanics of walking and running are substantially different, and it is the support/swing relationship which provides a good focus for any differentiation made between the two locomotory modes. Bipedal walking has a double-support imperative which dictates that the supporting limb remain in contact with the locomotor surface until the swinging limb strikes the ground (Broer 1966). Running on the other hand, has no such double-support imperative and consequently involves a period of "flight" during which both limbs are airborne. Thus, a period of double-support and a period of flight are unique to the gaits of walking and running respectively.

Walking is typified by a falling forward of the body followed by a displacement of a lower limb into a position under the trunk so as to establish a new base of support (Steindler 1955). Unlike a wheel, which changes its point of support continuously while bearing weight, the human leg changes its point of support all at once and must be unloaded to do so (Raibert & Sutherland 1983). During walking, one limb provides support and balance in order that the contralateral limb be free to swing forward to create the next step, ultimately establishing a new foundation for continued support (Murray 1967). The initial forward momentum of the walking action is generated by the push of the supportive foot against the locomotor surface coincident with a falling forward of the body due to the force of gravity, and is realised via muscular contraction and an absorption of energy. As the result of friction, there is an equal but opposite surface reaction force which propels the body forwards and upwards. The vertical displacement of the body, in conjunction with a flexion of the knee of the swinging limb, allows for an adequate foot-floor clearance facilitating an unhindered swinging forward of the non-supportive extremity (Murray 1967). The potential energy generated by the vertical and upward displacement of the body's centre of mass is reconverted back into kinetic energy during the late swing phase of the cycle as the non-supportive limb is brought forward into the next step. Coincidental with the late swing phase of the step is a falling forward of the body. This forward motion is accelerated by the force of gravity and is arrested as the swinging limb ultimately contacts the ground. During this double-support phase both potential and kinetic energies are near zero. This cycle completed, the body is again lifted as the centre of mass is once more translated forwards to a position above the supporting limb. Simultaneously, a vertical and upward displacement of the body provides the foot-floor clearance necessary to allow the trailing limb to swing forward into the next step preparatory to providing a new base of support (Margaria 1976).

A running gait differs quite considerably from the pattern of walking as outlined above. The initial step in running is, as with walking, generated by the push of the supportive limb against the locomotor surface, and is realised by muscular contraction and an absorption of energy. An equal but opposite reaction force is provided by surface friction, and the body is propelled forwards and upwards. However, the initial propulsive force (and the resulting reaction force) is greater in the running gait than in the walking gait by virtue of a greater involvement of the gluteal muscles (Margaria 1976). As a consequence, the upward momentum generated in running is sufficient to project the body into the air. The properties of inertia ensure that the body will continue its motion through the air until surface contact is once more established by virtue of gravitational forces. When the upward momentum of the body reaches zero the potential energy of the system is very high, and the body will descend at an ever increasing rate due to gravitational acceleration. This accelerating descent of the body is arrested as the swinging limb strikes the ground. Upon impact, the extensor muscles of the supportive lower limb contract to prevent excessive flexion of the knee, and energy is stored in the locomotor muscles and tendons. This energy is released almost immediately via an elastic recoil of the muscles and tendons, and, as in a recoiling spring, the stored energy of the system is reconverted to kinetic energy as the body is once again propelled upwards and forwards into the next step.

It is clear from the above that the kinetics of walking and running, although in many respects very similar, have a number of unique attributes distinguishing them. Besides the obvious distinctions with respect to the double-support (walking) and no-support (running) phases, there are a number of other mechanical differences. In both walking and running there is a contribution to energy input from an elastic recoil of the involved musculature. However, the contribution of this recoil effect is far greater in a running gait and is relatively insignificant when walking. This is because the forces generated in a walking gait tend to be too small to appreciably stretch the locomotor muscles and tendons (Boje 1944, Asmussen & Bonde-Petersen 1974, Cavagna & Kaneko 1977, Alexander 1980, Cavanagh & Kram 1985b, Van Ingen Schenau 1986, Goslin 1987). It is for this reason that running gaits are reported as being more efficient a means of progression than are walking gaits (Menier & Pugh 1968, Cavagna & Kaneko 1977). Running efficiency is suggested as ranging from about 50% - 70%, compared to the 35% - 40% associated with walking (Cavagna & Kaneko 1977, Ito et al. 1983). This discrepancy in locomotor efficiency is largely due to the fact that during walking the role played by the contractile machinery (absorption of energy) prevails over that of the elastic recoil effect (release of energy), while the opposite holds true for running.

A further distinguishing feature in the mechanics of walking and running relates to the magnitude of the propulsive forces generated by the supportive limb at the initiation of the locomotor step. For any given speed the mechanical work required to accelerate the body is greater in walking than in running (Cavagna & Kaneko 1977). During running, a pendulum effect is generated by virtue of the considerable energy derived via the elastic recoil of the locomotor musculature. Thus, the external work required at each step in running at a given speed is considerably less than is required to walk at the same speed (Boje 1944, Cavagna & Kaneko 1977).

Another difference between the gaits of walking and running concerns the nature of the interchange of kinetic and potential energies. The total energy expended during locomotion is represented by the resultant changes in kinetic energy (due to the swinging of the limbs and the horizontal oscillations of the trunk) and in potential energy (due to the vertical displacement of the body's centre of mass) (Dean 1965). When running at a constant speed, the work done against gravity (potential energy) and the work necessary to sustain the forward momentum of the body (kinetic energy) are both provided by contraction and elastic recoil of the involved locomotor musculature and take place simultaneously. In walking however, the changes of the potential and kinetic energies are substantially in opposition, and forward acceleration (increased kinetic energy) takes place coincidentally with the lowering of the body's centre of mass (decreased potential energy), while the rise in the body's centre of mass (increased potential energy) coincides with forward deceleration (decreased kinetic energy) (Cavagna & Margaria 1966). In other words, during running the increase/decrease of the body's potential and kinetic energies occur simultaneously, whereas in walking they occur out of phase (Sakurai & Miyashita 1985).

With respect to this difference in the absorption/release of potential and kinetic energies, the action of walking has been likened to the motion of a rolling egg, while a running gait is favourably compared to the motion of a bouncing ball (Margaria 1976, Ito et al. 1983). As an egg rolls end over end across a level surface, kinetic energy is converted into potential energy as it rises, and reconverted back into kinetic energy as it falls (Elftman 1939). With respect to the walking action, kinetic energy is converted into potential energy during the early single-support phase of the cycle as the body is propelled upwards. The potential energy is then reconverted back into kinetic energy during the late single-support phase of the cycle as the body descends due to the "pull" of gravitational forces. On the other hand, as a rubber ball bounces across a level surface, it undergoes a repetitive cycle of deformation and reformation as it contacts the ground. The deformation of the ball as it strikes the surface is short-lived, and the elastic recoil which occurs as the ball regains its shape inputs energy into the system and so fuels (partially) the continued motion. Hence, as the kinetic energy of the system is decreasing due to surface resiliency, the potential energy of the system is simultaneously increasing as the result of an elastic recoil. Similarly, as the swinging limb strikes the ground during running (decreased kinetic energy), the muscles and tendons of the limb deform (contract) temporarily so as to prevent an absorption of energy via flexion of the knee (increasing the potential energy). The recoil effect as these muscles and tendons regain their tone contributes to an input of energy to the system, and consequently sustains the forward progression of the body with little further input from muscular (ATP) energy.

The effects of air resistance and surface friction tend to increase the energy expended during both walking and running quite considerably, especially when the rate of locomotor progression is high. If the effects of this air and surface resistance were totally eliminated (ie. in a vacuum), any moving object would coast forward at a constant speed indefinitely with no dependence upon any further input of energy (Hay 1978, Cooper et al. 1982). However, terrestrial animals do not locomote in vacuums, and when they move they must constantly touch the ground and pass through the air - and in so doing they lose much of the forward energy they have generated. Therefore, to reinstate the desired forward momentum, a locomoting animal must initiate a stepping-action as it contacts the locomotor surface. This sequence of stepping places a further demand upon the energy producing mechanisms of the system. Since a walking gait is characterised by greater periods of support (foot-floor contact) than is a running gait, it might be argued that the former is typified by a greater loss of energy as the result of frictional resistance. However, the greater locomotor speeds associated with running tend to elicit a greater increment in energy expenditure as the result of a greater air resistance. It would appear therefore, that the resistive forces contributing to a loss of energy from the locomoting system are not significantly different for walking and running gaits. This is because the former is associated with a greater surface friction, while the latter is associated with a greater air resistance.

A final difference between walking and running gaits has to do with the quantity of the involved locomotor musculature. During walking, the lower extremities constitute the major contributor to the total energy changes of the system, while the trunk and upper extremities play a very much more subdued role which is geared primarily towards the maintenance of stability and balance. During running, on the other hand, the lower limbs strive towards the conservation of energy, and the trunk and upper appendages are the major protagonists in the total energy fluctuations of the body (Sakurai & Miyashita 1985). The arm-action and thoracic excursion in walking and running serve to counteract the tendency of the body to rotate due to an off-centre application of force by the foot on the locomotor surface (Broer & Zernicke 1979). The walking gait is thus characterised by a pendulum action of the arms reciprocating with a contralateral action of the lower extremities. In running however, the arm-action is often exaggerated by virtue of an excessive muscle participation which is realised in order to complement the running action by contributing to the vertical displacement (lift) of the body (Murray 1967, Hinrichs et al. 1987). Further, as the result of a relatively short cycle time, running gaits are typified by a vigorous trunk and upper-extremity involvement in order to counterbalance the rapid cyclic action of the lower limbs. However, since the arm-action during locomotion is largely a function of gravity and inertia, it contributes only minutely to the energy expended for all but the fastest speeds of walking and running (Broer & Zernicke 1979).

The optimisation of any locomotor mode is achieved via the process of eliminating any useless or counterproductive movements of the body or its segments (Daniels 1985). It is self-evident that the fewer the number of movements characteristic of any motor-pattern, the smaller will be the number of motor units recruited and the more cost-efficient the activity becomes. Thus, when walking or running, the organism strives towards the (subconscious) elimination of those movements which impinge upon the efficiency of the locomotor gait. Saunders et al. (1953) have identified six characteristics of human ambulation which collectively contribute to the minimisation of the vertical and horizontal displacements of the body, thereby optimising the efficiency of the bipedal walking gait. These six determinants are pelvic rotation, pelvic tilt, knee flexion, hip flexion, knee and ankle interaction and lateral pelvic displacement, and they combine to facilitate an unhindered forward swing of the non-supportive limb preparatory to its providing a new base of support. They further contribute to a minimisation of the vertical displacement of the body's centre of mass, and a consequent reduction in the energy expended to lift the body against gravity at each step. In running, the "flight" phase of the cycle provides sufficient foot-floor clearance for the unhindered forward swing of the non-supportive limb. As a result, the six determinants of gait as identified by Saunders and his associates do not manifest themselves during running. Consequently, the gait pattern typical of running is characterised by an obvious vertical undulation of the body's centre of mass, although the input of energy from the elastic recoil of the locomotor musculature renders the running gait no less efficient a means of progession than walking.

In summary, it may be said that both walking and running gaits are realised via the contraction of locomotor musculature and a subsequent transfer of kinetic and potential energies (Elftman 1939, Murray 1967). Much of the energetic input during locomotion is expended in raising the body against gravity and in accelerating and decelerating its limbs through space (Taylor & Rowntree 1973, Bennett 1985). As an animal locomotes, its body loses kinetic energy at some stages of the stride and gains potential energy at others, but only a portion of this energy is stored in the interim - the rest is degraded into heat and lost to the body as useful input (Alexander 1985). This storage and transfer of energy contribute to a more cost-efficient locomotor action. The total amount of mechanical energy that would otherwise be expended during locomotion may be much reduced by either or both of two mechanisms: i) an interchange of kinetic and potential energies typical of a pendular action, and ii) a storage and recovery of elastic energy typical of the action of a spring (Alexander 1985). All locomotion must be considered with respect to this interchange of potential and kinetic energies (Cavagna & Margaria 1966), and must further be interpreted with respect to the interplay of gravity, inertia, surface friction, ground reaction and air resistance (Liberson 1965). Unless an equilibrium between all such elements can be achieved, controlled locomotion of the organism can never fully be realised.

ii) Kinematic Considerations

As with energetic responses to locomotion, the influence of speed upon the spatial and temporal factors of human gait is very dramatic. A locomotor gait is defined by Hildebrand (1985) as a regularly repeated sequence and manner of moving the body in walking or running. One can consider gait kinematics, therefore, as the speed-related interaction of multi-linked segments of a motile organism in a cycle of events which repeats itself with each stride (Charteris 1982). The temporal (in time) and spatial (in space) parameters of gait, such as stride length, cadence, cycle time, support time, swing time etc., are all extremely labile and very much speed dependent. This is to say that progression at any given locomotor speed is uniquely characterised by a definite and significant interaction of numerous kinematic variables.

By definition, the supporting limb during bipedal walking must remain in contact with the locomotor surface until the opposite limb strikes the ground (Broer 1966, Grieve & Gear 1966, Murray 1967). It follows, therefore, that a walking gait is characterised by recurring periods of double-support interspersed with periods of single-support, and that there is no period of "flight" (when both feet are simultaneously airborne). As soon as the locomotor gait involves an instant in time when neither foot is in contact with the ground, then the mode of locomotion is termed running (Broer 1966). Thus, a running gait is characterised by recurring periods of single-support interspersed with periods of flight - there is no period of double-support (Grieve & Gear 1966).

It is clear from these definitions of walking and running that the human locomotory gait can be broken down into alternating phases of support and swing. The prerequisite of double-support in bipedal walking dictates that the supporting limb remain in contact with the locomotor surface until the swinging limb strikes the ground. There immediately follows a short period during which both feet are in contact with the ground (double-support), a situation which allows the body (trunk) to be moved forward into a position over the leading limb, thereby providing the impetus and balance for the forward swinging action of the non-supportive limb (Murray 1967). Thus, a walking gait is typified by a sequence of single-support phases interspersed with periods of double-support, the latter allowing for the controlled transfer of the body mass and a contralateral reversal of the supporting and swinging limb actions. In bipedal running there is no double-support prerequisite, and an airborne phase instead allows for this reversal of the supporting/swinging limb actions. A running gait is consequently typified by a series of single-supports interspersed with periods during which no contact is maintained with the locomotor surface.

A characteristic of "normal" locomotion is that there is no significant difference between the left and right support (and hence swing) durations (Grainger et al. 1983). Such an asymmetry of foot-floor contacts would in fact be typical of a limping gait (Murray et al. 1964, Charteris 1979). This said however, human walkers, not being symmetrical robots, will naturally display a definite kinematic variability with respect to such features as left versus right patterns of foot-floor contact.

In normal locomotion the initial foot-floor contact and initiation of the gait cycle is marked by a left or right heel-strike (Charteris et al. 1982). The time interval between two successive heel contacts of the same foot is termed the cycle time or stride time (Murray et al. 1964, Brown & Yavorsky 1987). There exists a very definite inverse relationship between the speed of locomotion and cycle time - in other words, increments in walking and/or running speed elicit proportional decreases in the time interval between successive left (or right) heel strikes. Further, the cycle time in running tends to be less than that for walking, unless the two modes of progression are performed at the same speed (ie. within the locomotor interface), in which case the walking cycle is completed more quickly due to a greater frequency of step (Candler 1986).

Stride length is defined as the linear distance between two consecutive points of foot-floor contact by the same foot during any gait cycle (Murray et al. 1964, Charteris et al. 1982, Wall et al. 1987). In a normal gait, the stride length is measured as the linear distance between two successive heel strikes by the same foot. Step length, on the other hand, is the linear distance between two consecutive points of foot-floor contact (ie. heel strike) of alternate feet (Murray 1967, Charteris et al. 1982). It follows, therefore, that each stride is made up of two steps and that stride length is equal to two times step length. The rapidity with which successive steps are taken can be measured in terms of step frequency or cadence (Murray 1967). At all but the fastest speeds of walking or running, there is a reciprocal relationship between stride length and cadence, and an increase in one tends to elicit a proportional decrease in the other. From this relationship it is apparent that:

i) locomotor speed is a function of the product of the length and the frequency of stride, and

ii) cycle time is a constant function of the speed-specific length of stride.

From the preceeding observations it is clear that:

1. **speed = stride length * (2 * cadence)**

2. **speed = stride length ÷ cycle time**

Both stride length and cadence vary proportionately with increments in locomotor speed (Erickson et al. 1946, Bobbert 1960, Dean 1965, Alexander 1976, Andriacchi et al. 1977, Ito et al. 1983, Taves et al. 1983, McArdle et al. 1986). In fact, the speed of locomotion is a direct function of the interaction between the length and frequency of step (Burke & Berger 1976). However, during walking, increments in the rate of progression are realised largely via an increased cadence, while during running the length of stride becomes the more important mechanism via which to increment the locomotor speed (Boje 1944, Erickson et al. 1946, Knuttgen 1961, Fukanaga et al. 1980, McArdle et al. 1986). In other words, increments in the speed of walking are characterised by a more pronounced increase in the rate of step, while increments in the speed of running are characterised by a more pronounced increase in the length of step (Ogasawara 1934). This is because the length of step during a walking gait is restricted by limitations associated with pelvic rotation, and it is mechanically advantageous to increase the frequency of step rather than the length of step in order to realise any increment in the rate of progression. In this respect, Dean (1965) suggests that during walking the length of step cannot exceed two times the length of the lower limb. However, in running, in which a double-support phase is not a prerequisite, the constraints of pelvic rotation are rendered insignificant by virtue of a locomotory action which allows the body to "glide" through the air. When running, therefore, it is preferential to realise increased speeds of progression via increments in the length of stride.

However, the above holds true only for progression at speeds below the aerobic limits set for walking and running at about 2.50 and 5.55m.s^{-1} respectively (Cavagna & Kaneko 1977). While increased cadence is an effective means of realising increments in the speed of walking, there does exist a limit to the rate at which the cyclic movements of the gait mechanism can be made. Once these cadence-limits are approached (during fast walking), further speed increments are more effectively realised via an increased stride length (Charteris et al. 1982). Competition walkers progress at rates wherein such cadence-limits are reached, and they have evolved a technique of "rolling" the pelvis which enables them to exaggerate the walking step length. When running at speeds above the aerobic limit of approximately 5.55m.s^{-1}, increments in speed are facilitated not by an increased stride length (as is typical at lower running speeds), but by an increased cadence (Fukanaga et al. 1980). This means of accelerating the running gait effectively eliminates the considerable "hopping/bounding" which would result were the increased running speeds realised via incremented lengths of stride.

It is clear from the discussion thus far that acceleration of the body during walking and running can be achieved via an increased stride length or an increased cadence (or both). In the final analysis, however, increments in locomotor speed are facilitated by increases in both the length and frequency of step - the locomotory mode dictating which of the two contributes most significantly to the body's acceleration.

Increased cadence is brought about simply by an increased rate of muscular contraction. Stride length, however, may be increased by either one or a combination of any of three mechanisms (Hogberg 1952), these mechanisms being:

i) an increased rotation of the pelvis, coupled with an exaggerated forward stretching of the swinging limb,

ii) an increased angle of the thigh in the sagittal plane, and

iii) an increased propulsive drive of the supporting limb.

The first of these mechanisms is ineffective because it takes too long for the body's centre of mass to come into a position such that it lies above the supporting limb. This position is essential, as it allows the application of force by the supporting limb to be directed backwards, thereby providing a propulsive force in the direction of desired progression. The second of the mechanisms outlined above is similarly ineffective, as increasing the length of stride by increasing the angle of the thigh generates an exaggerated twisting movement of the pelvis. This excessive pelvic rotation requires a compensatory shoulder movement, which results in the innervation of a larger than necessary number of motor units rendering the movement inefficient. The third mechanism of using the propulsive force of the supporting limb to increase the stride length is consequently the most effective means of incrementing the speed of locomotion (Hogberg 1952). This increased propulsive force is complemented by a contraction of the quadriceps muscle which acts to "pull" the body forward (Basmajian 1967)

The swing phase is that period of the stride during which either foot is airborne and moving forward to create the next step (Murray 1967). During walking, the prerequisite of double-support dictates that the swing time be less than 50% of the total cycle time. As soon as the swing phase of a locomotor cycle exceeds 50%, a segment of the stride is of necessity characterised by a period of flight and the gait pattern is typical of running. Alexander (1980) has coined the term "duty factor" to express that fraction of the stride for which either foot is on the ground. In walking, this duty factor must be greater than 0.5, whereas in running it is generally less than 0.5 (ie. in walking the support phase must constitute no less than 50% of the total stride cycle, while in running the support phase tends to constitute considerably less than 50% of the cycle). However, as with all kinematic parameters of a bipedal gait, swing time (whether expressed absolutely or as a percentage of the gait cycle) is labile and very much dependent upon the speed of locomotion.

At preferred walking speeds the support phase constitutes as much as 60% of the stride cycle, with the swing phase contributing the remainder (Brown & Yavorsky 1987). This represents a duty factor of 0.6, and generates a support-to-swing ratio of 1.5. This support/swing ratio tends towards 2.0 at very slow walking speeds, and towards 1.0 at very fast speeds. This suggests that as the rate of progression increases, a smaller fraction of the walking cycle is represented by the support phase. In running, the swing time (relative to the support time) is increased quite considerably by virtue of the fact that the gait has no double-support prerequisite. In fact, during running the swing time invariably exceeds 50% of the gait cycle, and as a consequence relatively little time is spent in contact with the locomotor surface. Thus, running gaits are typified by duty factors of less than 0.5, and generate support/swing ratios of less than 1.0 (the support/swing ratio tending to decrease proportionately with increments in the running speed). Hence, as is the case with walking gaits, the support phase during running tends to decrease as the speed of progression increases (Andriacchi et al. 1977).

PSYCHOLOGICAL RESPONSES TO LOCOMOTION

i) The Perception of Physical Exertion

The study of "man-in-motion" has over the years captured the imagination of numerous researchers. Early studies tended to examine the motive being from the perspective of a primarily physiological and/or biomechanical domain - choosing to analyse human movement with respect to energetic, kinetic and/or kinematic variables. However, movement in the human context implies a psychosocial dimension without which the essential humanity of the moving organism is incomprehensible (Charteris et al. 1976). Contemporary research has therefore concerned itself very much more readily with the investigation of the effects of human locomotion upon psychological (and social) behaviour patterns.

Significant steps have been taken to integrate the physiological, biomechanical and psychological responses within the framework of human movement (Charteris et al. 1976, Shephard 1984). One particular area in which this integrative approach to the interpretation of human movement has been successful, is that concerning the the measurement of physical effort. Physiologists regard effort in terms of energy expenditure, and usually express it is a respiratory ($\dot{V}O2$), metabolic (kcal) or cardiovascular (heart-rate) variable. Ergonomists define effort with respect to work-output variables which describe the size, shape and weight of materials in conjunction with the duration, distance and frequency characteristics of their handling. During the past half century psychologists have contributed to the analysis of physical effort via an input from experimental investigations evaluating psychophysical responses to different workloads, and the scaling of related variables such as task difficulty and task intensity (Fleishman et al. 1984). Central to this psychobiological focus, is the idea that knowing what individuals "think" they are doing is often just as important as what in fact they "are" doing (Rejeski 1981). In other words, human movement research should concern itself not only with the physiological correlates of a given activity, but also with how people feel about what they are doing, what aches and pains they experience during performance, and how difficult they perceive their work to be (Borg 1982).

The perception of physical effort is defined by Morgan (1973) as one's subjective rating or interpretation of the intensity with which a given workload is performed. This perception of exertion is the end-product of an integration of information derived via the many signals emanating from the working muscles and joints, from the cardiovascular and respiratory systems, as well as from the central nervous system (Borg 1982). All these signals, perceptions and experiences are combined into a configuration or "gestalt" of perceived exertion, resulting in a subjective , quite personal and extremely complex cognitive estimation of physical effort (Morgan 1973).

Sensory responses to all forms of exercise, be they brief static contractions or repeated dynamic contractions, are a function of the neuromuscular system (Caferelli 1982). However, although physiological functions very obviously account for a significant portion of the sensory input to the perception of effort, the subjective psychological contribution to this perceptual experience cannot be overlooked (Rejeski 1981). There exists considerable evidence to support a very strong association between the physiological and the psychological indicators of workload. Carton and Rhodes (1985) report a psychobiological correlation coefficient of between 0.81 and 0.83, while Fleishman et al. (1984) report a correlation of between 0.70 and 0.80 for the same variables. It is fairly clear, therefore, that the physiological abd psychological correlates of physical exertion are tightly meshed, and that to arrive at a full and meaningful understanding of "man-at-work" we must investigate not only objective movement responses, but subjective "feelings" too.

The mechanisms via which man perceives the intensity of physical exertion are extremely complex and relatively poorly understood (Morgan 1973). What is actually perceived and subjectively rated by the subject remains largely unknown, since so many physiological responses increase in a linear fashion with increments in workload (Skinner <u>et al</u>. 1973a). Many different variables have been identified as constituting the primary sensory cue for the perception of effort. Early research by Borg (1962) proposed that heart-rate was the physiological correlate most closely linked to the effort sense as an index of exercise strain. This suggestion has recently met with widespread criticism, contemporary researchers contending that heart-rate and perceived exertion are not closely correlated under all exercising conditions (Noble <u>et al</u>. 1973a, Mihevic 1981, Robertson 1982, Carton & Rhodes 1985). Alternative physiological variables have been reported as providing the key input for the effort sense - these include an incremented oxygen consumption, an increased inspiratory volume, elevated ventilatory rate and depth, dyspnea, increased blood-lactate concentration, a decreased blood pH, increased levels of catecholamines and endorphins, and decreased levels of muscle glycogen, adenosine triphosphate (ATP) and creatine phosphokinase (CP) (Carton & Rhodes 1985). Other investigators propose that cognitive cues deriving from the activity of mechano- and chemoreceptors, as well as from tendon, joint, skin and ligament receptors (ie. proprioceptive and kinesthetic feedback via a muscle "sentience"), contribute most significantly to the perception of physical effort (Pandolf 1978, Mihevic 1981).

From the evidence cited above it is clear that much controversy exists with respect to identifying the single physiological variable which provides the key input to the effort sense. In addressing this problem, Mihevic (1981) postulates that:

> "...while the conscious awareness of certain discrete physiological cues is likely to affect the evaluation of perceived exertion, the total exercise demand as determined by the conscious and/or subconscious integration of multiple physiological responses may well represent a more critical basis for the perception of effort". **(page 150)**

In other words, man does not attend directly to any single metabolic or respiratory cue as the basis for an estimation of physical effort, but rather to the coincidental input from a large number of interrelating physiological variables. It is the combined effect of several circulatory, respiratory, metabolic and kinesthetic signals which ultimately shapes the effort sense (Robertson 1982).

It is important to note that only those physiological processes available to conscious monitoring are likely to exert any potent impact upon the cognitive perception of exertion (Mihevic 1981). Hence, metabolic responses which escape conscious "awareness", such as elevated blood-lactate concentrations, are likely to provide very little in the way of direct input to the estimation of workload intensity. Rather, man attends to the externalisation of these subconscious processes, including increments in variables such as ventilation, metabolic rate and muscle and skin temperature (Noble et al. 1973a).

In an attempt to differentiate between the cardiorespiratory and muscular/metabolic contributions made to the psychological estimation of exercise intensity, Ekblom and Goldbarg (1971) have proposed a two-factor model for the perception of physical effort. Their model distinguishes between a sensory input from "central" and from "local" cues. The central factors manifest themselves as sensations associated primarily with the cardiorespiratory system, while the local factors are associated with peripheral sensations of strain in the exercising muscles and joints. In some exercises, central cues such as heart-rate and ventilation appear to be the dominant factors contributing to the perception of physical effort, whereas other forms of exercise are characterised by a dominance of local cues such as increased blood-lactate levels and metabolic acidosis (Pandolf 1978). The two-factor approach to the interpretation of the effort sense is thus an appropriate and effective means of evaluating the roles played by central (cardiorespiratory) and local (muscular/joint) cues for a particular type and mode of activity. However, it must be recognised that the specific central/local interaction of the organism's sensory cues is very much situationally dependent - the contribution of each to the overall estimation of effort will vary from activity to activity, from one condition to another, and also from one subject to the next.

Current research suggests that the dominance of either central and/or local factors in the subjective estimation of physical exertion appears to be related, in part, to the amount of muscle mass employed by the given activity. In work involving small muscle groups, local factors seem to dominate, while work involving a large musculature tends to stress the cardiorespiratory system and thus "adds" central input to the local strain (Pandolf 1978). In other words, small-muscle activity is mediated by a local perception of exertion, whereas movement recruiting a large muscle mass is governed by a central estimation of effort. Further, short duration exercise tends to stress the local perception of exertion as the result of sensory input from the skin, muscles and joints, whereas long-term activity is dominated by a central perception of effort originating from a sensory input offered by the organs of circulation and respiration (Carton & Rhodes 1985). This theory is augmented by Robertson (1982), who suggests that local factors constitute the primary sensory signals mediating effort perception, while central factors act as an "amplifier" or "gain modifier" that potentiate the local signals in proportion to the aerobic metabolic demand.

As the intensity of any activity increases, the input from central factors to the estimation of physical effort is proportionately incremented (Pandolf 1978). In support of this contention, Carton and Rhodes (1985) propose that local factors mediate the effort sense as long as the exercise undertaken is aerobic in nature. As soon as the anaerobic threshold is attained, central factors begin to dominate the cognitive perception of exertion. In this regard, Noble et al. (1973a) argue that the perception of effort remains relatively stable at exercise intensities between about 48% and 60% of maximal aerobic capacity, whereafter they tend to increase sharply with increments in workload due to an ever-increasing input from central (cardiorespiratory) perceptual cues.

Clearly, the perception of effort cannot be adequately described in terms of physiological input alone. Morgan (1973) suggests that physiological variables account for only 67% of the total variation in perceptions of physical exertion. Noble et al. (1973a) and Rejeski and Ribisl (1980) support this contention, proposing that multiple physiological indices account for approximately 65% of the variance in perceived exertion. The remaining variability in estimations of the effort sense can be attributed to non-physiological variables, the nature of which will be discussed in a later section.

ii) Rating Scales of Perceived Exertion

Having recognised the importance of psychological perceptions with respect to the evaluation of physical effort, numerous investigators have endeavoured to create appropriate rating scales via which the effort sense can be quantified. The use of such scales allows for the recording of subjective and self-reported estimates of energy expenditure and/or exercise intensity. This permits researchers to measure not only objective physiological responses to activity, but also subjective psychological "feelings" describing the nature of the work done.

The earliest such scale was introduced by Gunnar Borg in 1962. This scale consisited of 21 categories of effort, and was based upon the high correlation (r = 0.8-0.9) reported by Borg to exist between heart-rate and the perception of effort during exercise on a bicycle ergometer. This 21-point scale was revised by Borg in 1970, and replaced with a scale consisting of only 15 categories. This updated rating scale for perceived exertion ranged from 6 to 20, with every second (odd) number on the scale anchored with verbal expressions of physical effort such as "very light", "somewhat hard" and "very, very hard". Although other rating scales for the perception of exertion have been introduced in more recent years, such as two 9-point scales developed by Stamford and Noble (1974) and Robertson et al. (1979), and a 10-point scale developed by Borg (1982), the 15-category scale as proposed by Borg in 1970 (see Appendix 3) remains the most popular and widely used scale for the rating of perceived exertion.

Borg's RPE scale was demonstrated as a valid measure of the effort sense by Michael and Eckhardt (1972), who exercised six male subjects (three trained and three untrained) for 15 minutes at a work intensity considered to be "hard" at a 0% grade on a motor-driven treadmill. When asked to reproduce an equivalent level of work at a 10% grade via the verbalisation of physical effort as derived from Borg's RPE scale, no significant difference was found between the exercise intensities of the two locomotor protocols. The reliability of Borg's RPE scale has been evidenced in a research by Lollgen et al. (1975), who demonstrated a test-retest correlation coefficient of 0.92 following exercise on a cycle ergometer, and also by Candler (1986) who found no significant difference between test and retest subjective ratings of perceived locomotor exertion. Further, Skinner et al. (1973b) have demonstrated both the validity and reliability of the Borg scale for exercise of a progressive nature wherein workloads ranged from about 24.5 Watts to a self-imposed maximum.

iii) Ratings of Perceived Exertion and Locomotion

Although the psychological perception of physical effort has engendered much investigation over the past few years, relatively little research has concerned itself with the effects of locomotion and locomotor intensity upon the rating of perceived exertion. The literature that does exist generally supports the contention that cognitive estimates of physical exertion, including such physiological responses as heart-rate and oxygen consumption, tend to increase in a linear fashion with increments in workload (Morgan 1973, Noble et al. 1973a, Pandolf 1978, Borg 1978, Rejeski 1981, Faria & Drummond 1982, Carton & Rhodes 1985). Considering the strong correlation between the physiological and psychological indicators of physical effort (Borg 1978, Fleishman et al. 1984), it follows that increments in the rate of locomotion will tend to elicit proportional increments in the associated ratings of perceived exertion. However, the perception of effort during locomotion is not solely a function of metabolic strain, but also of the stress placed upon local musculature during the accomplishment of the locomotor task (Noble et al. 1973b, Pandolf 1978).

Ratings of perceived exertion for a low intensity walking gait tend to be driven by local cues related to muscle and joint function, whereas fast walking and running gaits are dominated by primarily central cues related to circulorespiratory fatigue. However, for any locomotor gait, an increase in locomotor progression is characterised by an increased input to the effort sense from both local and central cues (Mihevic 1981). It would seem therefore, that during horizontal locomotion at slow to moderate speeds of walking and running, local cues dominate the perception of exertion. However, once fast locomotor speeds are attained, central cues related to cardiorespiratory stress begin to contribute more significantly to the effort sense.

At the locomotor interface, it appears that perceptions of exertion are greater for walking gaits than they are for running gaits - despite similar rates of progression (Candler 1986). In other words, at the same locomotor speeds running gaits are perceived less taxing than are walking gaits, despite the fact that both locomotor modes may elicit the same heart-rate (Carton & Rhodes 1985). This is possibly a result of the dominant input from central factors to the perception of effort during fast walking. Noble et al. (1973b) report that the curves for the RPEs of walking and running tend to intersect at about $1.92 m.s^{-1}$, as compared to the heart-rate intersection point of approximately $2.22 m.s^{-1}$. This discrepancy between the heart-rate and RPE walk/run intercept speeds is likely the result of central circulorespiratory discomfort during fast walking, coincident with the fact that central fatigue tends to overshadow muscle/joint strain when the locomotor rate (walking) is high.

Pandolf (1978) suggests that there is no significant difference in central and local ratings of perceived exertion during submaximal walking speeds between about 1.11 and $1.56 m.s^{-1}$, whereafter central factors tend to drive the effort sense. He further postulates (1982) that across the entire spectrum of submaximal (aerobic) running speeds there is no significant difference between local and central perceptions of physical exertion.

In comparing the ratings of perceived effort of treadmill locomotion to those derived via other exercise modalities, some interesting points arise. Skinner et al. (1973a) suggest that at a given oxygen consumption, the ratings of perceived exertion for cycling tend to be greater than those for treadmill locomotion. This is probably due to the involved musculature characteristic of the two modes of exercise. During a cycling task, the body mass is supported and the work is realised largely by the muscles of the lower limbs. Local (peripheral) cues are, therefore, likely to drive the perception of exertion during cycling, while central (cardiorespiratory) cues tend to be less pronounced (Pandolf 1982, Carton & Rhodes 1985). During locomotion, however, work must be done to lift and balance the body as well as to propel it forward. Walking and running consequently involve a relatively large musculature and tend to be characterised by a central perception of exertion complemented by less dominant local cues.

In summary, it would appear that human locomotion is largely governed by a central input to the perception of effort, unlike a cycling activity which is mediated by a more dominant local (muscular) sense (Carton & Rhodes 1985). However, the input of local factors in walking and running cannot be ignored, and they tend to become more pronounced as the rate of locomotor progression is incremented and the gaits are fuelled by ever more dominant anaerobic sources.

THE INTERACTION OF LOCOMOTOR RESPONSES

The previous sections reported independently the documented effects of horizontal locomotion upon selected physiological, biomechanical and psychological human responses. Contemporary thought motivates that any interpretation of human movement proceed from the framework of an integrative multidisciplinary perspective, rather than from the standpoint of only one of the physical, biological or social sciences (Charteris et al. 1976, Shephard 1984). To study "man-in-motion" therefore requires an understanding of the interdependence/interaction of physiological, biomechanical and psychological movement variables. The study of human movement is inherently complex, as the many parameters that can be observed in a locomoting subject are at the same time labile and interrelated (Andriacchi et al. 1977). For example, it is well documented that manipulation of the kinetic characteristics of any given locomotor gait tends to elicit significant variations in the related expenditure of energy. Similarly, variations in the locomotor energetics are likely to produce alterations in the associated ratings of perceived physical effort.

i) $\dot{V}O2$ and Stride Length

It is well documented that physiological locomotor efficiency is optimised through an individual but specific combination of stride length and frequency (Hogberg 1952, Bobbert 1960, Knuttgen 1961, McDonald 1961, Cavanagh & Williams 1962, Van der Walt & Wyndham 1973, Burke & Berger 1976, Astrand & Rodahl 1977, Cavanagh & Kram 1985b, McArdle et al. 1986). Accordingly, for any given subject at any given speed of progression, there tends to exist an optimum combination of stride length and cadence at which energy expenditure is minimised. Any deviation from this optimum tends to elicit significant increments in the related locomotor oxygen cost.

It is clearly documented in the literature that from an energetic point of view it is more costly to overstride than it is to understride during running, although both will ultimately render the locomotion less efficient (Daniels 1985, McArdle et al. 1986). Overstriding is a costly means of increasing the rate of progression due to the excessive rotational displacements of the pelvic and shoulder girdles, coincident with an exaggerated vertical displacement of the body's centre of mass (Ogasawara 1934, Boje 1944, Hogberg 1952, Murray 1967, Burke & Berger 1976). Understriding, on the other hand, requires an elevated frequency of stepping which is itself costly due to a rapid and inefficient rate of muscular contraction - as speed of muscular contraction is doubled the related expenditure of energy increases threefold (Elliot & Blanksby 1976). This partly explains why a quick walk ($>2.5m.s^{-1}$), which necessitates both an increased length and an increased frequency of step, is more costly from an energetic point of view than is a slow run at the same speed.

ii) $\dot{V}O2$ and Cadence

An area that has been poorly investigated relates to the specific effects of stride length and cadence upon the energetics of human locomotion. It is clearly understood that increments in locomotor speed will elicit proportional increases in the energetic cost of the movement. However, it remains arguable as to whether these increments in energy cost are the function of an increased length of stride or an increased rate of stride, or whether both contribute equally. With respect to cycle ergometry, it is suggested that oxygen consumption rises as a linear function of the rate of pedalling (Rejeski 1981, Carton & Rhodes 1985). A logical parallel would be that oxygen consumption increases in a linear fashion with locomotor cadence (and not stride length). This assumption has been put forward by Ogasawara (1934), who contends that at a given rate of progression, whether walking or running, each step taken necessitates the same expenditure of energy. Consequently, faster rates of progression are more costly by virtue of a greater number of steps per unit distance. In a study of level and grade walking (with and without loads), Kamon and Belding (1971) realised a significant reduction in inter-individual variability with respect to walking energy expenditures when metabolic cost was expressed relative to cadence (kcal.step^{-1}). Similar findings are reported by Heglund *et al*. (1982), who postulate that mass-specific work per stride (or step) is the same for large and small animals moving at the same speed - which suggests that relative energy cost is a function of locomotor cadence. This lends support to the contention that variations in cadence (metabolic input) and not in the length of stride (mechanical input) generate the major contribution to locomotor energetics. Further evidence for this theory is proposed by Taylor *et al*. (1982) who suggest that:

> "...small animals have to take many more steps to cover a given distance because of their shorter legs. Therefore, when walking at the same speed small animals should have higher step frequencies and consume energy at higher levels." (page 2)

iii) Stride Length, Cadence and RPE

The optimal combination of stride length and cadence at any given speed differs quite considerably from one subject to another. Athletes are able to self-optimise a given locomotor gait by manipulating certain "style" variables in order to maximise the efficiency of movement (Cavanagh & Kram 1985b). Hence, the length of stride freely and subconsciously chosen by the subject at any given rate of progression tends to be the least costly in terms of energy expenditure (Hogberg 1952, Bobbert 1960, McDonald 1961, Cavanagh & Williams 1962, Burke &

Berger 1976, McArdle et al. 1986). This self-selection of locomotor stride length is achieved via sensory feedback and is directly linked to the cognitive input governing the perception of physical effort (Cavanagh & Kram 1985b). It follows, therefore, that the self-selection of optimal stride length during locomotion at any given speed should be demonstrated not only in physiological variables, but also in the the psychophysical subjective ratings of perceived exertion. This premise is augmented by research undertaken by Messier et al. (1986), who examined the effects of deviations from optimal stride length on the perception of locomotor effort. Their results suggest that both overstriding (optimal plus 7%) and understriding (optimal minus 14%) elicited significant changes in the associated estimates of physical exertion. They concluded that the increased sensitivity of the sensory mechanism to overstriding is a function of the increased muscular activity of the lower limbs, which is associated with a proportionately greater local input. Understriding, on the other hand, is less obviously perceived by the sensory mechanism due to a decreased vertical oscillation of the body's centre of mass resulting in a local input of a relatively small magnitude. Consequently, small decreases in locomotor stride length appear not to alter significantly the subject's estimated level of local muscular effort, whereas small increments in stride length are very precisely perceived. Thus, athletes very definitely perceive (consciously) differences in the exertion imposed by variations in stride length. However, whether or not they are able to use this sensory information to make locomotor adjustments in order to maximise efficiency of movement remains unknown.

iv) $\dot{V}O2$ and RPE

It is clear from the previous section that during physical activity psychological responses (such as RPE) tend to correlate fairly strongly with physiological responses (such as heart-rate and oxygen consumption). In fact, early research suggests that exercise heart-rate and oxygen uptake represent the single most important variables driving the cognitive estimate of physical effort (Singer et al. 1973a, Borg 1978, Pandolf 1978, Mihevic 1981). Borg (1978) reports a correlation coefficient of between 0.8 and 0.9 between heart-rate and RPE in healthy males during cycle ergometry. Pandolf (1978) proposes an equally strong correlation (r = 0.92-0.97) between energy cost and RPE during both continuous and intermittent exercise. However, recent research (Robertson 1982, Carton & Rhodes 1985) contends that both heart-rate and oxygen consumption are only indirectly related to the perception of physical effort, and that other physiological variables provide a more salient input. It would appear, therefore, that the exact nature of the relationship between oxygen consumption and ratings of perceived locomotor exertion (both local muscular and central cardiorespiratory) remains poorly researched and understood.

THE VARIABILITY OF LOCOMOTOR RESPONSES

Characteristic of any empirical study of human movement is an inherent variability of responses both within and between subjects. Unlike the physical properties of chemicals wherein function and response are virtually 100% consistent, the human system is considerably less predictable. Biological systems are typified by the necessity to adapt to variable environmental stressors. This, in turn, promotes a variability of responses within a given species (Wall et al. 1986). Although investigators of "man-in-motion" may strive to factor-out this innate variability in order to interpret the specific effects of a given stimulus upon the human organism, such research continues to reveal both within-subject variation (from day to day) and between-subject variation (from individual to individual).

The variability of human responses to a given stimulus can be partitioned into several sources, two of which are biological variation and technological error (Katch et al. 1982). Biological variation, or biovariation, is reflective of the inherent biological fluctuations characteristic of all living matter. Technological error, on the other hand, is representative of the variability in motor responses which results from protocol and/or measurement inconsistencies, examples of which include instrument faults, uncontrolled environmental factors and recording errors. In most cases technological error is fairly constant, and can be effectively eliminated by the investigator via a carefully designed pilot programme. Biological variation, however, is very much more difficult to control due to an inherent inconsistency - it tends to increment in proportion to the magnitude of the absolute response measured (Katch et al. 1982).

In a study by Katch et al. (1982) it was demonstrated that biological variation (Si) and technological error (Se) combine to generate a total variance in maximal aerobic power of 5.6%. However, biovariation was shown to account for 90% of this variance, while technological error contributed only 10%. It can consequently be concluded that under carefully controlled laboratory conditions the extent of the variability in energy expenditure ($\dot{V}O2$) due to technological error is small and relatively inconsequential. The largest and most significant variability in the human response to a given motor task can be attributed to the inherent biological tendency for individual responses to vary about a theoretical true score (Taylor 1944, Henry 1959, Katch et al. 1982).

The exact causes of biological variability are very much dependent upon the nature of the movement pattern investigated, and are on the whole poorly understood. With respect to human movement, biovariation can be divided into between-subject (inter-individual) and within-subject (intra-individual) variability (Daniels 1985). Both inter- and intra-individual variation with respect to human responses to a given stimulus must be understood by the investigator of "man-in-motion" as impinging to some degree upon the validity of the data captured.

i) Inter-Individual Variation

It is widely and correctly understood that genetic evolution, coincident with the learning process which results from a specific but individual organism-environment interaction, ensures that no two biological systems will respond to a given stimulus in an exactly consistent manner. This contention is supported by Cavanagh and Kram (1985a), who suggest that it is not possible to precisely partition human variability (between individuals) into particular patterns, because each subject has a unique set of coefficients for those factors contributing to the economy of movement. In other words, each subject will respond to any given stimulus in accordance with unique and personal constraints enforced upon him by factors such as morphological structure, movement history, genetic endowment and psychosocial background. The specific influence of morphological characteristics upon human responses to movement will be discussed in the next section. Following is a description of other factors which may contribute to the significant inter-individual variation which exists with respect to human locomotor responses.

Variability in human locomotor responses between subjects may have a genetic foundation. It is often argued that world class athletes "are born and not bred", which is to say that success in athletics stems not from dedicated physical training but from a favourable genetic endowment (Stampfl 1955). That such inheritance has considerable influence upon the energetics of movement cannot be denied. The steady-state oxygen consumption attained during sub-maximal locomotion (locomotor economy) varies quite dramatically from subject to subject, and is purported to be a useful criterion by which to predict athletic potential (Sjodin & Svedenhag 1985, Goslin 1987). Daniels (1985) reports that the absolute cost of performing a given task may vary by as much as 50% between subjects - and even when expressed relative to body mass this variation in energy expenditure may stiil exceed 30%. Passmore and Durnin (1955), Wyndham et al. (1971) and Cavanagh and Kram (1985a) also recognise this inter-individual variation in movement energy cost, and they collectively report coefficients of variation in exercise oxygen consumption between 12% and 17% for any given workload. Similar findings are reported by Leger and Mercier (1984), who propose that a $10ml.kg^{-1}.min^{-1}$ range exists between individuals with respect to task-specific oxygen consumption. Genetic factors contributing to this energetic inter-individual variability may be attributed to such physiological characteristics as the number and activity of the muscle mitochondria, the effectiveness of aerobic and anaerobic enzymes, muscle fibre type, and concentrations of blood haemoglobin - all of which are hereditary and largely independent of training (Goslin 1987).

There exists considerable controversy concerning the effects of training and level of fitness upon human responses to locomotor movement patterns. Such trainability can be defined as: "...the ability or capacity of an organism to adapt via repeated exposure to a training stimulus" (Bouchard et al. 1981). Numerous investigators (Boje 1944, Bobbert 1960, Ekblom et al. 1968, Gregor & Costill 1973, Bransford & Howley 1977, Dolgener 1982) propose that the oxygen cost of a given locomotor task is lower in trained athletes than it is in unconditioned subjects. However, contemporary opinion, based upon the findings of several research studies (McDonald 1961, Knuttgen et al. 1973, Holloszy 1975, Astrand & Rodahl 1977, Davis et al. 1979, Mayhew et al. 1979, Weltman & Katch 1979, Skinner & McLellan 1980, Jones et al. 1984, Wilcox & Bulbulian 1984, McArdle et al. 1986), tends towards an understanding that the oxygen consumption required to complete a given sub-maximal workload is constant and independent of one's level of fitness. Accordingly, the steady-state oxygen uptake ultimately attained during the performance of any sub-maximal exercise remains the same despite possible changes in the fitness-level of the athlete. However, it may well be that the physically conditioned athlete attains this steady-state more quickly than does his untrained counterpart (McArdle et al. 1986).

Variations in locomotor oxygen cost as the result of training are reported by Erickson et al. (1946) to be less than 3%. Margaria et al. (1963) suggest that trained athletes are only about 5% to 7% more efficient than are unconditioned subjects, a finding which compares favourably with the 8% reported by Mayhew (1977). It would appear therefore, that when expressed in relative terms, the energy required to move at a given locomotor speed is largely constant, and only marginally influenced by athletic training.

The (marginal) improvements in locomotor efficiency as the result of training are more likely due to a mechanical self-optimisation than to a physiological adjustment. In other words, via manipulation of locomotor style and skill variables, the athlete is able to minimise the expenditure of energy associated with any given locomotor effort. As the result of a process of trial and error, trained athletes "learn" to optimise a given locomotor pattern, thereby eliminating unwanted and counterproductive muscular contractions. As a consequence, the athlete's locomotor gait is rendered more economical and less expensive from an energetic point of view (Daniels 1985). This line of thinking is revealed in research completed by Dillman (1975), Elliot and Blanksby (1976) and Williams (1985), who report that experienced runners are more economical by virtue of a mechanically oriented increase in relative locomotor stride length. This incremented length of stride is the result of training, and is facilitated by a decreased frequency of step and a consequent reduction in the rate of muscular contraction and expenditure of energy. Further, trained runners tend to display smaller vertical displacements with respect to the centre of mass of the body, another "style" variable which contributes to an improved locomotor efficiency (Bransford & Howley 1977).

The effects of training have also been examined with respect to cognitive perceptions of physical effort. There appears to be a general consensus that little difference in ratings of perceived exertion exists between trained and untrained subjects exercising at the same intensity (Mihevic 1981, Rejeski 1981, Fleishman et al. 1984). However, Carton and Rhodes (1985) postulate that post-training RPE scores tend to be lower at a given sub-maximal exercise intensity, but only in the trained limbs. In other words, training may elicit significant decreases in local (muscle and joint) ratings of physical effort.

Age is another factor which may contribute to an inter-individual variability with respect to human locomotor responses. It is fairly well documented that the relative expenditure of energy during locomotion tends to increment with increased age (Bobbert 1960, McDonald 1961, Cavanagh & Kram 1985a, Daniels 1985, McArdle et al. 1986). This age-induced increase in locomotor energy cost is likely the combined result of a reduced maximal oxygen uptake, a reduced maximum heart-rate, an impaired joint flexibility and an increased proportion of body fat (McArdle et al. 1986). It is further reported that cognitive ratings of perceived exertion are greater in older subjects for any given workload (Rejeski 1981, Carton & Rhodes 1985). Once again this is very likely facilitated by a decreased maximal oxygen uptake, a decreased maximum heart-rate and an impaired joint flexibility.

With respect to the kinematics and perception of effort during locomotion, it would appear that certain psychological characteristics have a considerable and measurable influence. The personality traits of the subject, for example, may significantly affect his perception of physical effort. Morgan (1973) and Rejeski (1981) suggest that extroverts tend to have higher thresholds of pain and consequently suppress their estimates of physical exertion for any given workload, while introverts, who have lower pain thresholds, tend to elevate such perceptions. Further, type-A personalities are likely to report lower ratings of exertion for a given task than are type-B personalities (Rejeski 1981, Carton & Rhodes 1985). Motivation, too, plays a major role in moulding the effort sense. Ratings of perceived exertion are generally higher following success than they are following failure, as athletes often describe exertion in terms of ability. This may be attributed to a protection of self-image - successful athletes tend to attribute their success to physiological effort, while athletes who fail are more inclined to attribute their failure to a lack of psychological resolve (Rejeski 1981).

Other subjective psychometric variables, such as anxiety, neuroticism and somatic perception, may similarly influence the the human response to any given motor task. For instance, it is well documented that depressed subjects tend to locomote (walk) with a "shuffling" gait which is characterised by a decreased length of stride, a decreased speed of movement and an exaggerated lifting-action of the limbs with minimal propulsive effort (Sloman et al. 1982). On the whole, however, the influence of psychological variables upon the response of the human organism to locomotor patterns of movement is relatively poorly understood (Morgan 1973).

ii) Intra-Individual Variation

It is widely accepted that a considerable variation in movement responses exists within any individual with respect to repeated exposure to a given motor task (Durnin & Namyslowski 1958). In other words, on a test-retest basis, any given individual is likely to respond in a manner which is not entirely consistent when exposed to any given workload. This is because the human system, not being a pre-programmed robot, is characterised by a range of "normal" responses which are governed by a unique but specific organism/environment interaction. As a result, a significant intra-individual variation prevails relative to the performance of any standardised workload - a variability which is the product of numerous interrelating factors.

Considerable empirical evidence alludes to the fact that lower animals and man exhibit physiological and psychological rhythms which possess a significant relationship with solar and/or lunar cycles of 12 or 24 hours

(Faria & Drummond 1982, Winget et al. 1985). As a consequence, diurnal variations may dramatically influence the response of the human organism to any given task. Arousal tends to be greatest in the late afternoon and lowest in the early hours of the morning (Winget et al. 1985). Optimal peaks in muscle temperature, pattern recognition, reaction time and the generation of muscular force tend to correspond with these peaks in subjective levels of arousal. Accordingly, both cardiorespiratory responses and ratings of perceived effort tend to be lower (optimal) in the late hours of the afternoon (Faria & Drummond 1982, Goslin 1987). Diurnal variations appear not to affect significantly the efficiency of muscular contraction or the expenditure of energy associated with any given motor task (Durnin & Namyslowski 1958). In fact, diurnal variation has been shown to account for less than 3% of the variability in oxygen uptake at any prescribed locomotor intensity (Erickson et al. 1946). Further, Armstrong et al. (1983) propose that day-to-day variations in submaximal oxygen consumption and inspired ventilatory volume are less than 3.8% and 4.8% respectively during running. It is interesting to note that diurnal variations in ratings of perceived exertion do not correlate significantly with similar variations in exercise heart-rate, suggesting that the daily fluctuations in the estimation of physical effort are the product of factors other than physiological stress (Faria & Drummond 1982).

Grainger et al (1983) and Murray et al. (1985) report that kinematic variables such as cadence and stride length show very little day-to-day or stride-to-stride variability. The mean absolute deviation in selected kinematic measures of the human gait was shown by Bates et al. (1979) to be less than 5% for three consecutive stride cycles during running at $4.5 m.s^{-1}$. Further, independent research by Bobbert (1960) and Yamasaki and Sasaki (1982) suggests that no significant variation in successive lengths of stride occurs during locomotion at any prescribed locomotor speed. It may be concluded therefore, that diurnal variations with respect to the temporal and spatial characteristics of the human gait are relatively inconsequential.

Sociocultural influence is another factor which may contribute quite considerably to the variability in human locomotor responses. Factors such as mood, peer-pressure and self-image tend to affect both kinematic and psychophysical responses to human movement quite significantly

(Rejeski 1981). Task aversion may also influence the response of the human system, specifically with respect to the psychological perception of physical effort (Pandolf 1982). Mood state, especially, may manipulate certain locomotor responses. The relationship between mood and body posture is well understood - in fact, the German word "haltung" is purposely used to describe the relationship between internal attitude and external carriage. Sloman et al. (1982) suggest that variations in mood significantly affect the kinematics of human gait, proposing that depressed subjects ambulate at slower speeds and with a decreased length of stride.

The dynamic action of food ingested prior to performance is another factor which may elicit a variability in responses with respect to the energetics of a given work task. McDonald (1961) purports that a carbohydrate intake immediately (2 hours) prior to exercise tends to increase the contractile efficiency of the locomotor musculature, while Consolazio et al. (1963) propose that a vitamin-rich diet renders the energetics of walking more cost-efficient. On the whole, it would appear that the dynamic action of a pre-exercise ingestion of food tends to influence the expenditure of energy during prolonged locomotion quite significantly - very possibly by as much as 400 calories per minute (McDonald 1961). With respect to the perception of exertion during physical activity, the dynamic action of food has been relatively poorly investigated. However, it is suggested that the ingestion of glucose (pre-exercise) tends to elicit a decrease in the estimation of effort during prolonged activity. This is possibly the result of a sensory input from glucose receptors in the body, along with the fact that long-term muscular fatigue is closely correlated with a hypoglycaemic condition (Carton & Rhodes 1985).

A further factor contributing to an intra-individual variability of responses characteristic of human locomotion concerns the type of clothing worn by the subject during exercise. Clearly, to run in heavy clothing such as a tracksuit would be more costly from an energy cost point of view than would running at the same speed in unrestrictive clothing such as a vest and shorts. Not only would the tracksuit hinder efficient movement and generate a warm and humid microclimate adjacent to the skin, but it would also represent an added mass which the athlete would have to lift at each step (Stevens 1983). Similarly, the type of shoe worn during locomotion may considerably influence the energetics and kinematics of the locomotor gait (Ogasawara 1934, Bobbert 1960, Shields 1982, Cavanagh & Kram 1985b, Noakes 1986). Research undertaken by Costill and Fox (1969) reveals that the addition of a 1kg mass to a man's footwear produces a similar increment in locomotor energy expenditure as does the addition of a 4kg mass to a load carried on the back. Moreover, an increase of 175g to the mass of a running shoe is sufficient to increment the energy expended during locomotion by as much as 33% (Berg & Sady 1985).

Also pertinent to the effects of variation in footwear on locomotor performance is the use of specially designed air-sole training shoes. Goslin (1987) reports that the use of such shoes can reduce the oxygen cost of running at $4.5m.s^{-1}$ by as much as 2.8%. This is because when locomoting barefoot or in hard-soled shoes, a greater muscular effort is required to provide a cushioning of the forces generated upon impact of the foot with the locomotor surface. This excess muscular exertion may be eliminated by wearing specially designed shoes which effectively absorb the energy generated via successive foot-floor contacts (Clarke et al. 1982, Cavanagh & Kram 1985b).

The environment imposes an obvious stress with respect to human movement. Any inconsistency with respect to the environment in which one exercises is, therefore, very likely to elicit a significant intra-individual variation in movement responses. The energy expenditure for any prescribed task tends to fluctuate quite considerably according to changes in the ambient temperature, pressure and humidity. Generally speaking, as ambient temperature and humidity increase (and barometric pressure decreases), a given workload is accomplished via a greater expenditure of energy. Similarly, exercise in very cold conditions tends to increment the expenditure of energy for a given task, as heat must be generated via a "shivering thermogenesis" to maintain organism homeostasis (Daniels 1985, McArdle et al. 1986, Noakes 1986). However, in a study conducted by Kamon and Belding (1971), it was reported that variations in the ambient temperature did not significantly affect the metabolic cost of walking either with or without loads, although locomotor heart-rate did fluctuate significantly relative to the different thermal conditions. Ratings of perceived exertion, too, appear to be environment dependent. Both increased temperature and increased altitude (decreased barometric pressure) have been shown to elicit proportional and significant increments in the psychological estimation of physical effort (Noble et al. 1973a, Carton & Rhodes 1985).

The effects of air resistance with respect to physiological, biomechanical and psychological locomotor responses can be quite substantial, depending upon the rate of progression. The air resistance opposing the forward momentum of the body tends to increase as the square of locomotor speed (Van Ingen Schenau 1980, McArdle et al. 1986, Noakes 1986). During running, the energy required to overcome air resistance may constitute as much as 5% to 8% of the total energy expended (Davies & Thompson 1979, Daniels 1985, Mahler & Loke 1985). Heglund et al. (1982), however, propose that overcoming air resistance accounts for less than 2% of the total energy expended during locomotion at a speed of $2.8 m.s^{-1}$, and up to 8% at a speed of $8.3 m.s^{-1}$. It would appear, therefore, that the effects of air resistance are insignificant for all walking speeds, and for any running speeds below about $3.0 m.s^{-1}$ (Margaria 1976). The reasons for the increased expenditure of energy associated with running against any substantial air resistance appear to be the combined result of: i) leaning forward into the wind, and ii) a shortened length of stride. Thus, not only has the athlete to overcome a greater relative force opposing his forward motion, but he is also forced to deviate substantially from the optimal combination of stride length and stride frequency - both of which necessitate an increased input of metabolic energy (Noakes 1986).

Another source of intra-individual variation imposed by the environment concerns the nature of the locomotor surface. Firstly, it is well established that the terrain over which one locomotes affects both physiological and kinematic locomotor responses quite considerably. Subjects tend to prefer slower rates of progression and shorter lengths of stride when locomoting over a pebbled terrain or through long grass, sand, water and snow etc. (Soule & Goldman 1972, Charteris et al. 1982, Wygand et al. 1985). Furthermore, locomotion at any given speed over such surfaces is more costly in terms of the energy expended. In fact, McArdle et al. (1986) suggest that progression through loose sand may be twice as costly as progression at the same speed on a hard surface. The increased expenditure of energy associated with locomotion over a "loose" terrain is the result of a decreased friction between the foot and the locomotor surface. Such a decrease in surface friction tends to elicit a shorter length of stride, and generates a greater consumption of oxygen as more energy is wasted in lifting the body and less energy is available to move the body forwards.

A second point regarding the locomotor surface concerns the controversy surrounding the use of the motor-driven treadmill as a simulator for overground walking and running. The advantages of the treadmill for use in studies of human locomotion are obvious. Firstly, the treadmill provides a convenient means of capturing physiological, biomechanical and psychological data from a locomoting subject without the necessity of having to physically follow the subject with the often cumbersome recording equipment. Secondly, workloads with respect to both locomotor speed and gradient can be accurately prescribed and reliably replicated. However, much research has concerned itself with the question as to whether or not human responses to treadmill locomotion can be validly extrapolated with respect to overground walking and running.

The novice treadmill user experiences three basic phases of adjustment (Charteris & Taves 1978, Schieb 1986):

i) an awkward first few steps during initial exposure,

ii) a gradual process of accomodation, and

iii) an eventual, long-term locomotor habituation.

First-time locomotion on the motor-driven treadmill is largely characterised by a faltering, balance-regaining action which persists for up to one minute. This "tripping" gait is the result of an attempt by the subject to generate as much contact as possible with the surface of the treadmill in order to maximise the support phase and consequently optimise the balance prerequisites of the locomotor action. Following this initial adjustment, a period of accomodation continues during which time the subject makes several kinematic modifications until a stable and consistent gait pattern with minimal stride-to-stride variability is achieved (Schieb 1986). This accomodation phase is facilitated by an improved confidence in the subject, yet is nonetheless characterised by an atypical locomotor gait in which both a shortened length of stride and an increased frequency of step contribute to greater support times and an improved stability (Nelson et al. 1972, Dal Monte et al. 1974, Elliot & Blanksby 1976, Wall & Charteris 1980, Murray et al. 1985, Schieb 1986). During both the initial adjustment and the accomodation phase, the treadmill locomotion is associated with an incremented expenditure of energy as the result of deviations from the optimal length of stride coincident with excessive vertical displacements of the body's centre of mass. The increased expenditure of energy during early treadmill adjustment may be as much as 10% over and above that energy required during overground locomotion at the same speed (McDonald 1961).

The accomodation process continues until such time as the subject is fully habituated and has had sufficient practice so as to eliminate any significant within-day or between-day kinematic differences as evidenced from stride to stride. The time required for this long-term habituation to treadmill locomotion is dependent upon a number of factors, but Wall and Charteris (1980, 1981) recommend a period of discontinuous practice totalling no less than 60 minutes. Furthermore, a warm-up session of 1-2 minutes is advised prior to the capture of energetic and/or kinematic data, even when the subject is fully habituated (Wall & Charteris 1981, Schieb 1986).

To conclude, it would appear that following a suitable habituation programme, no significant differences exist in locomotor responses between overground and treadmill locomotion. Any differences which do manifest themselves are purely a function of air resistance, which is obviously zero when locomoting indoors on a treadmill. However, as discussed earlier, the effects of air resistance tend to be negligible for locomotor speeds below about $3.0 m.s^{-1}$ (Margaria 1976, Heglund et al. 1982). For all intents and purposes, therefore, habituation to treadmill locomotion would appear to produce a constancy of gait which is not significantly different from that of overground locomotion (Erickson et al. 1946, Nelson et al. 1972, Van Ingen Schenau 1980, Wall & Charteris 1980, 1981, Bassett et al. 1985, Murray et al. 1985, Schieb 1986).

HUMAN MORPHOLOGY AND THE RELATIVISATION OF LOCOMOTOR SPEED

Any investigation of human movement must consider as a focus of attention the relationship that exists between the structure of the organism and the functions it displays (Oxnard 1979). The physical size and shape of any animal in some way predetermine a particular repertoire of movement patterns, and a thorough understanding of the interaction that prevails between morphology and behaviour is consequently of paramount importance in the study of mammalian locomotion (Preuschoft 1979). The human system is basically a coordinated, adapted and integrated ensemble of structures and functions (Jouffroy & Lessertisseur 1979), and a careful examination of the manner in which both form and behaviour interact is prerequisite to any attempt to analyse the movement patterns which characterise motile man.

Locomotion is a movement pattern typical of all mammals, and is a topic which has engendered much research over the years. In all mammals the act of locomotion is both mediated and limited by the structural and functional characteristics of the locomotor apparatus (Preuschoft 1979). The function of the locomotor system is, after all, to realise the performance of controlled motion. Frequently occuring movements such as running and jumping are typical of the locomotor gaits of most animals, but the range of potential behaviour patterns in any species is largely governed by the environment within which the animal moves - for example, tree-climbing is only possible if there are trees in the habitat of the animal (Gomberg et al. 1979). Further, the frequently occuring behaviour patterns of a given animal are facilitated by specifically adapted morphological traits in those parts of the body that are relied upon to perform the movements. For instance, jumping is accomplished primarily by the hindlimbs in mammals, and the best jumpers are consequently characterised by long and powerful back legs (Preuschoft 1979).

In man, one such frequently occuring behaviour pattern is orthograde bipedal locomotion. This motor pattern is recognised as one of the most important movement characteristics of the species hominidae. Accordingly, the structure and function of many human features are specialised and have likely adapted to facilitate the upright gait (Kimura et al. 1979). It follows therefore, that differences in body shape and size may exert a significant influence upon the determination of human gait patterns (Charteris et al. 1982). Consequently, a thorough understanding of human locomotion must necessarily include an examination of those differences in morphology which may partially account for variations inherent in the movement patterns typical of the human organism.

Stature is a morphological feature which lends itself most appropriately to an analysis of inter-individual variability with respect to the energetics and kinematics of human locomotion. Although certain investigators have proposed that stature is a poor predictor of locomotor energy cost (Wyndham et al. 1971, Van der Walt & Wyndham 1973, Coté et al. 1987), there is considerable evidence to suggest that the same raw locomotor speed taxes short and tall subjects differently - shorter subjects tending to expend more energy per kilogram body mass per unit speed for a given locomotor mode than their taller counterparts (Miller & Blyth 1955, Brockett et al. 1956, Grieve & Gear 1966, Charteris 1982, Charteris et al. 1982, Williams 1987). Considering the high correlation ($r = 0.965$) reported to exist between stature and lower-limb length (Van der Walt & Wyndham 1973), it might be argued that the energetics of locomotion are influenced by variations in the length of the locomotor appendages in the same way that they are influenced by variatons in stature. Accordingly, subjects with longer legs (a greater lower-limb length) would appear to be at an energetic advantage when locomotiong at any prescribed speed.

It is argued by Dean (1965) and Charteris et al. (1982) that for preferred locomotor speeds, stride length is a constant function of stature for all subjects irrespective of variations in size. In other words, at preferred rates of walking and running, the expression of stride length relative to stature (L/St) tends to be constant and independent of morphological variability. It follows, as a result of the speed-specific reciprocal relationship between step length and frequency, that progression at any freely chosen speed will be characterised by a cadence which is a constant but inverse function of subject stature. The lower oxygen uptake associated with the locomotion of subjects of a greater stature (or lower-limb length) can, therefore, be attributed to the related pattern or combination of step length and frequency. Since animals with longer legs tend to move with greater lengths of step and lower cadence (Murray et al. 1964, Murray 1967, Rosenrot et al. 1980), it may be inferred that at any prescribed locomotor speed, larger animals (taller subjects) take fewer steps per unit distance by virtue of a greater length of stride, and as a consequence tend to expend energy at lower rates. This has in fact been evidenced in research undertaken by Workman (1963) and Shields (1982), who report a reciprocal relationship between stature and cadence at any preferred locomotor speed. Recent research has tied this variation in locomotor cadence to the energetics of movement, contending that small animals expend more energy per kilogram of body mass per unit speed as the result of a greater number of steps required per unit distance (Taylor et al. 1982).

One means of factoring out the differences in locomotor energetics due to morphological variation is via the use of relative speed equations. Relative speed can be defined as that expression of walking or running speed in which the rate of progression is proportional to some given morphological dimension. The first attempt to relativise locomotor speed on a morphological basis was made by Grieve and Gear (1966), who suggested that the speed of progression be expressed in statures per second (U/St). A subject locomoting at a speed of one stature per second would, in effect, be moving at a rate proportional to his own stature (ie. a person 1.80 meters in height would progress at $1.80 m.s^{-1}$). This method of relativising speed effectively "normalises" human locomotion via the elimination of that variability in energy cost imposed by subject stature. The relativisation of speed using lower-limb length has also been proposed as an effective means of normalising human locomotion (Rosenrot et al. 1980, Alexander 1984, Candler 1986). A subject progressing at one lower-limb length per second (U/LLL) would, in effect, be moving at a speed proportional to some linear measure of his own lower limb.

With respect to the significant speed-specific relationship which is reported to exist between oxygen consumption and cadence for both walking and running gaits (Taylor et al. 1982), many researchers have attempted to relativise locomotor speed on the basis of the number of steps required to cover a given distance. Heglund et al. (1982) suggest that the energy expended per gram of body mass per step at any given running speed is approximately the same for all animals irrespective of differences in size. Hence, for any prescribed locomotor speed, the relative oxygen cost realised per step is constant and independent of the absolute size of the moving animal. Thus, both short and tall subjects tend to consume equal amounts of oxygen for every step they take during running, and the taller subjects tend to be advantaged at any given running speed by virtue of a greater length and lower frequency of step.

Another method of normalising the speed of progression relative to some morphological characteristic of a moving organism was introduced by Alexander (1976). This relative speed expression is based upon the principle of physical similarity, an inference of which is that two moving objects are kinematically similar only when their speeds of progression are relative to their linear dimensions. Since the relationships applying to physical systems of different size are best expressed in dimensionless terms (Duncan 1953), an investigation of the movement patterns of similarly shaped animals differing in size necessitates the use of a non-dimensional parameter to serve as the criterion for physical comparability (Alexander 1976). One such dimensionless parameter is the Froude number ($U^2/g.l$), which is used by nautical engineers to analyse the movement characteristics of vessels which are influenced by the combined effects of inertia and gravity. This Froude number (where "U^2" represents the acceleration of the system, "g" is a gravitational constant, and "l" a characteristic length) describes the movement in terms which express the rate of progression relative to the linear dimensions of the vessel.

Since an interaction of inertia and gravity is an integral feature of human locomotion (Wells 1971, Hay 1978, Cooper et al. 1982), a derivation of the original Froude number would possibly be useful to investigators of human movement who wish to compare the locomotor energetics and kinematics of differently sized subjects. With this in mind, Alexander (1976) has modified the (nautical) Froude number such that the rate of horizontal progression (U) represents the characteristic speed of the organism, while stature and lower-limb length represent two of several possible choices for the characteristic length (h). Accordingly, the dimensionless $U/\sqrt{g.h}$ is preferred to the original Froude number as an appropriate parameter for studies of locomotion (the quantity $U/\sqrt{g.h}$ being the square root of the original Froude number).

This method of relativising locomotor speed dictates that the rate of progression of a moving animal be proportional to any one of several morphological features (eg. stature, lower-limb length, foot length etc.). Recent research (Alexander 1984, Candler 1986, Williams 1987) suggests that the locomotor Froude quantity $(U/\sqrt{g.h})$ may be an effective means of minimising morphologically imposed variability with respect to the energetics of bipedal walking and running. Further, this method is a useful tool for the normalisation of human locomotion in that progression relative to the Froude number elicits a length of stride which is proportional to the linear dimensions of the locomoting subject. Hence, the between-subject variability in locomotor energy cost as the result of differences in the length of stride (and therefore cadence) is effectively eliminated via the use of this Froude expression of locomotor speed (Alexander 1976).

It is widely accepted that body mass is the single most important determinant of locomotor energy cost, and that there exists a linear relationship between the mass of an animal and the energy it requires to move at a given rate (Miller & Blyth 1955, Ralston 1958, Bobbert 1960, Cotes & Meade 1960, Grimby & Soderholm 1962, Wyndham et al. 1971, Van der Walt & Wyndham 1973, Mayhew et al. 1979). Correlation coefficients of between 0.76 and 0.99 have been reported between oxygen consumption and the speed of walking and running (Wyndham et al. 1971, Van der Walt & Wyndham 1973) - further corroboration of the significant influence of body mass upon the energetics of movement. Thus, at any given locomotor speed, heavier (more massive) animals consume oxygen at higher rates than do their smaller counterparts. An effective means of reducing this mass-specific variability in locomotor oxygen cost is to express the expenditure of energy in units relative to body mass $(ml.kg^{-1}.min^{-1})$. This relativisation of locomotor oxygen consumption effectively reduces the inter-individual variability in energy expenditure reported at any given exercise intensity (Durnin 1958, Rasch & Pierson 1962, Wyndham & Heyns 1969, Margaria 1976, Mayhew et al. 1979, McArdle et al. 1986).

However, it is has been suggested that even when energy expenditure is expressed relative to body mass, small animals tend to consume more oxygen (per unit mass) when performing any prescribed movement task. Even at rest the the relative metabolic rate of small animals tends to be greater than it does for larger animals of similar shape (Taylor et al. 1970). In other words, smaller animals expend more energy per unit body mass for a given workload than do larger animals (Taylor et al. 1972, Fleagle 1979). For example, a 10kg monkey expends less energy per unit body mass in running a given distance than does a 5kg monkey. This difference is likely related to the absolute size of the organism. The smaller animal tends to be energetically disadvantaged by virtue of it's shorter legs and higher speed-specific cadence, while the larger animal is less taxed at the same speed since it can adopt a lower cadence due to a greater length of stride. Since the expenditure of energy is a direct function of the number of steps taken per unit distance, it is clear that the lower cadence associated with larger animals renders their movement more cost-efficient (relative to that of the smaller animal).

Body surface area (BSA) is another morphological feature which has been investigated with respect to the energetics of human locomotion. In fact, resting metabolic rate (BMR) is suggested as being directly proportional to body surface area in mammals (Taylor et al. 1970). However, in consideration of the high correlation ($r = 0.88-0.96$) reported to exist between body surface area and mass (Durnin 1958), it appears that body surface area is no more useful a predictor of energy expenditure than is body mass alone (Rasch & Pierson 1962, Martin et al. 1984). Other indices such as lean body mass (LBM) have been suggested as more appropriate references for the expenditure of energy during mammalian movement. Since fat is an inert non-contractile component of the body, it adds significant mass to an animal without at the same time contributing to the generation of energy (Miller & Blyth 1955). Consequently, obese subjects expend more energy per unit mass for a given task than do lean subjects of the same overall body mass. It remains arguable, therefore, as to whether variations in lean body mass significantly influence the energetics of locomotion during progression at any given speed (Martin et al. 1984).

It is fairly clear from the observations outlined in this section that the relativisation of locomotor speed to some morphological characteristic should be an effective means of minimising the inter-individual variability which exists with respect to the energetics and kinematics of human locomotion. Although considerable research has been geared towards an examination of the effects of certain morphological features (such as stature, lower-limb length and body mass) upon the expenditure of energy during walking and running, very little investigation has concerned itself with the effects of morphology in general upon locomotor energetics and kinematics. It remains arguable, therefore, as to whether such features as bi-acromial diameter, bi-iliac diameter, and androgyny index significantly influence the energetics and kinematics of the locomoting organism.

CHAPTER THREE

EXPERIMENTAL METHODS AND PROCEDURES

INTRODUCTION

Twenty male caucasian students volunteered to participate in this study. Subjects were recruited on the basis of stature, with ten subjects categorised as "short" (<170cm) and ten subjects categorised as "tall" (>185cm). Each subject was required to complete and informed consent form prior to participation in this study (see Appendix 1).

Personal data, in the form of anthropometrical measures, were recorded prior to the actual testing. From this information, derived data pertaining to locomotor speeds expressed relative to a number of morphological characteristics (relative speeds) were predicted. Further, a rigorous treadmill habituation programme was included in order to familiarise the subjects with both walking and running on the motor-driven treadmill used in this study. Each subject was thereafter required to report to the laboratory for testing purposes. The research protocol, therefore, can be divided into three sections:

i) a series of anthropometric measurements,

ii) a dicontinuous 60-minute habituation programme, and

iii) a battery of six five-minute walking and running treatments on the motor-driven treadmill during which energetic, kinematic and psychophysical locomotor data were captured.

A steady-state measure of oxygen consumption ($\dot{V}O2$) was considered a valid indication of the metabolic demands of the work-tasks performed, as all locomotor speeds were set below the aerobic limits of walking ($2.5m.s^{-1}$) and running ($5.6m.s^{-1}$) as proposed in the literature (Menier & Pugh 1968, Cavagna & Kaneko 1977, Mayhew et al. 1979). Other physiological measures included carbon-dioxide production ($\dot{V}CO2$), inspired ventilatory volume ($\dot{V}I$), breathing frequency ($\dot{V}f$), tidal volume (Vt) and respiratory exchange ratio (R-value), though these data were not extrapolated with respect to the relative speed treatments. The kinematic data included measures of cadence, stride length, cycle time, support time, swing time and the support/swing ratio. A record of central and local subjective ratings of perceived exertion (RPE) constituted the psychophysical responses to the locomotor treatments.

ENVIRONMENTAL VARIATION

All testing was conducted on the motor-driven treadmill in the Work Physiology Laboratory of the Department of Human Movement Studies at Rhodes University, wherein ambient conditions tend to remain relatively stable with time. Data collection was completed over a period of about four months (May - August). It was considered unnecessary to standardise the time of day at which to test, as diurnal variations with respect to energy expenditure and locomotor kinematics have been found to be relatively insignificant (Durnin & Namyslowski 1958, Armstrong et al. 1983, Grainger et al. 1983, Kram et al. 1985, Winget et al. 1985). The mean environmental conditions to which the two subject groups were exposed during the testing protocol are reflected in Table II.

INTER-INDIVIDUAL VARIATION

Young male subjects (n = 20) were selected for participation in this study from the student population at Rhodes University. In order that as large as possible a range in morphological characteristics was attained, these subjects were selected on the basis of stature, with ten subjects in each of a "short" group (<170cm) and a "tall" group (>185cm). The mean physical characteristics of the two stature-specific groups as recorded prior to completion of the locomotor treatments are reflected in Table III. Suitability for selection was further based upon willingness

TABLE II: the mean environmental conditions to which the two stature groups were exposed during testing.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
DRY BULB TEMPERATURE (°C)	18.91	1.959	18.25	1.749
WET BULB TEMPERATURE (°C)	15.83	1.259	15.27	1.889
BAROMETRIC PRESSURE (mmHg)	715.96	3.851	717.73	3.856
RELATIVE HUMIDITY (%)	72.72	11.935	71.98	11.363

to participate for the duration of the testing, evidence of generally sound health, and absence of illness or injury which could adversely affect the locomotor responses to treadmill walking and running.

INTRA-INDIVIDUAL VARIATION

Each subject was requested to report to the laboratory for testing suitably attired for unhindered locomotion on the treadmill (ie. in shorts and running vest/tee-shirt). All testing necessitated barefoot locomotion, and consequently variation with respect to the choice of running shoe (Clarke et al. 1982, Nigg et al. 1983, Frederick 1985, Noakes 1986) was not a factor impinging upon the results of the study. Further, subjects were requested to refrain from vigorous exercise and excessive eating 2-3 hours before testing.

TABLE III: the mean physical characteristics as recorded for the two stature groups prior to testing.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
* AGE (yrs)	20.24	3.251	21.65	1.955
* RESTING HEART-RATE (b/min)	64.11	8.171	66.10	12.922
STATURE (cm)	165.43	4.599	190.21	3.627
BODY MASS (kg)	59.63	4.719	77.63	8.367
LEG LENGTH (cm)	44.91	2.633	52.99	2.450
LOWER-LIMB LENGTH (cm)	85.10	3.258	101.07	3.273
BI-ACROMIAL DIAMETER (cm)	36.55	1.535	41.19	1.781
BI-ILIAC DIAMETER (cm)	26.44	1.649	28.61	1.228
ANDROGYNY INDEX (%)	83.00	4.557	91.89	4.638
BODY SURFACE AREA (m^2)	1.66	0.079	2.05	0.109
* RECIPROCAL OF PONDERAL INDEX ($cm/\sqrt[3]{kg}$)	42.41	1.070	44.73	1.509

* No significant difference (P <0.05) between the two stature categories

INFORMED CONSENT

Before any candidate was permitted to participate as a subject in this study he was requested to review a detailed informed consent information sheet and to sign an appropriate subject consent form (see Appendix 1). The information sheet was employed to familiarise the subjects with the proposed research protocol and to outline the risks inherent in any study of this nature. The consent form was subsequently signed by the subject and countersigned by the researcher, the project supervisor and a witness. Participation as a subject was entirely voluntary and subjects were at liberty to withdraw at any time and for any reason.

TREADMILL HABITUATION

It is well documented that subjects who are naive to treadmill locomotion should undergo a period of habituation prior to the collection of locomotor data (Wall & Charteris 1980, 1981, Schieb 1986). A Quinton "643" motor-driven treadmill (24-72) was used for all testing purposes, and all subjects were required to accomodate to both walking and running on the treadmill at various speeds.

Habituation should involve distributed practice for periods totalling not less than 60 minutes when kinematic parameters are of import to the research (Wall & Charteris 1981). A discontinuous habituation programme was consequently conducted for each subject prior to data capture. The habituation involved six 10-minute practice sessions in the following sequence:

i) walking at $0.83m.s^{-1}$ ($3km.hr^{-1}$) - 10 minutes
ii) running at $2.50m.s^{-1}$ ($9km.hr^{-1}$) - 10 minutes
iii) walking at $1.39m.s^{-1}$ ($5km.hr^{-1}$) - 10 minutes
iv) running at $3.06m.s^{-1}$ ($11km.hr^{-1}$) - 10 minutes
v) walking at $1.94m.s^{-1}$ ($7km.hr^{-1}$) - 10 minutes
vi) running at $3.61m.s^{-1}$ ($13km.hr^{-1}$) - 10 minutes

TOTAL TIME = 60 minutes

This method of habituation was discontinuous in that the six 10-minute speed sessions were completed on two consecutive days - three conditions on each day. Further, the subjects were required to rest between each of the 10-minute sessions, during which time the prescribed treadmill speed was pre-set for the next bout.

In addition to mastering locomotion on the treadmill, subjects had also to adapt to the mouthpiece of the gas analysis system and to the footswitch insoles of the telemetric gait analysis system. Hence, subject habituation included respiration via a two-way pulmonary valve for the final five minutes of each of the 10-minute locomotor sessions. In order to adapt the subjects to the resistance associated with breathing through the entire apparatus, the gas analysis system was operative throughout the duration of the habituation programme. Further, the habituation required subjects to walk and run wearing specially designed and appropriately sized footpads attached carefully to the feet, and secured by means of suitably prepared elastic socks. These footpads were worn for the entire duration of the latter two 10-minute habituation sessions.

PILOT TESTING

In order to establish the reliability of data-capture, and also to ensure procedural consistency, a pre-test pilot study was undertaken. A test-retest design was employed in which the testing protocol remained the same for two successive testing conditions, but all speed treatments were randomly assigned in order to eliminate any sequential bias that may otherwise have resulted.

Three volunteer subjects were used for the pilot study, and each was required to report to the laboratory for testing on each of two successive days. The pilot study itself was divided into two separate sections: an anthropometric component and a locomotor component. Each subject had been previously habituated to treadmill locomotion, and was required to sign an appropriate informed consent form prior to any participation.

The following anthropometric measures were recorded using a methodology proposed by Tanner (1951) and Montagu (1960): stature, body-mass, leg length, lower-limb length, bi-acromial diameter and bi-iliac diameter. Each measure was taken twice, with a third measure recorded if the initial readings differed by more than the accepted tolerance limit (Tanner 1951). If repeated measures fell within this tolerance limit, the first measure was recorded. If a third measure was required, then the mean of the two closest measures was recorded. This procedure was followed on each of the two successive days (ie. for both the test and the retest protocols). The reliability of these test-retest data was established via the application of one-factor analyses of variance (ANOVAs) with repeated measures at the 0.05 level of probability, as well as via the use of coefficients of variation (C.V.s) (Ferguson 1981).

For the second (locomotor) component of the pilot study, the three volunteer subjects each completed three walking treatments (0.83, 1.39 and $1.94 m.s^{-1}$) and three running treatments (2.50, 3.06 and $3.61 m.s^{-1}$) on a motor-driven treadmill on each of two successive (test-retest) days. Each treatment required of the subjects five minutes of horizontal locomotion, with data-capture during the final 60 seconds of each bout. Expired gas samples and patterns of foot-floor contact were collected for later analysis, as were measures of resting and locomotor heart-rate. Finally, both central (cardiorespiratory) and local (muscular/joint) ratings of perceived exertion were recorded for each of the speed treatments.

Two-factor analyses of variance (ANOVAs) with repeated measures on both factors (Ferguson 1981) were performed on the two sets of data (test and retest) in order to establish whether or not significant differences existed between:

i) the test and retest measures of locomotor energetics ($\dot{V}O2$, HR, R-value and $\dot{V}I$) at any given speed,

ii) the test and retest measures of locomotor kinematics (stride length, cadence, cycle time and the support/swing ratio) at any given speed, and

iii) the test and retest measures of locomotor RPE (local and central) at any given speed.

The test-retest protocol allowed for the demonstration of research reliability, whilst simultaneously providing for the development of procedural consistency. Any test-related problems were thus surmounted prior to the actual collection of research data.

THE ABSOLUTE SPEED TREATMENTS

The research protocol involved completion by the subjects of a battery of six locomotor treatments (three walking and three running) on a motor-driven treadmill. Each of these speed treatments was completed for a duration of five minutes, during which time the prescribed locomotor data were captured. The absolute speed treatments (both walking and running) as selected for this study are tabulated below (in $m.s^{-1}$):

WALK	**RUN**
0.83	2.50
1.39	3.06
1.94	3.61

These absolute speeds were arbitrarily selected such that a range of **aerobic** locomotor rates of progression was encompassed from slow through to fast (for both walking and running). Contemporary research defines the aerobic cut-off speeds for walking and running as 2.50 and $5.55m.s^{-1}$ (9 and 20 $km.hr^{-1}$) respectively (Menier & Pugh 1968, Cavagna & Kaneko 1977). It is clear from the above table that the locomotor speeds selected for the purposes of this study fall well within these documented "limits", and can consequently be described as **aerobic** in nature. Further, the six locomotor treatments were selected such that equal increments existed between consecutive speed treatments (ie. consistent increments of $0.555m.s^{-1}$ between successive treatments). This procedure ensured that a large range of aerobic locomotor speeds was encompassed, and that the consecutive speed increments were of sufficient magnitude so as to represent measurable increases in exercise intensity.

The locomotor speeds were accurately set for testing purposes by means of a modified voltmeter wired directly to the drive-motor of the treadmill. In this way, each speed of the treadmill belt was presented visually in a digital form as a voltage reading on the display screen of the voltmeter. By incrementing or decrementing the electrical current supplied to the drive-motor, the speed of the treadmill belt was easily and accurately regulated. The treadmill speed was marginally reduced by the added mass of the subject on the belt, and to compensate for this discrepancy, the voltmeter was pre-set at a reading slightly greater than that prescribed by appropriate treadmill speed/voltage conversion tables. As a final precaution, the treadmill speeds were displayed continuously via the display monitor of a South-West Texas "6800" microcomputer. The procedure thus undertaken for the setting of the treadmill speed allowed for the realisation of pre-determined rates of progression accurate to the nearest $0.00278 m.s^{-1}$.

CHOICE OF RELATIVE SPEEDS

Having measured the locomotor responses to absolute rates of progression ($m.s^{-1}$), extrapolations were made to evaluate the energetic and kinematic responses to locomotor speeds expressed relative to a number of morphological characteristics. For each subject, one-independent regression analyses (Ferguson 1981) were performed between the locomotor mode (walking or running) and selected energetic and kinematic variables. Thus, for each subject at each mode of horizontal progression, appropriate regression formulae were derived to facilitate the prediction of energetic ($\dot{V}O2$) and kinematic (stride length and cadence) data from known absolute locomotor speeds. From these regression equations, the locomotor responses (both energetic and kinematic) to nine pre-determined speeds expressed in relative terms were extrapolated.

Relative speed is broadly defined as that speed expressed with respect to some linear measure of size, and as such is used to effectively "normalise" human locomotion (Grieve 1968). Traditionally, relative speed is most readily expressed as that fraction of stature (meters) covered overground during locomotion per second (U/St) (Grieve & Gear 1966). This expression of relative speed is based upon the premise that the same raw speed ($m.s^{-1}$) will tax short and tall subjects differently (Miller & Blyth 1955, Brockett et al. 1956, Grieve & Gear 1966, Charteris 1982, Charteris et al. 1982, Williams 1987). For this traditional use of relative speed, stature represents one of several possible choices for the linear measure with respect to which the locomotor rate may be expressed. Other morphological dimensions may just as easily, though possibly not as effectively, be incorporated in the expression of speed in relative terms. The linear morphological measures selected for the purposes of this study included stature, leg length, lower-limb length, bi-acromial diameter and bi-iliac diameter. From these absolute data derived measures were calculated - these included body surface area and androgyny index. Suitable relative speed expressions were subsequently designed via manipulation of these measures.

Alexander (1984) has suggested that the acceleration of free-fall (ie. gravity) has an important influence with respect to locomotion, and should consequently be incorporated in any expression of relative speed. One means of introducing gravitational acceleration into the expression of speed in relative terms is via the use of a Froude number, a method successfully used for the purposes of this research.

If meaningful comparisons are to be made between geometrically similar systems of different size, an apporopriate non-dimensional parameter is needed to serve as a criterion for physical comparability (Alexander 1976). One such dimensionless parameter is the Froude number, as used in the field of nautical engineering and which applies to any situation wherein both inertia and gravity interact. The Froude number is expressed:

$$\mathbf{U^2/g.l}$$

where "**U**" is the speed of the system ($m.s^{-1}$), "**g**" is the acceleration of free-fall ($9.81m.s^{-2}$), and "l" is a characteristic length (m) - in nautical engineering the hull length.

During terrestrial locomotion the interaction of inertia and gravity is of paramount importance. With this in mind, the Froude number has been modified (Alexander 1976) for use by locomotion specialists, such that the characteristic length (l) becomes a measure of the height of an animal's hip from the ground (h). The Froude number thus becomes:

$$U^2/g.h$$

The theory of physical similarity proposes that the movements of animals of a geometrically similar form but different size will only be comparable if the animals move at the same Froude number $U^2/g.h$; that is, when the squares of their speeds are proportional to their linear dimensions (Alexander 1976). In studies of human locomotion, the rate of horizontal progression ($m.s^{-1}$) is the most obvious choice for the characteristic speed (U), and stature and lower-limb length are two of several possible choices for the characteristic length (h). Hence, because relationships applying to physical systems of different sizes are best described in dimensionless terms (Duncan 1953), the following dimensionless expression is preferred to the traditional Froude number as an appropriate parameter for studies of human locomotion (the quantity being the square root of the original nautical Froude number):

$$U/\sqrt{g.h}$$

Considering the obvious influence of inertia and gravity on human locomotion (Hay 1978), it was decided for the purposes of this study to include expressions of relative speed based upon the dimensionless approach formulated by Alexander (1976, 1984). Using both stature and lower-limb length as the characteristic length measures, relative speed can be expressed:

$$RS1 = U/\sqrt{g.h}$$

where "**U**" represents any given absolute speed ($m.s^{-1}$), "**g**" is the acceleration of free-fall ($9.81 m.s^{-2}$), and "**h**" the stature or lower-limb length (m) of the subject.

Morphological features other than stature and lower-limb length may have some significant influence upon the energetics and/or kinematics of locomotion. It is clearly documented that marathon runners tend to be slight of build, whereas sprinters tend to be more massive (Tanner 1964, Hay 1978). This is because distance runners sacrifice powerful musculature in the interests of rendering their locomotion over long distances more cost-efficient, while sprinters tend towards the development of a more massive morphology at the expense of a long-term efficiency of movement. The physiological advantages realised by distance runners of a lower body mass are thoroughly researched (Erickson *et al* 1946, Bobbert 1960, Wyndham *et al* 1971, Van der Walt & Wyndham 1973), and are the result of the significant correlation which exists between energy expenditure and body mass at any given rate of horizontal progression (Durnin & Namyslowski 1958, Wyndham & Heyns 1969, Wyndham *et al* 1971). Thus, the size discrepancy between the distance runner and the sprinter appears to be energetically founded, but it may have considerable influence upon the kinematic responses to horizontal locomotion too.

Variations in energy expenditure due to differences in body mass may be effectively eliminated if the energy cost of a given task is expressed relative to that mass (ie. in $ml.kg^{-1}.min^{-1}$) (Astrand & Rodahl 1977, Mayhew 1977, McArdle *et al*. 1986). However, despite this relative expression of energy expenditure, it remains arguable as to whether a less massive runner is both energetically and kinematically (not to mention psychologically) advantaged with respect to aerobic locomotion. An effective measure of body size which incorporates the interaction of both stature and mass is the body surface area (BSA). Body surface area is most accurately determined via the invasive method of skin dissection, but a mathematical formula proposed by DuBois and DuBois in 1916 has recently been validated as an accurate estimation or prediction of surface area (Martin *et al*. 1984). This formula, as used for the purpose of predicting body surface area in this study, is represented as follows:

$$BSA = 71.84 * (BM^{0.425} * St^{0.725})$$

where "BSA" is the predicted body surface area (m^2), "BM" the body mass (kg), and "St" the stature of the subject (m).

The body surface area thus predicted was incorporated into an expression of relative speed in conjunction with the dimensionless approach proposed by Alexander. In this case, the Froude speed was determined with the characteristic length (h) manifesting itself as stature cubed divided by body surface area ($St^3.BSA^{-1}$). The following relative speed equation was thus derived:

$$RS9 = U/\sqrt{g.[St^3/BSA]}$$

where **"U"** represents any given absolute speed ($m.s^{-1}$), **"g"** the acceleration of free-fall ($9.81m.s^{-2}$), "St" the subject's stature (m), and **"BSA"** the subject's predicted body surface area (m^2).

A further morphological characteristic which may possibly exert some influence upon the energetics and kinematics of human locomotion is the androgyny index as proposed by Tanner (1951). The androgyny index is simply the relation of hip width to shoulder width, and thus serves as a good criterion by which to compare similarly shaped individuals of different size. Since a narrow hip width (bi-iliac diameter) has purported advantage with respect to the kinematics of locomotion (Tanner 1964, Hay 1978), it may be useful to standardise rates of progression relative to this measure. It is further suggested that quality distance runners tend to be slight of build with characteristically narrow shoulders (as compared to sprinters). Accordingly, the interaction of narrow hip (bi-iliac diameter) and narrow shoulder (bi-acromial diameter) may well contribute significantly to the optimisation of locomotor energetics and kinematics. With this in mind, a method of relativising speed of locomotion was formulated wherein the effects of both stature and androgyny index are significant.

The androgyny index (AI) is anthropometrically determined using the following formula as proposed by Tanner (1951):

$$AI = (3 * BA) - BI$$

where "AI" represents the androgyny index (%), "BA" the bi-acromial diameter (m) and "BI" the bi-iliac diameter (m). The relative speed equation derived via use of measures of stature and androgyny index is as follows:

$$RS6 = U/(AI.St)$$

where "U" represents any given absolute speed ($m.s^{-1}$), "AI" the androgyny index (%), and "St" the stature (m) of the subject.

THE RELATIVE SPEED EXPRESSIONS

Ten methods of expressing rate of locomotion were selected for the purposes of this study - one absolute speed expression and nine relative speed expressions. Each relative speed method expressed a given rate of horizontal progression with respect to one (or any combination of) various morphological characteristics. The justifications for the selection of these specific relative speed expressions are clearly outlined in the previous section. Following is a summary of the methods used in this research to express locomotor speed:

1. Metres per second (m/s): that fraction of horizontal distance (m) covered overground during locomotion per unit time (s).
2. Statures per second (St/s): that fraction of stature (m) covered overground during locomotion per unit time (s) (Grieve & Gear 1966).
3. Leg lengths per second (LL/s): that fraction of leg length (m) covered overground during locomotion per unit time (s). It should be noted that leg length is correctly understood as the height of the tibial point from the ground.

4. Lower-limb lengths per second (LLL/s): that fraction of the lower-limb length (m) covered overground during locomotion per unit time (s). It should be noted that lower-limb length is correctly understood as the height of the trochanteric point from the ground.

5. Bi-acromial diameters per second (BAD/s): that fraction of the bi-acromial diameter (m) covered overground during locomotion per unit time (s).

6. Bi-iliac diameters per second (BID/s): that fraction of the bi-iliac diameter (m) covered overground during locomotion per unit time (s).

7. Androgyny index/statures per second (AI.St/s): that fraction of the androgyny index multiplied by stature (m) covered overground during locomotion per unit time (s).

8. Froude speed 1 (stature): a dimensionless expression in which the rate of progression (U) is proportional to the square root of stature (m) multiplied by a gravitational constant ($9.81 m.s^{-2}$).

9. Froude speed 2 (lower-limb length): a dimensionless expression in which the rate of progression (U) is proportional to the square root of lower-limb length (m) multiplied by a gravitational constant ($9.81 m.s^{-1}$).

10. Froude speed 3 (stature/body surface area): a dimensionless expression in which the rate of progression (U) is proportional to the square root of the cube of stature (m^3) divided by body surface area (m^2) multiplied by a gravitational constant ($9.81 m.s^{-2}$).

In order that a given absolute speed ($m.s^{-1}$) be inferred or derived from the above expressions of relative speed, it was necessary to generate appropriate equations. Below is a summary of the speed equations used in this study to extrapolate the absolute rate of progression (as derived from the definitions outlined above):

1. **m per second:** .... AS = U
2. **St per second:** .... RS1 = U/St

3. **LL per second:** .... RS2 = U/LL
4. **LLL per second:** .... RS3 = U/LLL
5. **BAD per second:** .... RS4 = U/BAD
6. **BID per second:** .... RS5 = U/BID
7. **AI.St per second:** .... RS6 = U/ AI.St
8. **Froude speed 1 (St):** .... RS7 = $U/\sqrt{g.St}$
9. **Froude speed 2 (LLL):** .... RS8 = $U/\sqrt{g.LLL}$
10. **Froude speed 3 (St & BSA):** .... RS9 = $U/\sqrt{g.[St^3/BSA]}$

For each of these ten methods of expressing locomotor speed, six speed treatments were prescribed - three walking and three running. The range of each of these speed treatments was such that in absolute terms the slowest rate of walking approximated $0.8m.s^{-1}$, and the fastest rate of running approximated $3.9m.s^{-1}$. This range of locomotor speeds was chosen in an attempt to include as large a cross-section of aerobic speeds as possible (for both walking and running). Further, the speed range was such that there existed equal divisions between successive incremental speed treatments. The actual relative speed treatments prescribed for the purposes of this research are reflected in Table IV.

THE RESEARCH PROTOCOL

Once habituated to treadmill locomotion, subjects were requested to report back to the testing laboratory for the completion of data collection (consent forms having been signed by the subjects prior to any participation). The testing protocol was divided into four components - namely, an anthropometric analysis, an energetic analysis, a kinematic analysis and a psychophysical analysis.

TABLE IV: the slow, medium and fast locomotor speeds as prescribed for the purposes of this study. For each of ten methods of expressing speed, in both absolute and relative terms, six locomotor treatments were imposed.

	WALK			RUN		
AS (m/s)	0.83	1.39	1.94	2.50	3.06	3.61
RS1 (St/s)	0.50	0.80	1.10	1.40	1.70	2.00
RS2 (LL/s)	1.90	2.90	3.90	4.90	5.90	6.90
RS3 (LLL/s)	1.10	1.60	2.10	2.60	3.10	3.60
RS4 (BAD/s)	2.30	3.60	4.90	6.20	7.50	8.80
RS5 (BID/s)	3.40	5.30	7.20	9.10	11.00	12.90
RS6 (AI.St/s)	0.64	0.91	1.18	1.45	1.72	1.99
RS7 ($U/\sqrt{g.St}$)	0.20	0.34	0.48	0.62	0.76	0.90
RS8 ($U/\sqrt{g.LLL}$)	0.28	0.47	0.66	0.85	1.04	1.23
RS9 ($U/\sqrt{g.[St^3/BSA]}$)	0.16	0.26	0.36	0.46	0.56	0.66

i) Anthropometric Analysis

Prior to the capture of locomotor data, a collection of personal information was recorded for each subject. The age of the subject was recorded (in years), and the following anthropometric measures were recorded using a methodology as proposed by Tanner (1951), Montagu (1960) and Ross and Marfell-Jones (1982): stature, body mass, leg length, lower-limb length, bi-acromial diameter and bi-iliac diameter (see Table III).

Estimations of body surface area (BSA) and androgyny index (AI) were derived from the measured anthropometric data expressed above (see Table III). From these absolute and derived morphological measures, it was possible to extrapolate (for each subject) absolute speed values from the relative speed equations outlined in the previous section. In this way, the energetic and kinematic responses to locomotor speeds in relative terms were effectively derived.

The specific procedures followed for the measurement of the absolute anthropometric data are reported below:

STATURE was measured using a portable Harpenden Holtain stadiometer. The subject was instructed to stand in the anatomical position, as erect as possible, barefoot with heels together. The buttocks, scapulae and posterior aspect of the head were in contact with the vertical backboard of the stadiometer. The upper limbs were pendant and the feet flat on the base of the stadiometer. The head was maintained in the Frankfurt horizontal plane. Stature was then measured from the vertex in the medial sagittal plane using the stadiometer arm.

BODY MASS was measured using a Seca beam-balance scale. The subject stood on the the scale nude, without shoes, in the anatomical position.

LEG LENGTH was measured as the linear distance from the surface of the floor to the most superior point on the lateral border of the head of the tibia. Using a palpation technique, the tibial point was located and marked clearly with a dermographic pen. Leg length was then measured using a Harpenden Holtain digital anthropometer. The measure was taken from the tibial point to the floor with the subject standing erect in the anatomical position.

LOWER-LIMB LENGTH was measured as the linear distance from the surface of the floor to the most superior point on the greater trochanter of the femur. Using a palpation technique, the trochanteric point was located and clearly marked with a dermographic pen. Lower-limb length was then measured using a Harpenden Holtain digital anthropometer. The measure was taken from the trochanteric point to the floor with the subject standing erect in the anatomical position.

BI-ACROMIAL DIAMETER was measured as the linear (maximum) distance between the left and right acromiale. The blades of a Harpenden Holtain digital anthropometer were brought down onto the acromion points from above, and the measure was taken from behind with the subject standing erect with shoulders braced and upper limbs pendant.

BI-ILIAC DIAMETER was measured as the linear (maximum) distance between the left and right iliocristale. The blades of a Harpenden Holtain digital anthropometer were placed on the most lateral points of the iliac crest, and the measure was taken from the front with the subject standing erect with the heels togehter and the upper limbs pendant.

Each measure was taken twice, with a third measure taken if the initial readings differed by more than the accepted tolerance limits as defined by Tanner (1951). If repeated measures fell within the accepted tolerance limit, the first of the two measures was recorded. If a third measure was required, the mean of the two closest measures was recorded. Body mass was recorded in kilograms to the nearest gram. All lengths and diameters were recorded in centimeters to the nearest millimeter. In all cases, and for all subjects, the linear lengths were measured on the right side of the body.

ii) Energetic Analysis

The locomotor protocol comprised a battery of six separate speed conditions - three walking treatments (0.83, 1.39 and $1.94 m.s^{-1}$) and three running treatments (2.50, 3.06 and $3.61 m.s^{-1}$). The six speed treatments, each completed on a motor-driven treadmill, were randomly presented to each subject such that the more taxing running conditions were interspersed with less taxing walking conditions. This random presentation of the locomotor treatments ensured the elimination of any bias which may otherwise have impinged upon the validity of the data. A single-blind technique was used in that at no time during the study were the subjects informed as to the speed at which they were progressing. Further, throughout testing the energetic, kinematic and psychophysical responses to the prescribed speed treatments were unknown to the participating subjects, a precaution which effectively eliminated any bias in the data captured as the result of subject anticipation. Finally, throughout all data collection, pre-briefed laboratory assistants were on hand to render support should any subject experience difficulty whilst on the treadmill. The researcher was present at all times, and every reasonable precaution was taken to ensure the absolute safety of the subjects during testing.

Subjects were required to progress at each of the six speed treatments for a duration of five minutes, and data were captured during the final 60 seconds of each locomotor bout. Related research (McArdle *et al.* 1986, Goslin 1987) suggests that an exercise duration in excess of about 3-4 minutes is sufficient to allow even unconditioned subjects to attain a steady-state if the exercise is aerobic in nature, thus ensuring that any data capture is not coincidental with the metabolic adjustment of the subject as he adapts to the new activity. The six locomotor treatments were completed randomly in a discontinuous fashion. Following each speed condition, subjects were required to rest (supine) until heart-rate had returned to within 10 beats per minute of a previously measured resting value. Only once this had been observed were the subjects instructed to ready themselves for the next speed treatment.

The energetic data captured during the final 60 seconds of each locomotor treatment included measures of oxygen consumption ($\dot{V}O2$), carbon-dioxide production ($\dot{V}CO2$), respiratory exchange ratio (R-value), inspired ventilatory volume ($\dot{V}I$), breathing frequency ($\dot{V}f$) and tidal volume (Vt). These data were captured via the use of an on-line computer-aided technology. Measures of resting and locomotor heart-rate were recorded via the use of strategically positioned surface electrodes and a Respironics heart-rate monitor.

iii) Kinematic Analysis

Having completed the collection of energetic data, the six speed treatments were replicated for the capture of kinematic responses to locomotion. It was decided to collect the kinematic data during a re-run of the locomotor treatments over a shorter period of time. This was decided after consideration of the excessive pounding the somewhat fragile footswitch pads would have undergone had they been worn for the five-minute period prescribed for the analysis of locomotor energetics. Since the responses of human gait parameters adjust almost immediately to given locomotor speeds in habituated subjects (Schieb 1986), a 30-second period of locomotion was considered sufficient for the accurate capture of kinematic data.

Thus, once subjects had completed the energetic component of the research testing, they were readied for the collection of kinematic data. Suitably sized footswitch pads were securely taped to the soles of both feet, and specially manufactured socks were then donned to keep the footswitch pads in place. These socks had rubberised soles and were consequently very effective in maximising the friction between the foot and treadmill belt, thereby preventing the distortion of data via slipping. Once readied, subjects repeated the six prescribed locomotor treatments in a random fashion to facilitate the unbiased capture of kinematic data. These data, in the form of temporal and spatial measures of foot-floor contacts, were collected for several strides during a 30-second locomotor bout.

The kinematic data collected included measures of stride length, cadence, cycle time, support time, swing time and the support/swing ratio. These data were captured via the use of on-line computer aided telemetric footswitch apparatus.

iv) Psychophysical Analysis

Coincidentally with the capture of energetic data during the final 60 seconds of each six-minute locomotor treatment, subjective ratings of perceived exertion (RPE) were recorded. Prior to testing subjects were given a standard written instruction as to how to respond to the Borg scale (Borg 1970) (see Appendix 3). Subjects were requested to furnish both local (muscular/joint) and central (cardiorespiratory) perceptions of exertion by pointing to the ratings of their choice at about the fourth minute of each locomotor treatment. These values were verbally verified by the researcher before being recorded.

THE HARDWARE TECHNOLOGY: PRINCIPLES OF OPERATION

The accurate and reliable capture of energetic and kinematic data was made possible via the use of sophisticated computer aided technologies. Following is a brief description of the structure and function of the systems employed for the capture of energetic (oxygen-consumption and heart-rate) and kinematic data.

i) The Computer-Aided Analysis of Locomotor Energetics

Energetic responses to locomotion (both walking and running) were evaluated via the direct measure of respiratory parameters during exercise. This capture of locomotor metabolics was facilitated via the use of a computer-aided system developed by Goslin et al. (1984).

The hardware configuration (see Figure 2) enabled subjects to inhale ambient air through a Mijnhardt dry gasmeter where volume and temperature of the inspired air were measured. The inspired air then proceeded from the outlet port of the gasmeter through Collins ridged tubing (3cm diameter) to a two-way Hans Rudolph pulmonary valve (no. "2700"). From the pulmonary valve expired air was directed through a further length of ridged tubing to a four-litre perspex mixing-chamber. Within this chamber a small circulating fan ensured the complete mixing of the expired air. From the mixing-chamber the expired air was sampled for analysis at a rate of about $300ml.min^{-1}$. Upon exit from the mixing-chamber the expired air was chanelled through a final one-metre section of ridged tubing before venting to the room. This prevented

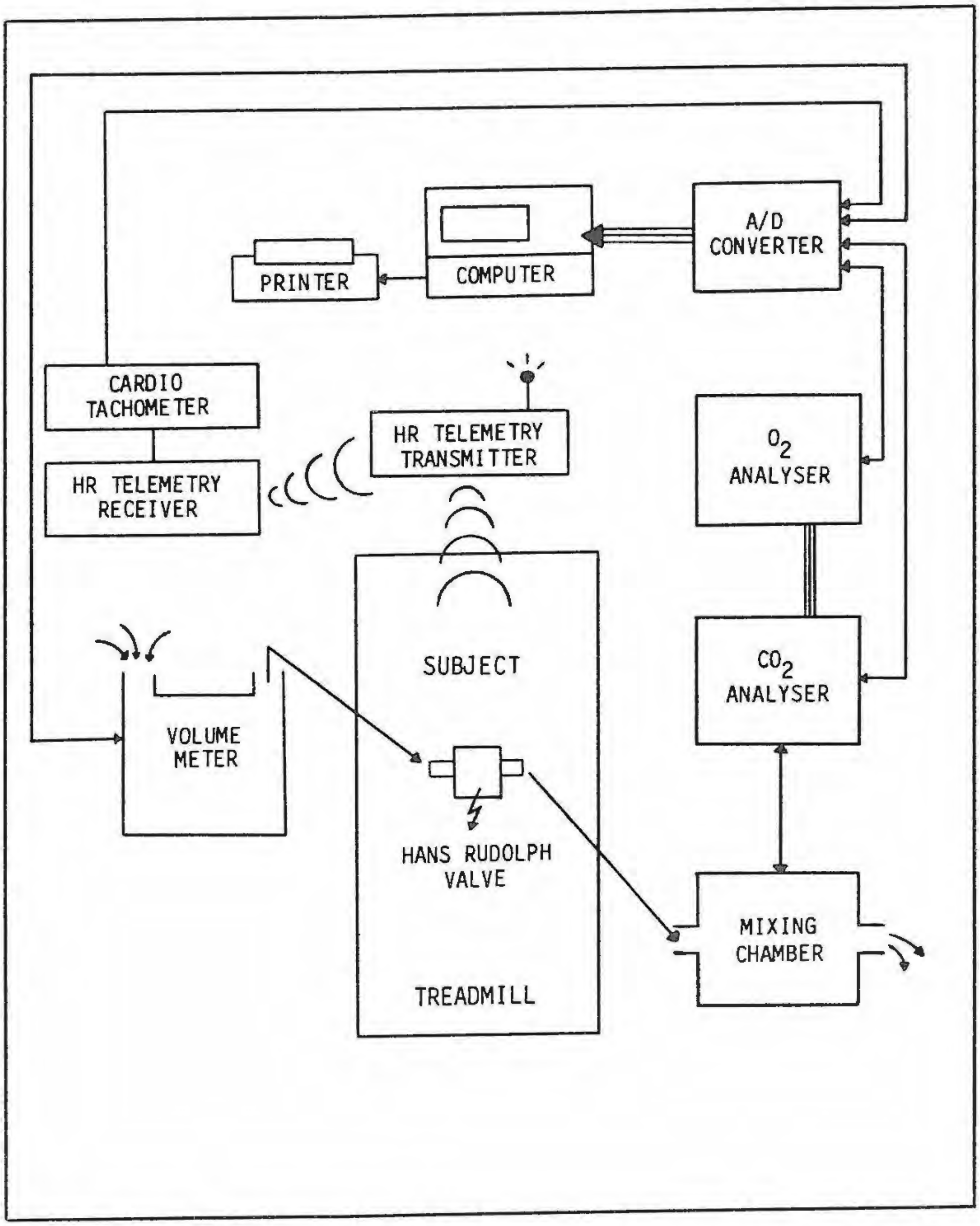


FIGURE 2: a schematic illustration of the on-line computer-aided apparatus as used for the capture of energetic data.

contamination of the expired air within the mixing-chamber with ambient room air.

Expired air analysis was performed by previously calibrated Applied Electrochemistry oxygen analyser (3-SAI) and Gould Capnograph carbon-dioxide analyser (mark III). Calibration of these analysers was achieved via the use of gases of known concentration from two different pressurised cylinders. Analogue signals from the gasmeter and from the two gas analysers were fed into a multiplexor and then into a 12-bit, 8-part analogue-to-digital (A/D) convertor. The subsequent digital signals were sequentially sampled by a South-West Texas ("6800") microcomputer at a rate of approximately 220 times per minute.

Visual feedback of oxygen-consumption, respiratory exchange ratio and elapsed time were provided for each gas sample on the computer's video display terminal. A hard-copy record of all measured and computed parameters was output to an Epson (Fx-80) printer immediately after each sample. These measured and computed parameters were corrected by the computer for variations in subject age, expired gas temperature, ambient partial-pressure of water vapour, barometric pressure and relative humidity.

ii) The Computer-Aided Analysis of Locomotor Heart-Rate

Measures of resting and locomotor heart-rate during testing were attained via the use of a Respironics heart-rate monitor (Exersentry) coupled to a South-West Texas ("6800") microcomputer.

The Exersentry is designed to recognise the electrical activity of the myocardium (specifically the R-wave to R-wave distance) as transmitted by carefully prepared and strategically placed surface electrodes. A modified lead II electrode configuration was used, wherein the positive electrode was affixed to the right clavicle, the negative electrode to the V5 position on the left side of the chest, and the reference (earth) electrode to the left clavicle. The Exersentry interprets the electrical impulses generated by the contraction of the heart (ventricular systole), and channels the computed heart-rate via an opto-isolator as digital input to the microcomputer.

On-going visual feedback of the heart-rate was provided via the the computer's video display terminal. Further, a hard-copy record of the resting and locomotor heart-rates were output to an Epson (Fx-80) printer following each test sample.

iii) The Computer-Aided Analysis of Locomotor Kinematics

Data capture of the temporal and spatial characteristics of foot-floor contact was facilitated via the use of a computer-aided radio-telemetric footswitch system (see Figure 3).

The footswitch telemetry system consisted of two subsystems: the transmitting system and the receiving system. The transmitting system was set up to sample data from each of eight in-sole footswitches - one switch each for the heel, base of fifth metatarsal (B5), base of first metatarsal (B1) and great toe of both left and right feet. These data, in the form of bursts of pulses representing switch closures, were sampled at a rate of one kilohertz (kHz). The receiving system was designed to code the various combinations of switch closures in the form of 8-bit binary numbers which were then input to an Apple (IIE) computer. Each 8-bit binary number (four bits for each footswitch) was manipulated such that each combination of switch closures was represented by a unique value ranging from zero (no switches closed - swing phase) to fifteen (all switches closed - foot-flat).

A hard-copy record of the locomotor kinematics representing several strides of the gait cycle was output to an Epson (Fx-80) printer.

STATISTICAL ANALYSIS

As outlined in a previous section, one-independent regression analyses were performed on the collected data in order to establish the relationships existing between energetic/kinematic responses and absolute rates of horizontal progression for each subject. This was necessary in

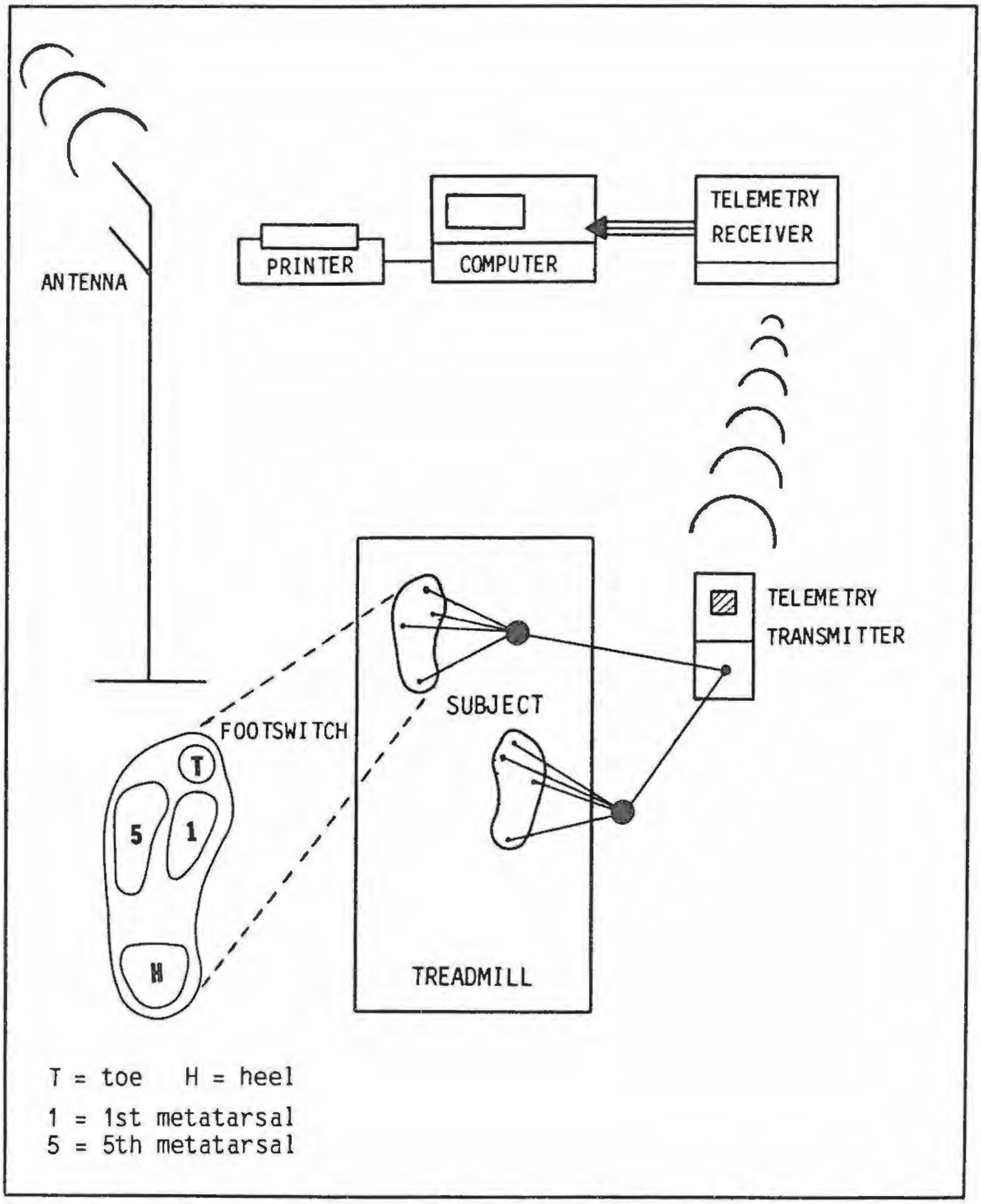
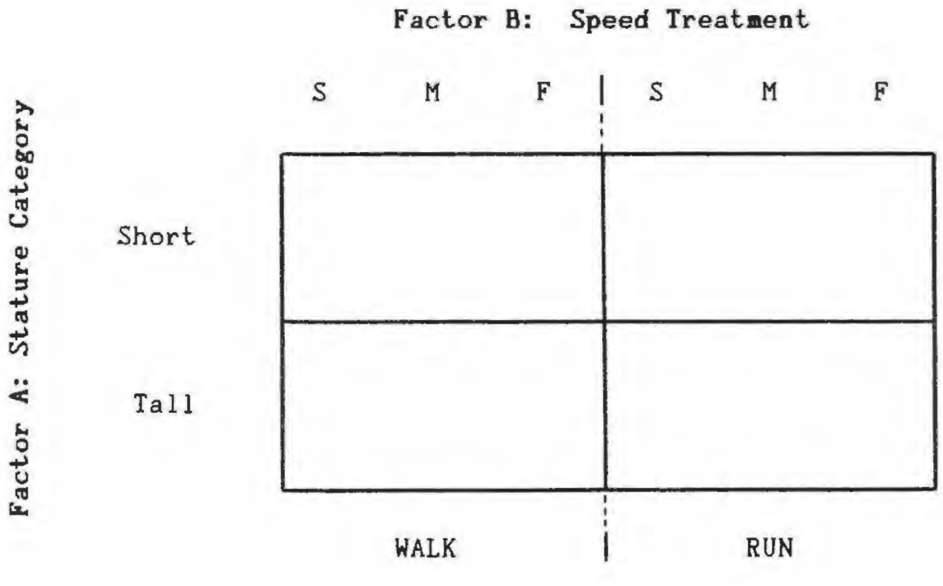


FIGURE 3: a schematic illustration of the on-line computer-aided apparatus as used for the capture of kinematic data.

order to make possible the extrapolation of energetic/kinematic locomotor responses to numerous speeds of a relative (morphology-normalised) nature. The following statistics were then performed to aid in the analysis and interpretation of both the measured (absolute speed) and extrapolated (relative speed) data.

Two-way analyses of variance (ANOVAs) with repeated measures on both factors, and coefficients of variation (C.V.s) (Ferguson 1981) were computed to determine whether or not significant differences existed between the test and retest data as recorded during the pilot study. This was necessary in order to determine the reliability of the testing procedures adopted for the measure of energetic, kinematic and psychophysical locomotor responses.

Two-way ANOVAs with repeated measures on only one factor (Ferguson 1981) were employed in order to establish whether or not significant differences existed between the stature groups with respect to the energetic, kinematic and psychophysical responses to each of ten methods of expressing locomotor speed (one absolute and nine relative speed expressions). Thus, for each of the ten speed expressions the following factorial design (2 X 6) was adopted:



NOTE: the speed treatments S, M and F represent the incremental slow, medium and fast absolute and relative locomotor speeds.

The ANOVAs thus employed enabled the author to establish within which methods of expressing speed (absolute and relative) significant energetic, kinematic and psychophysical differences existed between the "short" and "tall" stature categories. In other words, for each of the ten methods of expressing speed, an appropriately designed ANOVA was able to reveal any significant differences in energetic, kinematic and psychophysical locomotor responses between the two stature groupings.

In order to identify which method of expressing locomotor speed was most effective in minimising the across-sample inter-individual variation in energetic, kinematic and psychophysical responses, coefficients of variation (C.V.s) were established. The coefficients of variation enabled the author to evaluate the within-parameter variation (expressed as a percentage) across the entire sample group.

Finally, one-independent regression analyses (Ferguson 1981) were performed in order to establish the correlations and prediction formulae for the following parameters:

i) oxygen-consumption vs. speed,

ii) oxygen-consumption vs. cadence and stride length,

iii) speed vs. cadence and stride length, and

iv) speed vs. ratings of perceived exertion (local and central).

For all statistics the 0.05 level of significance was used in order to minimise the probability of committing a type-I error without at the same time increasing the probability of committing a type-II error (Ferguson 1981, Clarke & Clarke 1985).

CHAPTER FOUR

RESULTS AND DISCUSSION

THE PILOT STUDY

A carefully designed pilot study was conducted prior to the capture of experimental data in order to demonstrate the reliability of the testing protocol as employed in this investigation. Three subjects participated in this pilot study, each fulfilling the requirements of a standard protocol on a test/retest basis. Such pilot testing allowed the investigator to circumvent any procedural inconsistencies, and further provided the oppurtunity to establish the statistical reliability with which the anthropometric, energetic, kinematic and psychophysical data were captured.

The anthropometric measures were taken on each of the subjects three times on each of two consecutive days. The anthropometric test battery included measures of body mass, stature, leg length, lower-limb length, bi-acromial diameter and bi-iliac diameter. In each case intra-individual coefficients of variation were considerably less than 3% (see Table V). The reliability with which the anthropometrical data were gathered was further demonstrated in the results of "Student's" related t-tests (Ferguson 1981), which revealed no significant differences ($P < 0.05$) between the test and retest measures (see Table VI).

Energetic data were captured via the use of an on-line, computer-aided technology. The reliability of this system has been widely reported in previous research undertaken in the Department of Human Movement Studies at Rhodes University (Goslin et al. 1984, Rorke 1985, Candler 1986, Goslin 1987, Williams 1987). For the purposes of this study, the reliability with which the energetic data were captured was demonstrated in the results of two-way repeated measures analyses of variance (Ferguson 1981), which revealed no significant differences ($P < 0.05$) between the test and retest measures of oxygen consumption ($\dot{V}O2$), carbon-dioxide production ($\dot{V}CO2$), respiratory exchange ratio (R-value) and inspired ventilatory volume ($\dot{V}I$) (see table VII).

TABLE V: the coefficients of variation (%) as calculated from successive measures of selected anthropometric variables during the pilot study.

ANTHROPOMETRIC DATA	Subject 1	Subject 2	Subject 3
Stature	0.113	0.267	0.428
Body Mass	0.122	0.074	0.161
Leg Length	2.244	0.902	0.799
Lower-Limb Length	1.479	0.321	0.741
Bi-Acromial Diameter	0.509	0.538	1.245
Bi-Iliac Diameter	2.021	1.719	2.512

TABLE VII: results of the analyses of variance as performed on the physiological, kinematic and psychophysical test and retest pilot data. For each locomotor variable the observed f-ratio (fo) was less than the prescribed critical f-ratio (fc), suggesting that the data were reliably captured.

	fo	fo:fc	P <0.05
ANTHROPOMETRIC DATA			
Stature	1.31	fo < fc	test = retest
Body Mass	2.00	fo < fc	test = retest
Leg Length	0.57	fo < fc	test = retest
Lower-Limb Length	1.89	fo < fc	test = retest
Bi-Acromial Diameter	0.09	fo < fc	test = retest
Bi-Iliac Diameter	2.22	fo < fc	test = retest

where: fc (P <0.05) = 4.30

TABLE VI: results of the "Student's" related t-tests as performed on the anthropometrical test and retest pilot data. For each locomotor variable the observed f-ratio (fo) was less than the prescribed critical f-ratio (fc), suggesting that the data were reliably captured.

	fo	fo:fc	$P < 0.05$
PHYSIOLOGICAL DATA			
$\dot{V}$O2	0.53	fo < fc	test = retest
HR	0.08	fo < fc	test = retest
R-value	0.09	fo < fc	test = retest
$\dot{V}$I	1.09	fo < fc	test = retest
KINEMATIC DATA			
Cadence	3.86	fo < fc	test = retest
Stride Length	12.82	fo < fc	test = retest
Cycle Time	0.01	fo < fc	test = retest
Support:Swing Ratio	1.86	fo < fc	test = retest
PSYCHOPHYSICAL DATA			
RPE (local)	16.00	fo < fc	test = retest
RPE (central)	1.00	fo < fc	test = retest

where: fc ($P < 0.05$) = 18.51

Two-way repeated measures analyses of variance also demonstrated the reliability with which the kinematic data (cadence, stride length, cycle time and support/swing ratio) and the psychophysical data (central and local ratings of perceived exertion) were gathered. Again, no significant differences ($P < 0.05$) were revealed between the test and retest measures (see Table VII).

Overall, the pilot study was successful in confirming the reliability of both the equipment and the test protocol as employed in this research. Furthermore, data obtained on any given occasion during the experimental phase could be considered reliable, and representative of a subject's normal response to locomotion on the treadmill.

SUBJECT RESPONSES TO LOCOMOTOR SPEEDS EXPRESSED IN ABSOLUTE TERMS

i) Energetic Responses

The relationship between the energy cost of walking and the absolute rate of progression ($m.s^{-1}$) was clearly curvilinear in nature for both short and tall subjects ($r = 0.955$), while the locomotor energy cost for running tended to increase linearly with increments in absolute speed for both stature categories ($r = 0.847$) (see Figure 4). This curvilinear/linear trend in oxygen consumption with respect to the speed of walking/running is in accordance with the results of numerous studies as reported in the literature (Margaria et al. 1963, Menier & Pugh 1968, Shephard 1969, Astrand & Rodahl 1977, McArdle et al. 1986, Noakes 1986, Goslin 1987, Williams 1987). Such a speed/oxygen consumption relationship suggests that increments in the rate of locomotion (be it walking or running) elicit proportional increases in the related expenditure of energy. This is recognised as a typical biological response to increments in workload, and is purely a function of the greater amounts of oxygen required to "fuel" the exercising musculature as the intensity of activity is increased (Dill 1963, Astrand & Rodahl 1977, Lamb 1984, McArdle et al. 1986).

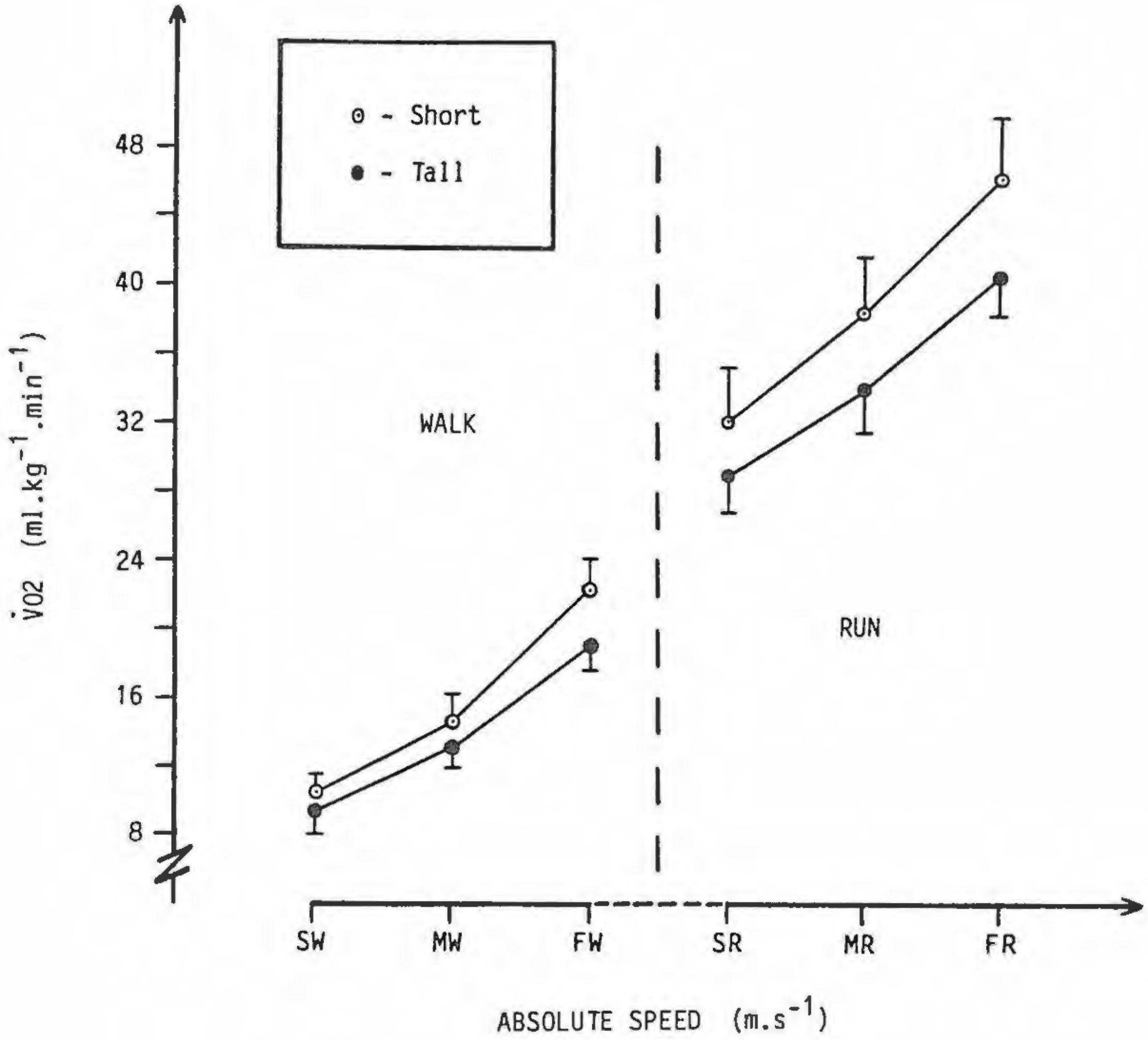


FIGURE 4: **the relationship between oxygen consumption and locomotor speed expressed in absolute terms.**

For all but the slow (SW) and medium (MW) walking conditions the short subjects consumed significantly greater amounts of oxygen per kilogram body mass per unit speed than did the tall subjects. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated a significant interactive effect. However, for both stature groups, oxygen consumption tended to increase as a curvilinear function of walking speed ($r = 0.955$), and as a linear function of running speed ($r = 0.847$).

However, statistical analyses revealed significant differences in oxygen consumption between the stature groups with respect to any given walking or running speed. It was clearly demonstrated that the shorter subjects consumed more oxygen per kilogram mass per minute at any given absolute speed than did their taller counterparts. In other words, for both walking and running gaits, the shorter subjects tended to be taxed more severely, and were consequently seen to consume oxygen at higher rates. It should be pointed out that the short subjects had a significantly smaller stature ($\bar{X}$ = 165.4cm) than did the tall subjects ($\bar{X}$ = 190.2cm). Accordingly, it would appear that differences in subject stature (and/or morphology) contribute quite substantially to the between-subject variability associated with the energetic cost of locomotion at any given absolute rate of progression - the energy cost of walking or running tending to increase as a reciprocal function of subject stature.

With specific respect to walking at absolute speeds, it is fairly evident (see Figure 4) that the significant difference in energy expenditure between the short and tall subjects did not manifest itself at either the "slow" ($0.83m.s^{-1}$) or the "medium" ($1.39m.s^{-1}$) locomotor speeds - only at the "fast" walk ($1.94m.s^{-1}$) was such a difference revealed. However, it must be pointed out that when evaluating walking speeds in general, the statistics revealed significant differences between the short and tall stature categories. With respect to running, it is clear that at all locomotor speeds (ie. "slow", "medium" and "fast" rates of progression), the tall subjects recorded a significantly lower consumption of oxygen than did the short subjects. It might be argued therefore, that when the rate of locomotor progression exceeds about 1.5 to $1.7m.s^{-1}$, variations in subject stature tend to significantly influence the energetics of locomotion. Above such locomotor speeds, the oxygen consumption per kilogram of mass per unit speed tends to decrease with increments in stature, suggesting that there exists a reciprocal relationship between energy expenditure and stature at any locomotor speed.

This assumption is in agreement with the findings of Brockett et al. (1956), who suggest that stature and locomotor oxygen consumption are significantly correlated. However, this contention is contrary to arguments offered by Wyndham et al. (1971) and Van der walt and Wyndham (1973), who postulate that subject stature is a poor predictor of locomotor energy cost, especially when variations in body mass are factored out. It is the author's opinion, however, that these and other investigations (Candler 1986, Goslin 1987), which suggest that short and tall subjects are taxed no differently at any given absolute locomotor speed, tend to be biased by limitations imposed as the result of the choice of both subject sample and locomotor protocol. In other words, size-specific significant differences in energy expenditure between subjects during horizontal locomotion are only realised when:

i) extremes in subject stature are realised, and

ii) a wide range of locomotor speeds is investigated.

Both of the the above considerations were characteristic of the present research project, and as a consequence these results tend to suggest that subject size influences the energetics of human locomotion quite considerably. If a subject pool is selected in which there exists little inter-individual variability with respect to stature (and/or morphology), then it is unlikely that statistical analysis would reflect a significant correlation between subject size and locomotor energy expenditure.

The results of this study suggest that when locomotor responses are related to speeds expressed in absolute terms (ie. $m.s^{-1}$), shorter subjects (<170cm) tend to consume significantly greater amounts of oxygen per kilogram of mass per unit speed than do their taller (>185cm) counterparts. Furthermore, as the speed of progression (aerobic) increases, this stature-related variability in locomotor energy expenditure tends to become more pronounced (see Figure 4). This would suggest that shorter subjects are more severely stressed by increments in locomotor speed than are significantly taller subjects adopting the same mode of progression.

The response of oxygen consumption to increments in the speed of walking or running tends to be closely paralleled by other physiological variables. The production of carbon-dioxide ($\dot{V}CO2$) for example, increased in a curvilinear fashion with increments in walking speed, and in a linear fashion with increments in running speed (see Figure 5). Again, this is a typical biological response to any increase in exercise intensity, inasmuch as that carbon-dioxide is recognised as the metabolic end-product of cellular oxidation (Dill 1963, Astrand & Rodahl 1977, Lamb

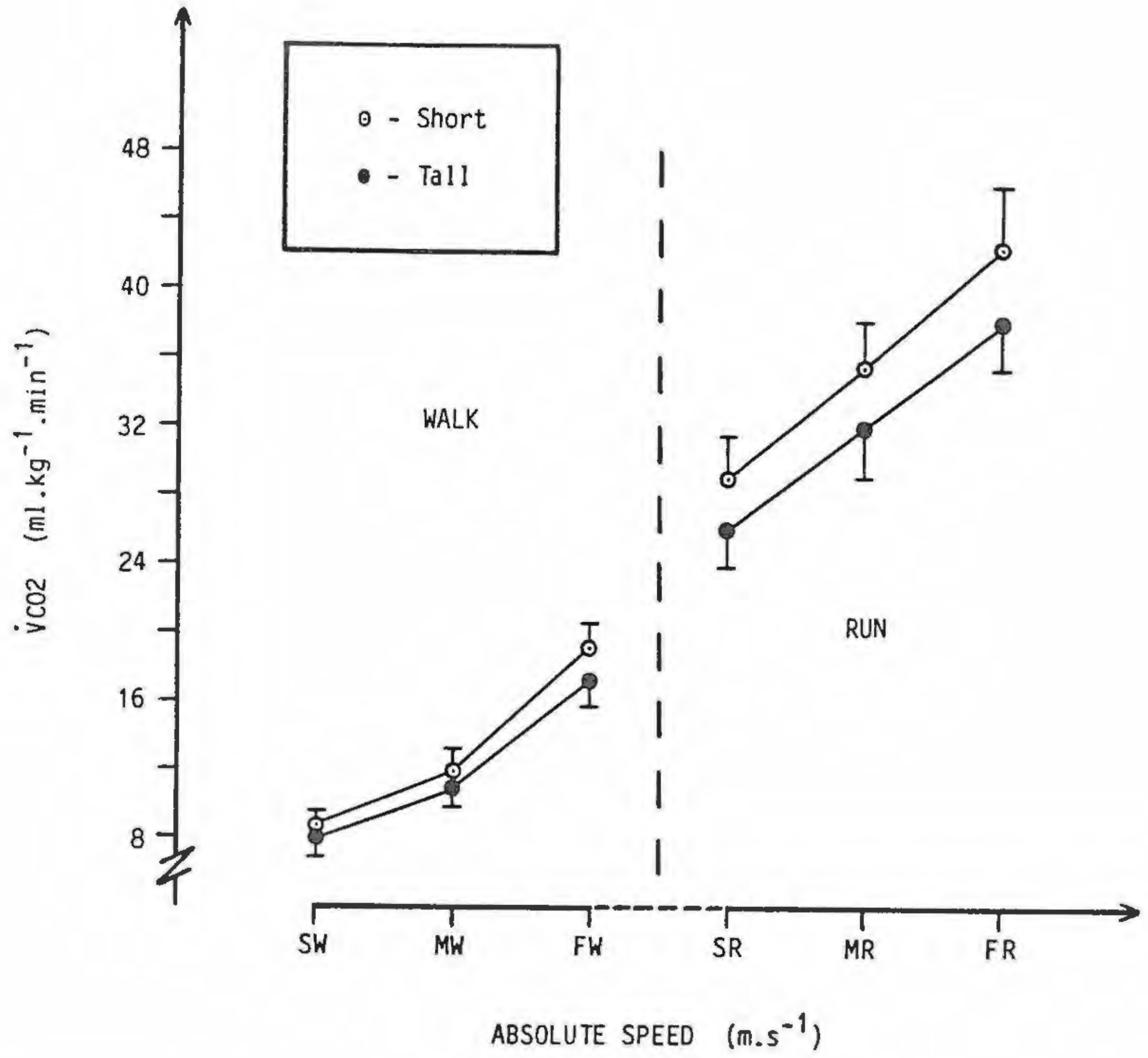


FIGURE 5: the relationship between carbon-dioxide production and locomotor speed expressed in absolute terms.

For all but the slow (SW) and medium (MW) walking conditions the short subjects produced significantly greater amounts of carbon-dioxide per kilogram body mass per unit speed than did the tall subjects. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated a significant interactive effect. However, for both subject groups, carbon-dioxide production tended to increase as a curvilinear function of walking speed, and as a linear function of running speed.

1984, McArdle et al. 1986). As with oxygen consumption, significant differences were revealed between the stature categories with respect to the carbon-dioxide produced at any given rate of progression above about 1.5 to $1.7m.s^{-1}$. Accordingly, for the "fast" walk and all the running treatments, the short subjects expired significantly greater amounts of carbon-dioxide per unit body mass. Once again, this would suggest that shorter subjects are more severely taxed when the rate of locomotor progression is expressed in absolute terms.

Despite the differences in both the consumption of oxygen ($\dot{V}O2$) and the production of carbon-dioxide ($\dot{V}CO2$) revealed between the stature categories at any given locomotor speed, the respiratory exchange ratios (R-value) as reported for the short and tall subjects were not significantly different (see Figure 6). In other words, at any given speed of walking or running the ratio of carbon-dioxide produced to oxygen consumed ($\dot{V}CO2/\dot{V}O2$) was approximately the same for the two stature groups. Further, it is evident in Figure 6 that the R-value tended to remain relatively stable despite increments in speed, but that it increased quite considerably as the mode of locomotion switched from walking to running. However, as reported in previous research investigating the energetics of human locomotion (Rorke 1985, Candler 1986, Goslin 1987), the R-value at any given locomotor speed is highly variable, and may be significantly influenced by factors such as the dynamic action of a pre-test meal and/or the subject's state of rest (both of which are difficult to control). As a consequence, the considerable within-group variability in the R-value for each of the locomotory modes may be such that it "clouds" any significant differences that might have occured between the stature categories had the pre-test diet and activity of the subjects been effectively controlled. However, on the basis of the available data, it must be reported that both short and tall subjects generated similar respiratory exchange ratios when walking or running at any given speed. Further, it is clear (see Figure 6) that for both walking and running, increments in the rate of progression did not elicit significant changes in the respiratory exchange ratio. This suggests that the ratio of carbon-dioxide produced to oxygen consumed tends to remain constant for all speeds (aerobic) during horizontal locomotion, although it clearly increases as the mode of progression changes from a walk to a run.

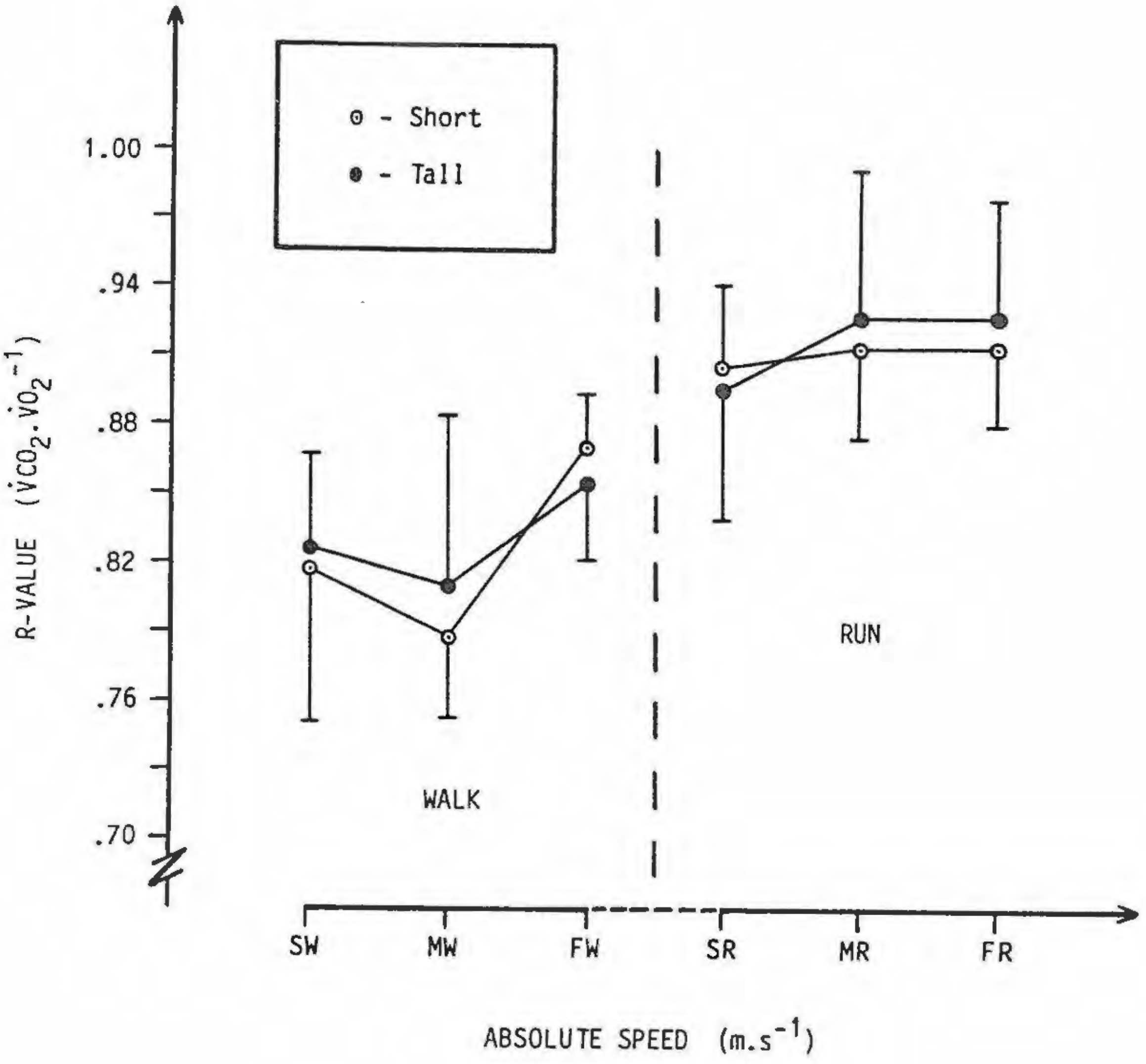


FIGURE 6: the relationship between respiratory exchange ratio and locomotor speed expressed in absolute terms.

For all conditions no significant differences were observed between the respiratory exchange ratios of the short and tall subjects. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated no significant interactive effect. Within both walking and running conditions, the respiratory exchange ratios remained relatively constant and independent of locomotor speed, although they were significantly higher for running than they were for walking.

Heart-rate is another physiological variable which typically parallels the response of oxygen consumption to increments in the speed of locomotion. It is clear from Figure 7 that locomotor heart-rate increased proportionately with increments in the rate of progression, there tending to be a curvilinear/linear relationship between heart-rate and the speed of walking/running respectively. This is once more a typical biological response to increments in the exercise intensity, and is the result of the workload-related stress placed upon the myocardium as it strives to deliver sufficient amounts of oxygen-saturated blood to the active musculature (Dill 1963, Astrand & Rodahl 1977, Lamb 1984, McArdle et al. 1986). Also evident from Figure 7 is the fact that the locomotor heart-rate tended to be significantly higher for the short subjects than it did for the tall subjects at any given rate of progression. This lends further credence to the assumptions previously made which propose that shorter subjects are more severely taxed at any given absolute speed than are their taller counterparts. This energetic advantage accorded the taller subjects prevailed despite the fact that there were no significant differences reported in the resting heart-rates between the short ($\bar{X}$ = 64.1bt.min^{-1}) and tall ($\bar{X}$ = 66.1bt.min^{1}) stature groups. Hence, there would appear no grounds for any argument supporting the notion that the taller subjects were energetically advantaged at any given locomotor speed by virtue of a superior physical conditioning. In other words, despite a relative parity with respect to level of fitness, the shorter subjects tended to be more severely taxed than were their taller counterparts when the rate of progression was expressed in absolute terms.

Reference to Figure 8 suggests that inspired ventilatory volume ($\dot{V}I$) increased linearly with increments in the speed of both walking and running. This is characteristic of any increase in movement intensity, as greater volumes of air need be inspired in order to furnish the organism with the increased oxygen required to "fuel" the exercising muscles (Dill 1963, Astrand & Rodahl 1977, Lamb 1984, McArdle et al. 1986). It should be noted that for all absolute walking speeds, no significant differences were revealed between the ventilatory volumes (inspired) of the short and tall subjects. However, once running was imposed as the mode of progression, taller subjects tended to inspire significantly greater volumes of air than did the shorter runners (see Figure 8). This discrepancy in ventilatory volume between the stature

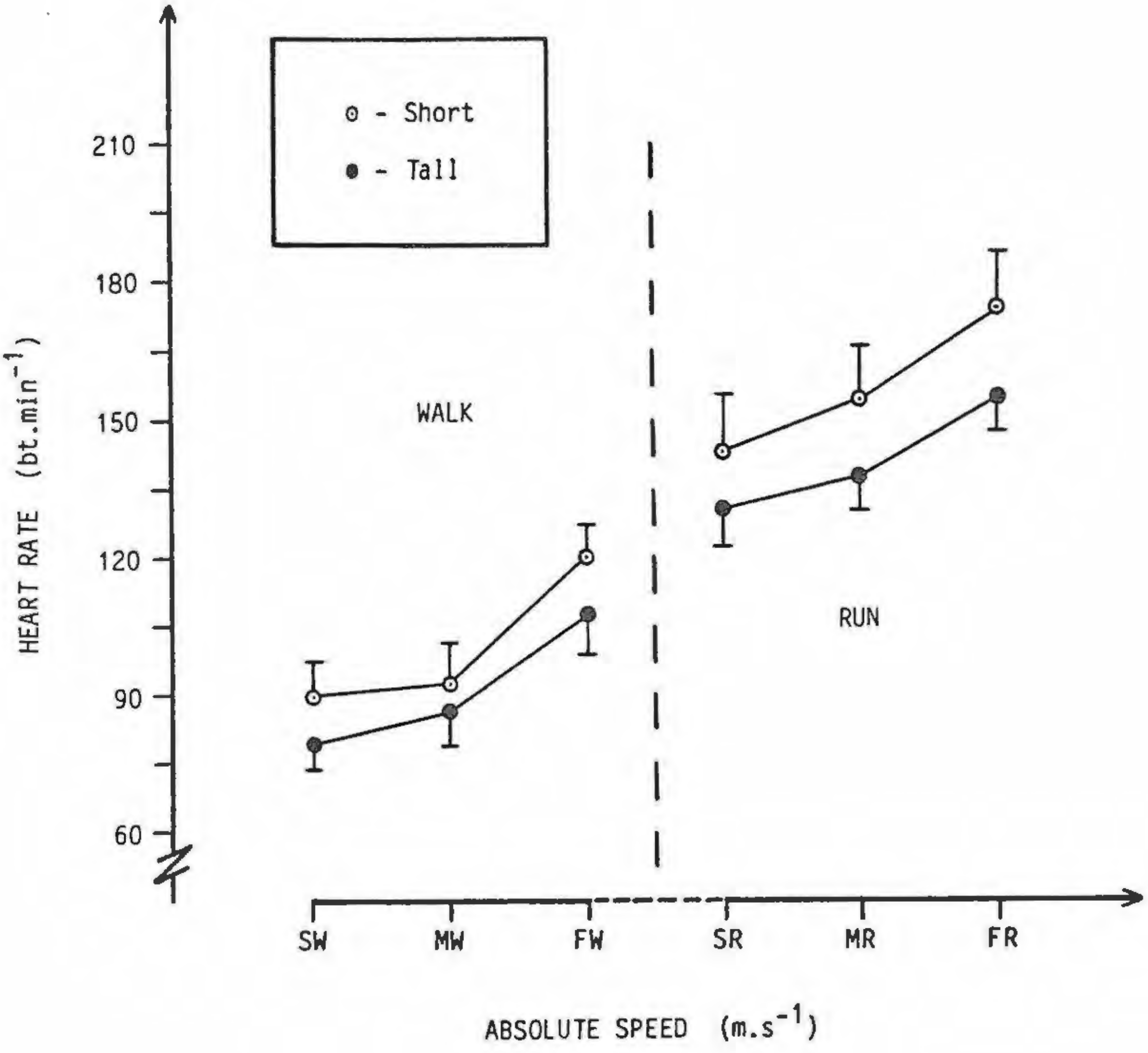


FIGURE 7: **the relationship between heart-rate and locomotor speed expressed in absolute terms.**

For all conditions the short subjects recorded a significantly greater locomotor heart-rate per unit speed than did the tall subjects. This was the case despite a previously reported parity between the stature groups with respect to resting heart-rate. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated a significant interactive effect. However, for both stature groups, heart-rate tended to increase as a curvilinear function of walking speed, and as a linear function of running speed.

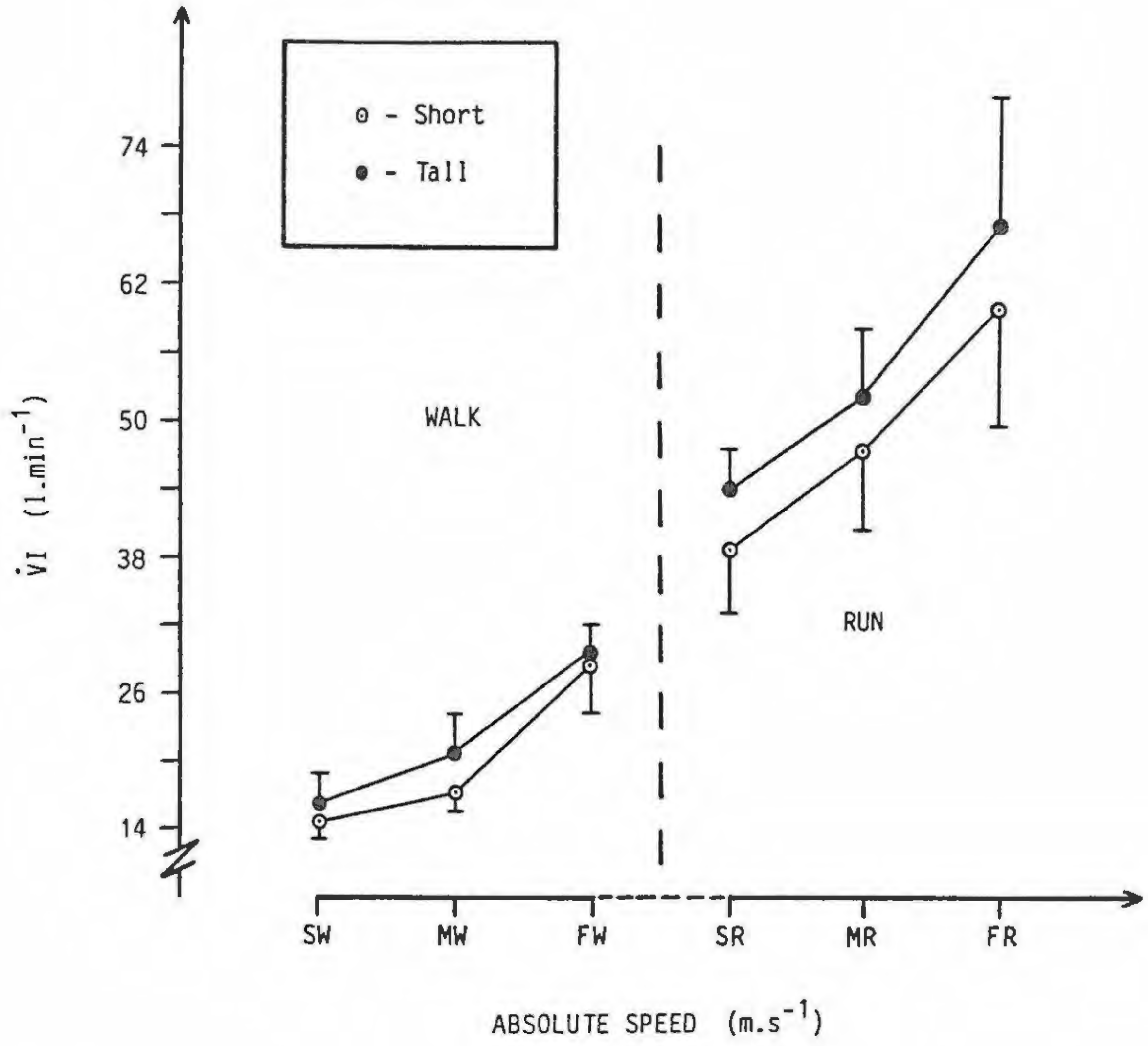


FIGURE 8: **the relationship between inspired ventilatory volume and locomotor speed expressed in absolute terms.**

For all walking conditions no significant differences were observed between the inspired ventilatory volumes of the short and tall subjects. For all running conditions, on the other hand, the tall subjects inspired significantly greater volumes of air than did the short subjects. The size-related difference in the volume of air inspired per unit speed is likely the result of variations in the lung capacity rather than variations in the demand for oxygen. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, the inspired ventilatory volume tended to increase as a linear function of walking and running speed.

categories is largely the result of differences in morphology, and may be attributed to two size-related factors. Firstly, it must be remembered that in an absolute sense taller subjects require more oxygen for any given workload by virtue of a greater body mass. In order to realise this greater absolute consumption of oxygen, taller subjects need necessarily inspire greater volumes of air than do shorter (and smaller) individuals. Secondly, it is well documented that lung-capacity in most animals is directly proportional to body size (Jacob et al. 1982, McArdle et al. 1986). In fact, Astrand and Rodahl (1977) propose that total lung capacity (TLC) varies approximately as the cube of a linear dimension of the body - such as stature. In other words, taller (larger) subjects are likely to inspire greater volumes of air per unit workload, although they may absorb smaller amounts of oxygen than do shorter subjects performing the same task. Thus, the greater inspiratory volumes typical of taller subjects at any given exercise intensity appear to be largely a function of an increased lung capacity (and increased body size) rather than an increased demand for oxygen.

The volume of inspired air is the product of the rate ($\dot{V}f$) and depth (Vt) of breathing (McArdle et al. 1986). Accordingly, increments in the inspiratory volume may be facilitated by either an increased frequency or depth of ventilation (or both). Astrand and Rodahl (1977) and McArdle et al. (1986) propose that during low intensity exercise, increments in the ventilatory volume are largely realised via an increased tidal volume (depth of breathing), while during high intensity activity the increment in ventilatory volume is achieved primarily as the result of an elevated breathing frequency. Figures 9 and 10 serve to augment this contention. Between the "slow" and "medium" speeds of walking (for all intents and purposes a low intensity activity), the breathing frequency ($\dot{V}f$) tended to remain relatively stable for both short and tall subjects despite the increment in locomotor workload (see Figure 9). At the same time, the depth of breathing (Vt) increased very dramatically as the speed of walking was incremented from "slow" to "medium" (see Figure 10). Thus, for low intensity walking, an increased ventilatory volume was realised via proportionately greater increments in tidal volume. With respect to the "fast" walking speed and all the running speeds (for all intents and purposes activities of a moderate intensity), the increased ventilatory volume was the product of both the frequency (see Figure 9) and the depth (see Figure 10) of breathing. In other words, for moderately intense

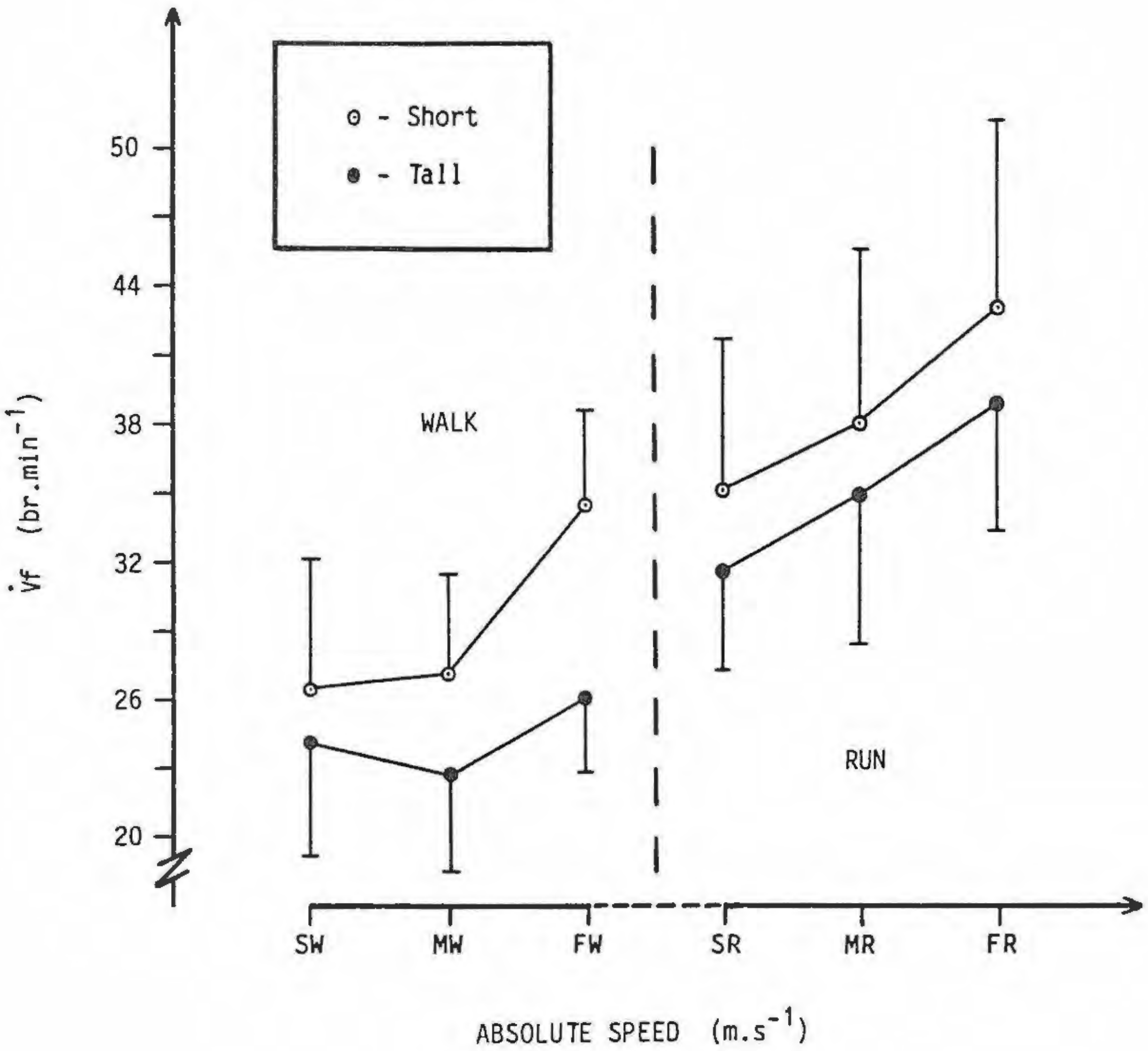


FIGURE 9: **the relationship between breathing frequency and locomotor speed expressed in absolute terms.**

For all conditions the short subjects recorded significantly higher breathing frequencies per unit speed than did the tall subjects. This size-related difference in the rate of breathing is likely the result of variations in the demand for oxygen. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, breathing frequency tended to increase as a curvilinear function of walking speed, and as a linear function of running speed.

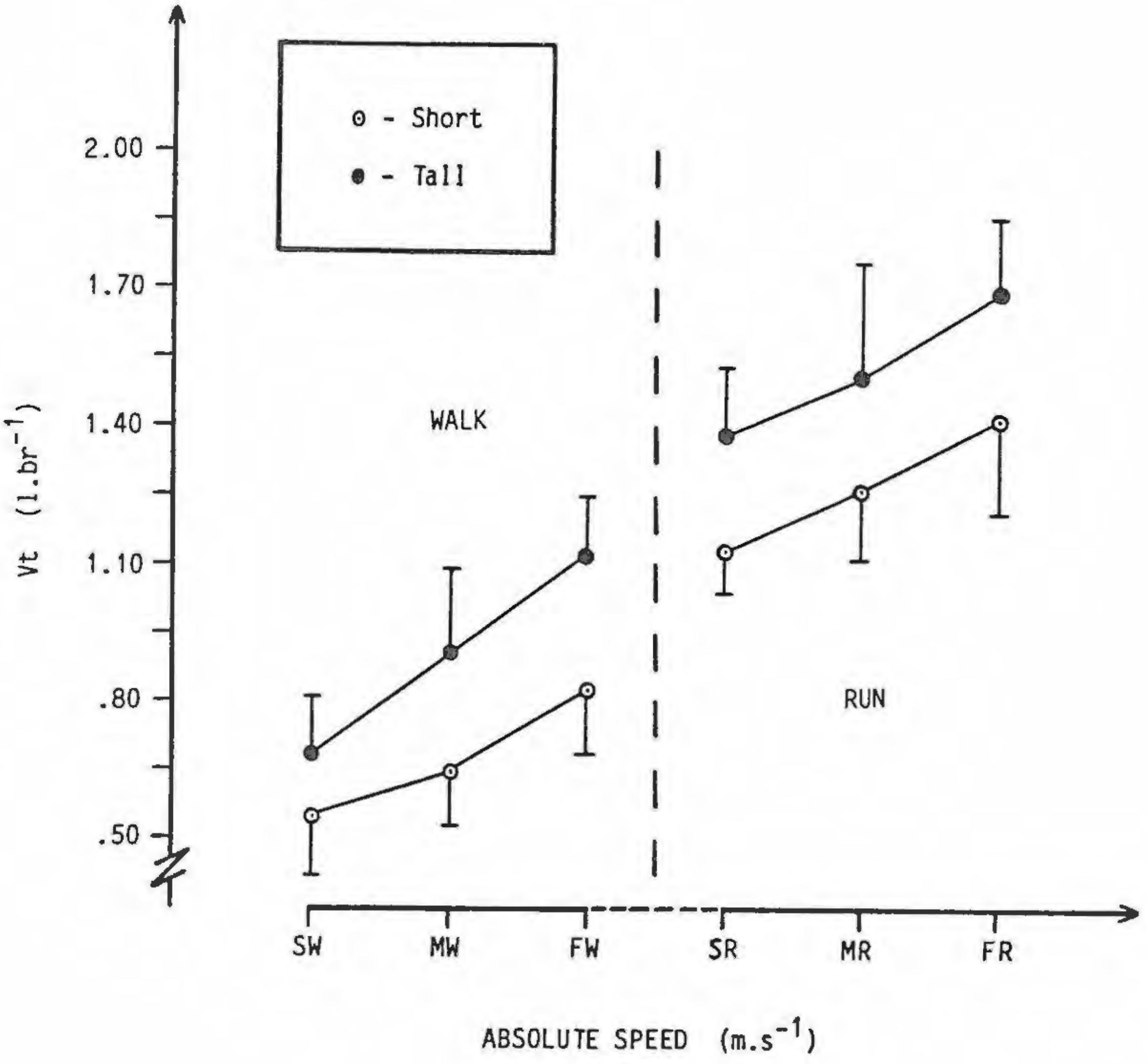


FIGURE 10: **the relationship between tidal volume and locomotor speed expressed in absolute terms.**

For all conditions the tall subjects recorded significantly greater tidal volumes per unit speed than did the short subjects. This size-related difference in the depth of breathing is likely the result of variations in lung capacity rather than variations in the demand for oxygen. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, tidal volume tended to increase as a linear function of walking and running speed.

locomotion, increments in the frequency and depth of breathing tend to contribute equally to the workload-imposed increase in ventilatory volume. It might be postulated that, had very intense locomotor speeds (ie. anaerobic) been included in this research, the depth of breathing would ultimately have plateaued, requiring that the frequency of breathing alone increase in order to facilitate the increment in ventilatory volume. It would appear therefore, that as the intensity of the locomotor activity is incremented, a greater demand is placed upon the breathing frequency (and lesser demand placed upon the tidal volume) to facilitate the workload-imposed increment in ventilatory volume.

Also evident from Figures 9 and 10 is the fact that significant differences were revealed between the stature groups with respect to both the frequency and depth of breathing across the entire spectrum of walking and running speeds. At any given rate of progression, the short subjects tended to ventilate significantly more rapidly than did the tall subjects (see Figure 9). This response once again suggests that the shorter subjects were energetically disadvantaged relative to their taller counterparts when compared at any locomotor speed expressed in absolute terms. Examination of Figure 10 reveals that, across the entire speed spectrum, the taller subjects generated a greater depth of breathing than did the shorter subjects. However, this can once again be attributed to the greater lung capacity of the taller (larger) subjects rather than to a greater relative demand for oxygen.

It is widely documented that the energy cost of running a given distance is constant and independent of the speed of progression (Margaria 1963, Margaria _et al_. 1963, Costill & Fox 1969, Margaria 1976, McMiken & Daniels 1976, Cavagna & Kaneko 1977, Mayhew 1977, Fellingham _et al_. 1978, Davies & Thompson 1979, Cavanagh & Kram 1985b, Daniels 1985, Montoye _et al_. 1985, McArdle _et al_. 1986). This caloric constant for running is reported by Davies and Thompson (1979) as $0.95 \text{kcal.kg}^{-1}.\text{km}^{-1}$, while Mayhew _et al_. (1979) put the figure at $1.04 \text{kcal.kg}^{-1}.\text{km}^{-1}$. However, the cost of running is generally expressed as about $1 \text{kcal.kg}^{-1}.\text{km}^{-1}$ (Margaria _et al_. 1963, Cavagna & Kaneko 1977, Cavanagh & Kram 1985b). It is clear from Figure 11 that the energy required to cover a given distance by the subjects participating in this research was in fact constant and independent of locomotor speed, although the specific caloric cost differed significantly between the short ($\bar{X} = 1.07 \text{kcal.kg}^{-1}.\text{km}^{-1}$) and tall ($\bar{X}$ = 0.96kcal.kg^{-1}.km^{-1}) stature categories. In other words, although the energy expended to run a given distance was independent of speed for all subjects, the actual caloric input was very obviously a function of stature - taller subjects expending fewer calories per kilogram of mass per unit distance (see Figure 11). It is interesting to note that the mean caloric expenditure recorded for running for all twenty subjects (ie. both short and tall) was approximately 1.01kcal.kg^{-1}.km^{-1}, a figure which compares very favourably with those reported in the literature. It is the author's contention, therefore, that although the caloric cost of running a given distance remains constant irrespective of the locomotor speed, the actual energy expended per unit distance is very much stature dependent - the caloric cost tending to decrease proportionately with increments in stature.

Unlike in running, the energy required to walk a given distance is very much dependent upon the rate of progession. Consequently, there must exist a speed of walking at which the energy expended per unit distance is minimised (Margaria et al. 1963, Margaria 1976). Further, as the speed of walking deviates from this optimum, the distance-specific caloric cost is substantially incremented. This tendency is clearly reflected in Figure 11, which suggests that the "medium" walking speed was less costly per unit distance than were both the "slow" and "fast" speeds. The caloric cost recorded for this "optimum" speed of walking (0.81kcal.kg^{-1}.km^{-1}) is considerably greater than the optimal caloric cost reported for walking (0.5kcal.kg^{-1}.km^{-1}) by Margaria et al. (1963) and Margaria (1976). However, it should be pointed out that the "medium" walking speed (1.39m.s^{-1}) was arbitrarily selected for the purposes of this research, and although it may have been the least costly of the three walking speeds prescribed in this study, there exist no grounds for suggesting that it represents the optimal and most cost efficient rate of walking for either the short or tall subjects.

Further evident from Figure 11 is the fact that there existed a significant difference between the short and tall subjects at each of the three walking speeds with respect to the locomotor energy cost. Accordingly, shorter subjects tended to expend more energy per kilogram mass per unit distance than did their taller counterparts. Again, the underlying assumption here is that at any given absolute speed of walking a greater energetic demand was placed upon the shorter subjects. Thus,

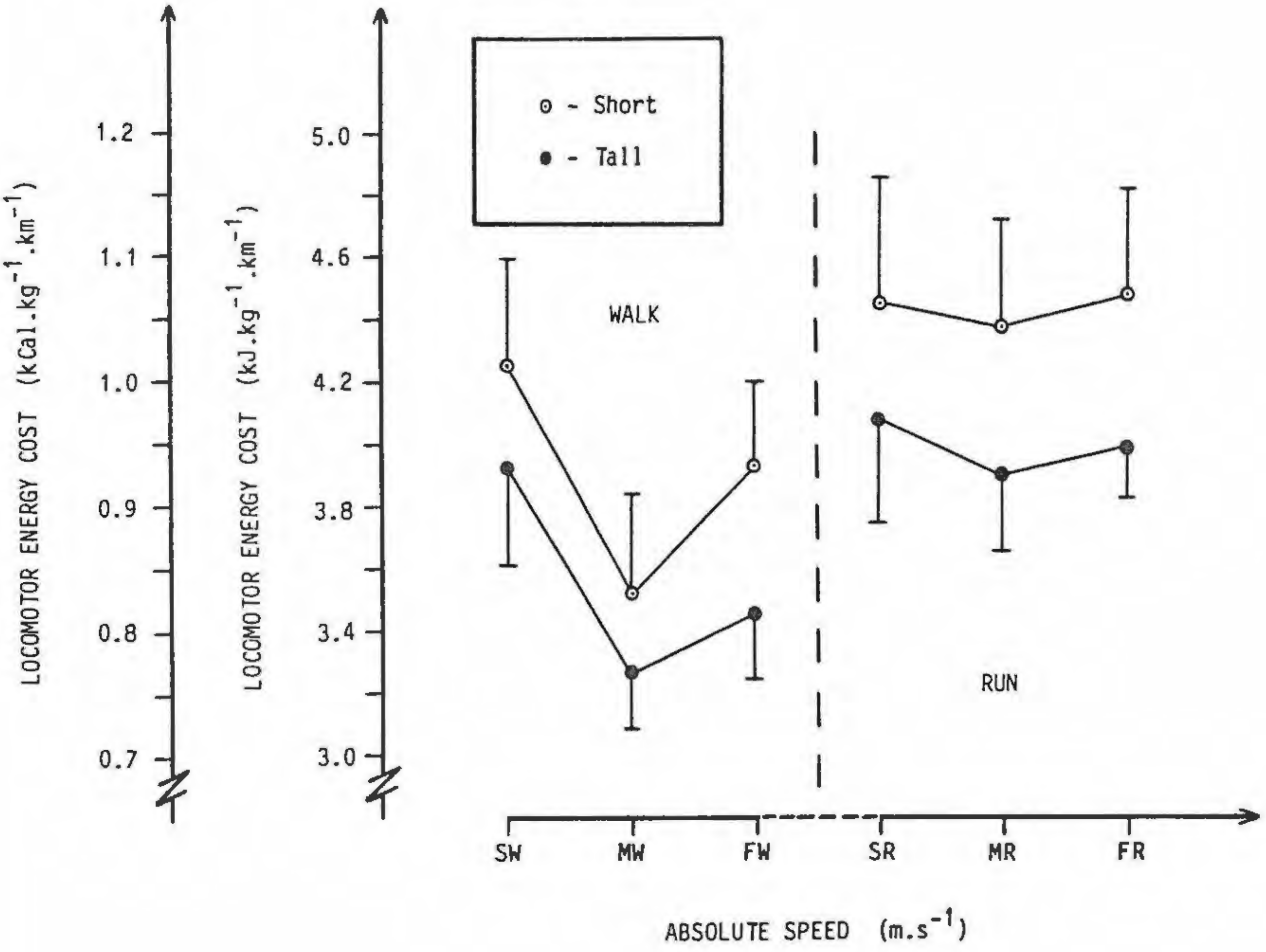


FIGURE 11: the relationship between locomotor energy cost and locomotor speed expressed in absolute terms.

For all conditions the short subjects expended significantly greater amounts of energy per kilogram body mass per kilometer travelled than did the tall subjects. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated no significant interactive effect. For the walking conditions, the locomotor energy cost was lowest for the medium speed (MW), suggesting that there is a speed of walking at which the expenditure of energy is optimal. For the running conditions, the locomotor energy cost was constant and independent of speed, suggesting that energy expended to run a given distance is the same regardless of the rate of progression. Consequently, the locomotor energy cost for walking is a function of both subject size and speed, while that for running tends to be a function of subject size only.

the caloric cost of walking appears to vary as a function of both locomotor speed and subject stature.

ii) Kinematic Responses

Evident from Figure 12 is the fact that as the absolute speed of walking was incremented, there was a proportionate and curvilinear decrease in locomotor cycle time. In other words, as the rate of walking was intensified, there was a relative decrease in the time between successive heel contacts of a given (left or right) foot. This decrease in cycle time was a direct function of the greater number of steps taken per unit time as the locomotor speed was increased. Thus, inasmuch as that the increased rate of progression in walking elicited an increased locomotor cadence (see Figure 13), it follows that the same increment in speed will also generate a very much reduced cycle or stride time. The same response cannot be reported for running, as is evidenced in Figures 12 and 13. For the running conditions, the cycle time tended to remain relatively constant despite increments in the locomotor speed (see Figure 12). Once again, this response was solely a function of the number of steps taken per unit time, and it is clear from Figure 13 that the locomotor cadence, too, remained relatively stable as the rate of progression (running) was incremented. It would appear, therefore, that increments in walking speed are largely realised via an increased cadence, while increments in the speed of running are considerably less influenced by this kinematic variable.

Evident in the literature is the fact that increments in the speed of walking or running are facilitated by either an increased cadence or an increased length of stride, or some combination of both (Bobbert 1960, Andriacchi et al. 1977, Astrand & Rodahl 1977, McArdle et al. 1986). From Figures 13 and 14 it is apparent that both cadence and stride length increased proportionately with increments in the locomotor speed. In fact, the frequency of step increased as a linear function of walking speed ($r = 0.917$), but as a curvilinear function of running speed ($r = 0.467$). On the other hand, the length of stride increased as a curvilinear function of walking speed ($r = 0.936$), but as a linear function of running speed ($r = 0.903$). In other words, the acceleration

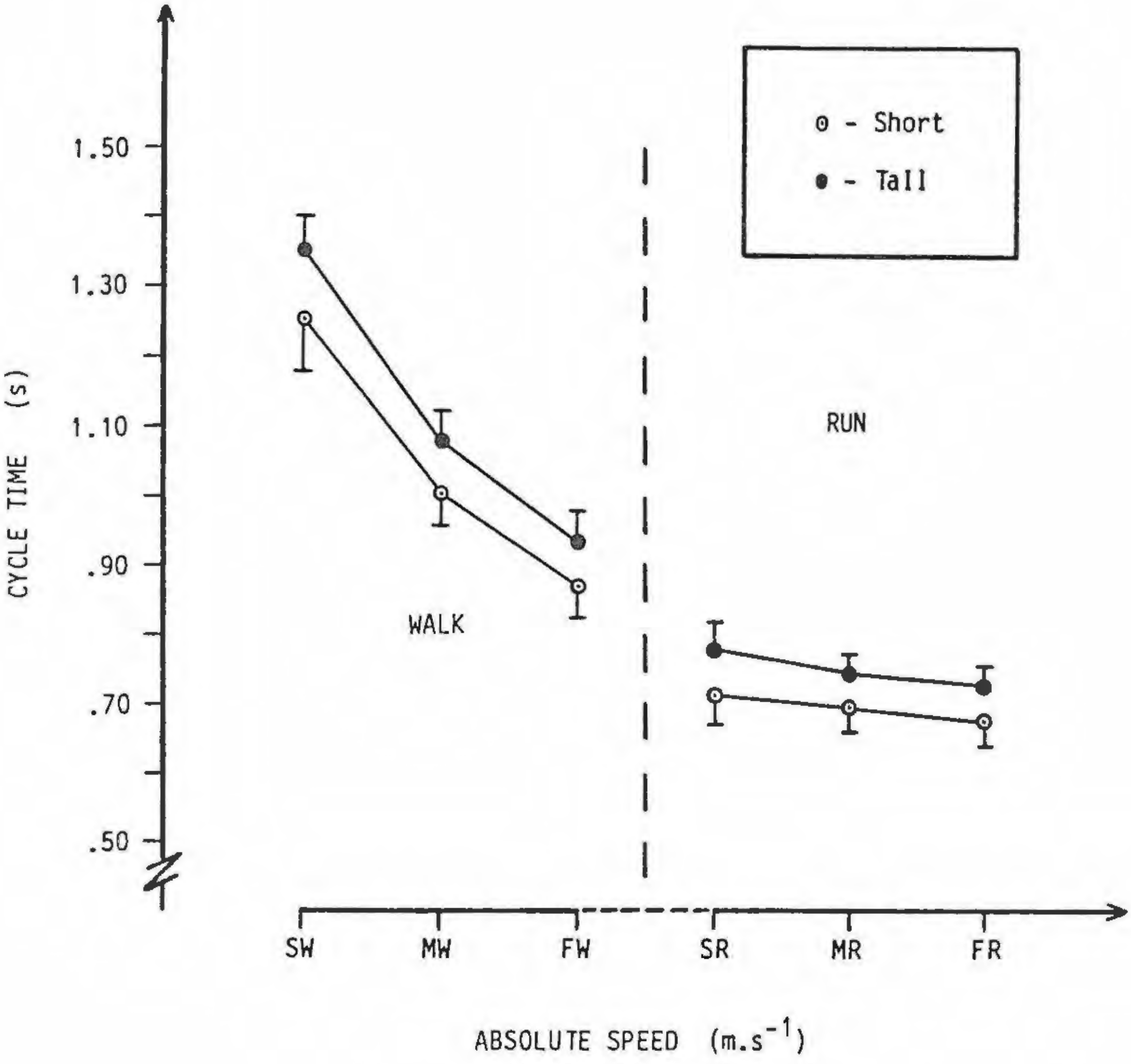


FIGURE 12: **the relationship between cycle time and locomotor speed expressed in absolute terms.**

For all conditions the tall subjects recorded significantly greater cycle times per unit speed than did the short subjects. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, cycle time tended to decrease as a linear function of walking speed, and to remain a relatively constant function of running speed.

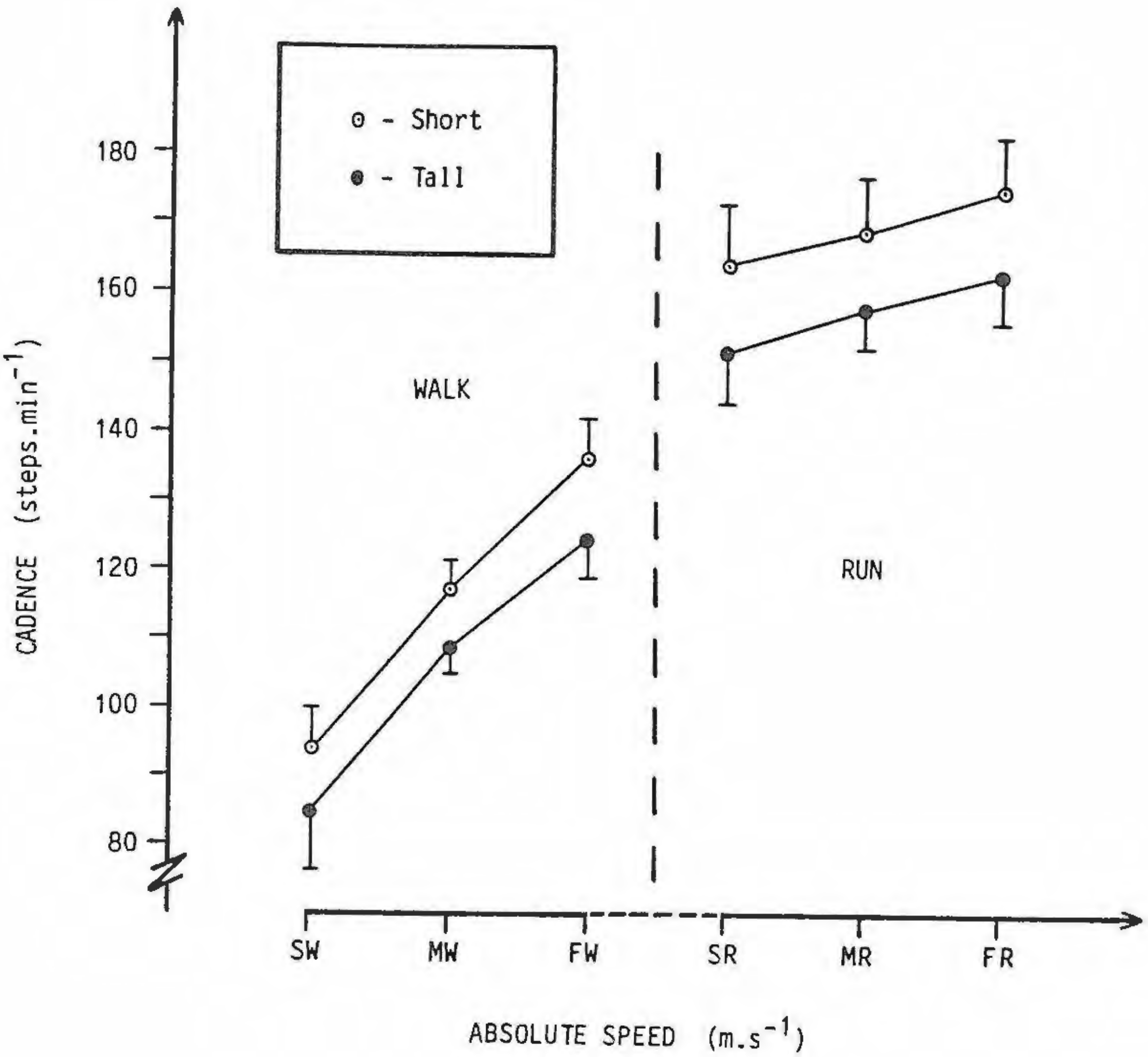


FIGURE 13: **the relationship between cadence and locomotor speed expressed in absolute terms.**

For all conditions the short subjects recorded significantly higher cadences than did the tall subjects. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, cadence tended to increase as a linear function of walking speed ($r = 0.917$), and remained a relatively constant function of running speed ($r = 0.467$).

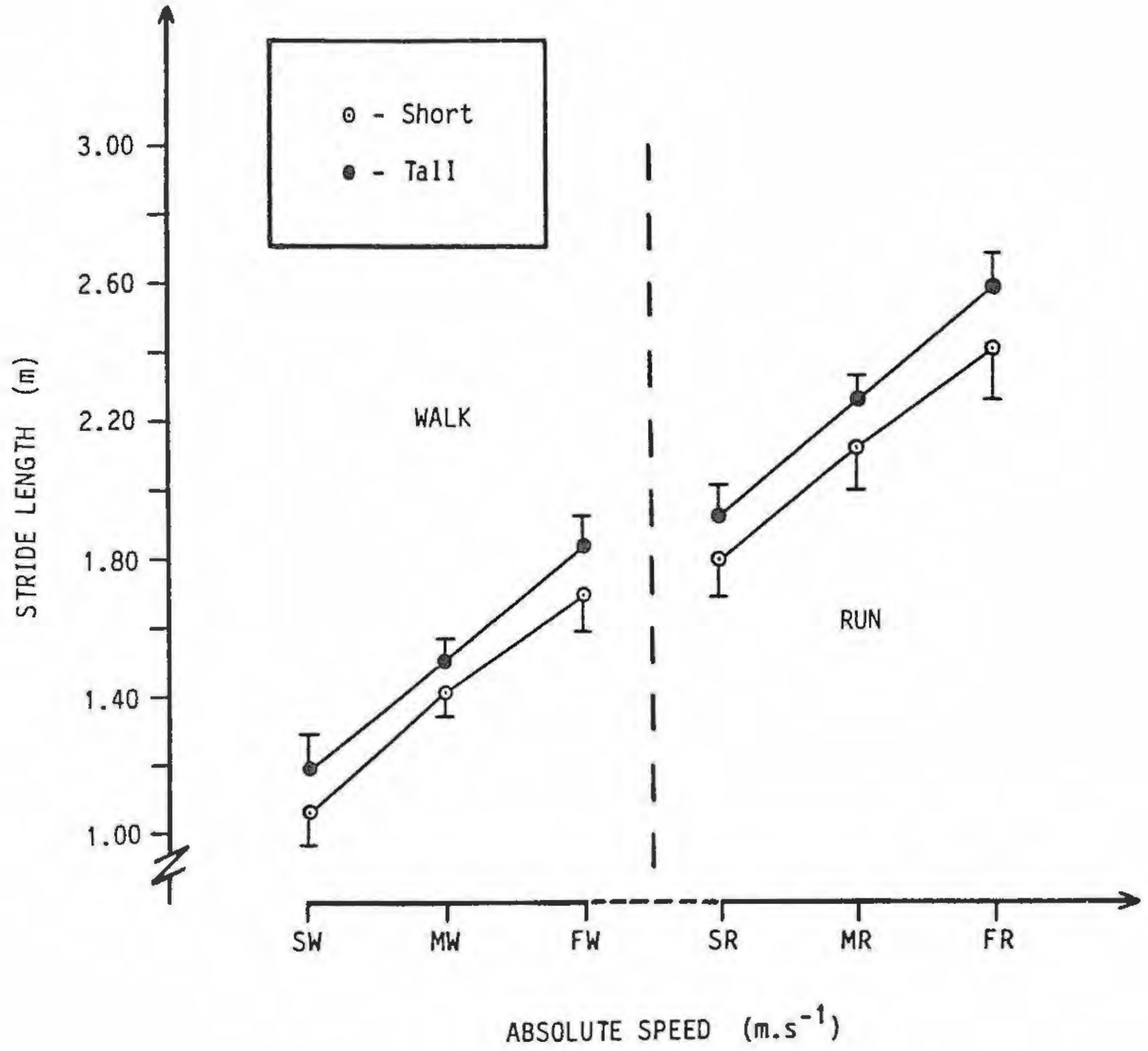


FIGURE 14: **the relationship between stride length and locomotor speed expressed in absolute terms.**

For all conditions the tall subjects recorded significantly greater stride lengths per unit speed than did the short subjects. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, stride length tended to increase as a linear function of walking ($r = 0.936$) and running ($r = 0.903$) speed.

in locomotor speed for both walking and running was facilitated via different combinations of the length and frequency of step - the particular locomotor mode dictating which of the two contributed most predominantly to increments in the rate of progression.

Furthermore, the exact relationship between the locomotor speed and cadence/stride length as revealed in this study tends to complement similar findings as reported in the literature. It is widely understood that increments in the speed of walking are largely realised via an increased locomotor cadence, while increments in the speed of running are the product of a more pronounced increase in the length of stride (Boje 1944, Erickson et al. 1946, Knuttgen 1961, Fukanaga et al. 1980, McArdle et al. 1986). This suggests that when the rate of locomotor progression is slow, increments in movement speed are effected via a more pronounced increase in the frequency of step, whereas changes in locomotor speed when the rate of progression is fast are primarily brought about by variations in the length of step. This tendency is reflected in Figure 13, which suggests that locomotor cadence increased quite sharply with increments in the speed of walking, but remained relatively stable with increments in the speed of running. Stride length, on the other hand, tended to increase as a linear function of speed for both walking and running. In other words, increases in cadence appear to have contributed gradually less to increments in the locomotor speed (and increases in the length of stride gradually more) as the rate of progression was accelerated.

This relationship between locomotor speed, cadence and stride length is the result of specific mechanical and energetic constraints placed upon the organism during horizontal locomotion. In a walking gait, there is a double-support prerequisite which dictates that the supporting limb remain in contact with the locomotor surface until the swinging limb strikes the ground. As a result of this double-support imperative, coincident with limitations placed upon pelvic rotation, the length of step in walking is restricted such that it becomes mechanically advantageous to realise an increase in speed via an increased cadence. Thus, at high speeds of walking a mechanically imposed "maximum stride length" is reached, beyond which increments in the rate of progression can only be realised via increases in the frequency of step. According to Dean (1965), this maximum length of stride is equivalent to two times the length of the lower-limb. However, for running gaits, which are not characterised by periods of double-support, the limitations placed upon pelvic rotation are rendered inconsequential by virtue of a locomotor action which allows the body to "glide" through the air. Hence, when running, an increase in both the frequency and the length of step are a suitable means of facilitating any increments in the rate of progression. Thus, in walking, variations in speed tend to be largely cadence-dependent, whereas in running (aerobic) variations in speed are very much dependent upon both the cadence and the stride length. It might be expected that in high intensity running (ie. sprinting), such variations in speed would become primarily dependent upon the length of stride (with cadence remaining relatively stable). This is because during sprinting an energetically imposed "maximum cadence" is likely reached, beyond which further increments in speed can only be realised via an increased length of stride.

In other words, just as there exist mechanical constraints which limit the effective length of stride during locomotion, there also exist energetic constraints which limit the effective frequency at which an animal can step. This is because the energy required to fuel human movement tends to increase in a curvilinear fashion with increments in the rate of muscular contraction - as the speed of muscular contraction is doubled, the related expenditure of energy is increased threefold (Elliot & Blanksby 1976). A point is ultimately reached, therefore, where it is energetically impossible to increment the rate of muscular contraction any further. In locomotor terms, a speed is reached beyond which it is no longer effective to increase the frequency of step, and increments in the rate of progression must consequently be facilitated solely via an increased length of stride. It is likely that this point of "maximum cadence" is attained only during very intense anaerobic locomotion (ie. sprinting), and is consequently not a factor influencing the energetics and kinematics of walking and running at sub-maximal speeds.

The preceding argument is more clearly expressed in Figure 15. For walking gaits, the locomotor cadence increased as a linear function of speed, while the locomotor stride length increased in a curvilinear fashion, tending to plateau at higher speeds. In other words, during walking, the stride length tended towards a <u>mechanically</u> imposed

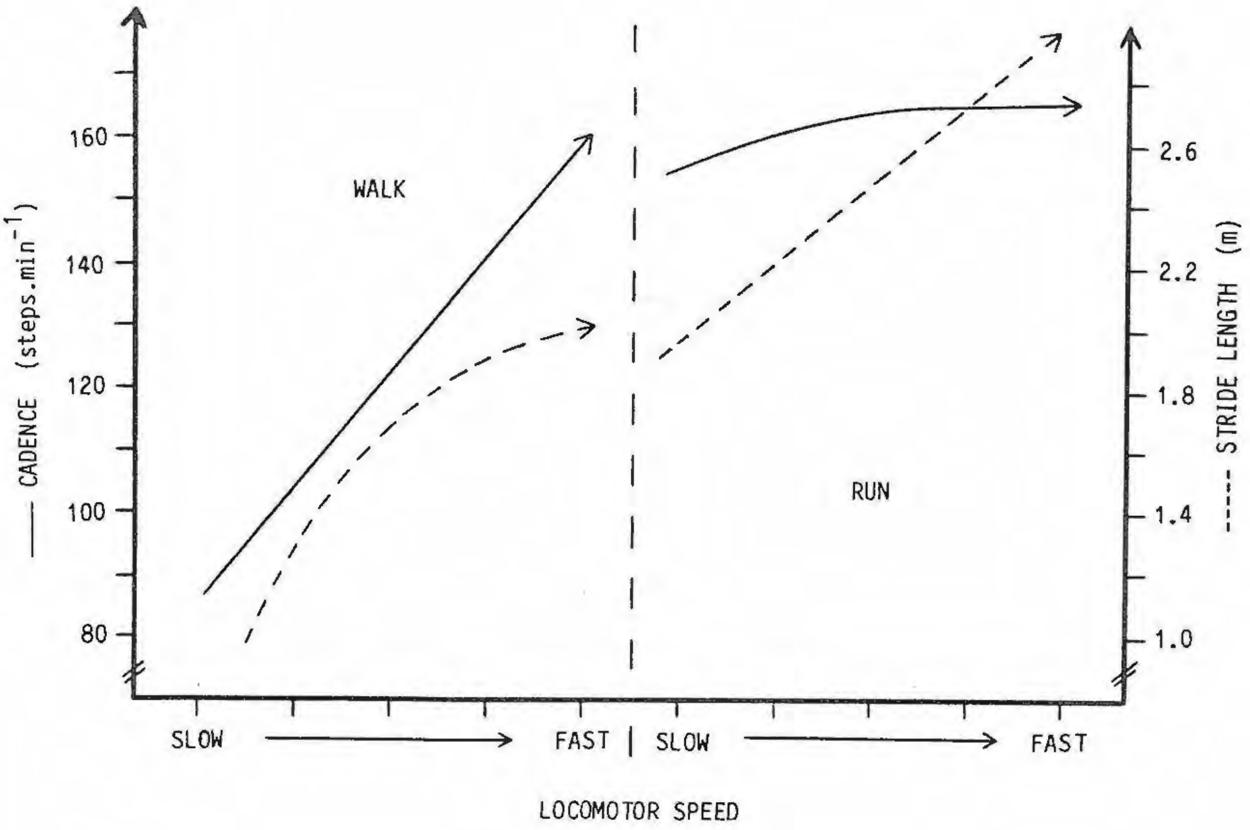


FIGURE 15: **a simplified extrapolation of the interactive relationship between cadence, stride length and locomotor speed expressed in absolute terms.**

For walking conditions, cadence tends to increase as a linear function of speed, while stride length tends to respond in a curvilinear fashion plateauing at fast speeds due to a mechanically imposed "maximum". For running conditions, on the other hand, stride length tends to increase as a linear function of speed, while cadence responds in a curvilinear fashion plateauing at fast speeds due to an energetically imposed "maximum".

"maximum", beyond which point increments in speed were facilitated via an increased cadence only. For running gaits, however, the opposite trend is observed. Stride length increased in a linear fashion with increments in the rate of progression, while cadence increased in a curvilinear fashion, tending to plateau at higher speeds. In other words, during running, the cadence tended towards an *energetically* imposed "maximum", beyond which point increments in speed were facilitated via an increased length of stride only. It would appear, therefore, that cadence becomes an ever more important means of increasing the speed of *walking* as the rate of progression is incremented. Stride length, on the other hand, becomes an ever more important means of increasing the speed of *running* as the rate of progression is incremented.

It is clear from Figure 12 that the cycle time for the short subjects was significantly lower than that for the tall subjects at any given absolute locomotor speed. Accordingly, at any specified rate of progression, shorter subjects completed each locomotor cycle significantly more quickly than did their taller counterparts. Once again, this would suggest that the same absolute speed of walking/running does not influence the gaits of short and tall subjects in exactly the same manner, and that short subjects tend to be more severely stressed per unit speed. The difference in cycle time between the two stature categories was a direct function of locomotor cadence, which was clearly higher at any given speed for the shorter subjects (see Figure 13). Thus, it would appear that any given locomotor intensity tends to elicit a greater frequency of step and reduced cycle time as the stature of the subject is decreased.

The lower cadence recorded for the taller subjects (as evidenced in Figure 13) was facilitated by a greater length of limb, and the consequent ability to move with significantly greater lengths of stride. In other words, by virtue of a greater length of lower-limb, the taller subjects were able to locomote at any given speed with a greater stride length which allowed them to reduce the number of steps required per unit time. The significantly greater stride lengths adopted by the taller subjects for any speed of walking or running are reflected in Figure 14.

The specific combination of cadence and stride length adopted by the subjects in this study for any given locomotor speed supports the findings of several investigators, who contend that smaller animals with shorter legs tend to move with a smaller length of stride and a greater cadence (Murray et al. 1964, Murray 1967, Rosenrot et al. 1980, Heglund et al. 1982, Taylor et al. 1982). In other words, in short subjects with short legs, the restricted length of stride is compensated for by an exaggerated frequency of step. On the other hand, taller subjects who have longer legs can afford to reduce their locomotor cadence by virtue of an ability to take longer steps.

It might have been expected that at any given absolute rate of progression the relative stride length (stride length as a fraction of stature) would have been the same for both short and tall subjects. However, it is clear from Figure 16 that this was not the case. In fact, for both walking and running, the shorter subjects tended to locomote with greater relative lengths of stride than did the taller subjects. Thus, even when expressed in terms relative to stature, there still existed a significant difference in the stride lengths of the two stature categories. This was the case for all speeds with the exception of the "slow" walk, at which the significant difference in relative stride length between the short and tall subjects did not materialise. However, for walking and running speeds generally, the relative stride length at any given speed tended to increase as an inverse function of subject stature. On the basis of this locomotor response, it may once again be argued that shorter subjects are more severely taxed when moving at any absolute speed of walking or running.

Some interesting responses were revealed with respect to the absolute durations of swing and support for both the stature groups at any given rate of progression. As would be expected, both swing and support time (absolute) decreased proportionately with increments in the speed of walking (see Figure 17). This response is a direct function of the previously reported speed-related decrease in locomotor cycle time. As the rate of progression was incremented, the duration of each successive locomotor cycle decreased and less time was made available for the absolute durations of both swing and support. The same cannot be reported for running, in which cycle time (and consequently the swing and support durations) tended to remain relatively stable despite significant increments in the locomotor speed (see Figures 12 and 17).

It was also revealed (see Figure 17) that for walking gaits, considerably more time was spent in the support phase of the locomotor cycle than in

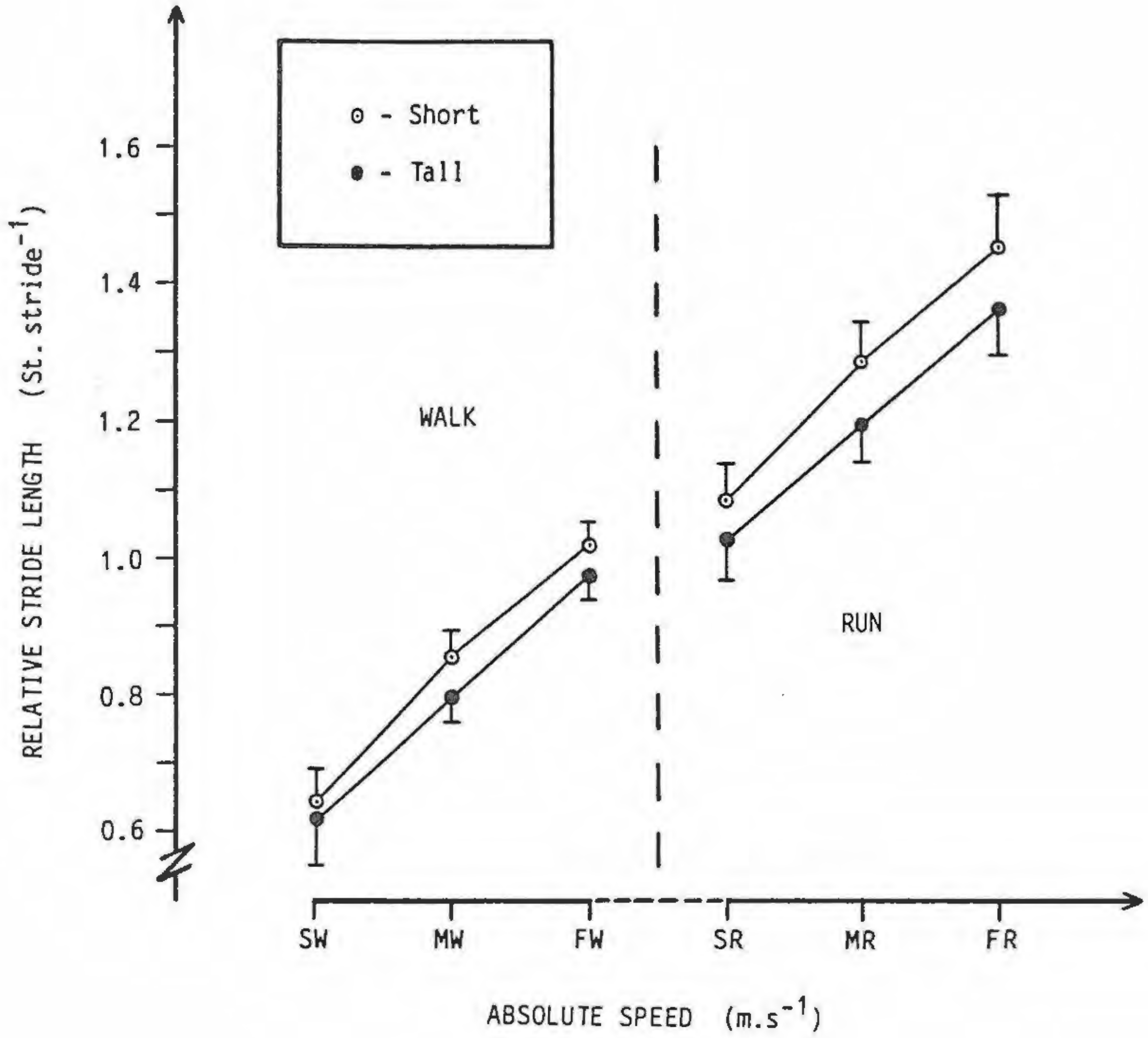


FIGURE 16: the relationship between relative stride length and locomotor speed expressed in absolute terms.

For all conditions the short subjects recorded significantly greater relative stride lengths per unit speed than did the tall subjects. When the rate of progression was expressed in absolute terms, locomotor speed and subject demonstrated no significant interactive effect. For both stature groups, relative stride length tended to increase as a linear function of walking ($r = 0.957$) and running ($r = 0.907$) speed.

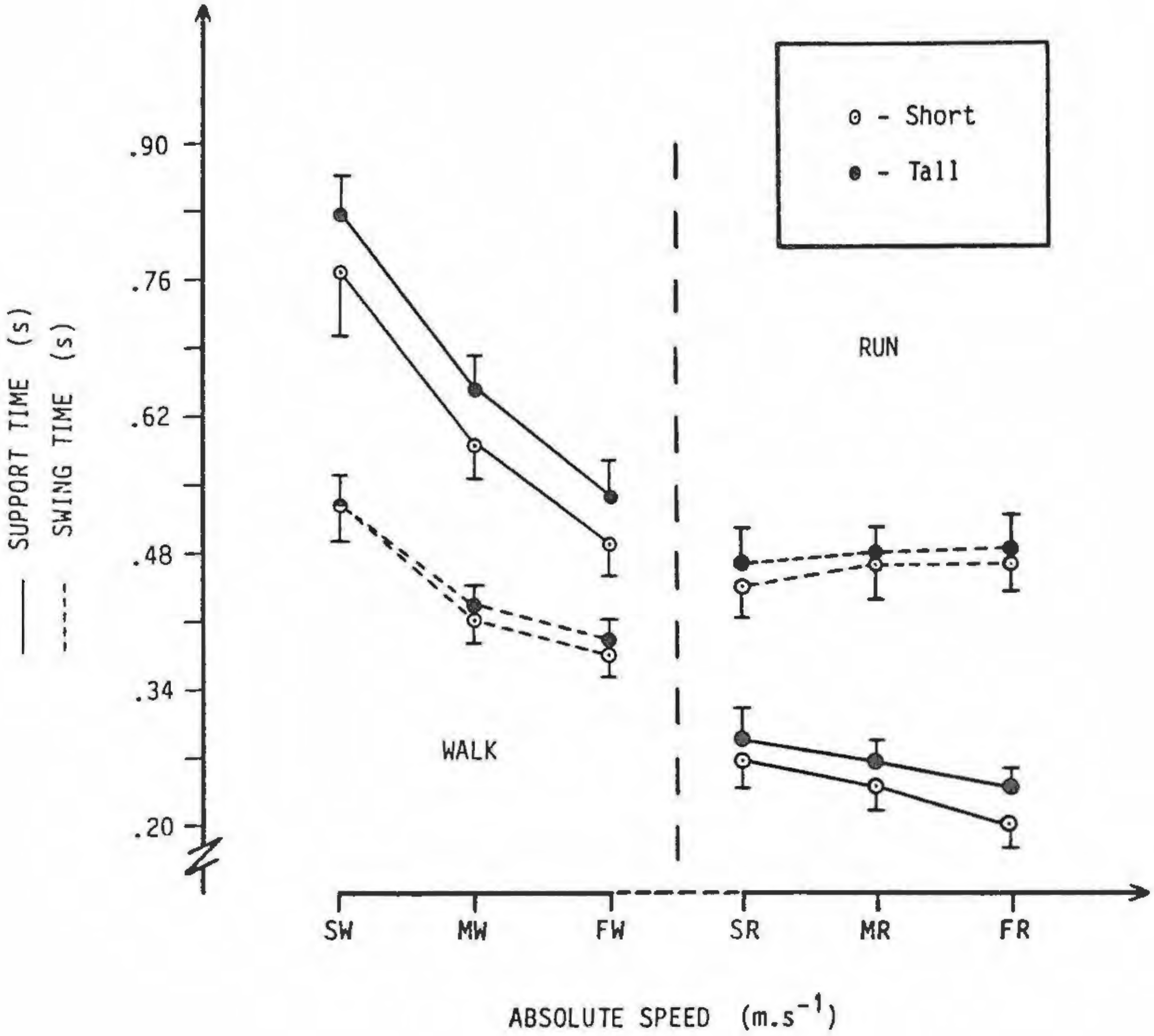


FIGURE 17: the relationship between support and swing times and locomotor speed expressed in absolute terms.

For all conditions the tall subjects recorded significantly greater support times per unit speed than did the short subjects. However, no significant differences were observed between the swing times of the short and tall subjects. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, support time and swing time tended to decrease as a linear function of walking speed, but remained a relatively constant function of running speed.

the swing phase, while for running gaits, the opposite was true and the majority of the cycle was spent in the swing phase. This is a function of the foot-floor contact prerequisites characteristic of the two locomotor modes. In walking, there is a double-support imperative which mechanically limits the length of stride, and dictates that increments in speed are more appropriately realised via increases in the frequency of step. As a consequence, the swing phase in walking tends to be "retarded", and is relatively short in duration compared to the contralateral support phase. In running, however, there is no double-support prerequisite, and an airborne phase renders increments in the length of stride an effective means of increasing the rate of progression. Consequently, the stride length in running can be exaggerated at the expense of an excessive frequency of step, and the duration (absolute) of support tends to decrease as more time is spent in the swing phase of the cycle.

The reduced support time and increased swing time characteristic of running gaits is clearly highlighted in Figure 17. However, the ratio of support time to swing time is more effectively demonstrated in Figure 18, which suggests that as the locomotor speed was incremented the support/swing ratio decreased proportionately. Clearly therefore, the support/swing ratio was greatest when the rate of locomotor progression was lowest, and tended to decrease as a fairly linear function of walking/running speed. Furthermore, the support/swing ratio was always greater for the walking gaits than it was for the running gaits, which suggests that as the locomotory mode changed from walking to running, a smaller fraction of the gait cycle was spent in the support phase.

It is interesting to note that no significant differences were reported between the two stature categories with respect to locomotor swing time, while such differences did manifest themselves for support time (see Figure 17). Accordingly, although tall subjects spent more time (absolutely) in support than did their shorter counterparts, the two stature categories spent similar times (absolutely) in the swing phase. This would suggest that at any given speed of walking or running, shorter subjects are inclined to "hurry" through the support phase of the locomotor cycle (relative to taller subjects). Consequently, the lower cycle times characteristic of the locomotor gaits of shorter subjects appear to be the function of a decrease in the absolute time spent in the

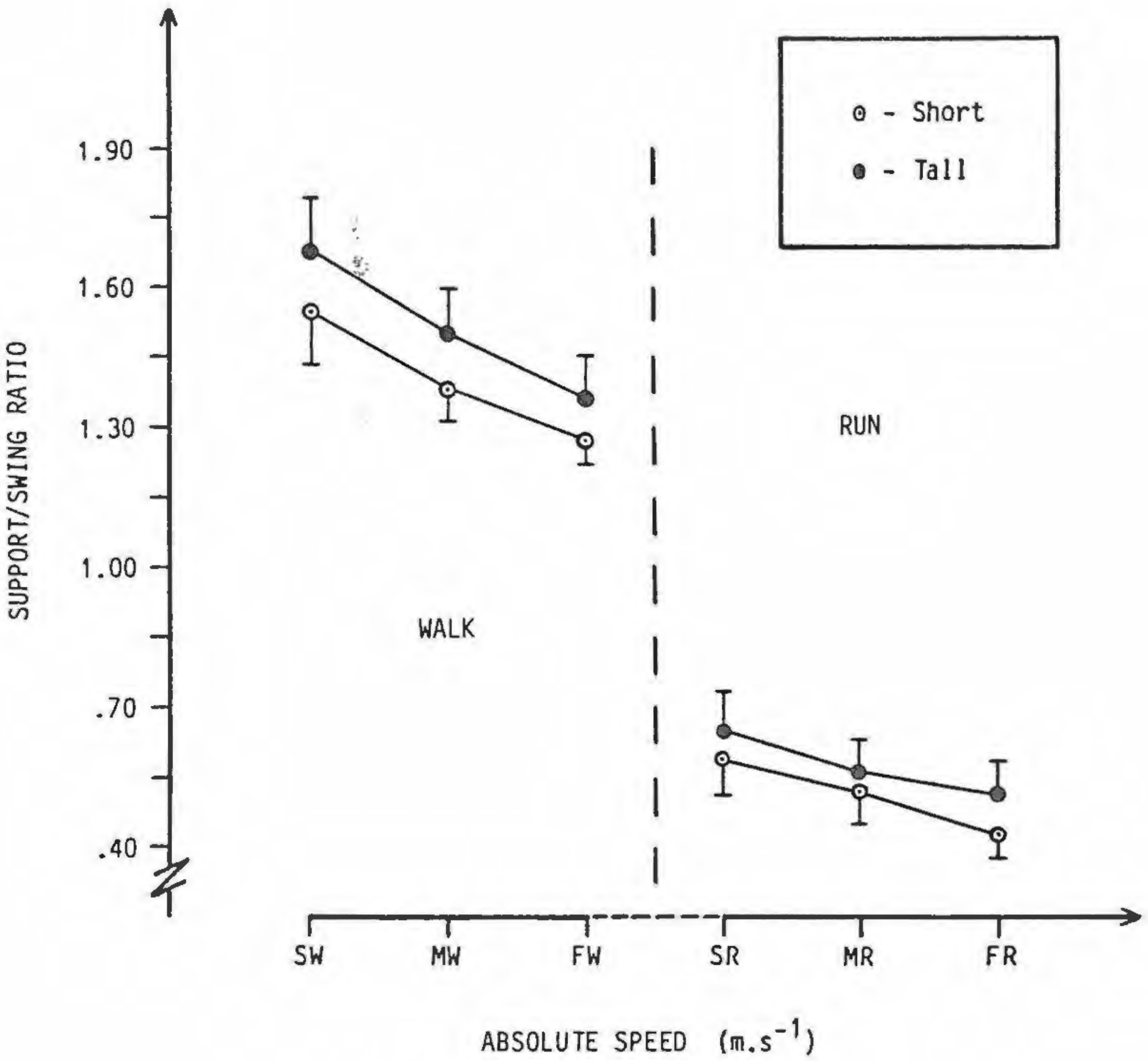


FIGURE 18: **the relationship between the support-to-swing ratio and locomotor speed expressed in absolute terms.**

For all walking conditions the tall subjects recorded significantly greater support-to-swing ratios per unit speed than did the short subjects. However, such differences did not manifest themselves for the running conditions. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, the support-to-swing ratio tended to decrease as a linear function of walking speed, but remained a relatively constant function of running speed.

support phase, rather than a decrease in the absolute time spent in the swing phase. Once again, this would suggest that the same raw speed ($m.s^{-1}$) does not influence the gait patterns of short and tall subjects in precisely the same way. Rather, shorter subjects tend to be more severely taxed when locomoting at any given absolute speed of walking or running.

iii) Psychophysical Responses

Figures 19 and 20 reveal that both central (cardiorespiratory) and local (muscular/joint) ratings of perceived locomotor exertion tended to increase in a curvilinear fashion with increments in the speed of walking and running. This suggests that the significant increments in the locomotor intensity were consciously monitored by the subjects, and accurately reported in terms of psychophysical estimations of effort. The ratings of perceived exertion were significantly correlated with locomotor speed for both walking and running, although the tightness of the fit tended to decrease as the rate of progression was incremented. This would suggest that ratings of perceived locomotor exertion may be effectively used to predict the intensity of "slow" to "medium" rates of progression, but that they tend to become less useful for the prediction of locomotor intensity as the rate of progression is increased.

It is interesting to note that the short and tall subjects reported similar ratings of perceived exertion at any given locomotor speed, and that there were no significant differences in either central or local ratings between the stature categories. This was the case despite previously reported significant differences in the locomotor oxygen cost between the short and tall subjects at any given speed. Thus, it would appear that ratings of perceived exertion and oxygen consumption are not highly correlated during locomotion. In fact, the correlations between RPE and oxygen consumption revealed in this research, although significant, were considerably lower than those suggested in the literature. This may be due to the fact that the subjects used in this study had no prior experience with respect to the psychological estimation of physical exertion, and may have inflated/suppressed their ratings by virtue of a poor understanding of the Borg scale as used for

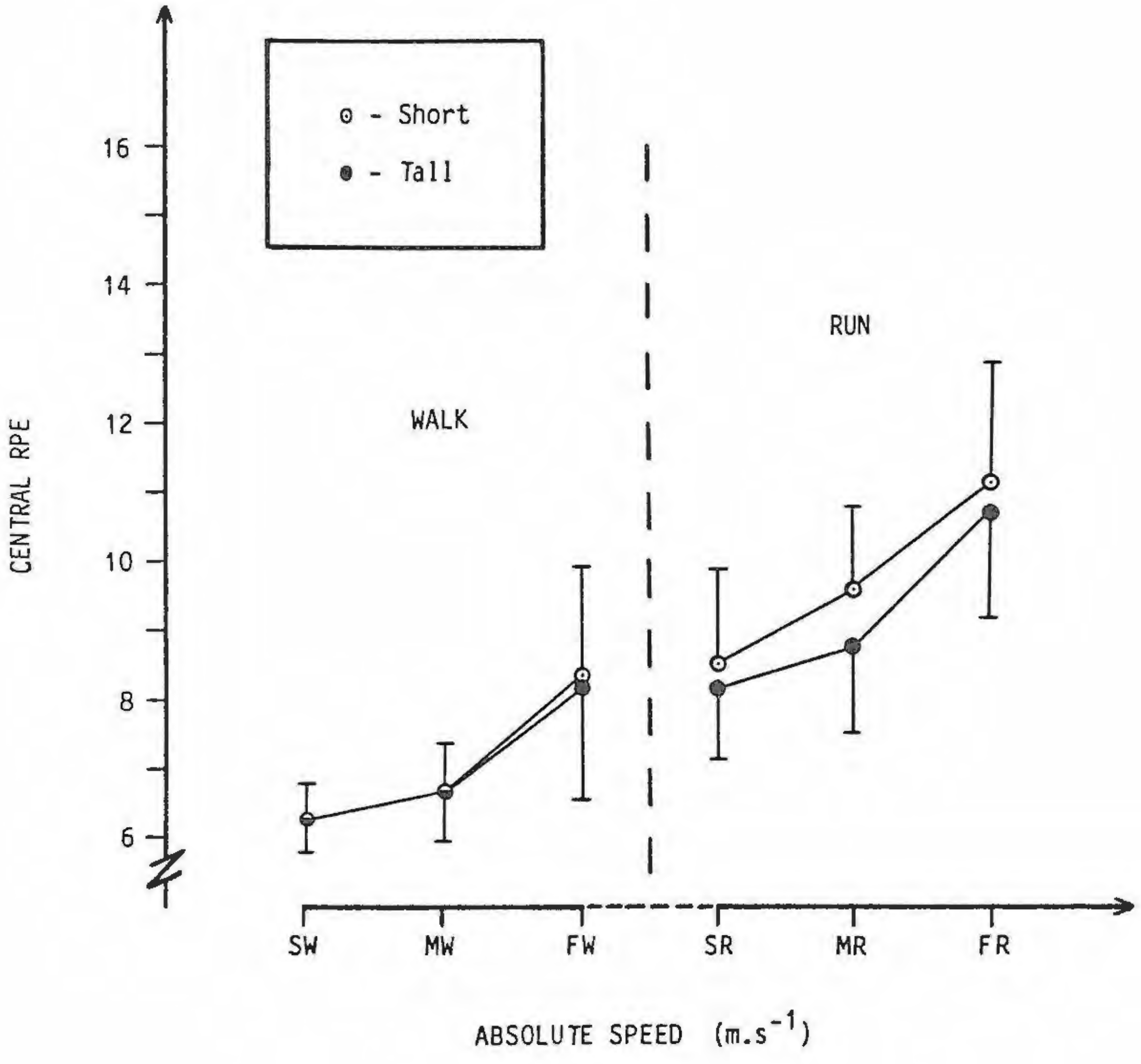


FIGURE 19: **the relationship between central ratings of perceived exertion and locomotor speed expressed in absolute terms.**

For all conditions no significant differences were observed between the central ratings of perceived exertion of the short and tall subjects. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, central RPE increased as a curvilinear function of walking ($r = 0.702$) and running ($r = 0.628$) speed.

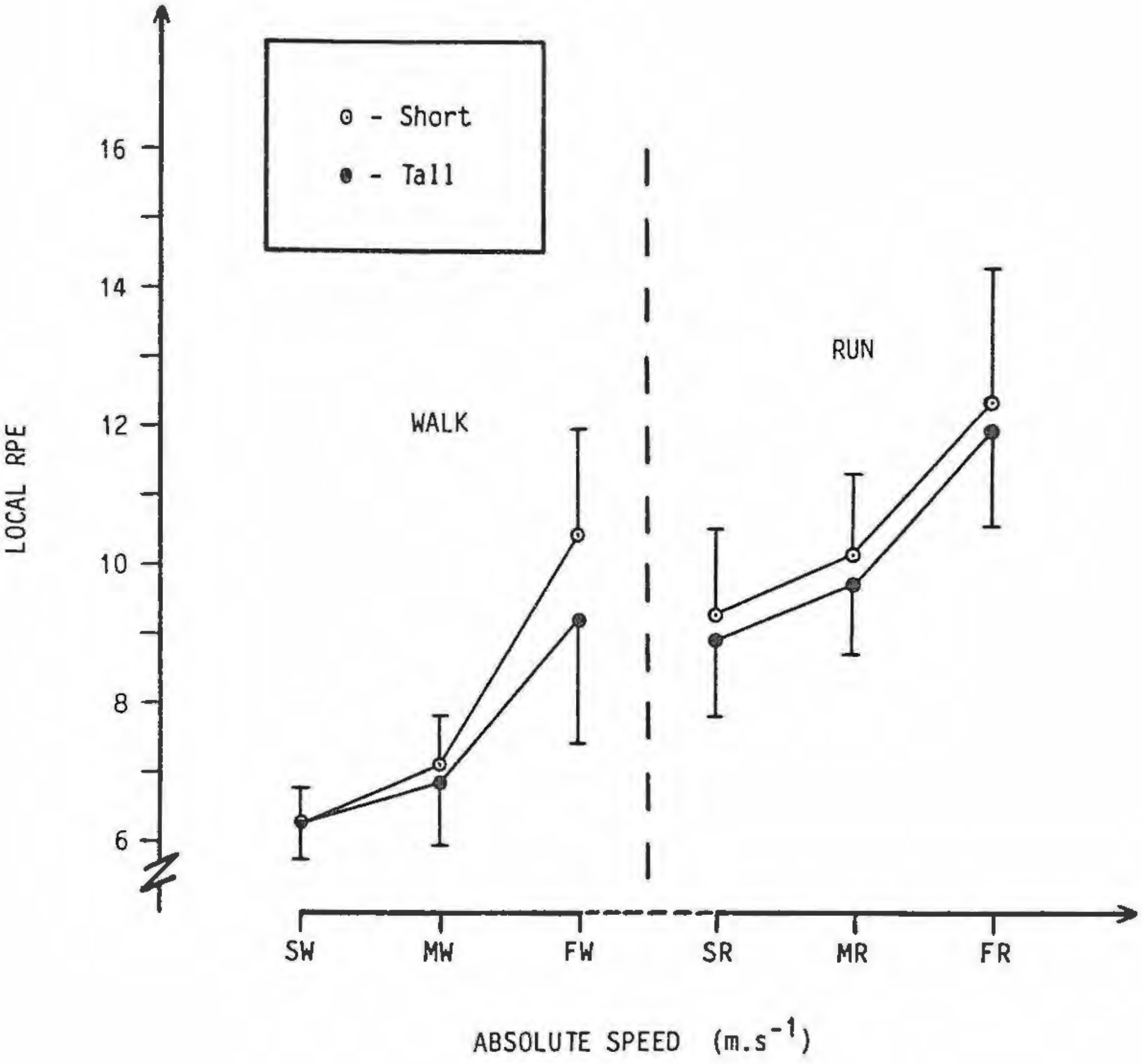


FIGURE 20: the relationship between local ratings of perceived exertion and locomotor speed expressed in absolute terms.

For all conditions no significant differences were observed between the local ratings of perceived exertion for the short and tall subjects. When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, local RPE tended to increase as a curvilinear function of walking ($r = 0.795$) and running ($r = 0.699$) speed.

the purposes of this study. This said however, it must be stressed that each subject was instructed to read an appropriate RPE instruction sheet (see Appendix 3) prior to experimentation.

Statistical analyses revealed that the correlation between local (muscular/joint) RPE and locomotor speed was greater than that reported between central (cardiorespiratory) RPE and the same speeds of walking and running. Further, it is clear from Figures 19 and 20 that the local ratings of locomotor exertion at any given speed were significantly greater than were the central ratings of exertion (especially at the higher locomotor intensities). From these observations it might be argued that the perception of exertion during low intensity locomotion (ie. "slow" walking) is mediated fairly equally by both local and central cues, while for higher intensity locomotion (aerobic) local cues tend to dominate the perception of effort. These findings are in agreement with assumptions made by Mihevic (1981), which propose that as the intensity of activity is incremented, the sensory input from local cues becomes gradually more influential. Thus, as the speed of locomotion (aerobic) is incremented, the sensations experienced in the working muscles and joints tend to contribute ever more significantly to the overall cognitive perception of locomotor strain. It would appear, therefore, that as long as the locomotor intensity remains aerobic in nature, local cues seem to dominate the effort sense. Further, only when locomotor speeds of and anaerobic nature are imposed (ie. fast walking and sprinting), do central cues become the primary cognitive cue driving the perception of exertion.

A final word on the psychophysical rating of exertion pertains to its use as a comparative tool in studies investigating the inter- and intra-individual variability characteristic of human movement. It is the author's contention that the use of a perceptual rating of physical effort has limited value in studies concerned with the between-subject variability in movement responses, as what one person perceives as "difficult" may be reported by other subjects as relatively "easy" (despite a possible parity with respect to physical conditioning). Further, subjects not experienced in the use of psychophysical ratings of exertion tend not to fully understand what is expected of them when asked to report numerically their perception of central or local effort, and they consequently fail to report such ratings consistently. On the other hand, subjects with considerable experience in the use of such rating scales tend to be influenced by an understanding that there generally exists a high correlation between psychological perception and physical effort, and they tend to bias their estimations accordingly. This is largely a function of the fact that the perception of work intensity tends to be a learned response (Rejeski 1981). It would appear, therefore, that the use of RPE as a measure of physiological stress has limited use with respect to inter-individual comparison (it tends to reflect more about the personality of the user than the intensity of the exercise). However, in terms of comparing the relative intensities of two different workloads with respect to one single individual (ie. on a within-subject basis), the use of RPE scales would be considerably more useful. For these reasons, and also because no significant differences were revealed between the two stature groups with respect to speed-related perceptions of local and central ratings of exertion, it was decided not to examine the relationship between the psychophysical perception of effort and locomotor speeds expressed relative to morphology.

iv) The Interaction of Locomotor Energetics and Kinematics

Thus far it has been suggested that, for both walking and running gaits, the energetic and kinematic responses of the short and tall subjects tend to significantly differ when the rate of progression is expressed in absolute terms. This significant between-group variability is largely the result of differences in the morphological make-up of the two stature-related groups, but they may be more obviously due to an interaction of certain energetic and kinematic variables.

Taylor et al. (1982) suggest that smaller animals expend more energy during locomotion at any given rate of progression than do larger animals by virtue of a shorter length of limb which manifests itself in a shorter stride length and higher cadence. This would suggest that the energy cost of locomotion responds as an inverse function of absolute limb length (or stature) - the energy cost of walking/running tending to increase as the length of the locomotor appendages decreases. It might be argued, therefore, that the variability in oxygen consumption between small and large animals moving at the same speed is purely a function of a difference in limb length, and can be directly attributed to associated differences in the number of steps taken per unit distance. In other words, the size-related variability in locomotor oxygen consumption is largely a function of a significant difference in locomotor cadence, which is itself a function of significant differences in the length of the locomotor appendages. This reasoning augments the findings of Heglund et al. (1982), which suggest that mass-specific locomotor energy cost per stride is the same for small and large animals moving at the same speed. More precisely, if the oxygen consumption at any given locomotor speed is reported as a fraction of the step frequency (ie. $\dot{V}O2$/cadence), then there will exist no significant differences between the energy expenditures of small and large animals.

Figure 21 clearly reflects this tendency, suggesting that at any given locomotor speed, the oxygen cost of walking or running was largely a function of the cadence freely adopted by the short and tall subjects. This effectively demonstrates that the oxygen consumed per step at any specific locomotor speed during either walking or running was approximately the same for both the short and tall subjects. Consequently, the greater amounts of oxygen consumed by the shorter subjects at any given absolute rate of progression was purely a result of the greater frequency of step adopted by these subjects. This increased cadence was, in turn, the function of a "retarded" length of step imposed by the relatively shorter length of limb. Hence, it is fairly apparent that as the length of the lower-limb (or the body) of an animal is increased, the gait pattern typical of that animal is characterised by a greater stride length, a lower cadence and a considerable decrease in the energy expended during locomotion. This would suggest that the energy expenditure of walking or running tends to increase as a reciprocal function of subject size, and as a linear function of subject cadence, with taller (larger) subjects tending to consume less oxygen per unit speed but the same oxygen per unit cadence than their shorter counterparts.

Also evident from Figure 21 is the fact that the oxygen cost per step increased as a linear function of locomotor speed (for both walking and running gaits). Accordingly, as the rate of progression was increased, more oxygen was required per step in order to fuel the motile system. In

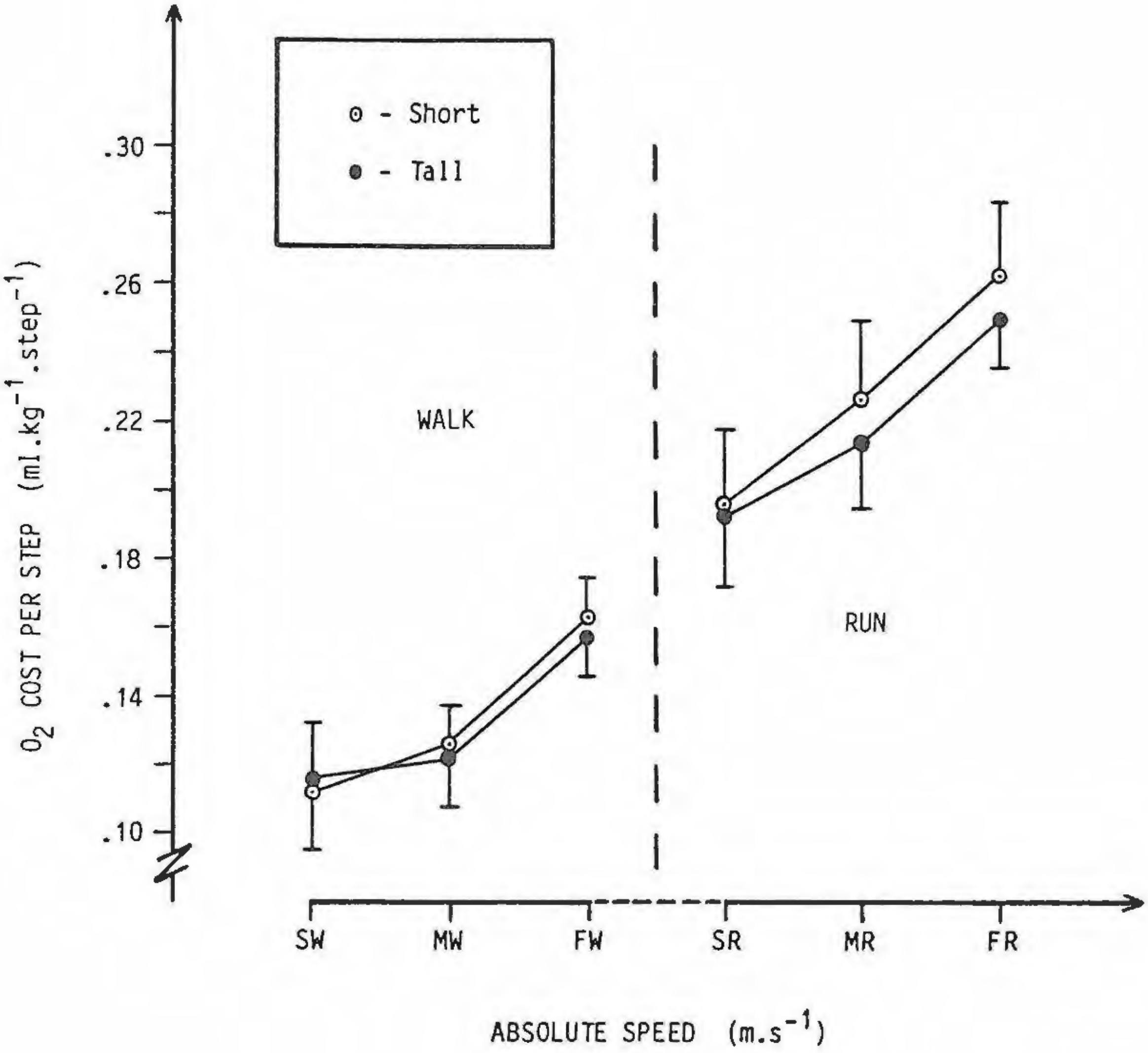


FIGURE 21: **the relationship between the oxygen consumed per step and locomotor speed expressed in absolute terms.**

For all conditions no significant differences were observed between the short and tall subjects with respect to the volume of oxygen consumed per step (per unit speed). When the rate of progression was expressed in absolute terms, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, the oxygen consumed per step tended to increase as a curvilinear function of walking speed (r = 0.804), and as a linear function of running speed (r = 0.796).

fact, significant across-sample correlation coefficients were revealed between the oxygen required per step and the speed of walking (r = 0.804) and running (r = 0.796). Thus, it would appear that cadence-specific oxygen consumption during horizontal locomotion tends to increase proportionately with increments in the rate of progression, and is approximately the same for all subjects despite possible variations (significant) in morphology.

Figure 22 demonstrates that the correlation between oxygen cost and locomotor cadence is considerably greater for walking (r = 0.91) than it is for running (r = 0.55). This is very likely due to the fact that during walking, increments in the rate of progression were largely realised via an increased cadence, whereas increments in the speed of running (aerobic) tended to be facilitated by increases in both cadence and stride length. As discussed earlier, the double-support prerequisite in walking limits the rotational capabilities of the pelvis and "retards" the length of step. Consequently, increments in walking speed are most effectively realised via an increased frequency of step, with the length of step remaining relatively constant. However, when running is adopted as the mode of progression, the double-support prerequisite is eliminated and the restraints associated with pelvic rotation are rendered largely inconsequential. Thus, in running, increments in speed are most effectively realised via increases in both the locomotor cadence and stride length (ie. a combined increase in both the frequency and length of step). This may account for the similar correlation coefficients reported between locomotor intensity and stride length for walking (r = 0.86) and running (r = 0.70) (see Figure 23). With respect to running of a maximal intensity (ie. sprinting), it might be argued that the correlation between locomotor intensity and stride length would be greater than that between locomotor intensity and cadence, suggesting that for running at maximum speed, incrememts in the rate of progression are largely facilitated via an increased length (rather than frequency) of step.

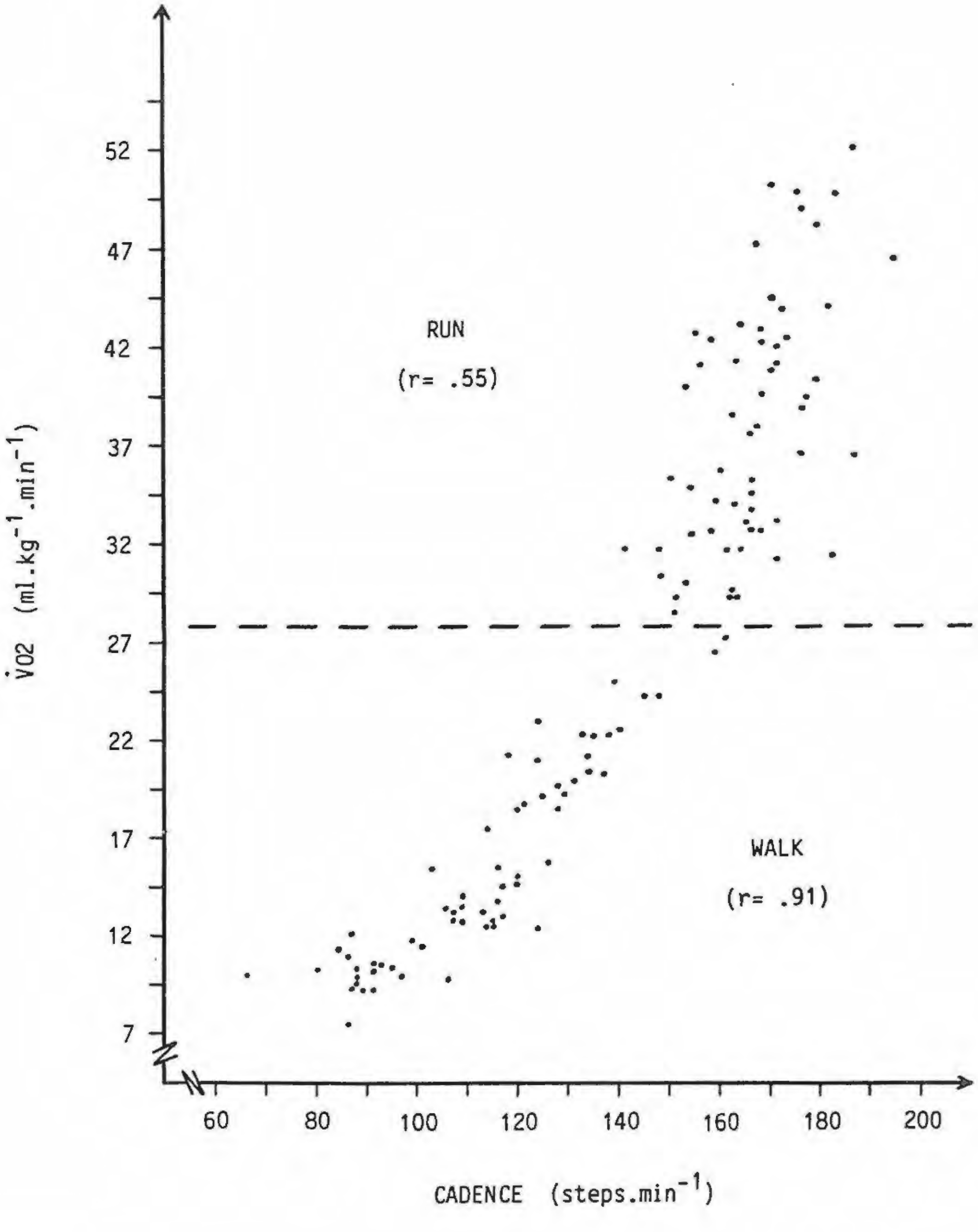


FIGURE 22: the relationship between cadence and locomotor intensity.

Cadence tends to increase as a linear function of locomotor intensity for walking gaits, but as a curvilinear function for running gaits. During fast running (sprinting), a point is reached when the contraction of muscle fibres attains an energetically imposed "maximum". Beyond this point, increments in the speed of running must be realised by factors other than an increased frequency of step.

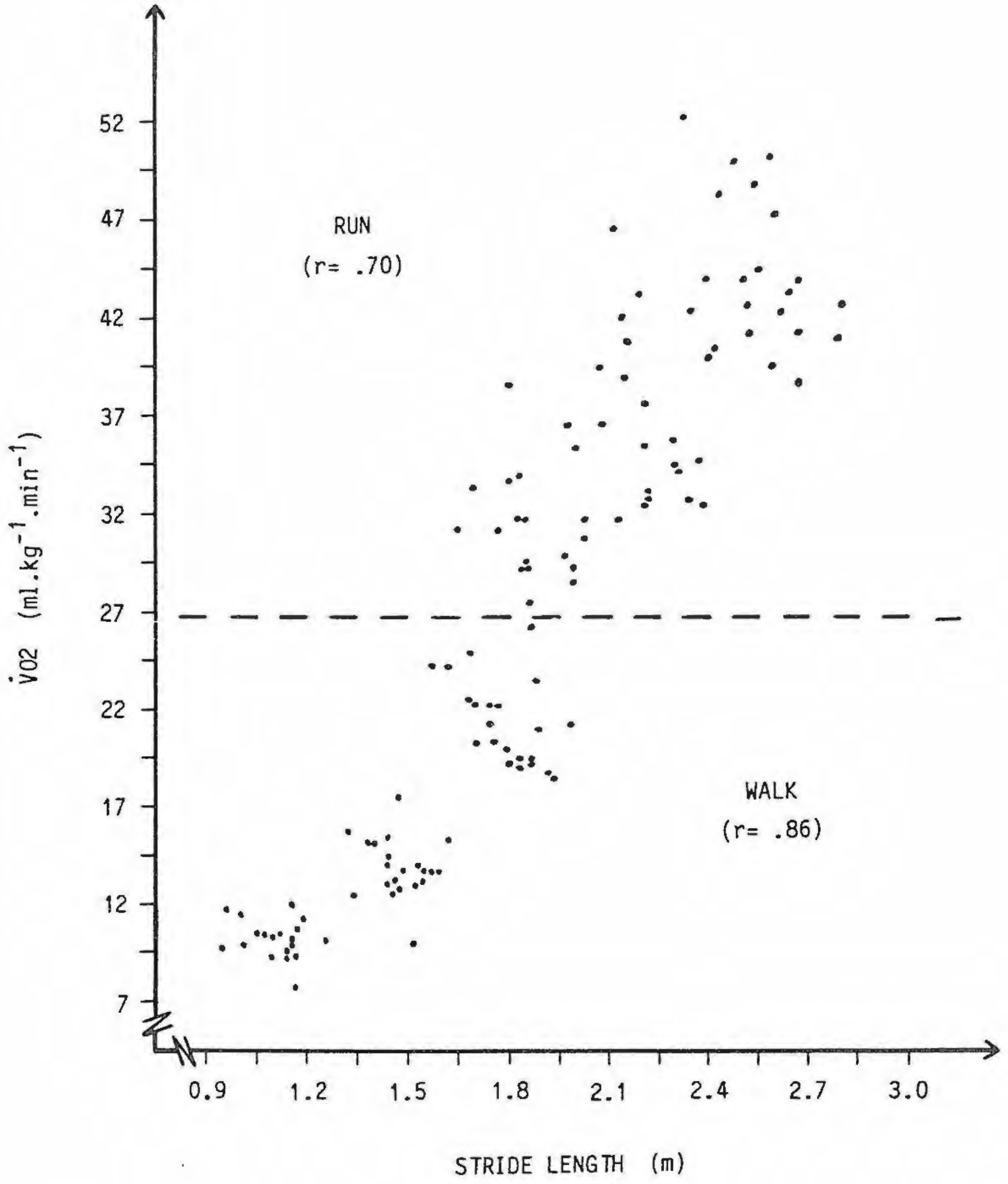


FIGURE 23: the relationship between stride length and locomotor intensity.

Stride length tends to increase as a curvilinear function of locomotor intensity during walking gaits, but as a linear function for running gaits. During fast walking, a point is reached when the stride length attains a mechanically imposed "maximum". Beyond this point, increments in the speed of walking must be realised via factors other than an increased length of step.

SUBJECT RESPONSES TO MORPHOLOGY-NORMALISED LOCOMOTOR SPEEDS

Having demonstrated that the same raw speed (ie. $m.s^{-1}$) influences the gaits of short and tall subjects in a dissimilar fashion, the primary aim of this research was to investigate the effects of a number of relative speed conditions upon the locomotor energetics and kinematics of the two stature categories. Relative speed is defined by Grieve (1968) as that rate of progression expressed with respect to some linear measure of size, and as such is used to "normalise" the speed of walking or running so as to reduce the inter-subject variability which may prevail in locomotor responses as the result of morphological differences. The assumption which follows, is that progression at speeds relative to some morphological dimension might be effective in minimising the variability in locomotor responses which generally manifests itself between morphologically similar subjects of unequal size.

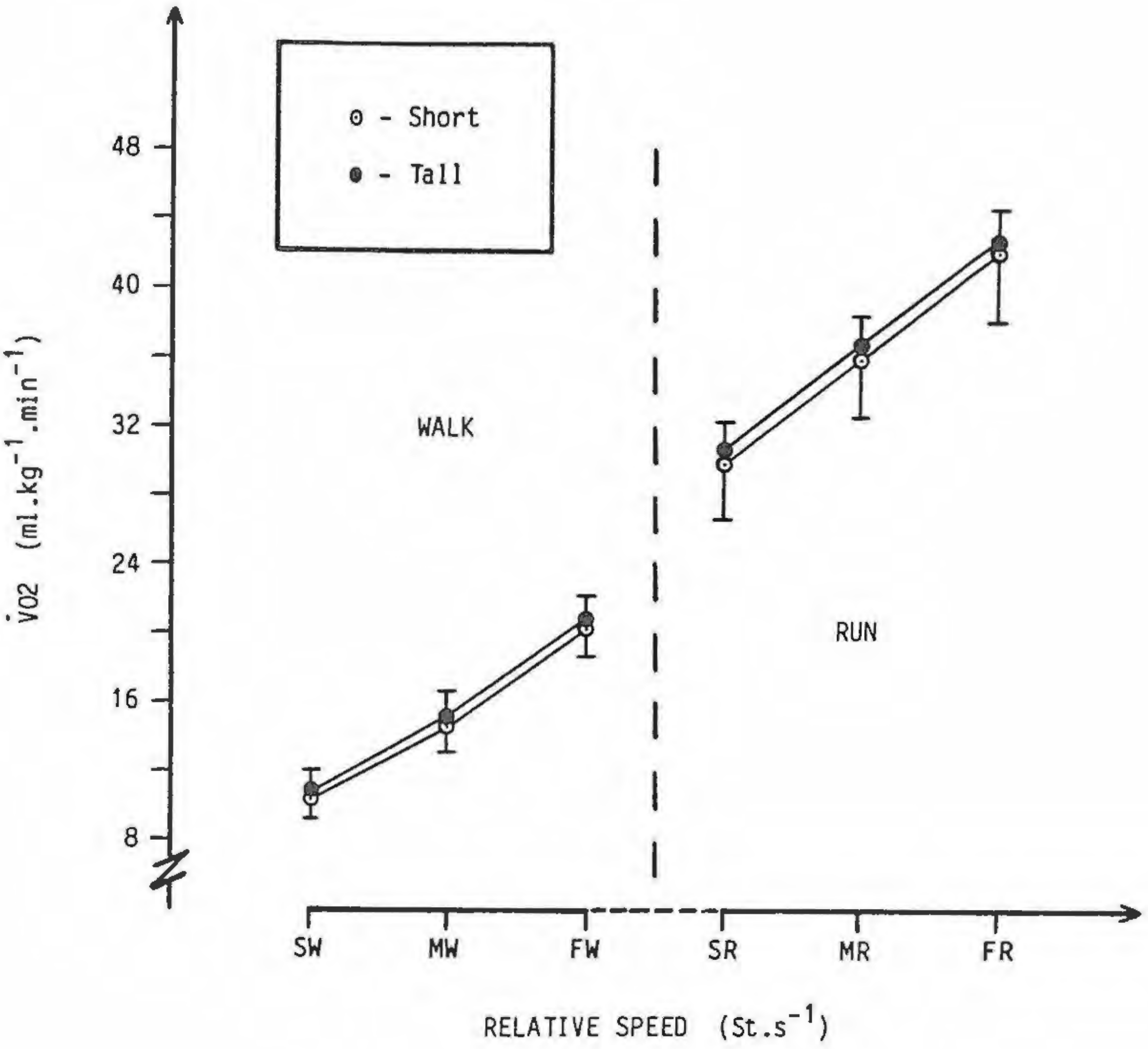
Each of the nine relative speed expressions as designed for the purposes of this study, described the rate of locomotor progression as a fraction of one or more linear morphological measures. It is evident from Table III that there existed statistically significant differences between the two stature categories with respect to the several morphological characteristics as selected for examination within the delimitations of this research. In other words, it may be confidently stated that the "short" and "tall" stature groups were made up of subjects differing very significantly in morphology. In essence, the "short" subjects were of a similar shape but significantly smaller size than were their "tall" counterparts. This established, the central focus of this investigation was to evaluate the between-group variability in the movement responses elicited following locomotion at morphologically-normalised rates of progression.

i) Energetic Responses

The most widely recognised function of any method of relativising locomotor speed is to "normalise" the rate of progression such that all subjects move at the same energetic cost, irrespective of differences in morphological make-up. In other words, any speed expressed in relative terms is designed such that it equalises the expenditure of energy associated with any mode of locomotion across the entire morphological spectrum. Since all rates of progression selected for the purposes of this study were aerobic in nature, it was considered appropriate to confine the energetic impact of relativising locomotor speed to one single physiological variable - namely oxygen consumption ($\dot{V}O2$). However, it might be argued that other physiological variables such as heart-rate (HR), carbon-dioxide production ($\dot{V}CO2$) and inspired ventilatory volume ($\dot{V}I$) would tend to mirror the trends observed with respect to oxygen consumption. Consequently, if relative speeds are effective in "normalising" locomotor oxygen consumption for all subjects irrespective of morphological differences, then they might be expected to "normalise" these other physiological variables equally well.

As can be seen from Figures 24 to 31, the use of several very different methods of relativising locomotor speed on a morphological basis were successful in eliminating previously demonstrated significant differences in the energetic cost of walking and running between short and tall subjects. That is to say, the relativisation of locomotor speed with respect to a number of morphological characteristics was effective in minimising quite considerably the inter-individual variability in energy expenditure ($\dot{V}O2$) typical of horizontal walking and running. In fact, for all but one of the relative speed expressions designed and prescribed for the purposes of this research, the locomotor rate was effectively "normalised" such that all subjects expended the same amount of energy per unit speed despite differences in morphology. Thus, when the rate of locomotor progression was expressed relative to some morphological dimension (such as stature), no significant differences were observed with respect to the oxygen consumptions of the short and tall subjects (see Table X, Appendix 4).

The only relative speed expression which was not successful in reducing the between-subject variability in speed-specific locmotor oxygen consumption, was that one which defined the rate of progression relative to the product of an androgyny index and stature (U/AI.St). In this instance, significant differences in oxygen consumption continued to manifest themselves between the short and tall subjects at any given relative locomotor speed. In fact, progression at a speed in units relative to the product of androgyny index (AI) and stature (St) tended



<u>FIGURE 24</u>: **the relationship between oxygen consumption and locomotor speed expressed relative to stature.**

For all conditions no significant differences were observed between the oxygen consumptions of the short and tall subjects. When the rate of progression was expressed relative to stature, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, oxygen consumption tended to increase as a linear function of that speed (walking and running) expressed as a fraction of stature.

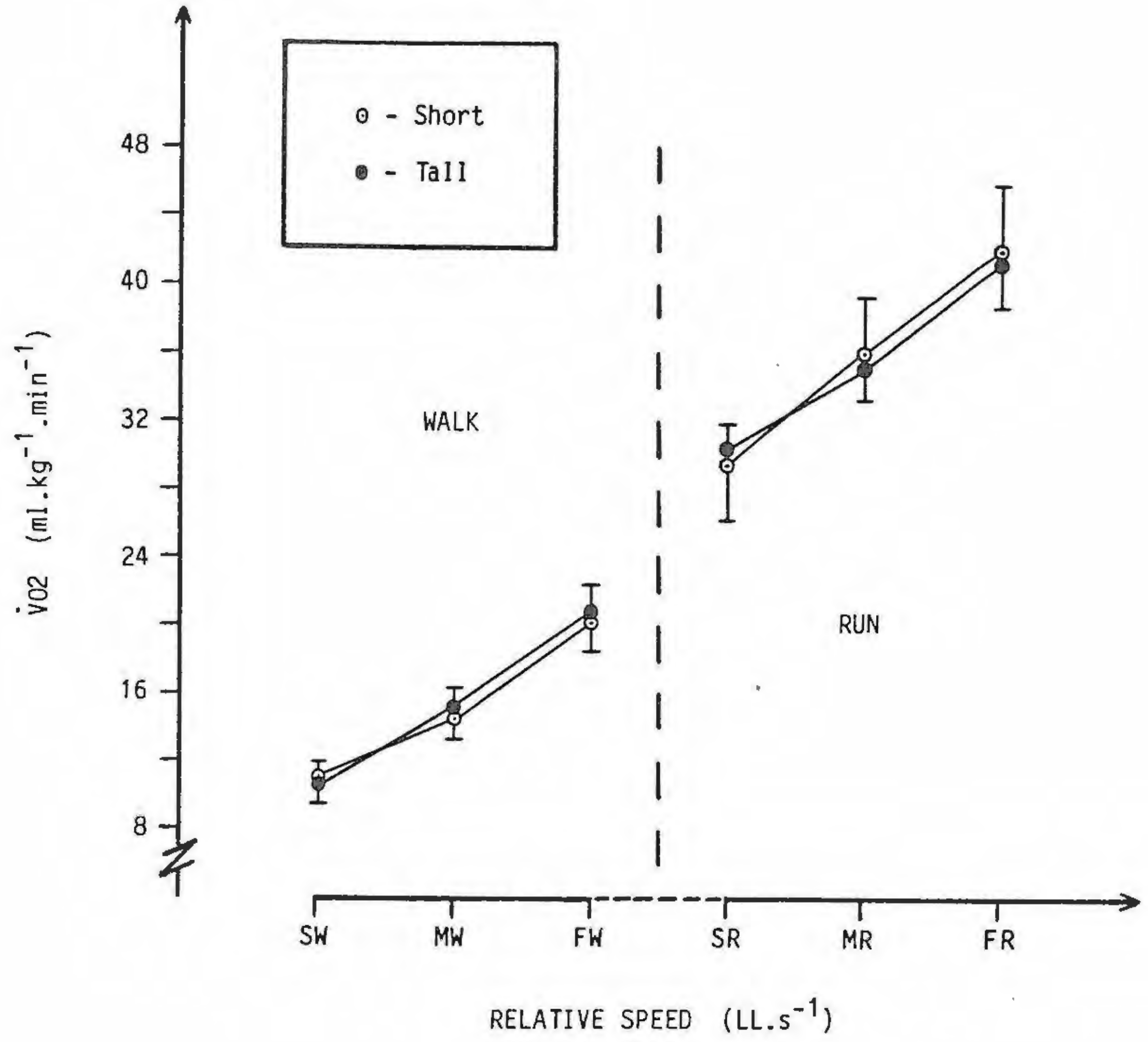


FIGURE 25: **the relationship between oxygen consumption and locomotor speed expressed relative to leg length.**

For all conditions no significant differences were observed between the oxygen consumptions of the short and tall subjects. When the rate of progression was expressed relative to leg length, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, oxygen consumption tended to increase as a linear function of that speed (walking and running) expressed as a fraction of leg length.

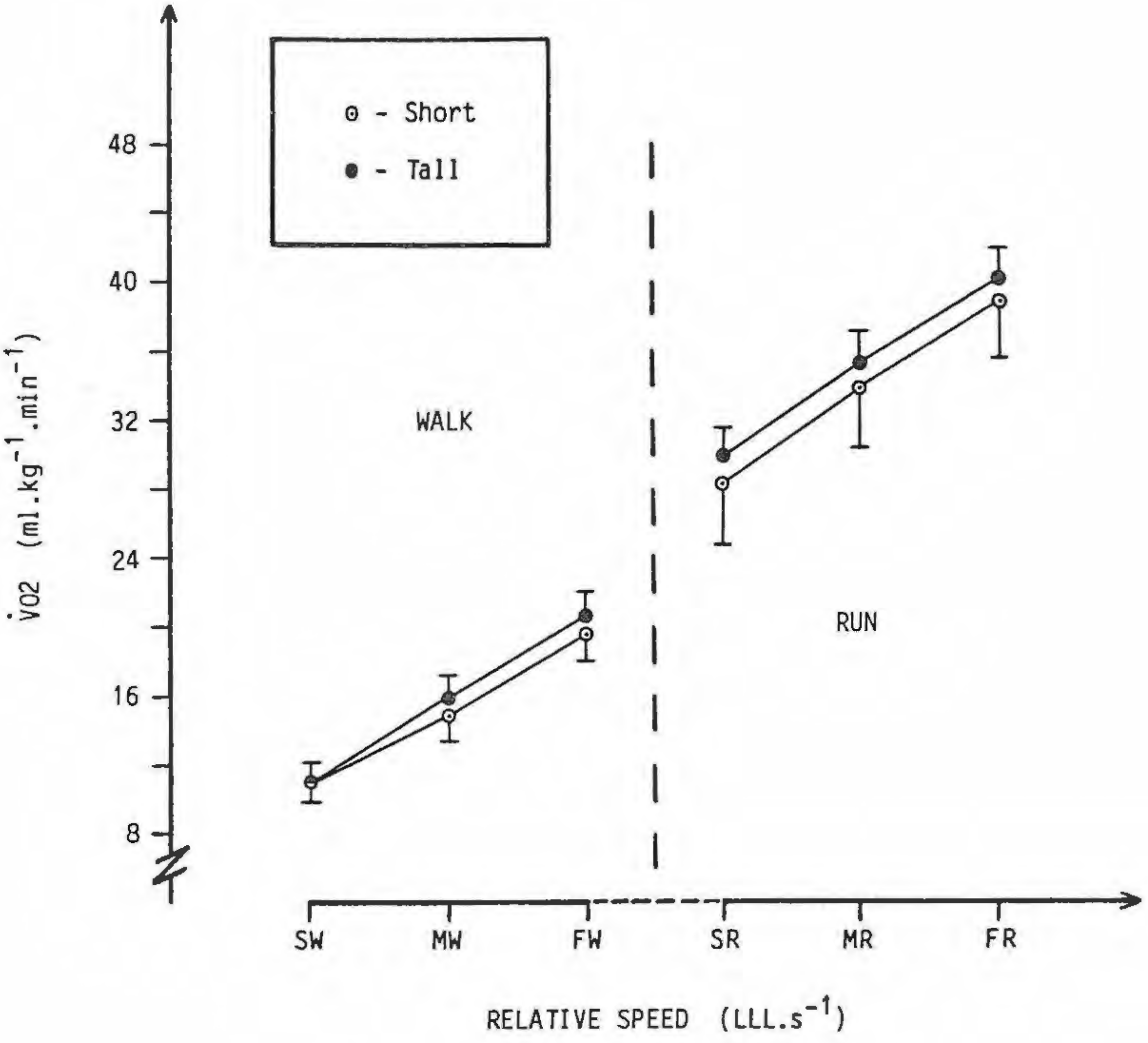


FIGURE 26: the relationship between oxygen consumption and locomotor speed expressed relative to lower-limb length.

For all conditions no significant differences were observed between the oxygen consumptions of the short and tall subjects. When the rate of progression was expressed relative to lower-limb length, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, oxygen consumption tended to increase as a linear function of that speed (walking and running) expressed as a fraction of lower-limb length.

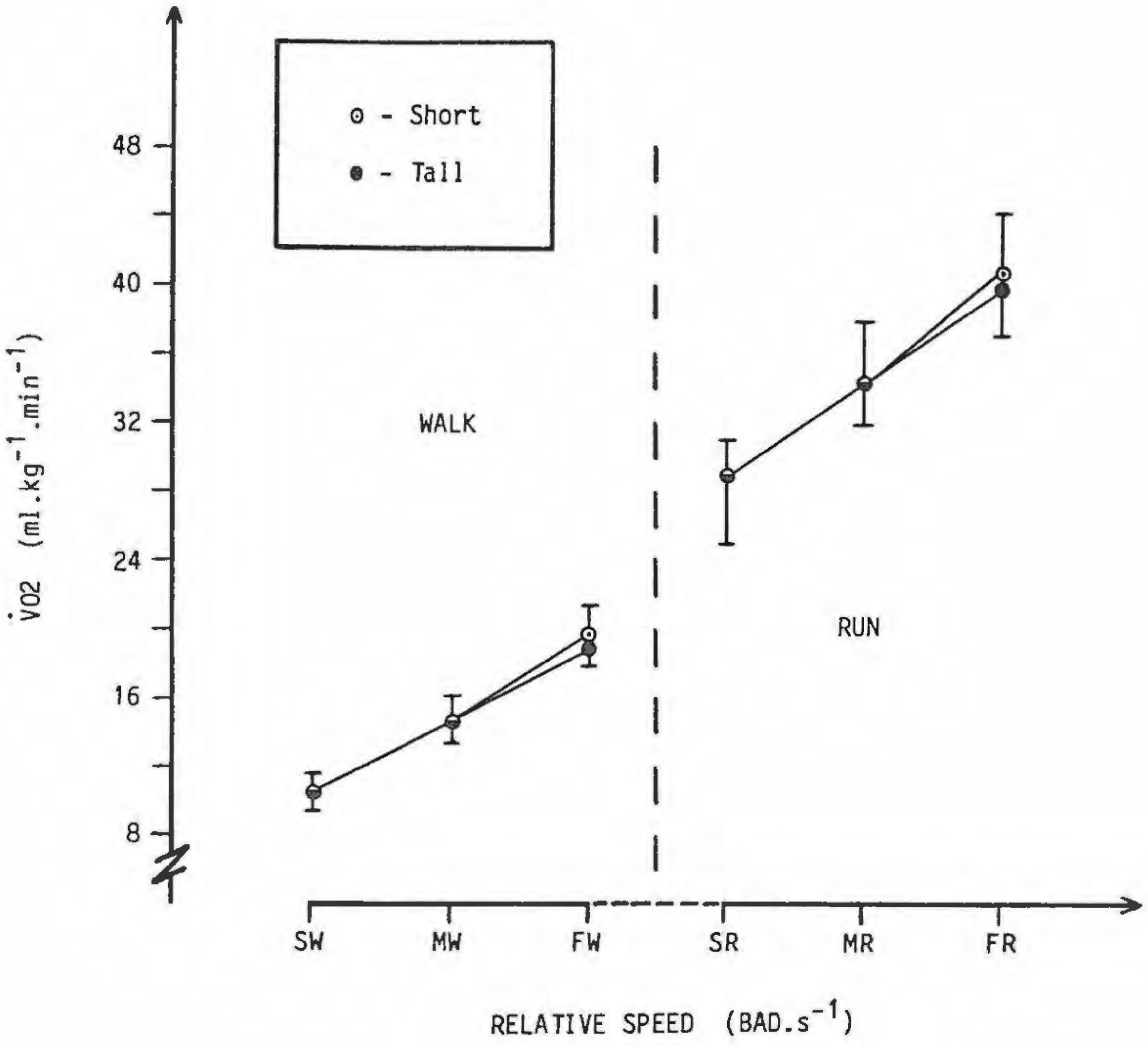


FIGURE 27: **the relationship between oxygen consumption and locomotor speed expressed relative to bi-acromial diameter.**

For all conditions no significant differences were observed between the oxygen consumptions of the short and tall subjects. When the rate of progression was expressed relative to bi-acromial diameter, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, the oxygen consumption tended to increase as a linear function of that speed (walking and running) expressed as a fraction of bi-acromial diameter.

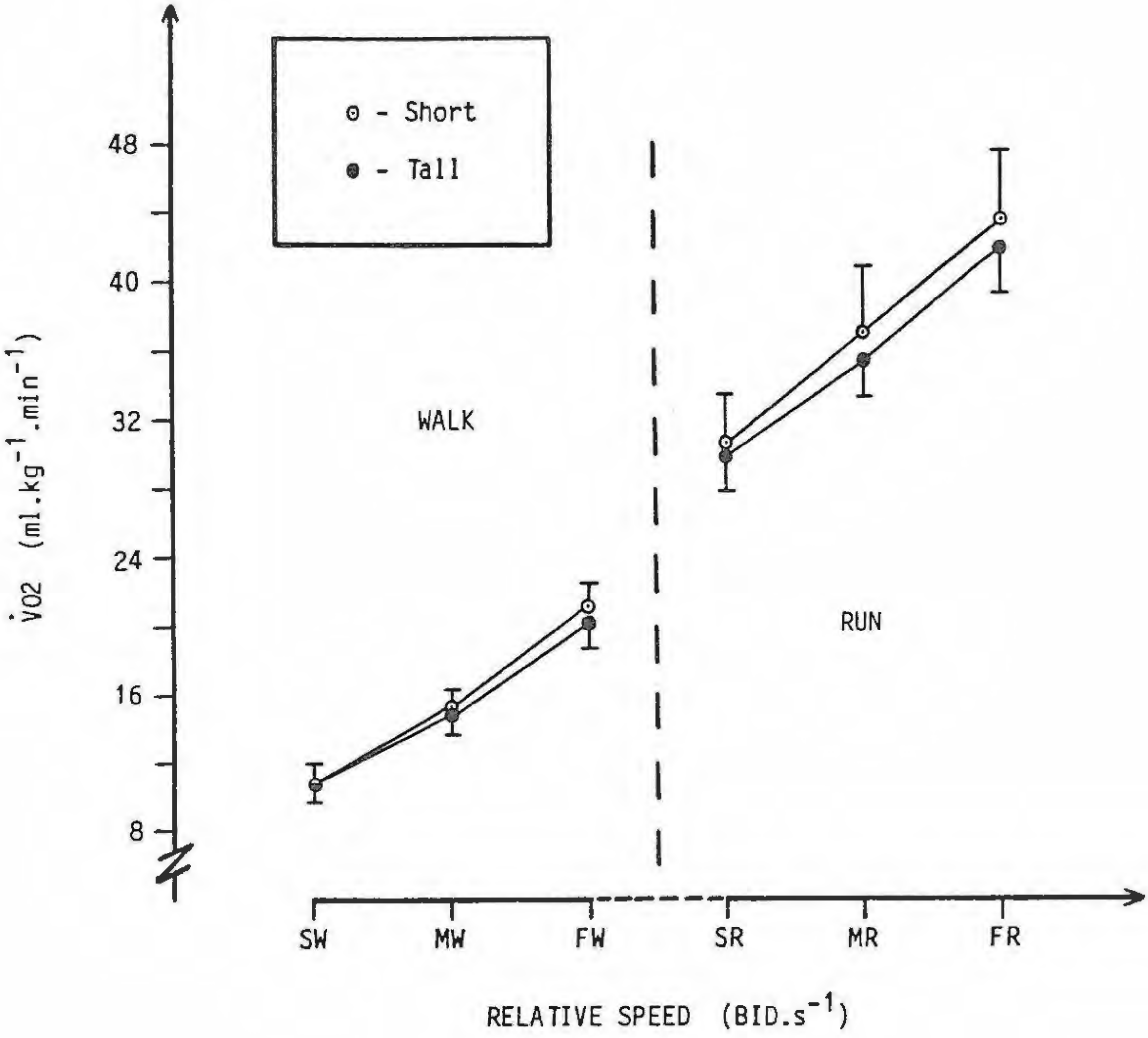


FIGURE 28: **the relationship between oxygen consumption and locomotor speed expressed relative to bi-iliac diameter.**

For all conditions no significant differences were observed between the oxygen consumptions of the short and tall subjects. When the rate of progression was expressed relative to bi-iliac diameter, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, oxygen consumption tended to increase as a linear function of that speed (walking and running) expressed as a fraction of bi-iliac diameter.

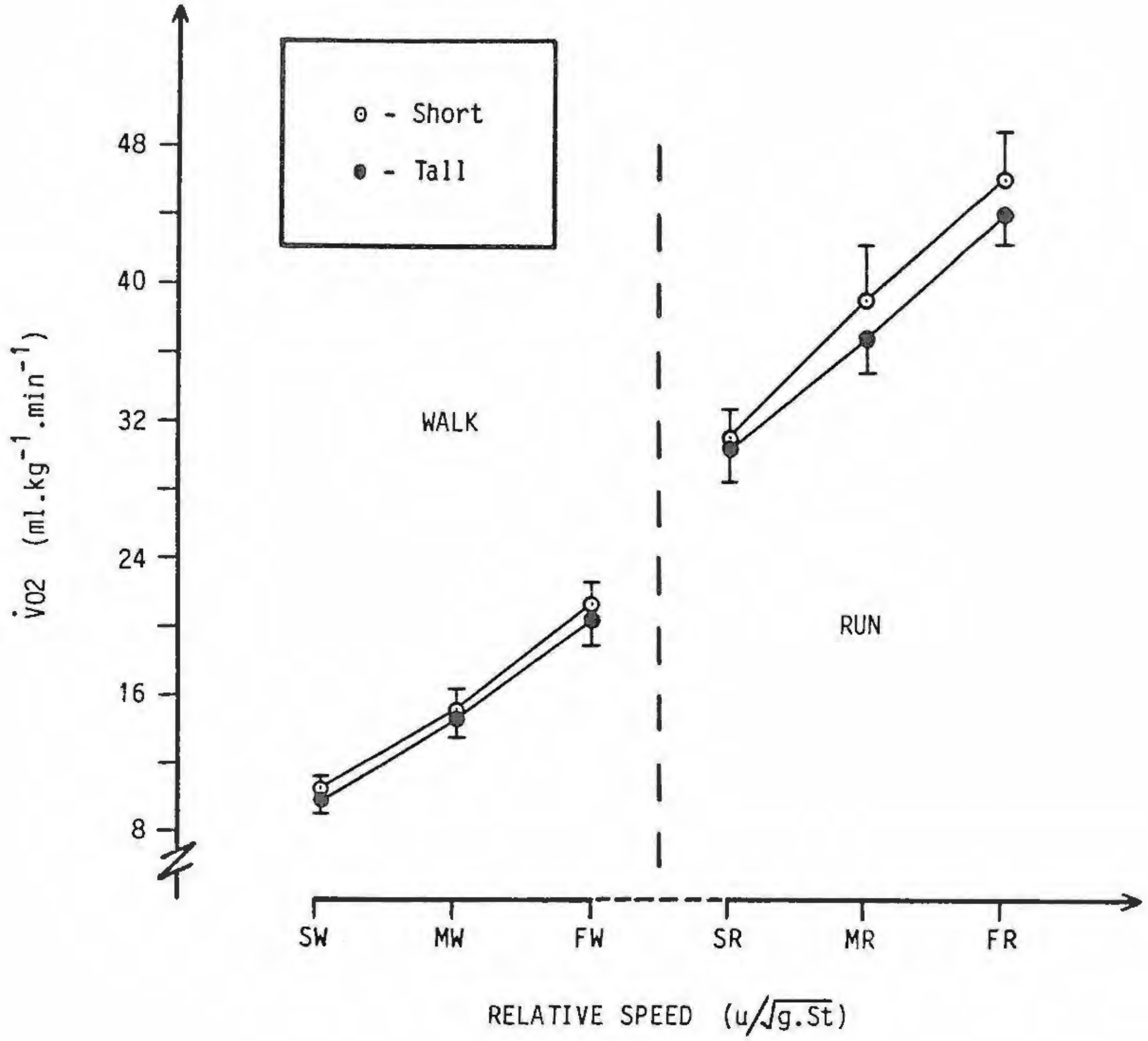


FIGURE 29: the relationship between oxygen consumption and locomotor speed expressed relative to a Froude number in which stature is used as the characteristic measure of size.

For all conditions no significant differences were observed between the oxygen consumptions of the short and tall subjects. When the rate of progression was expressed relative to a Froude number (and stature), locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, oxygen consumption tended to increase as a linear function of that speed (walking and running) expressed in terms of a Froude number using stature as the linear measure of size.

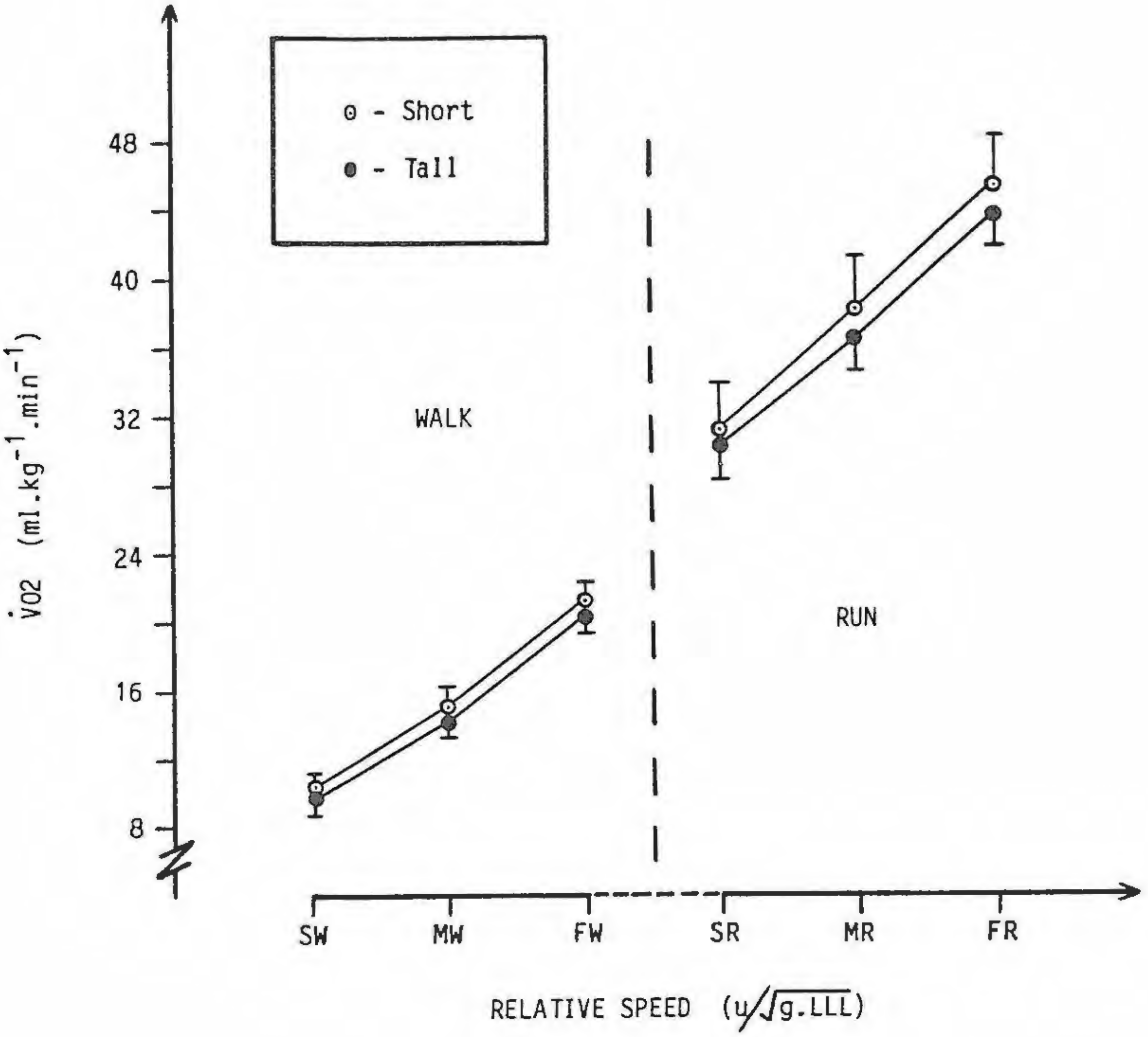


FIGURE 30: the relationship between oxygen consumption and locomotor speed expressed relative to a Froude number in which lower-limb length is used as the characteristic measure of size.

For all conditions no significant differences were observed between the oxygen consumptions of the short and tall subjects. When the rate of progression was expressed relative to a Froude number (and lower-limb length), locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, oxygen consumption tended to increase as a linear function of that speed (walking and running) expressed in terms of a Froude number using lower-limb length as the linear measure of size.

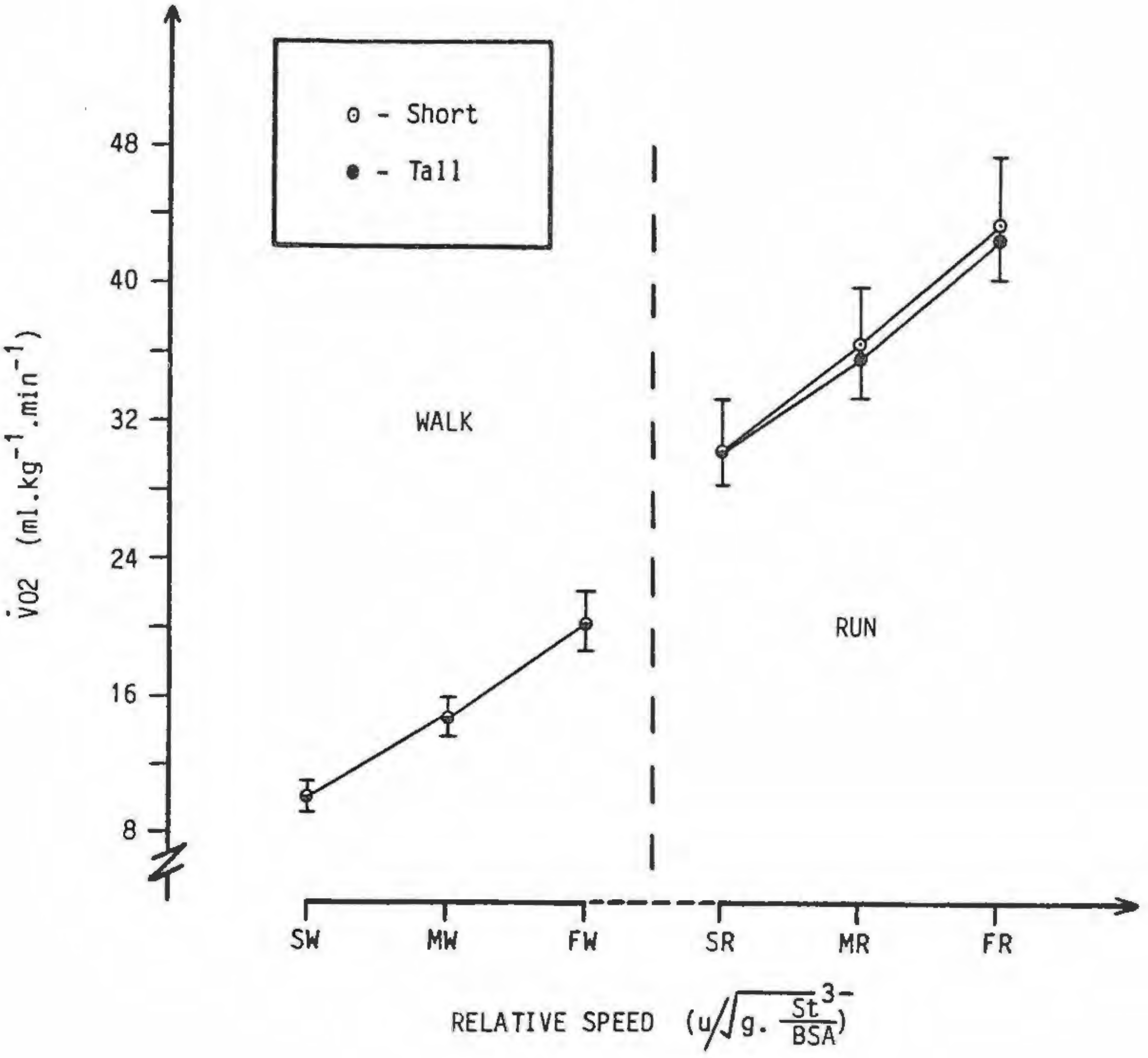


FIGURE 31: **the relationship between oxygen consumption and locomotor speed expressed relative to a Froude number in which the cube of stature divided by body surface area is used as the characteristic measure of size.**

For all conditions no significant differences were observed between the oxygen consumptions of the short and tall subjects. When the rate of progression was expressed relative to a Froude number (and the cube of stature divided by body surface area), locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, oxygen consumption tended to increase as a linear function of that speed (walking and running) expressed in terms of a Froude number using the cube of stature divided by body surface area as the linear measure of size.

to stress the taller subjects significantly more severely than the shorter subjects - so much so that the locomotor oxygen consumption of the taller subjects was rendered significantly greater than that of their shorter counterparts. This is clearly an inverse of the relationship which was demonstrated between stature-specific oxygen consumption and locomotor speeds expressed in absolute terms. The use of this method of relativising speed would, therefore, appear to be too stringent a method, as it relativises the rate of locomotor progression with respect to two morphological features, namely androgyny index and stature - both of which were significantly smaller for the short subjects. On the basis of these findings, it is difficult to comment on whether or not the androgyny index alone is a morphological measure (ratio) which significantly influences the energetics of locomotion. Clearly, when combined with a measure such as stature, the androgyny index becomes too potent a criterion on which to base any relativisation of locomotor speed.

Of the nine relative speed methods prescribed in this research, those expressing speed in terms of a Froude number were most successful in minimising the between-subject variability in locomotor oxygen consumption. Furthermore, the relativisation of speed in terms of a Froude number using stature ($U/\sqrt{g.St}$) as the characteristic measure of length generated the lowest across-sample coefficient of variation with respect to oxygen consumption for both walking and running speeds (see Figure 32). In other words, the least inter-individual variability in locomotor energy expenditure was realised when the rate of progression was expressed as a fraction of the square root of stature multiplied by a gravitational constant. However, clearly evident from Figure 32 is that all but one of the relative speed methods used in this research reduced the variability in locomotor oxygen consumption from that observed between subjects during locomotion at speeds expressed in absolute terms ($m.s^{-1}$). Consequently, the relativisation of locomotor speed on the basis of morphology appears to be an effective means of "normalising" locomotion with respect to energy expenditure. The effectiveness with which the relative speed methods expressing locomotor speed in terms of the Froude number reduced the variability in oxygen consumption suggests that the force of gravity is very influential with respect to the energetics of walking and running.

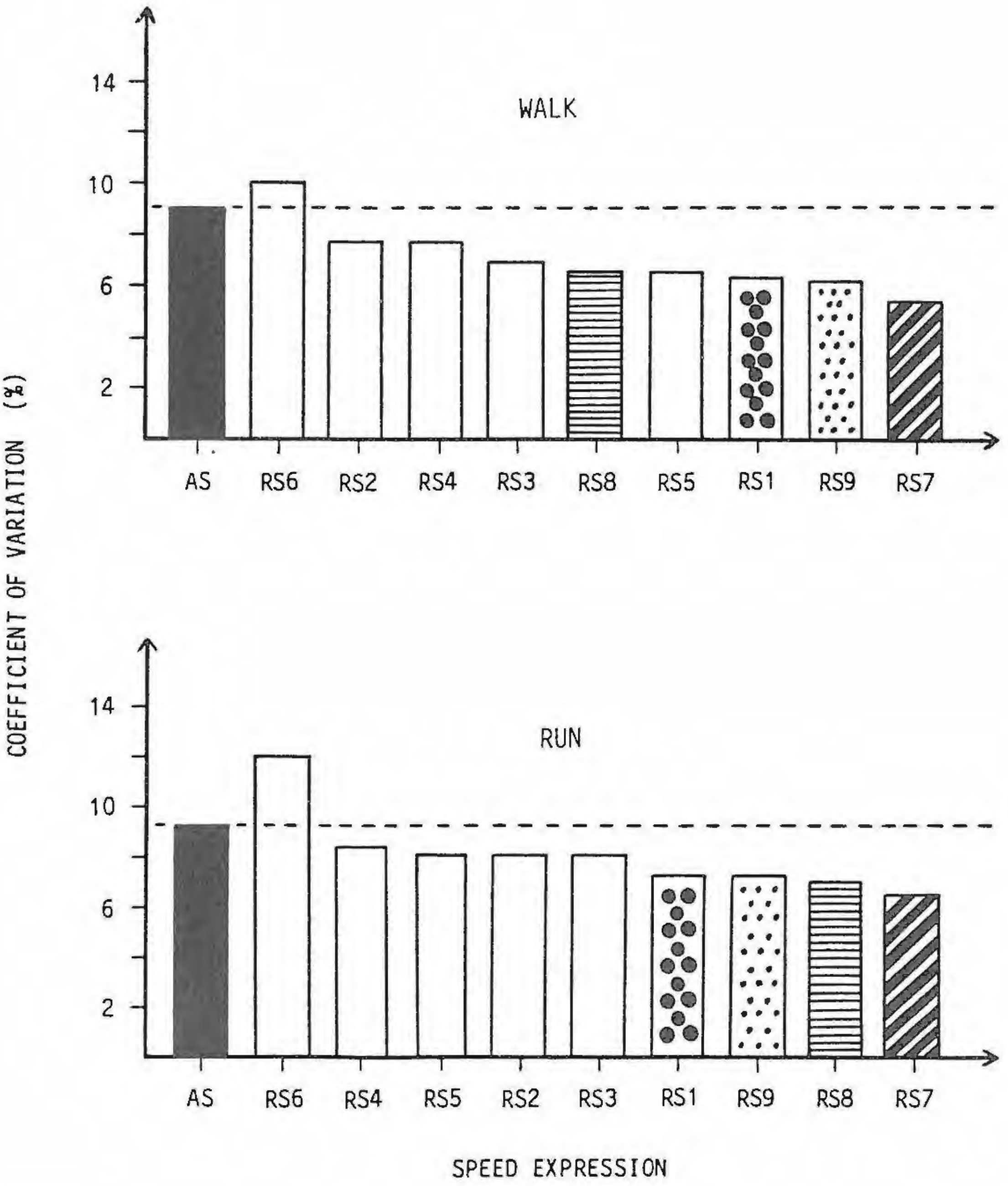


FIGURE 32: the inter-individual variability as reflected in oxygen consumption for each of the ten methods of expressing the locomotor speed of walking and running.

All but one (RS6) of the methods of relativising locomotor speed (morphologically) were effective in reducing the between-subject variability in oxygen consumption. For both walking and running, the least variability in oxygen consumption was achieved when the locomotor speed was expressed in terms of the Froude number in which stature is used as the linear measure of size (RS7).

ii) Kinematic Responses

It is interesting to note that a number of the relative speed expressions that were successful in eliminating the significant differences in locomotor oxygen consumption between the short and tall subjects were not successful in realising the same result with respect to locomotor cadence. In other words, although there was seen to be no significant variability in oxygen consumption between subjects when locomotor progression was relativised with respect to morphology, the same cannot be reported for the between-subject variability in cadence. In fact, the relativisation of locomotor speed on the basis of a number of morphological features was largely ineffectual in terms of reducing the inter-individual variability in speed-specific cadence. This suggests that trends in the relationship between locomotor energetics and movement speed are not closely mirrored by similar trends with respect to locomotor kinematics.

As demonstrated previously, the cadence adopted when walking or running at any given absolute speed is very dependent upon the stature (or lower-limb length) of the subject. Accordingly, shorter subjects move at any given absolute speed with a greater frequency of step than do their taller counterparts. It might be expected, therefore, that the relativisation of locomotor speed with respect to some morphological measure (such as stature) would be effective in minimising the between-subject variability in cadence typical of horizontal walking and running. However, few of the methods of relativising speed as prescribed for the purposes of this study were successful in "normalising" the rate of progression in this way (see Table XI, Appendix 4). In fact, only when speed was expressed relative to stature (U/St), lower-limb length (U/LLL) and to the product of an androgyny index and stature (U/AI.St), were there seen to be no significant differences in locomotor cadence between the short and tall subjects for both walking and running gaits (see Figures 33-35). When speed was expressed relative to leg length (U/LL), no significant differences were revealed in the cadences of the short and tall subjects for walking, yet such differences did manifest themselves for running (see Figure 36).

It would appear, therefore, that when the rate of progression is relativised with respect to stature or to the length of the locomotor appendages, the variability in cadence between subjects is effectively

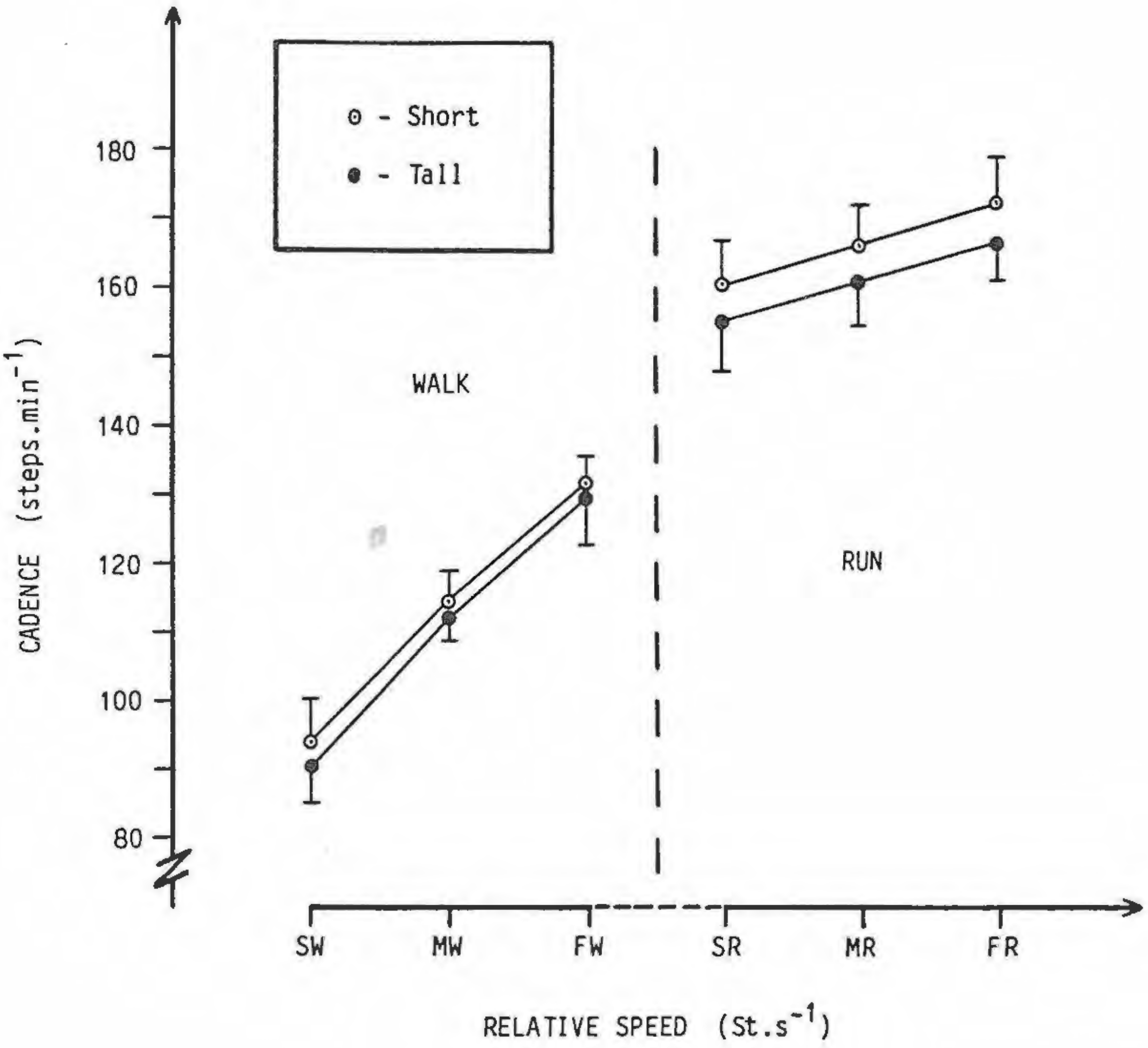


FIGURE 33: the relationship between cadence and locomotor speed expressed relative to stature.

For all conditions no significant differences were observed between the cadences of the short and tall subjects. When the rate of progression was expressed relative to stature, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, cadence tended to increase as a linear function of that speed (walking and running) expressed as a fraction of stature.

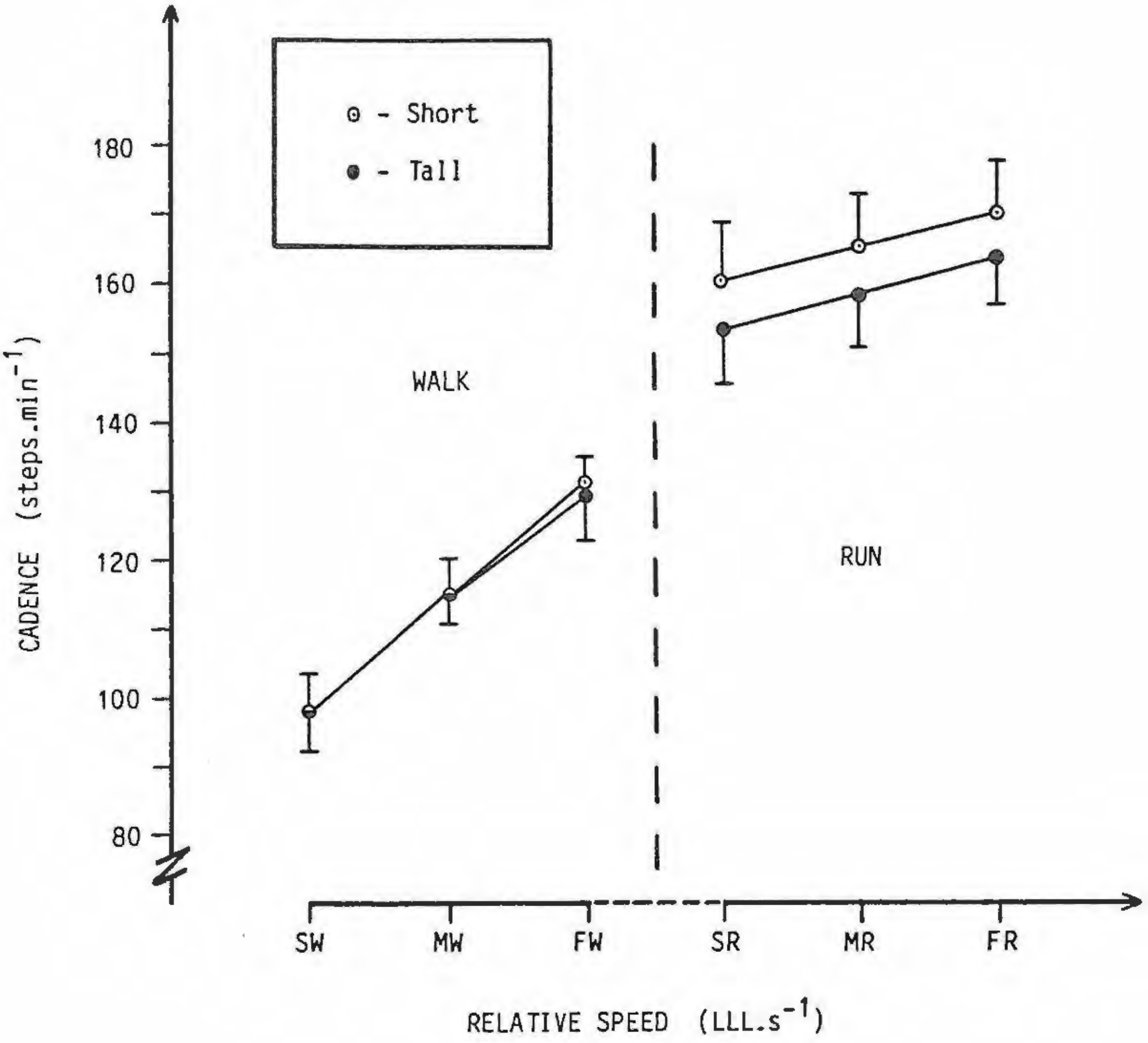
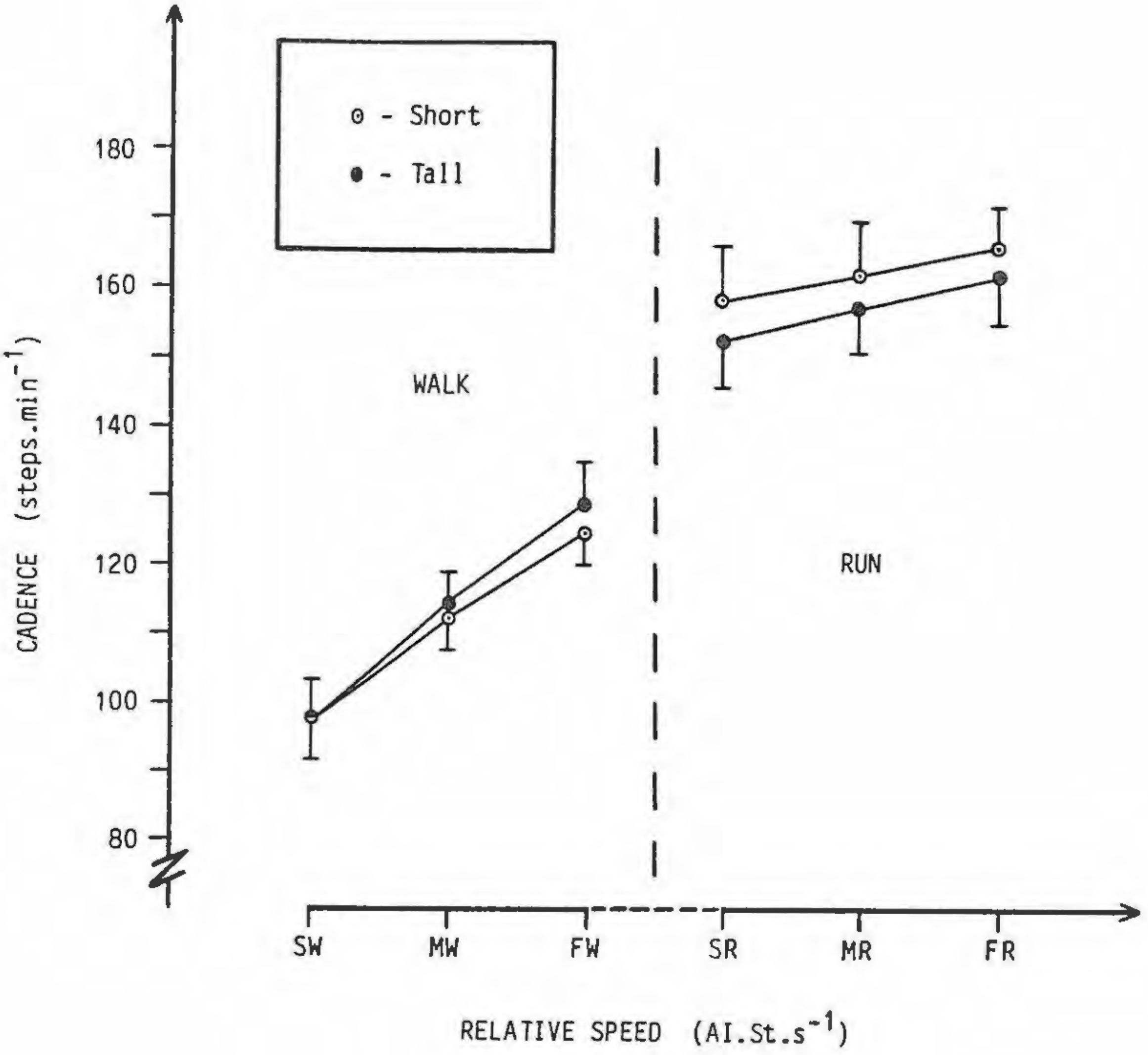


FIGURE 34: **the relationship between cadence and locomotor speed expressed relative to lower-limb length.**

For all conditions no significant differences were observed between the cadences of the short and tall subjects. When the rate of progression was expressed relative to lower-limb length, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, cadence tended to increase as a linear function of that speed (walking and running) expressed as a fraction of lower-limb length.



<u>FIGURE 35</u>: **the relationship between cadence and locomotor speed expressed relative to the product of an androgyny index and stature.**

For all conditions no significant differences were observed between the cadences of the short and tall subjects. When the rate of progression was expressed relative to the product of an androgyny index and stature, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, cadence tended to increase as a linear function of that speed (walking and running) expressed as a fraction of the product of an androgyny index and stature.

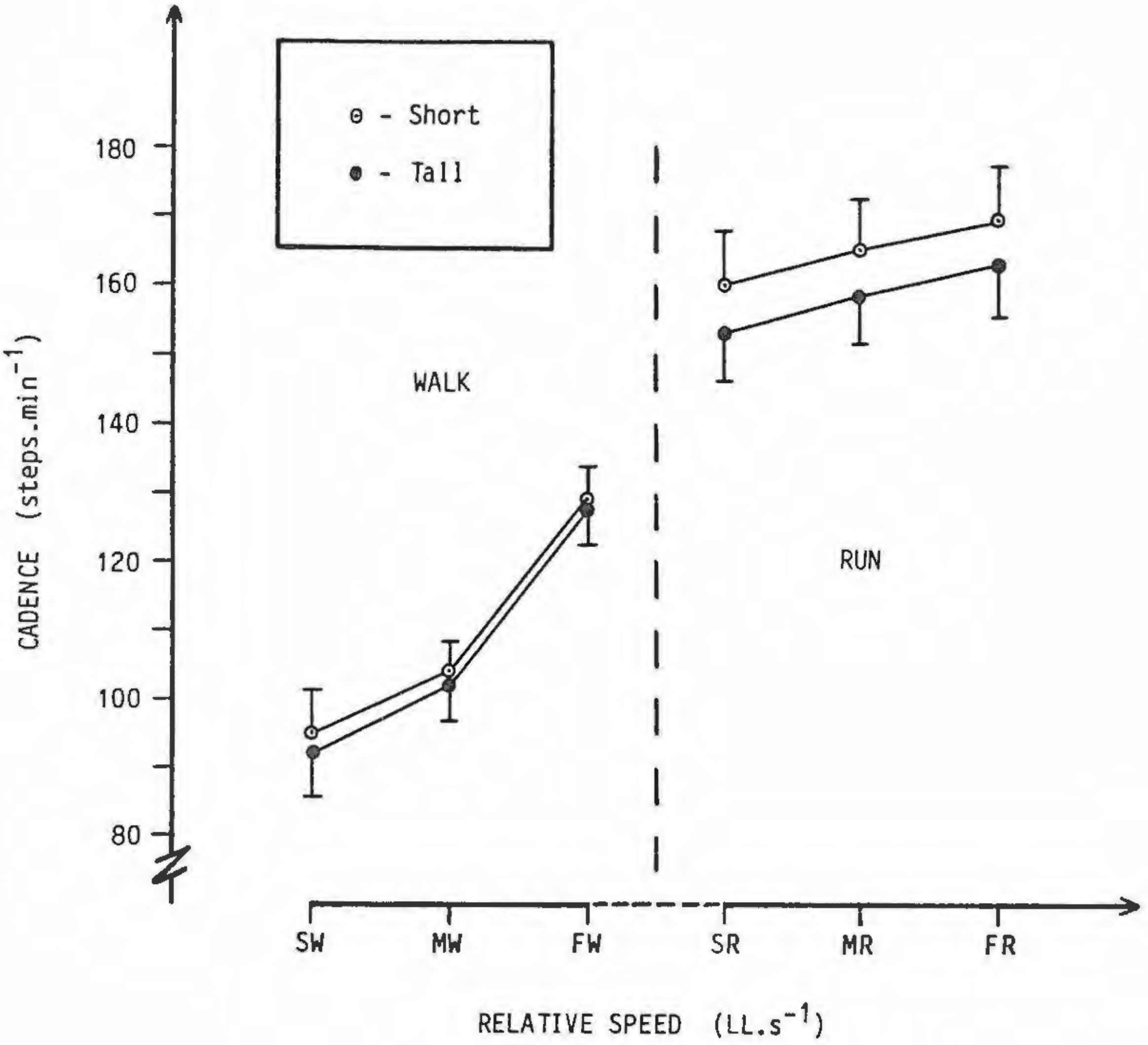


FIGURE 36: the relationship between cadence and locomotor speed expressed relative to leg length.

For all walking conditions no significant differences were observed between the cadences of the short and tall subjects. However, such differences did manifest themselves for the running conditions. When the rate of progression was expressed relative to leg length, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, cadence tended to increase as a curvilinear function of that walking speed expressed as a fraction of leg length. For the running conditions, the cadence responded in a linear fashion.

minimised. However, the relativisation of speed with respect to morphological features such as bi-acromial diameter (BAD), bi-iliac diameter (BID) and body surface area (BSA) tends to be less successful in minimising this between-subject variability in cadence. This is a fairly logical tendency, considering that locomotor kinematics are more likely to be influenced by variations in the length of the lower extremities than they are by variations in the length of the upper extremities and trunk. Consequently, the relativisation of speed on the basis of stature (St) or lower-limb length (LLL) would appear to be an effective means of "normalising" locomotion with respect to cadence.

For walking gaits, the least variability in locomotor cadence between subjects was realised when the rate of progression was expressed relative to lower-limb length (U/LLL), while for running gaits the least between-subject variability was attained via the relativisation of speed using stature (U/St) (see Figure 37). Since the relativisation of speed using the Froude number was not effective in reducing the variability in locomotor cadence, it would appear that the force of gravity does not influence considerably the frequency of step during walking or running. Interestingly, the relativisation of locomotor speed to the product of an androgyny index and stature (U/AI.St) was also a very effective method of reducing the variability in cadence between subjects. However, the influence of the androgyny index alone in this expression is largely unquantifiable, and it is very likely that the success of the equation can be attributed to the very dramatic effect that stature has upon the cadence of walking or running. Whether or not the ratio of bi-acromial diameter to bi-iliac diameter contributes directly to the subjects selection of cadence during locomotion at any given speed is questionable, but clearly the combined influence of this ratio and stature has important ramifications with respect to the cadence freely chosen by any subject at any prescribed rate of progression.

The effects of relativising speed upon the locomotor stride length during walking and running were quite dramatic. Clearly, the primary aim of expressing speed relative to some morphological measure is to "normalise" the locomotion such that all subjects walk/run at the same motor intensity. This situation is realised via a process which requires that energetically advantaged taller subjects move at greater absolute speeds, while disadvantaged shorter subjects progress more slowly. Consequently,

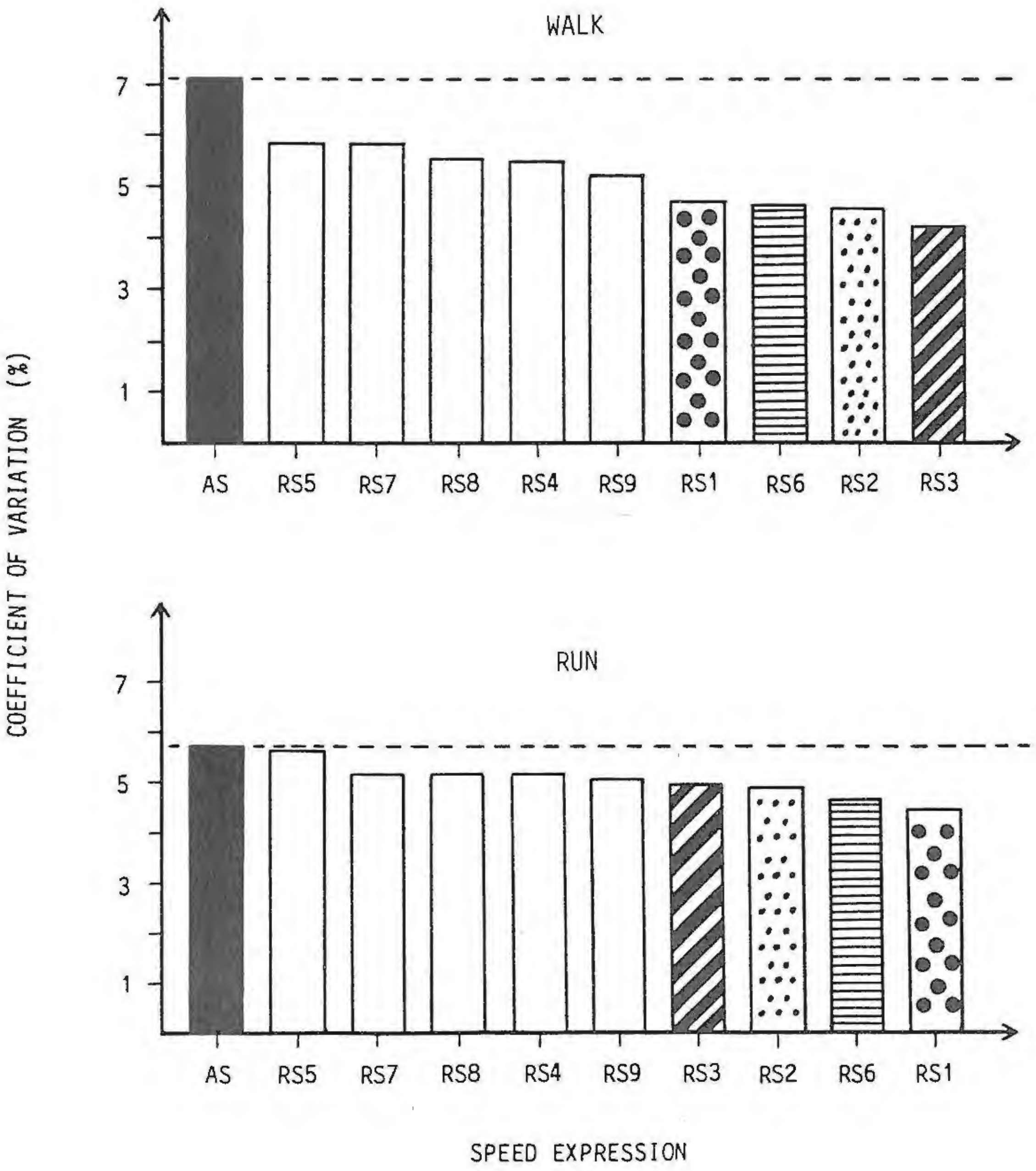


FIGURE 37: **the inter-individual variability as reflected in cadence for each of the ten methods of relativising the locomotor speed of walking and running.**

All methods of relativising speed (morphologically) were effective in reducing the between-subject variability in cadence. For walking, the least variability in cadence was achieved when the locomotor speed was expressed relative to lower-limb length (RS3). However, for running, the least variability in cadence was achieved when locomotor speed was expressed relative to stature (RS1).

for any given relative speed, the absolute rate of progression increases as a constant function of subject stature. Since increments in speed are realised in part via increases in the length of stride, the morphological relativisation of speed tends to exaggerate the between-subject variability in stride length (ie. the significant difference in stride length between the short and tall subjects when progressing at absolute speed is effectively increased when the locomotor speed is prescribed in relative terms) (see figure 38). With respect to (absolute) stride length therefore, it would appear that the relativisation of locomotor speed is ineffective in minimising the variability of responses between subjects (see Table XII, Appendix 4). Clearly, each of the nine methods of relativising locomotor speed served only to increase the between-subject variability in stride length (see Figure 39).

If one expresses the length of stride as a fraction of subject stature (ie. relative stride length), a much more meaningful locomotor response is realised. As with absolute stride length (m), significant differences were revealed in the relative stride length ($St.stride^{-1}$) between the two stature categories when a raw locomotor speed ($m.s^{-1}$) was prescribed (see Table XIII, Appendix 4). However, unlike the trends observed with respect to absolute lengths of stride, the expression of speed relative to morphology was effective in reducing the between-subject variability in relative stride length (see Figures 40-46). In other words, when the rate of locomotor progression was expressed relative to some linear measure of size, the length of stride adopted at any (relative) speed of walking or running tended to remain a constant fraction of stature for both short and tall subjects. Figure 47 reveals the relationships generated between absolute/relative locomotor speed and absolute/relative stride length. Clearly, the least inter-individual variability is realised when both the speed and the length of stride are expressed in relative terms. Hence, it would appear that the relativisation of speed on the basis of morphology is an effective means of "normalising" locomotion in terms of relative stride length.

The least between-subject variability in relative stride length was elicited when the rate of progression was expressed relative to a Froude number, in which either stature ($U/\sqrt{g.St}$), lower-limb length ($U/\sqrt{g.LLL}$) or the cube of stature divided by surface area ($U/\sqrt{g.[St^3/BSA]}$) was used as the characteristic length (see Figure 48). The relativisation of

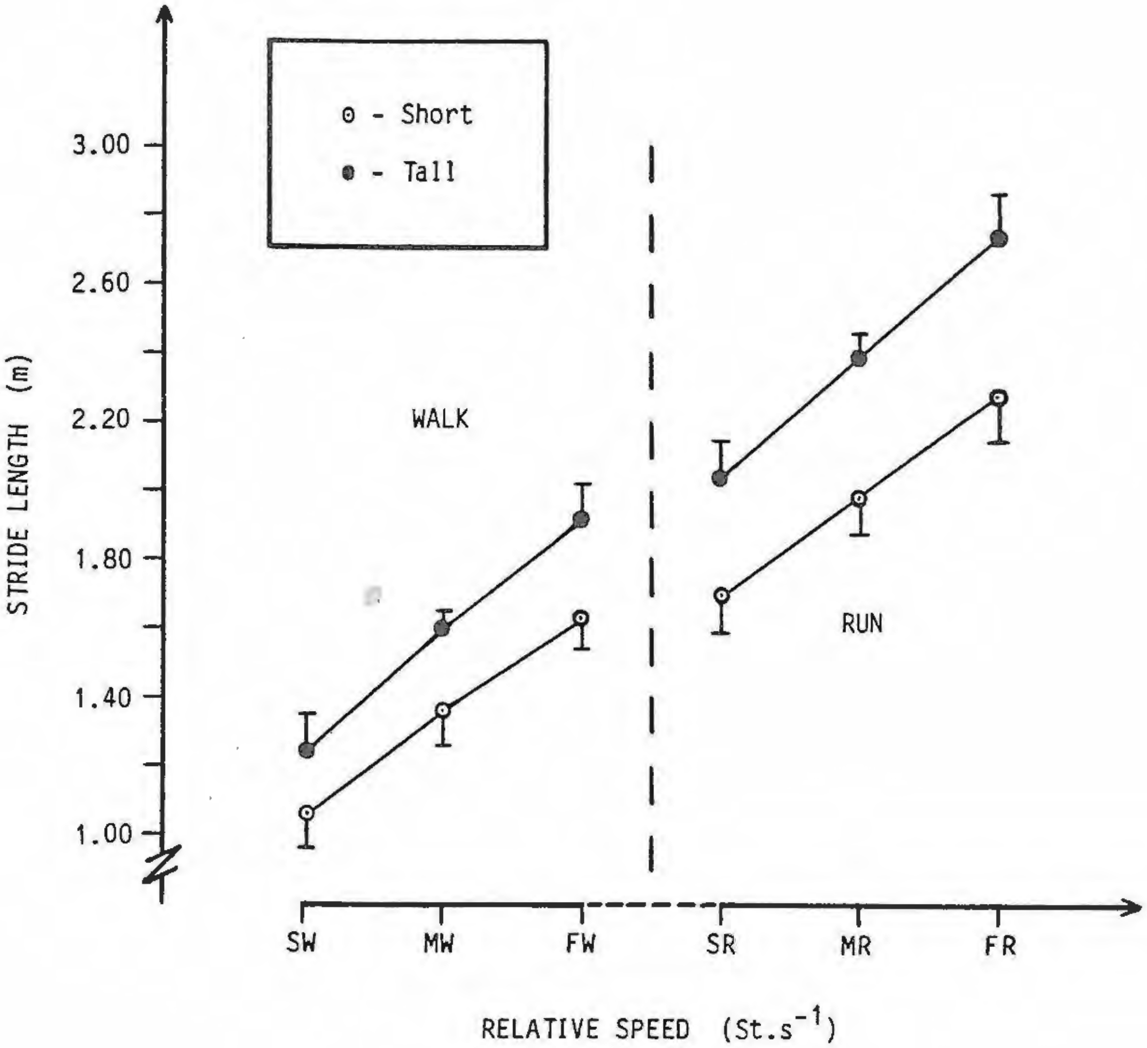


FIGURE 38: **the relationship between stride length and locomotor speed expressed relative to stature.**

For all conditions the tall subjects recorded significantly greater lengths of stride per unit speed than did the short subjects. When the rate of progression was expressed relative to stature, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, stride length tended to increase as a linear function of that speed (walking and running) expressed as a fraction of stature.

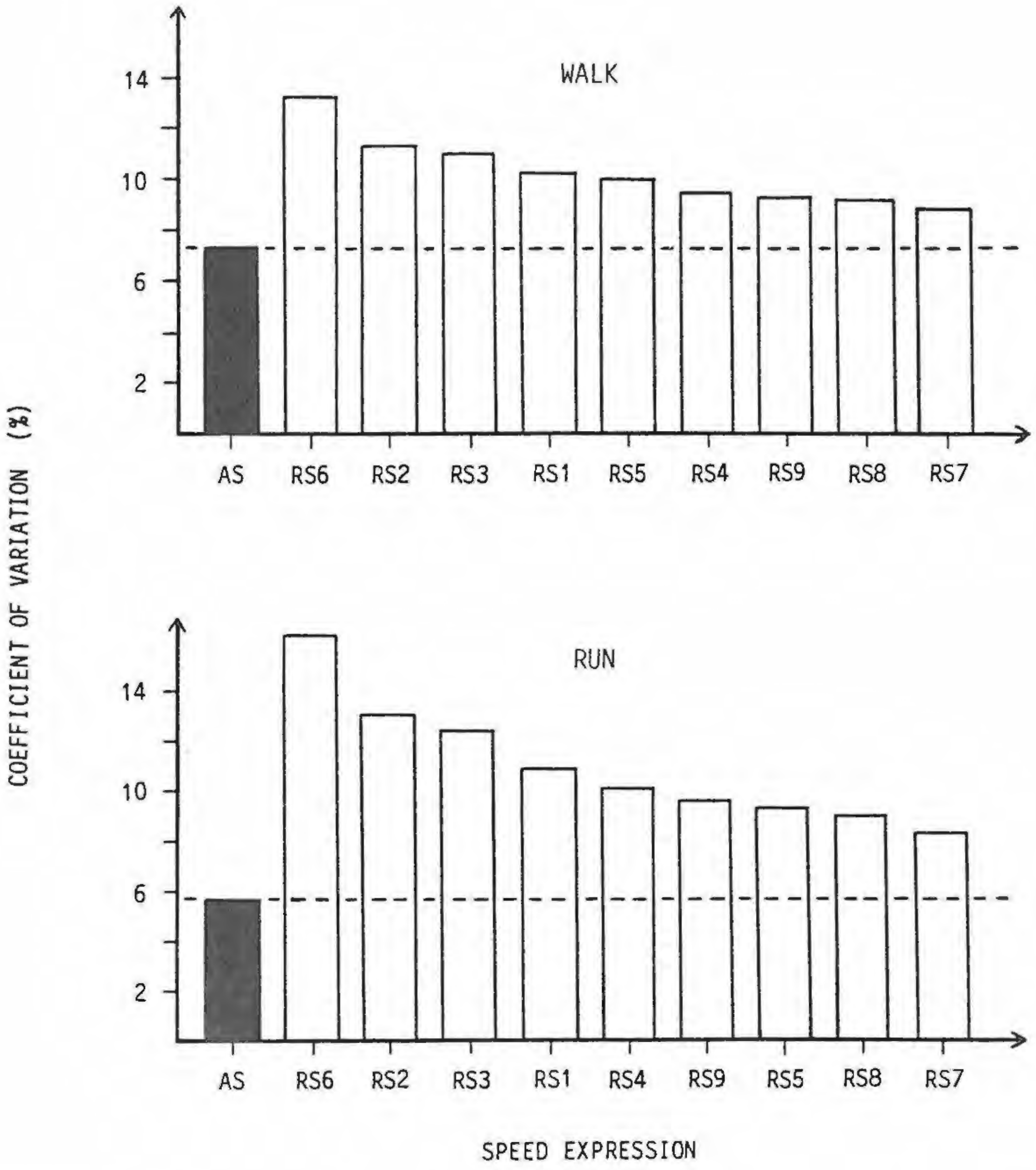


FIGURE 39: **the inter-individual variability as reflected in stride length for each of the ten methods of expressing the locomotor speed of walking and running.**

All methods of relativising the locomotor speed served only to increase the between-subject variability in stride length. For both walking and running, the least variability was achieved when the locomotor speed was expressed in absolute terms (AS).

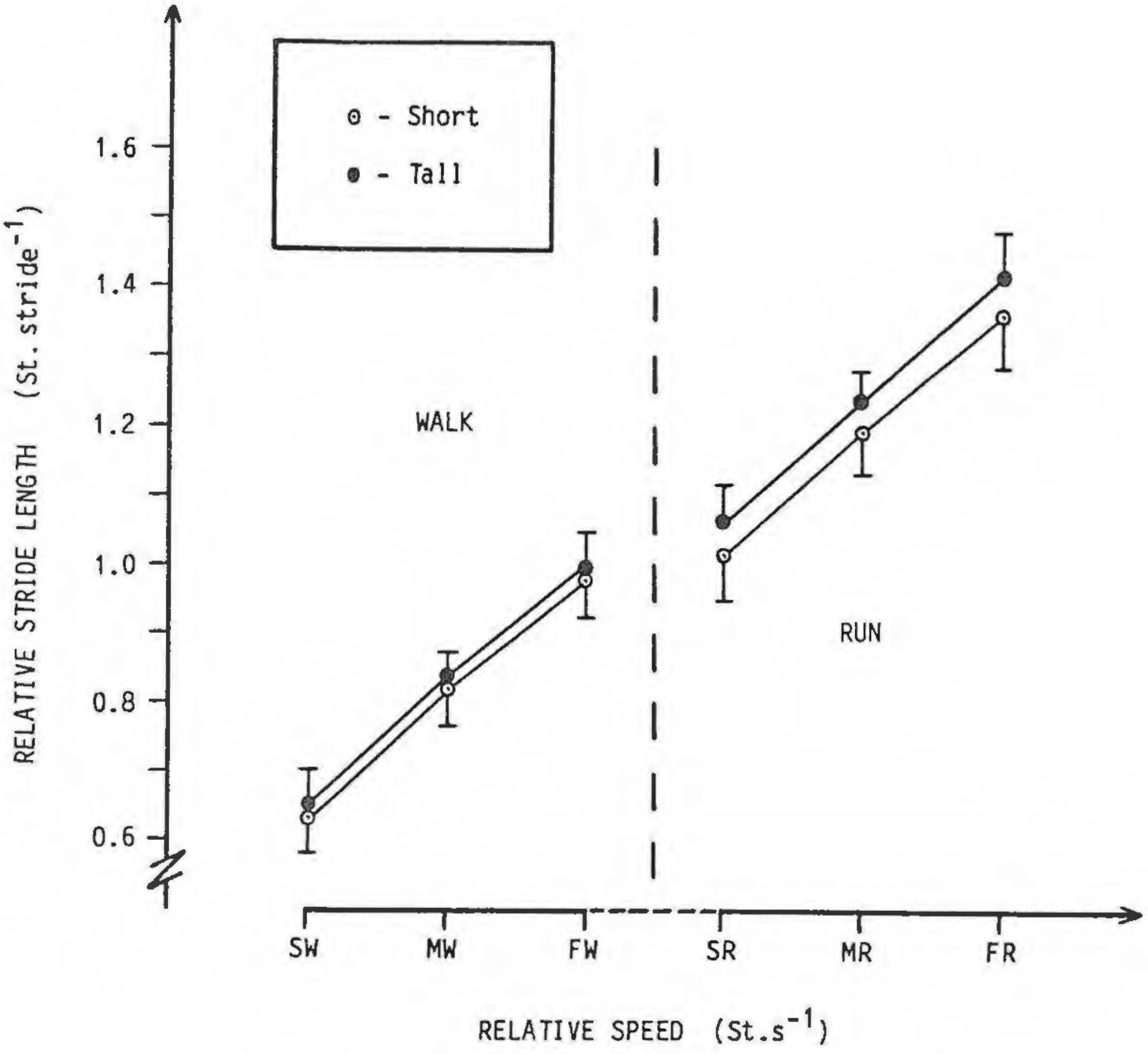


FIGURE 40: the relationship between relative stride length and locomotor speed expressed relative to stature.

For all walking conditions no significant differences were observed between the relative lengths of stride of the short and tall subjects. However, such differences did manifest themselves for the running conditions. When the rate of progression was expressed relative to stature, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, relative stride length tended to increase as a linear function of that speed (walking and running) expressed as a fraction of stature.

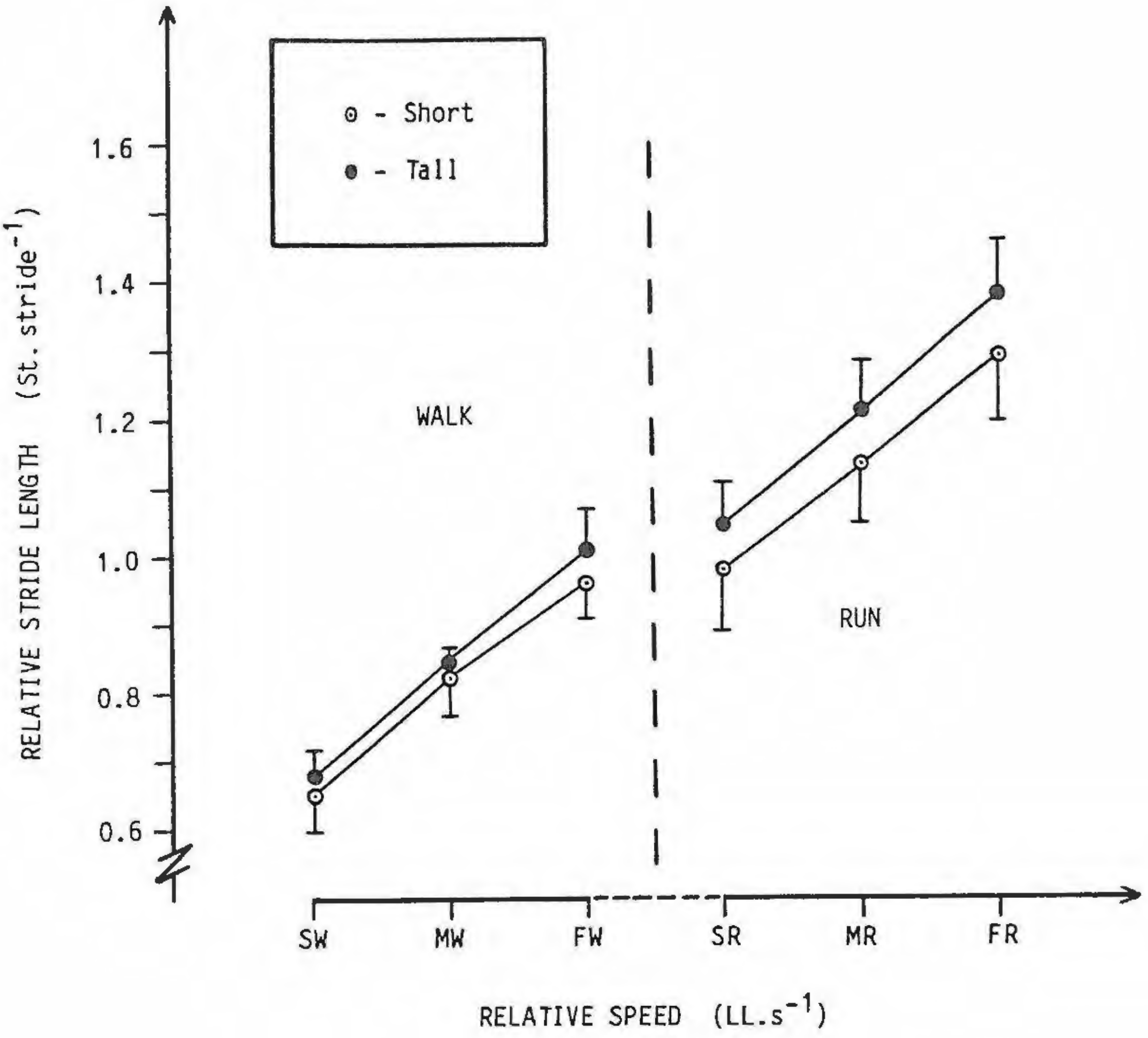


FIGURE 41: **the relationship between relative stride length and locomotor speed expressed relative to leg length.**

For all walking conditions no significant differences were observed between the relative lengths of stride of the short and tall subjects. However, such differences did manifest themselves for the running conditions. When the locomotor speed was expressed relative to leg length, locomotor speed and subject size demonstrated no significant interactive effect. For both subject groups, relative stride length tended to increase as a linear function of that speed (walking and running) expressed as a fraction of leg length.

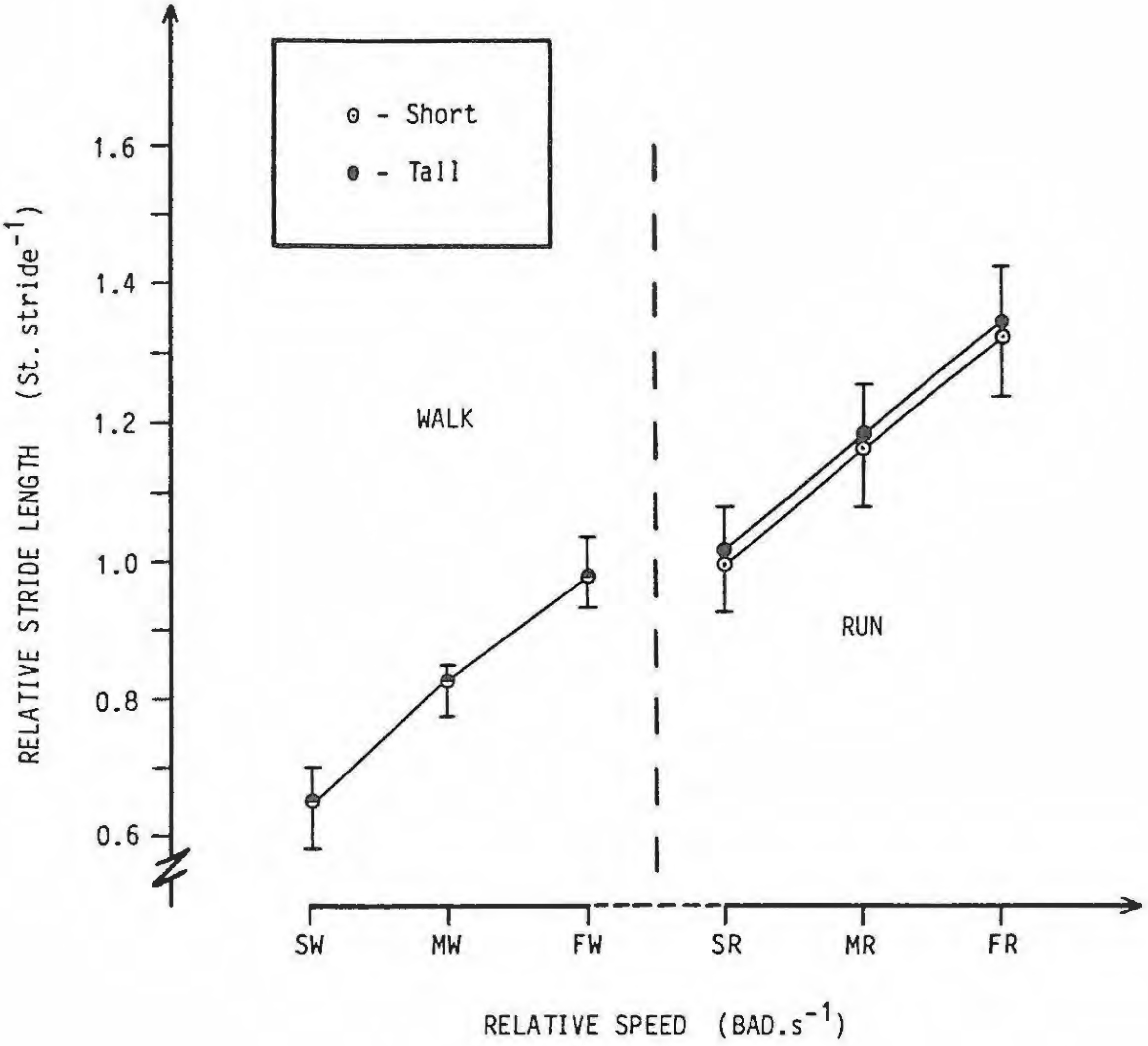


FIGURE 42: **the relationship between relative stride length and locomotor speed expressed relative to bi-acromial diameter.**

For all conditions no significant differences were observed between the relative lengths of stride of the short and tall subjects. When the rate of progression was expressed relative to bi-acromial diameter, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, relative stride length tended to increase as a linear function of that speed (walking and running) expressed as a fraction of bi-acromial diameter.

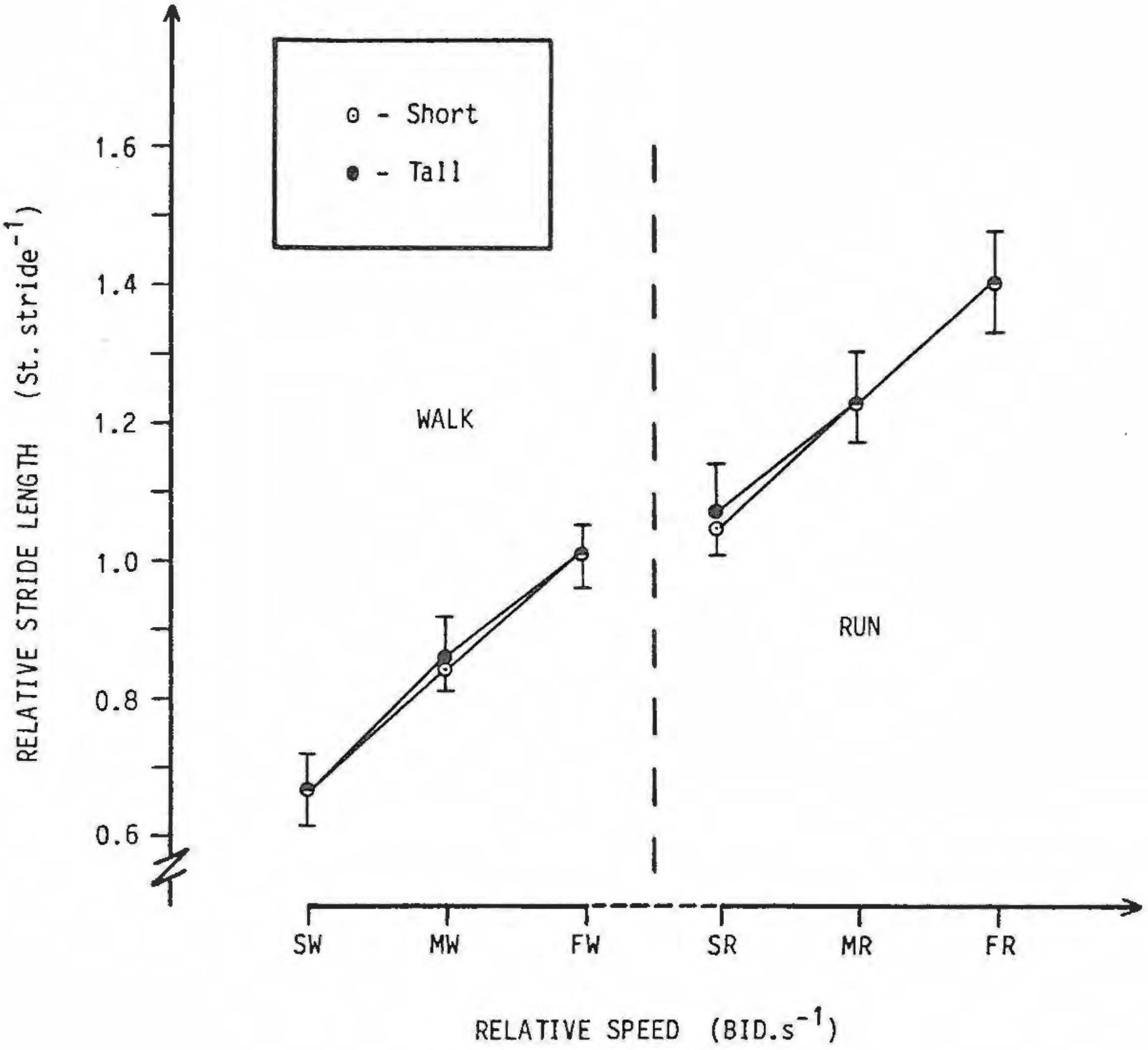


FIGURE 43: **the relationship between relative stride length and locomotor speed expressed relative to bi-iliac diameter.**

For all conditions no significant differences were observed between the relative lengths of stride of the short and tall subjects. When the rate of progression was expressed relative to bi-iliac diameter, locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, relative stride length tended to increase as a linear function of that speed (walking and running) expressed as a fraction of bi-iliac diameter.

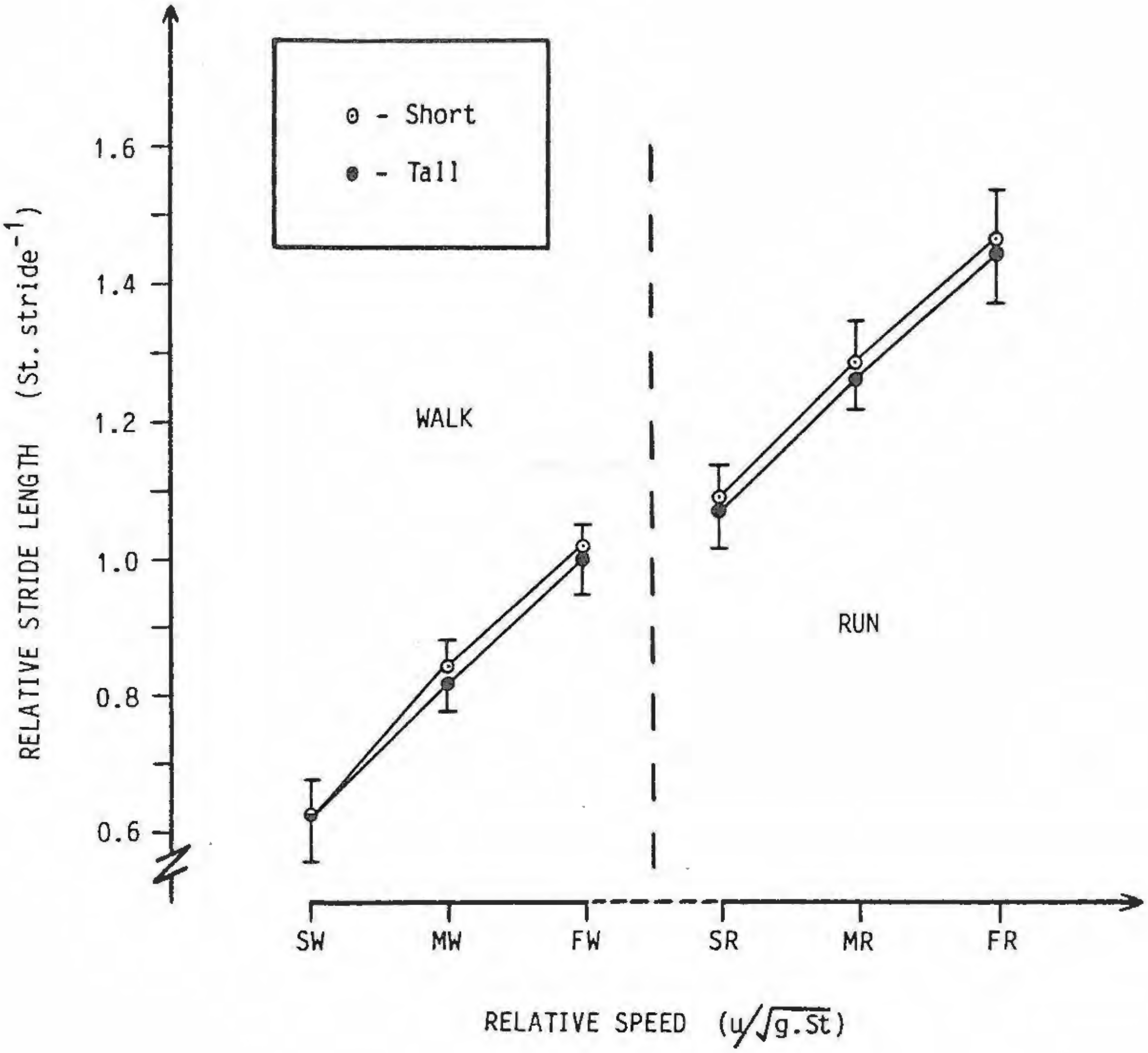


FIGURE 44: **the relationship between relative stride length and locomotor speed expressed relative to a Froude number in which stature is used as the characteristic measure of size.**

For all conditions no significant differences were observed between the relative lengths of stride of the short and tall subjects. When the rate of progression was expressed relative to a Froude number (and stature), locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, relative stride length tended to increase as a linear function of that speed (walking and running) expressed in terms of a Froude number in which stature represents the linear measure of size.

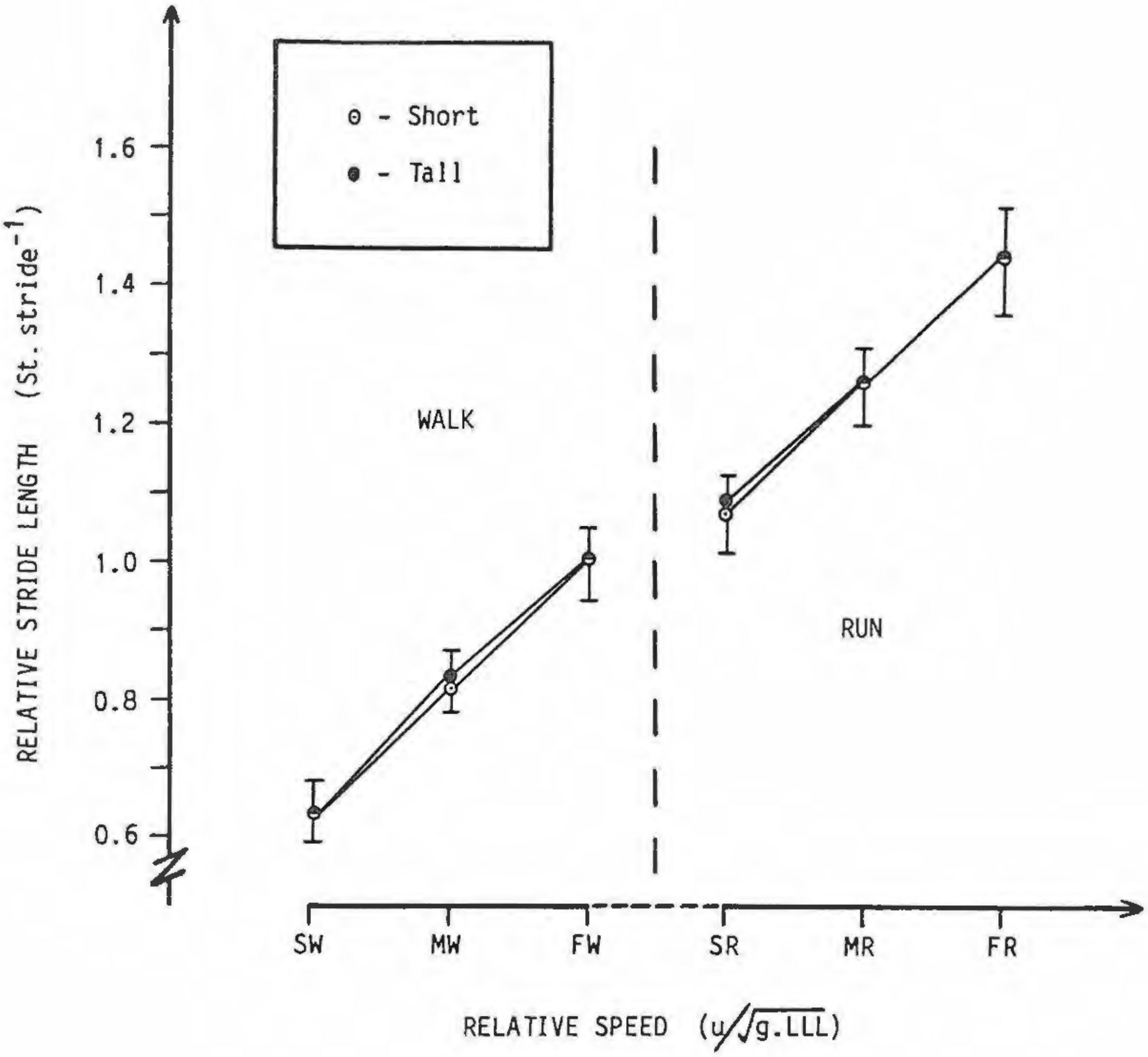


FIGURE 45: **the relationship between relative stride length and locomotor speed expressed relative to a Froude number in which lower-limb length is used as the characteristic measure of size.**

For all conditions no significant differences were observed between the relative lengths of stride of the short and tall subjects. When the rate of progression was expressed relative to a Froude number (and lower-limb length), locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, relative stride length tended to increase as a linear function of that speed (walking and running) expressed in terms of a Froude number in which lower-limb length represents the linear measure of size.

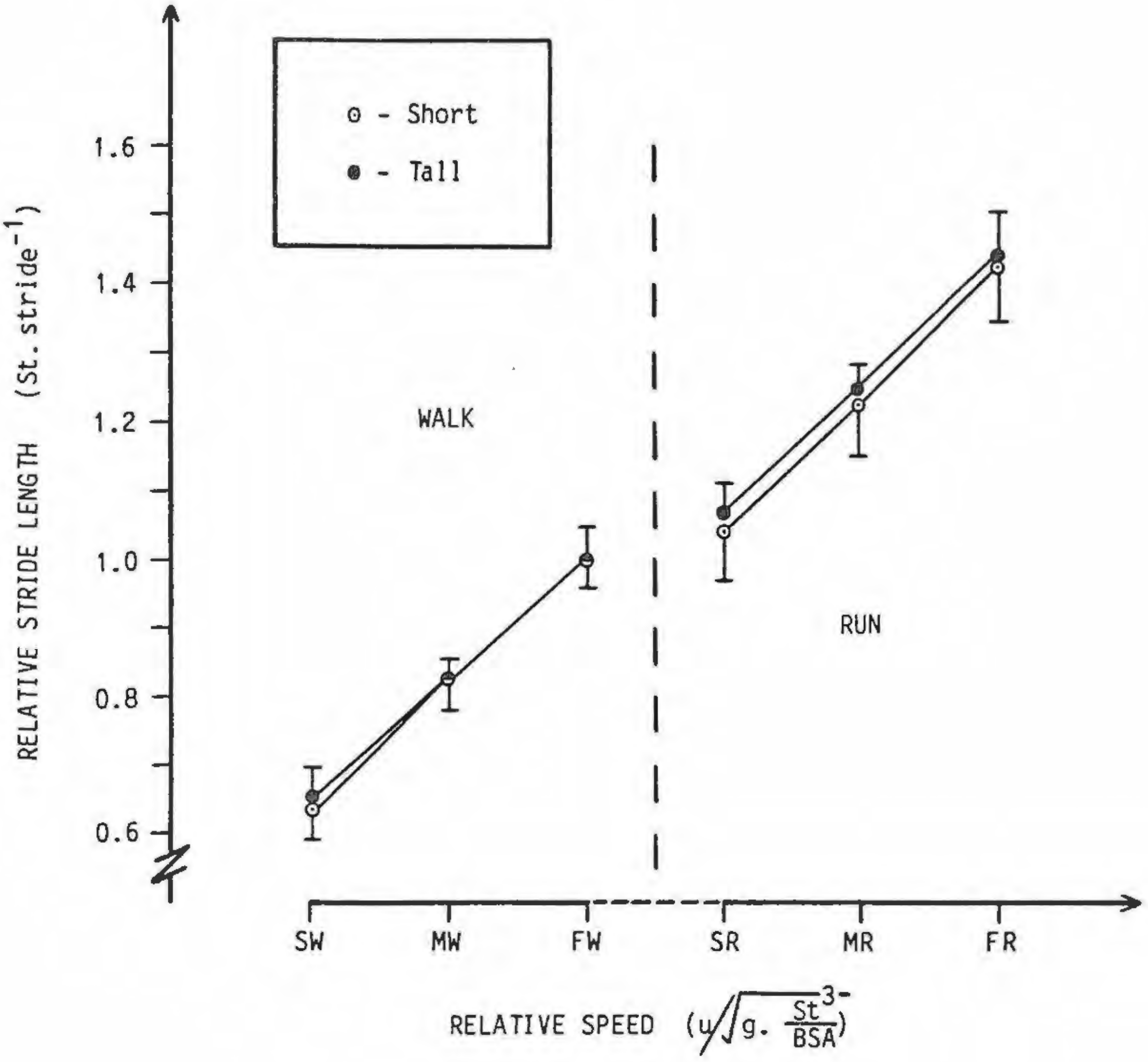


FIGURE 46: **the relationship between relative stride length and locomotor speed expressed relative to a Froude number in which the cube root of stature divided by body surface area is used as the characteristic measure of size.**

For all conditions no significant differences were observed between the relative lengths of stride of the short and tall subjects. When the rate of progression expressed relative to a Froude number (and St^3/BSA), locomotor speed and subject size demonstrated no significant interactive effect. For both stature groups, relative stride length tended to increase as a linear function of that speed (walking and running) expressed in terms of a Froude number in which the cube of stature divided by body surface area represents the linear measure of size.

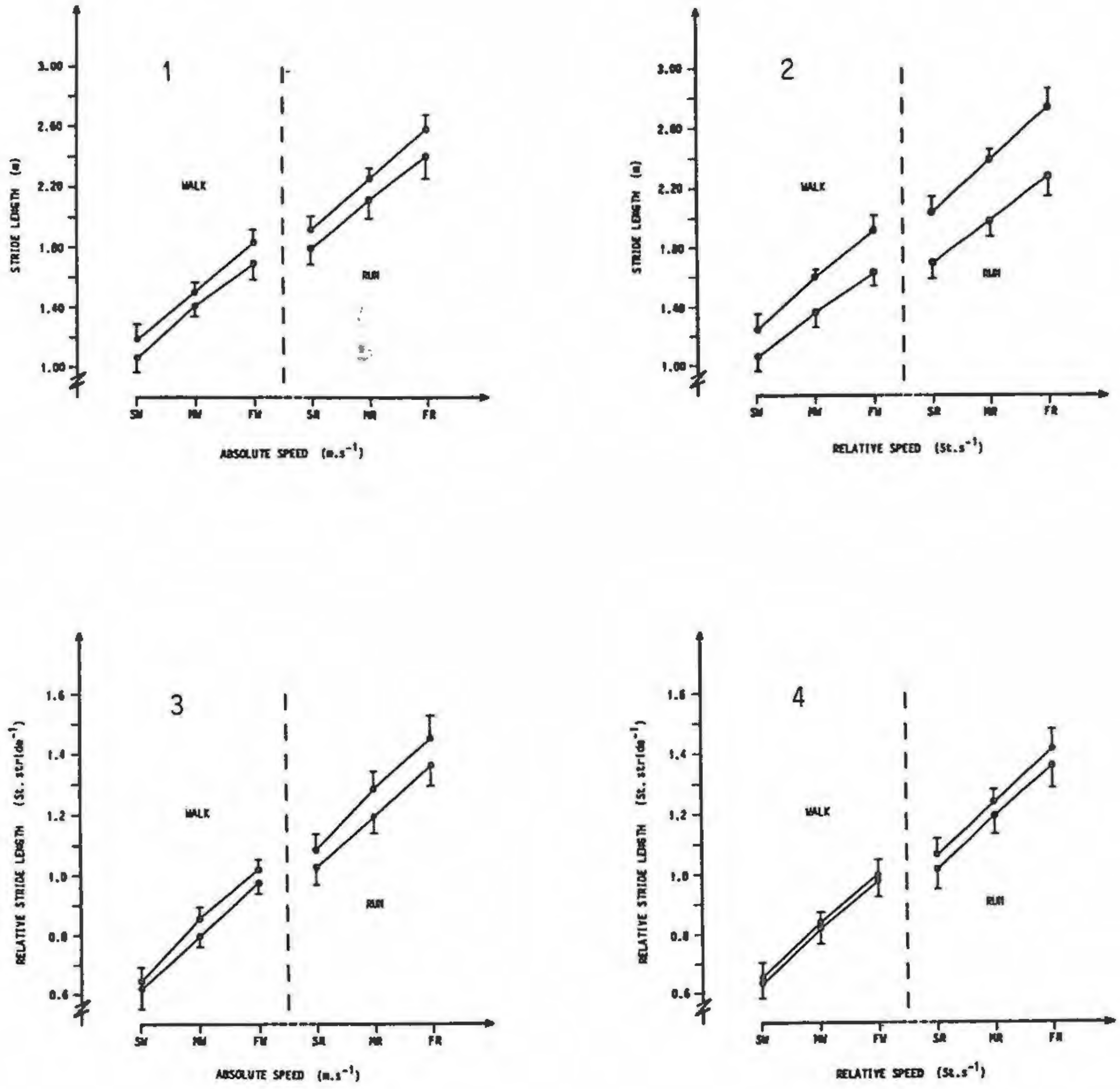


FIGURE 47: **the relationship between absolute/relative stride length and absolute/relative locomotor speed.**

When locomotor speed is expressed in absolute terms, significant differences in absolute stride length tend to occur between morphologically similar subjects of unequal size (1). When the rate of progression is expressed relative to some measure of morphological linearity, the between-subject variability in absolute stride length is intensified (2). Clearly, the least variability between subjects is achieved when both the stride length and the locomotor speed are expressed in relative terms (4).

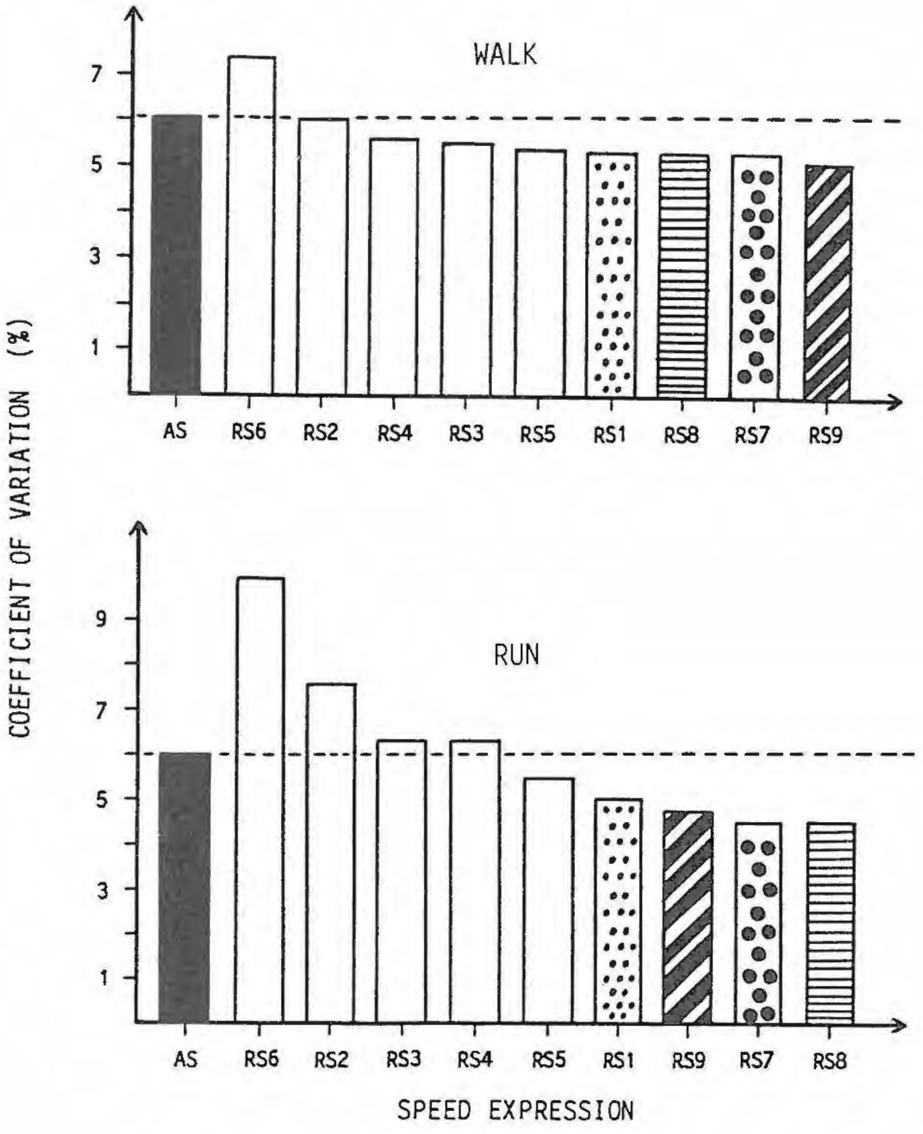


FIGURE 48: **the inter-individual variability as reflected in relative stride length for each of the ten methods of expressing the locomotor speed of walking and running.**

For walking, all but one (RS6) of the methods of relativising locomotor speed (morphologically) was effective in reducing the between-subject variability in relative stride length. The least variability in relative stride length was achieved when the walking speed was expressed in terms of a Froude number in which stature is used as the characteristic measure of size (RS7). For running, on the other hand, few methods of relativising locomotor speed (morphologically) were effective in reducing the between-subject variability in relative stride length. The least variability in relative stride length was achieved when the running speed was expressed in terms of a Froude number in which lower-limb length is used as the characteristic measure of size (RS8).

speed using stature only (U/St) was also found to be effective in reducing the variability between subjects with respect to relative lengths of stride. However, the remaining relative speed expressions tended not to decrease (and in fact to increase) this variability, especially when running was prescribed as the mode of locomotion (see Figure 48). The effectiveness of the Froude number in reducing the variability in stride length would suggest that the force of gravity tends to influence the length of step adopted during walking or running quite considerably.

DISCUSSION

In conclusion, it may be argued that the results of this research suggest that the relativisation of walking/running speed with respect to selected morphological measures is effective as a means of significantly reducing the between-subject variability inherent in both the energetics and kinematics of locomotion. Consequently, if one wishes to stress equally subjects differing significantly in body size and proportion, it is important to prescribe the rate of locomotor progression in terms relative to some morphological measure, such that each subject moves at a speed which is proportional to some characteristic of his own physical make-up. Indeed, this is the contention of numerous investigators who maintain that the response of short and tall subjects will only be energetically comparable if they move at speeds which are relative to their own stature or lower-limb length (Miller & Blyth 1955, Brockett et al. 1956, Charteris et al. 1979, Charteris 1982, Alexander 1984, Williams 1987).

The results of this research tend to augment further the assumption that human morphology influences considerably both the energetics and kinematics of locomotion. It has been demonstrated herein that the use of several very different methods of relativising locomotor speed on a morphological basis were generally successful in terms of reducing the inter-individual variability inherent in the human organism's response to speeds of both walking and running. In other words, the use of morphology-normalised speeds of horizontal locomotion were effective in "normalising" the rate of progression such that all subjects are equally stressed and respond in similar fashion when locomoting at any given relative speed - irrespective of any morphological diversity. Future research wishing to equalise the intensity of locomotion for all subjects would be well advised to express the rate of progression (be it for walking or running) in relative terms - that is, prescribe the locomotor speed as a fraction of some linear measure of morphology. Any of several methods of relativising locomotor speed are recommended, the choice of any one method depending upon the following criteria:

i) the importance attached to the necessity of attaining the least possible variability between subjects with respect to any given locomotor variable,

ii) the particular locomotor variable (energetic or kinematic) one wishes to "normalise", and

iii) the mode of locomotion (walking or running) prescribed by the research protocol.

It is the author's contention that the relativisation of speed using the Froude number is most effective in reducing the between-subject variability in locomotor energy cost. Specifically, the use of a Froude number in which stature represents the characteristic measure of length ($U/\sqrt{g.St}$) tends to most dramatically reduce the energetic variability for both walking and running. However, considering the complexity of this relative speed equation, it might be argued that other more easily prescribed methods of relativising speed would be more useful in studies of human locomotion. In this regard, the expression of speed relative to stature (U/St) might be considered the most useful method of "normalising" locomotor speeds with respect to energy expenditure. However, it should be pointed out that both these methods of relativising speed are effective in eliminating the significant differences which tend to manifest themselves between "short" and "tall" subjects when the rate of progression is expressed in absolute terms. Thus, either method (U/St or $U/\sqrt{g.St}$) is a useful means via which to "normalise" locomotor speeds with respect to the energetics of walking or running, and the selection of either one before the other would depend on whether simplicity of use (U/St) or the effectiveness with which the between-subject variability is reduced ($U/\sqrt{g.St}$) constitutes the more important criterion.

Further, it would appear that the relativisation of speed using lower-limb length (U/LLL) is no more effective a means of "normalising" locomotion energetically than is the relativisation of speed using stature (U/St). Both methods tend to reduce the variability in locomotor energy cost between subjects equally well, which is not surprising considering the high correlation ($r = 0.965$) reported between stature and lower-limb length (Van der Walt & Wyndham 1973). Therefore, in view of the difficulty often associated with the accurate and reliable measure of lower-limb length, it is suggested that the relativisation of locomotor speed using stature, which is easily and reliably measured, is the more useful and appropriate method of "normalising" human locomotion.

The relativisation of speed via the use of the Froude number appears to be of limited value with respect to reducing the between-subject variability in locomotor cadence. As demonstrated earlier, when the rate of progression was expressed in terms of the Froude number, the cadences of the short and tall subjects tended to remain significantly different. Hence, while gravity may significantly affect the energetics of locomotion (Alexander 1976, 1984), it appears to exert limited influence with respect to the frequency of step adopted during walking or running. Accordingly, the relativisation of speed using the Froude number is not recommended for those investigations wishing to equalise locomotor cadence for subjects differing significantly in size. Rather, an expression of speed relative to stature or lower-limb length would be most effective in reducing the variability in cadence between subjects. Again, however, the problems associated with the accurate and reliable measure of lower-limb length may render the use of this morphological feature for the relativisation of locomotor speed impractical. Thus, the use of speed relative to stature (U/St) is once again recommended as an appropriate means of "normalising" locomotion with repect to cadence.

The expression of speed relative to the product of androgyny index and stature (U/AI.St) was also found to be an effective method of reducing the inter-individual variability associated with locomotor cadence. It may be that the ratio of bi-acromial diameter (BAD) to bi-iliac diameter (BID) has important ramifications with respect to the cadence freely chosen by the subject during walking and/or running. The mechanical advantages possibly associated with a narrow hip and broad shoulders may contribute to one's ability to increment the length of stride during locomotion, thereby facilitating a lower frequency of step per unit speed. Consequently, the expression of speed relative to this bi-acromial/bi-iliac ratio may represent an appropriate means of "normalising" locomotion such that subjects differing significantly in size move at any relative speed with the same locomotor cadence. However, since the androgyny index was combined with stature as a means of relativising speed for the purposes of this research, the absolute influence of the bi-acromial/bi-iliac ratio in this respect is largely unquantifiable, and it is very likely that the obvious effects of stature upon the kinematics of locomotion may well have contributed most dramatically to the success of this morphology-normalised expression of locomotor speed.

With regard to relative stride length, it was demonstrated once again that the relativisation of speed using the Froude number was most effective in reducing the between-subject variability. However, if ease of use is considered more important than ensuring the minimum degree of variability, then investigators would be well advised to relativise the locomotor speed using the simple measure of stature (U/St). Although the former method would generate a lower across-sample coefficient of variation with respect to the relative length of stride, the complexity of the relative speed equation might limit its use as a practical tool in studies of human locomotion. However, it should be stressed that the relativisation of locomotor speed using the Froude number and the simple measure of stature were both effective in reducing the variability in relative stride length between subjects at any given speed of walking or running.

On the whole, it may be concluded that the relativisation of speed with respect to some linear morphological measure is an effective method of reducing the inherent between-subject variability associated with human responses (both energetic and kinematic) to locomotion. Any one of several relative speed expressions may be prescribed in this respect, the most appropriate method being very much dependent upon the specific nature of the research. Generally speaking, therefore, it may be reported on the basis of the findings of this study, that human morphology is very instrumental with respect to the energetic and kinematic responses of the human organism to both walking and running locomotory modes. Further, such morphological influence may be effectively factored out if the rate of progression is prescribed to some linear measure of body size rather than in absolute terms.

CHAPTER FIVE

SUMMARY AND CONCLUSIONS

AIMS OF THE STUDY

This study sought to investigate the influence of selected measures of morphological linearity upon physiological, biomechanical and psychological responses of the human organism to speeds of horizontal walking and running. In so doing, it was possible to identify whether or not subjects differing significantly in morphological make-up respond energetically ($\dot{V}O2$), kinematically (cadence and stride length) and psychophysically (local and central RPE) in an identical fashion when progressing at any given speed of walking or running expressed in absolute terms.

A further aim of the study concerned the effectiveness of relativising speed in order to normalise locomotion for all subjects irrespective of a possible morphological disparity. Thus, if morphologically similar subjects of unequal size were seen to respond differently to any given locomotor speed when the rate of progression was expressed in absolute terms, how effectively could such differences be eliminated if the rate of progression were expressed with respect to some linear measure of body size?

The questions addressed in this study were consequently pertinent to both of two movement responses. Firstly, the relationship between selected locomotor variables and rates of progression expressed absolutely, and secondly the relationship between the same locomotor variables and morphology-normalised (relative) speeds. Ultimately, the research sought to establish which of several methods of expressing locomotor speed (absolutely or relatively) was most successful in reducing the inter-individual variability inherent in the energetic, kinematic and psychophysical responses of the human organism to both walking and running modes of progression.

The following hypotheses were developed in order to investigate the influence of absolute and relative speeds upon morphology-specific responses to horizontal locomotion:

Hypothesis One

That there is no significant interactive effect between subject size and locomotor speed with respect to selected energetic, kinematic and psychophysical responses to walking or running.

Hypothesis Two

That morphologically similar subjects of unequal size respond (energetically, kinematically and psychophysically) in an identical fashion when walking or running at locomotor speeds expressed in absolute terms.

Hypothesis Three

That morphologically similar subjects of unequal size respond (energetically, kinematically and psychophysically) in an identical fashion when walking or running at locomotor speeds expressed in relative terms.

RESEARCH METHODOLOGY

Twenty caucasian males volunteered to participate as subjects in this study - ten in each of a "short" stature category ($\bar{X} = 165.4$cm) and a "tall" stature category ($\bar{X} = 190.2$cm). Prior to testing, subjects were familiarised with the research protocol and requested to sign appropriate consent forms. A battery of anthropometric tests was then conducted, during which selected morphological measures were recorded. All subjects were subsequently habituated to horizontal progression on a motor-driven treadmill (60 minutes), before completing randomly each of six five-minute locomotor treatments - "slow", "medium" and "fast" walking (0.83, 1.39 and 1.94m.s^{-1}) and running (2.50, 3.06 and 3.61m.s^{-1}) conditions. During each of these locomotor treatments, physiological data ($\dot{V}$O2, $\dot{V}$CO2, R-value, $\dot{V}$I, $\dot{V}$f, Vt and heart-rate), kinematic data (cadence, stride length, cycle time, support time and swing time) and psychophysical data (local and central RPE) were captured. From these absolute variables numerous derived measures were calculated, namely relative stride length, support/swing ratio, locomotor energy cost and the oxygen cost per step.

Having established the linear/curvilinear line of best fit for each subject with respect to the relationship between absolute speed and energetic, kinematic and psychophysical locomotor responses, prediction equations were used in order to extrapolate the relationship between the same locomotor variables and nine different methods of relativising (morphologically) the speed of walking or running. In terms of these relative speed expressions, the rate of locomotor progression was described as a fraction of one of a number of linear morphological measures. Hence, the rate of walking or running was expressed relative to either stature, leg length, lower-limb length, bi-acromial diameter, bi-iliac diameter, an androgyny index or body surface area (or to any combination of these measures).

Multi-variable statistics (two-way repeated measures analyses of variance, correlation coefficients, coefficients of variation and post-hoc Scheffé tests) and single-variable statistics (means and standard deviations) were performed ($P < 0.05$) in order to facilitate a between-group comparison of data, and to allow for an interpretation of the relationships found to exist between absolute/relative speed and selected energetic, kinematic and psychophysical locomotor responses.

SUMMARY OF RESULTS

The principal findings of this investigation may be summarised as follows:

1. The relationship between oxygen consumption and the absolute speed of walking was curvilinear in nature ($r = 0.955$) for both the short and tall subjects. However, for the "fast" walking speed, the locomotor

oxygen consumption of the short subjects was significantly greater than was that recorded for the tall subjects. Generally speaking, therefore, increments in the speed of walking tended to stress the short subjects more severely than they did the tall subjects. A significant interactive effect was reported for oxygen consumption between subject size and the locomotor speed of walking.

The following equations were derived for the prediction of locomotor oxygen consumption ($\dot{V}O2$) ($ml.kg^{-1}.min^{-1}$) from known absolute speeds ($m.s^{-1}$) for walking:

$\dot{V}O2$ = 5.9231 * EXP(0.6782 * SPEED) - "short" subjects (r = 0.962)
$\dot{V}O2$ = 5.6442 * EXP(0.6421 * SPEED) - "tall" subjects (r = 0.973)
$\dot{V}O2$ = 5.7836 * EXP(0.6599 * SPEED) - subjects generally (r = 0.955)

2. The relationship between oxygen consumption and the absolute speed of running was linear in nature (r = 0.847) for both short and tall subjects. However, for the "slow", "medium" and "fast" running speeds, the locomotor oxygen consumption of the short subjects was significantly greater than was that recorded for the tall subjects. Generally speaking, therefore, increments in the speed of running tended to stress the shorter subjects more severely than they did the tall subjects. A significant interactive effect was reported for oxygen consumption between subject size and the locomotor speed of running.

   The following equations were derived for the prediction of locomotor oxygen consumption ($\dot{V}O2$) ($ml.kg^{-1}.min^{-1}$) from known absolute speeds ($m.s^{-1}$) for running:

   $\dot{V}O2$ = -0.5703 + (13.1484 * SPEED) - "short" subjects (r = 0.884)
   $\dot{V}O2$ = 2.5964 + (10.7231 * SPEED) - "tall" subjects (r = 0.933)
   $\dot{V}O2$ = 1.0251 + (11.9313 * SPEED) - subjects generally (r = 0.847)

3. The locomotor energy cost ($\dot{V}O2$ per unit distance) was lowest (optimal) for the "medium" walking speed, and tended to be

significantly greater for both "slow" and "fast" rates of progression. Further, the locomotor energy cost at any given speed of walking was significantly greater for the short subjects than it was for the tall subjects. Thus, the energy expended per unit distance during walking appears to have been a function of both absolute locomotor speed and subject morphology.

The locomotor energy cost reported for running, on the other hand, was approximately the same for the "slow", "medium" and "fast" rates of progression. However, as was the case for walking, the locomotor energy cost for running was significantly greater for the short subjects than it was for the tall subjects at any given speed. Thus, the energy expended per unit distance during running appears to have been independent of the absolute locomotor speed, but very definitely a function of subject morphology. No significant interactive effect was reported for locomotor energy cost between subject size and the locomotor speed of walking or running.

4. Cadence increased as a linear function of absolute walking speed ($r = 0.914$), but as a curvilinear function of absolute running speed ($r = 0.467$). Stride length, on the other hand, was seen to seen to follow the opposite trend, tending to increase as a curvilinear function of walking speed ($r = 0.937$), but as a linear function of running speed ($r = 0.902$). This would suggest that as the rate of progression for walking is increased, the length of stride tends towards a <u>mechanically</u> imposed "maximum", and cadence gradually becomes more important as a means of facilitating increments in locomotor intensity. However, as the rate of progression for running is increased, the cadence tends towards an <u>energetically</u> imposed "maximum", and stride length gradually becomes more important as a means of facilitating increments in locomotor intensity.

   It was also revealed that for both walking and running gaits, short subjects tended to locomote with a significantly higher cadence and a significantly shorter length of step (relative to their taller counterparts). Accordingly, as the stature (or lower-limb length) of the subject decreased, the locomotor pattern tended to be characterised by proportionately shorter lengths of stride coincident with relatively higher cadences. Thus, the length and frequency of step during locomotion appear to have been a function of both absolute locomotor speed and subject morphology. No significant interactive effect was reported for either cadence or stride length between subject size and the locomotor speed of walking or running.

The following equations were derived for the prediction of locomotor cadence (CAD) (steps.min^{-1}) and stride length (SL) (m) from known absolute speeds (m.s^{-1}) for walking and running:

WALKING

$\mathrm{CAD} = 62.9940 + (38.6582 * \mathrm{SPEED})$ - "short" subjects ($r = 0.949$)

$\mathrm{CAD} = 55.7982 + (36.7801 * \mathrm{SPEED})$ - "tall" subjects ($r = 0.946$)

$\mathrm{CAD} = 59.3961 + (37.7191 * \mathrm{SPEED})$ - subjects generally ($r = 0.914$)

$\mathrm{SL} = 0.7580 * \mathrm{EXP}(0.4251 * \mathrm{SPEED})$ - "short" subjects ($r = 0.960$)

$\mathrm{SL} = 0.8492 * \mathrm{EXP}(0.4075 * \mathrm{SPEED})$ - "tall" subjects ($r = 0.951$)

$\mathrm{SL} = 0.7970 * \mathrm{EXP}(0.4206 * \mathrm{SPEED})$ - subjects generally ($r = 0.937$)

RUNNING

$\mathrm{CAD} = 141.1699 * \mathrm{EXP}(0.0637 * \mathrm{SPEED})$ - "short" subjects ($r = 0.546$)

$\mathrm{CAD} = 130.7508 * \mathrm{EXP}(0.0649 * \mathrm{SPEED})$ - "tall" subjects ($r = 0.612$)

$\mathrm{CAD} = 135.8604 * \mathrm{EXP}(0.0643 * \mathrm{SPEED})$ - subects generally ($r = 0.467$)

$\mathrm{SL} = 0.3966 + (0.5677 * \mathrm{SPEED})$ - "short" subjects ($r = 0.920$)

$\mathrm{SL} = 0.4356 + (0.6083 * \mathrm{SPEED})$ - "tall" subjects ($r = 0.957$)

$\mathrm{SL} = 0.4161 + (0.5880 * \mathrm{SPEED})$ - subjects generally ($r = 0.902$)

5. Relative stride length increased as a linear function of both walking speed ($r = 0.957$) and running speed ($r = 0.907$) for the two stature categories. However, significant differences in relative stride length were revealed between the short and tall subjects at any given locomotor speed. Thus, even when expressed as a fraction of stature (St.stride^{-1}), the stride length for any given rate of progression differed significantly between morphologically similar subjects of

unequal size. Generally speaking, the relative stride length tended to be greater for shorter subjects when progressing at any prescribed locomotor speed. This would suggest that the same absolute rate of progression tends to stress short subjects more severely than it does tall subjects. No significant interactive effect was reported for relative stride length between subject size and the locomotor speed of walking or running.

6. For any given absolute speed of walking or running, the oxygen consumed per step ($\dot{V}O2$ as a fraction of cadence) was approximately the same for the short and tall subjects. This would suggest that the previously observed morphology-related significant variability in locomotor oxygen consumption was largely a function of the difference between the short and tall subjects with respect to the number of steps taken per unit distance. In other words, the significantly greater oxygen consumption reported for the short subjects at any given locomotor speed was a direct function of the greater cadences adopted by these subjects. Thus, the speed-specific oxygen consumption during walking and running would appear to be a function of locomotor cadence, which is in turn a direct function of subject morphology. No significant interactive effect was reported for the oxygen consumption per step between subject size and the locomotor speed of walking or running.

   The following equations were derived for the prediction of the oxygen consumed per step ($\dot{V}O2.step^{-1}$) ($ml.kg^{-1}.min^{-1}$) from known absolute locomotor speeds ($m.s^{-1}$) for walking and running:

   $\dot{V}O2.step^{-1} = 0.0750 + (0.0420 * SPEED)$ - for walking ($r = 0.802$)

   $\dot{V}O2.step^{-1} = 0.0514 + (0.0571 * SPEED)$ - for running ($r = 0.792$)

7. Both local (muscular/joint) and central (cardiorespiratory) ratings of perceived exertion increased in a curvilinear fashion with increments in the locomotor speed of walking and running. Further, for either locomotory mode, the local ratings of exertion were

significantly greater than were the central ratings at any prescribed rate of absolute progression. This speed-specific difference in the local and central ratings of perceived locomotor effort tended to increase fairly proportionately with increments in the rate of progression. This would suggest that as the speed of walking or running (aerobic) increases, local ratings of physical exertion (emanating from the locomotor muscles and joints) tend to contribute a greater input to the effort sense.

No significant differences were revealed between the two stature groups with respect to either local or central ratings of perceived locomotor exertion. Thus, at any given speed of walking or running, short and tall subjects appear to perceive locomotor intensity equally. This was the case despite previously observed significant differences between the stature groups with respect to locomotor oxygen consumption. It would appear, therefore, that during walking or running at speeds expressed in absolute terms, the between-subject variabilty in locomotor energetics is not matched by a similar between-subject variability with respect to the psychophysical estimation of effort. No significant interactive effect was reported for either local or central ratings of perceived exertion between subject size and the locomotor speed of walking or running.

The following equations were derived for the prediction of ratings of local and central perceptions of exertion (RPE) from known absolute speeds ($m.s^{-1}$) for walking and running:

$$\text{RPE (loc)} = 4.3274 * \text{EXP}(0.4003 * \text{SPEED}) \text{ - for walking } (r = 0.795)$$
$$\text{RPE (loc)} = 4.5966 * \text{EXP}(0.2648 * \text{SPEED}) \text{ - for running } (r = 0.699)$$

$$\text{RPE (cen)} = 4.9734 * \text{EXP}(0.2548 * \text{SPEED}) \text{ - for walking } (r = 0.702)$$
$$\text{RPE (cen)} = 4.3747 * \text{EXP}(0.2495 * \text{SPEED}) \text{ - for running } (r = 0.628)$$

8. The use of morphology-normalised speeds of walking and running were effective in reducing the between-subject variability with respect to locomotor energetics. For both walking and running, the least variability in locomotor oxygen consumption was realised when the locomotor speed was expressed in terms of a Froude number in which

stature was used as the linear measure of length ($U/\sqrt{g.St}$). It would appear, therefore, that both subject stature and the force of gravity have considerable influence upon the energetics of human locomotion.

9. The use of morphology-normalised speeds of walking and running were effective in reducing the between-subject variability with respect to locomotor cadence. For both walking and running, the least variability in cadence was realised when the locomotor speed was expressed as a fraction of stature (U/St) or lower-limb length (U/LLL). It would appear, therefore, that subject stature (and/or lower-limb length) has a considerable influence upon the locomotor cadence freely chosen during walking and running. Morphological measures associated with the trunk and upper appendages, on the other hand, tend to affect the locomotor cadence to a much lesser degree. Considering the ineffectiveness with which the relative speed methods based on the Froude number reduced the between-subject variability in cadence, it would appear that the force of gravity tends not to significantly influence the frequency of step during human locomotion.

10. The use of morphology-normalised speeds of walking and running served only to increase the between-subject variability with respect to locomotor stride length (absolute). However, the morphological relativisation of speed was successful in reducing the variability in relative stride length between subjects. For both walking and running, the least variability in relative stride length was realised when the locomotor speed was expressed in terms of a Froude number in which stature ($U/\sqrt{g.St}$) or lower-limb length ($U/\sqrt{g.LLL}$) is used as the linear measure of length. This would suggest that both stature (or lower-limb length) and the force of gravity have considerable influence on the length of stride freely chosen during locomotion. Morphological measures associated with the trunk and upper appendages, on the other hand, would appear to affect the locomotor stride length to a much lesser degree.

TENTATIVE ACCEPTANCE/REJECTION OF THE RESEARCH HYPOTHESES

On the basis of the findings of this study, the research hypotheses should be tentatively accepted or rejected as follows:

Hypothesis One

For all the locomotor variables investigated, with the exception of oxygen consumption, the null hypothesis is tentatively accepted ($P < 0.05$). It is consequently inferred that, with respect to oxygen consumption, subject size and locomotor speed expressed in absolute terms demonstrated a significant interaction. For all other variables (energetic, kinematic and psychophysical), no significant interactive effect was demonstrated between subject size and the locomotor speed of walking or running.

Hypothesis Two

For the energetic and kinematic locomotor variables, the null hypothesis is tentatively rejected in favour of the alternative hypothesis ($P < 0.05$). It is consequently inferred that morphologically similar subjects of unequal size respond (energetically and kinematically) in a significantly different fashion when walking or running at locomotor speeds expressed in absolute terms.

However, with respect to the psychophysical locomotor variables, the null hypothesis is tentatively accepted ($P < 0.05$). It is consequently inferred that morphologically similar subjects of unequal size respond (psychophysically) in an identical fashion when walking or running at locomotor speeds expressed in absolute terms.

Hypothesis Three

For all the locomotor variables investigated, the null hypothesis is tentatively accepted ($P < 0.05$). It is consequently inferred that morphologically similar subjects of unequal size respond (energetically, kinematically and psychophysically) in an identical fashion when walking or running at locomotor speeds expressed in relative terms.

CONCLUSIONS

Based on the findings of this study, it can be concluded that morphologically similar subjects of unequal size respond in a significantly different fashion with respect to the energetics and kinematics of horizontal locomotion when the speed is expressed in absolute terms. Generally speaking, "short" subjects (<170cm) tend to be more severely stressed when walking or running at any given absolute rate of progression than do their "tall" counterparts (>185cm). The same cannot be reported with respect to psychophysical responses to locomotion, which tend to remain constant for all subjects at any given absolute speed irrespective of differences in morphology.

Further, the relativisation of locomotor speed with respect to measures of morphological linearity are effective in reducing the inter-individual variability inherent in the response of the human organism to both walking and running locomotory modes. For energetic ($\dot{V}O2$) and kinematic (cadence and stride length) locomotor variables, the morphological normalisation of speed is a successful means of eliminating the significant size-related variability between subjects. Consequently, unless locomotor speed is relativised on a morphological basis, significant energetic and kinematic differences are likely to manifest themselves between morphologically similar subjects of unequal size.

RECOMMENDATIONS

With respect to any future study pertaining to energetic, kinematic and psychophysical responses of the human organism to locomotor speeds, the author feels that the following recommendations merit careful consideration:

1. To complete a thorough understanding of the relationship that exists between locomotor energetics and kinematics, research investigating the morphology-specific response of the human organism to running speeds of an anaerobic nature (ie. sprinting) should be undertaken.

2. The relationship between the rate of locomotor progression and cadence/stride length should be investigated across the entire spectrum of walking and running speeds. Data in the present research suggest that the linear/curvilinear trends in locomotor cadence/stride length for walking tend to become reversed (curvilinear/linear) during running.

3. The influence of absolute and relative speeds of walking and running upon locomotor kinetics should be investigated. Do the forces generated during locomotion differ significantly between morphologically similar subjects of unequal size?

4. The locomotor energetics and kinematics should be evaluated using subjects falling between the short and tall cut-off statures as prescribed in this study (ie. between 170cm and 185cm). In this way, a critical stature differential might be identified, above which it would be beneficial to use relative speed as a means of reducing inter-individual variability, but below which absolute speeds might be more appropriate.

5. The results of this study were derived via data captured from a limited subject-sample during indoor locomotion on a motor-driven treadmill. It is important to establish whether or not the principles herein observed can be extrapolated to encompass the male population generally. Further, it is important to determine whether or not the results attained via this treadmill study can be extrapolated with respect to overground walking and running outside of the laboratory.

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APPENDICES

APPENDICES

APPENDIX 1

PRE-TEST SUBJECT INFORMATION

APPENDIX 2

DATA RECORDING SHEETS

APPENDIX 3

PERCEIVED EXERTION DOCUMENTATION

APPENDIX 4

A SUMMARY OF THE MEAN RESEARCH DATA

APPENDIX 5

SOME USEFUL EQUATIONS

APPENDIX 1

Subject Consent Information Sheet

Prior to participation in this research, subjects were requested to read an appropriate information sheet outlining the basic research protocol, the risks likely encountered and the benefits to be gained.

Subject Consent Form

Prior to participation in this research, subjects were requested to sign an appropriate consent form thereby waiving any legal recourse against the researcher or Rhodes University. This consent form was signed by the subject, the researcher, the project supervisor and a witness.

RHODES UNIVERSITY

DEPARTMENT OF HUMAN MOVMENT STUDIES

INFORMED CONSENT INFORMATION SHEET

PROJECT: **"Energetic and kinematic responses to morphology-normalised speeds of walking and running."**

1. GENERAL: the project you are about to take part in is an in-depth examination of the role played by morphology in the energetics and kinematics of human walking and running. The study will attempt to evaluate to what extent linear morphological dimensions (eg. stature, leg length, lower-limb length, bi-iliac diameter and bi-acromial diameter) affect the energetic and kinematic responses to human locomotion. It is further hoped that this study will elucidate the importance of relative speed as a means of "normalising" human locomotion for all subjects irrespective of morphological make-up. Please note that you are by no means committed once you have agreed to take part (ie. you are at liberty to withdraw your participation at any time prior to or during experimentation).

2. PROCEDURE: as a subject you will be required to complete the following:

    i) furnish measures of your mass, stature, leg length, lower-limb length, bi-iliac diameter (hip width) and bi-acromial diameter (shoulder width), as well as other pertinent information such as age and resting heart-rate.

    ii) undergo an extensive habituation programme to accomodate yourself to treadmill walking and running, wearing specially adapted footswitch pads, for periods totalling no less than 60 minutes (six 10-minute sessions).

    iii) furnish values for analysis of expired gas, analysis of the temporal and spatial characteristics of the walking and running gait cycles, and ratings pf perceived locomotor exertion (RPE) at each of six predetermined walking and running speeds (ranging from a slow walk of 3km/hr to a brisk run of 13km/hr).

    iv) the experimental protocol will continue as follows: you will be required to walk and run for five minutes at each of six predetermined speeds (three walking and three running). During each five-minute session, your expired gas and gait pattern will be analysed via on-line computer aided apparatus, and your ratings of perceived locomotor exertion will be recorded verbally. Following each five-minute speed treatment, you will be requested to rest until such time as your recovery heart-rate has returned to within 10 beats/min of the resting value.

v) you will be required to inform the researcher of any injury sustained prior to or during the test protocol.

vi) you will be required to refrain from any form of vigorous exercise on the day of testing (ie. report for testing in a well rested condition). You will also be required to avoid excessive intake of food 2-3 hours prior to testing.

vii) you will be requested to report for testing dressed suitably for exercise of an aerobic nature - namely, in shorts, running vest or tee-shirt and "sensible" shoes.

3. RISKS: because the testing is of an aerobic nature you will at no time be expected to exercise maximally - the most taxing condition involves a brisk five-minute run at 13km/hr. There are therefore no extraordinary risks involved, and you are assured that all reasonable precautions will be taken to ensure your safety. However, since the testing involves locomotion on a motor-driven treadmill, the following must be considered:

   i) there is a possibility of injury due to falling/slipping on the treadmill.

   ii) there is a possibility of muscle-strain (an adequate warm-up is therefore strongly advised).

   iii) you will experience physiological discomforts such as elevated heart-rate and blood-pressure - these are unavoidable.

4. BENEFITS: you will receive feedback with respect to your physiological and kinematic responses to a number of locomotor speeds, as well as personal data such as: i) your energetic responses to each of the prescribed speed treatments, ii) your kinematic responses to each of the prescribed speed treatments, and iii) your psychophysical responses to each of the prescribed speed treatments.

Your participation as a subject would be most appreciated.

Thank you for your time,

MARTIN ANDREW WILLIAMS

RHODES UNIVERSITY

DEPARTMENT OF HUMAN MOVEMENT STUDIES

SUBJECT CONSENT FORM

I, ... having been fully informed of the nature of the research entitled:

"Energetic and kinematic responses to morphology-normalised speeds of walking and running."

do hereby give my consent to act as a subject in the abovenamed study. I am fully aware of the procedures involved, as well as the the potential risks and benefits attendant to my participation as explained to me both 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 realise that it is necessary for me to report promptly to the said researcher any signs or symptoms indicating any abnormality or distress.

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

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

SUBJECT:	.... (print name)	.... (sign)	.... (date)
RESEARCHER:	.... (print name)	.... (sign)	.... (date)
WITNESS:	.... (print name)	.... (sign)	.... (date)
SUPERVISOR:	.... (print name)	.... (sign)	.... (date)

APPENDIX 2

Pilot Study: Data Sheet

During the pilot study, selected energetic and kinematic data were captured following completion of both walking and running locomotor treatments.

Habituation: Data Sheet

During the habituation programme, measures of oxygen consumption and cadence were recorded following 60 minutes of discontinuous treadmill walking and running.

Research Protocol: Data Sheet

During the research testing proper, anthropometric data were collected prior to the completion of six five-minute locomotor treatments. During the treatments (three walking and three running) energetic, kinematic and psychophysical data were captured.

RHODES UNIVERSITY

DEPARTMENT OF HUMAN MOVEMENT STUDIES

PILOT STUDY: DATA SHEET

NAME: ....

DATE: ....

AGE: ....   SUBJECT CODE: ....

CONDITION: ....

1. PHYSIOLOGICAL DATA

SPEED	$\dot{V}$O2	HR	R- VALUE	$\dot{V}$I
....	....	....	....	....
....	....	....	....	....
....	....	....	....	....
....	....	....	....	....
....	....	....	....	....
....	....	....	....	....

2. KINEMATIC DATA

SPEED	CAD	SL	CT	SUPP/SWIN
....	....	....	....	....
....	....	....	....	....
....	....	....	....	....
....	....	....	....	....
....	....	....	....	....
....	....	....	....	....

RHODES UNIVERSITY

DEPARTMENT OF HUMAN MOVEMENT STUDIES

HABITUATION: DATA SHEET

NAME: ....

DATE: ....

AGE: ....   SUBJECT CODE: ....

PROTOCOL

SPEED	DURATION	WALK/RUN	$\dot{V}O2$	CAD
....	....	....	....	....
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....	....	....	....	....
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....	....	....	....	....
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COMMENTS

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RHODES UNIVERSITY

DEPARTMENT OF HUMAN MOVEMENT STUDIES

RESEARCH PROTOCOL: DATA SHEET

NAME: ....

DATE: ....

AGE: ....   SUBJECT CODE: ....

STATURE (cm): ....   MASS (kg): ....

SITTING HEIGHT (cm): ....

LEG LENGTH (cm): ....

LOWER-LIMB LENGTH (cm): ....

BI-ILIAC DIAMETER (cm): ....

BI-ACROMIAL DIAMETER (cm): ....

BODY SURFACE AREA (m^2): ....

LOCOMOTOR PROTOCOL

1. .... $m.s^{-1}$ 4. .... $m.s^{-1}$

2. .... $m.s^{-1}$ 5. .... $m.s^{-1}$

3. .... $m.s^{-1}$ 6. .... $m.s^{-1}$

RESTING HEART-RATE .... bt.min^{-1}

RATINGS OF PERCEIVED LOCOMOTOR EXERTION

LOCAL		CENTRAL	
0.83m.s^{-1}	....	0.83m.s^{-1}	....
1.39m.s^{-1}	....	1.39m.s^{-1}	....
1.94m.s^{-1}	....	1.94m.s^{-1}	....
2.50m.s^{-1}	....	2.50m.s^{-1}	....
3.06m.s^{-1}	....	3.06m.s^{-1}	....
3.61m.s^{-1}	....	3.61m.s^{-1}	....

GENERAL COMMENT

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APPENDIX 3

RPE Instruction Sheet

Prior to the capture of the research data, subjects were requested to read a carefully drawn-up instruction sheet outlining what information was required of them with respect to the psychological estimation of physical effort.

RPE Scale (Borg)

During the final 30 seconds of each locomotor treatment, ratings of perceived exertion were recorded indicating a numerical representation of the subjects' psychological estimation of exercise (locomotor) intensity.

INSTRUCTIONS FOR USE OF THE BORG SCALE FOR RATINGS OF PERCEIVED EXERTION

"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. You will be asked to furnish us with two values of exertion - a central value describing the exertion you associate with the cardiorespiratory system, and a local value describing the exertion you experience with respect to your exercising muscles and joints. Try to estimate both central and local ratings 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 your exertion as accurately as possible. When you are asked to rate your effort, you should do so by giving the numerical value on the Borg scale in front of you which you feel indicates your evaluation of your perceived exertion at that moment. A rating of 6 corresponds with feelings of exertion associated with standing quietly on the treadmill. A rating of 20 reflects the feelings of exertion associated with a maximal effort. Ratings between 6 and 20 reflect gradually incrementing levels of physical effort."

THE RATING SCALE FOR PERCEIVED EXERTION

06	
07	VERY VERY LIGHT
08	
09	VERY LIGHT
10	
11	FAIRLY LIGHT
12	
13	SOMEWHAT HARD
14	
15	HARD
16	
17	VERY HARD
18	
19	VERY VERY HARD
20	

(from Borg 1970)

APPENDIX 4

The Two-Way Repeated Measures Analysis of Variance (ANOVA)

An example of the two-way repeated measures analyses of variance as performed on the energetic, kinematic and psychophysical variables for both walking and running at locomotor speeds expressed in absolute terms.

Significant Differences: Short vs. Tall Subjects

For each of the ten methods of expressing locomotor speed, suitable ANOVAs were performed in order to establish whether or not significant differences existed between the two stature groups with respect to both energetic and kinematic locomotor responses.

Research Data

A summary (mean and standard deviation) of the energetic, kinematic and psychophysical data as captured for locomotor speeds of an absolute nature, and as extrapolated for locomotor speeds expressed relative to morphology.

SUMMARY OF ABBREVIATIONS

The following abbreviations are used in many of the tables included in the appendices which appear herafter:

PHYSIOLOGICAL VARIABLES

$\dot{V}O2$ - oxygen consumption ($ml.kg^{-1}.min^{-1}$)
$\dot{V}CO2$ - carbon-dioxide production ($ml.kg^{-1}.min^{-1}$)
$\dot{V}I$ - inspired ventilatory volume ($l.min^{-1}$)
$\dot{V}f$ - breathing frequency ($br.min^{-1}$)
Vt - tidal volume ($l.br^{-1}$)
R-value - respiratory exchange ratio ($\dot{V}CO2.\dot{V}O2^{-1}$)
LEC - locomotor energy cost ($kcal.kg^{-1}.km^{-1}$)
$\dot{V}O2$/step - oxygen cost per step ($ml.kg^{-1}.step^{-1}$)
HR - heart-rate ($bt.min^{-1}$)

ANTHROPOMETRIC VARIABLES

BSA - body surface area (m^2)
BA - bi-acromial diameter (m)
BI - bi-iliac diameter (m)
AI - androgyny index (%)
RPI - reciprocal of ponderal index ($m.\sqrt[3]{kg^{-1}}$)
St - stature (m)
BM - body mass (kg)
LL - leg length (m)
LLL - lower-limb length (m)

KINEMATIC VARIABLES

CAD - cadence ($step.min^{-1}$)
CT - cycle time (s)
SL - stride length (m)
RSL - relative stride length ($St.stride^{-1}$)
Supp/Swin - support-to-swing ratio

STATISTICAL VARIABLES

fo - observed f-ratio
fc - critical f-ratio
R - row effects (ANOVA)
C - column effects (ANOVA)
S - subject effects (ANOVA)
RxCxS - interactive effect (ANOVA)
P - level of significance
CV - coefficient of variation (%)
$\bar{X}$ - mean
Sd - standard deviation

TABLE VIII: the observed (fo) and critical (fc) f-ratios as recorded via analyses of variance performed on the dependent variables collected during the absolute walking conditions.

	RxS (stature) fc = 4.41	CxS (speed) fc = 3.26	RxCxS fc = 3.26
PHYSIOLOGICAL VARIABLES			
$\dot{V}$O2	16.41	645.14	5.15
$\dot{V}$CO2	18.26	634.21	5.19
R-value	0.18	19.11	0.81
$\dot{V}$I	5.06	234.69	3.69
$\dot{V}$f	10.91	15.41	4.60
Vt	21.51	91.90	4.85
HR	40.18	234.59	0.23
$\dot{V}$O2/step	0.11	123.79	1.02
LEC	15.96	46.85	1.11
KINEMATIC VARIABLES			
Cadence	25.49	385.12	0.71
Cycle Time	17.26	719.28	0.58
Stride Length	25.42	444.29	0.69
RSL	10.28	510.14	1.59
Swing Time	4.64	225.88	0.72
Support Time	17.63	903.22	2.55
Support:Swing Ratio	4.69	269.67	2.58
PSYCHOPHYSICAL VARIABLES			
RPE (local)	1.94	85.32	2.79
RPE (central)	0.09	47.31	0.09

where: R = row effects C = column effects S = subjects

TABLE IX: the observed (fo) and critical (fc) f-ratios as recorded via analyses of variance performed on the dependent variables collected during the absolute running conditions.

	RxS (stature) fc = 4.41	CxS (speed) fc = 3.26	RxCxS fc = 3.26
PHYSIOLOGICAL VARIABLES			
V̇O2	15.02	484.96	5.05
V̇CO2	11.39	314.65	1.98
R-value	0.02	5.14	0.75
V̇I	3.36	146.32	0.56
V̇f	1.39	56.66	0.15
Vt	18.16	35.47	0.10
HR	34.32	147.90	14.20
V̇O2/step	1.13	216.41	1.61
LEC	14.43	3.63	0.87
KINEMATIC VARIABLES			
Cadence	15.66	90.58	0.42
Cycle Time	16.20	73.00	0.96
Stride Length	15.49	795.90	1.35
RSL	11.69	762.19	1.85
Swing Time	3.06	6.03	0.39
Support Time	10.08	295.65	1.32
Support:Swing Ratio	2.34	149.92	0.01
PSYCHOPHYSICAL VARIABLES			
RPE (local)	0.58	52.53	0.02
RPE (central)	0.65	52.62	0.44

where: R = row effects C = column effects S = subjects

TABLE X: results of analyses of variance as performed on the oxygen consumption data recorded or predicted for each of the ten methods of expressing locomotor speed.

	WALK		**RUN**	
	fo	$P < 0.05$	fo	$P < 0.05$
AS (m/s)	16.42	SIG	15.02	SIG
RS1 (St/s)	0.92	NON SIG	0.58	NON SIG
RS2 (LL/s)	3.41	NON SIG	2.34	NON SIG
RS3 (LLL/s)	3.94	NON SIG	2.97	NON SIG
RS4 (BAD/s)	0.18	NON SIG	0.14	NON SIG
RS5 (BID/s)	1.70	NON SIG	0.89	NON SIG
RS6 (AI.St/s)	12.17	SIG	9.81	SIG
RS7 ($U/\sqrt{g.St}$)	2.77	NON SIG	2.05	NON SIG
RS8 ($U/\sqrt{g.LLL}$)	1.33	NON SIG	1.16	NON SIG
RS9 ($U/\sqrt{g.[St^3/BSA]}$)	0.29	NON SIG	0.17	NON SIG

where: $fc\ (P < 0.05) = 4.41$

TABLE XI: results of analyses of variance as performed on the cadence data recorded or predicted for each of the ten methods of expressing locomotor speed.

	WALK		RUN	
	fo	P <0.05	fo	P <0.05
AS (m/s)	25.49	SIG	15.66	SIG
RS1 (St/s)	1.89	NON SIG	4.12	NON SIG
RS2 (LL/s)	0.58	NON SIG	5.70	SIG
RS3 (LLL/s)	0.20	NON SIG	4.25	NON SIG
RS4 (BAD/s)	6.69	SIG	9.31	SIG
RS5 (BID/s)	6.03	SIG	8.00	SIG
RS6 (AI.St/s)	1.38	NON SIG	2.57	NON SIG
RS7 $(U/\sqrt{g.St})$	11.37	SIG	12.21	SIG
RS8 $(U/\sqrt{g.LLL})$	8.71	SIG	9.76	SIG
RS9 $(U/\sqrt{g.[St^3/BSA]})$	5.56	SIG	8.93	SIG

where: fc (P <0.05) = 4.41

TABLE XII: results of analyses of variance as performed on the stride length data recorded or predicted for each of the ten methods of expressing locomotor speed.

	WALK		RUN	
	fo	P <0.05	fo	P <0.05
AS (m/s)	25.42	SIG	15.49	SIG
RS1 (St/s)	63.05	SIG	75.16	SIG
RS2 (LL/s)	49.71	SIG	44.52	SIG
RS3 (LLL/s)	63.61	SIG	76.88	SIG
RS4 (BAD/s)	44.63	SIG	29.05	SIG
RS5 (BID/s)	35.05	SIG	28.29	SIG
RS6 (AI.St/s)	67.82	SIG	61.59	SIG
RS7 $(U/\sqrt{g.St})$	47.59	SIG	42.85	SIG
RS8 $(U/\sqrt{g.LLL})$	53.88	SIG	47.54	SIG
RS9 $(U/\sqrt{g.[St^3/BSA]})$	49.98	SIG	56.44	SIG

where: fc $(P < 0.05) = 4.41$

TABLE XIII: results of analyses of variance as performed on the relative stride length data recorded or predicted for each of the ten methods of expressing locomotor speed.

	WALK		**RUN**	
	fo	P <0.05	fo	P <0.05
AS (m/s)	10.28	SIG	11.69	SIG
RS1 (St/s)	2.11	NON SIG	6.78	SIG
RS2 (LL/s)	3.95	NON SIG	6.86	SIG
RS3 (LLL/s)	5.79	SIG	14.67	SIG
RS4 (BAD/s)	0.05	NON SIG	0.24	NON SIG
RS5 (BID/s)	0.02	NON SIG	0.01	NON SIG
RS6 (AI.St/s)	12.72	SIG	17.31	SIG
RS7 $(U/\sqrt{g.St})$	0.57	NON SIG	0.21	NON SIG
RS8 $(U/\sqrt{g.LLL})$	0.28	NON SIG	0.08	NON SIG
RS9 $(U/\sqrt{g.[St^3/BSA]})$	0.03	NON SIG	1.19	NON SIG

where: fc (P <0.05) = 4.41

TABLE XIV: mean data as recorded for the short subjects when walking speeds were expressed in absolute terms.

	SLOW		MEDIUM		FAST	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.	$\bar{X}$	Sd.
PHYSIOLOGICAL VARIABLES						
$\dot{V}$O2	10.64	0.083	14.70	0.045	22.60	0.043
$\dot{V}$CO2	8.81	0.482	11.53	0.877	19.50	1.445
R-value	0.82	0.067	0.79	0.035	0.87	0.022
$\dot{V}$I	14.31	1.269	17.36	1.033	28.98	3.854
$\dot{V}$f	26.40	5.777	27.32	4.448	34.84	4.077
Vt	0.55	0.114	0.65	0.102	0.83	0.128
HR	89.83	6.973	93.77	8.994	121.54	6.770
$\dot{V}$O2/step	0.11	0.014	0.13	0.014	0.17	0.012
LEC	4.29	0.327	3.53	0.322	3.95	0.288
KINEMATIC VARIABLES						
Cadence	94.54	6.573	117.92	4.886	137.48	6.569
Cycle Time	1.28	0.083	1.02	0.045	0.88	0.043
Stride Length	1.06	0.093	1.42	0.060	1.70	0.081
RSL	0.64	0.046	0.86	0.034	1.03	0.031
Swing Time	0.50	0.037	0.42	0.019	0.38	0.017
Support Time	0.79	0.060	0.60	0.029	0.50	0.028
Support:Swing	1.59	0.125	1.43	0.053	1.31	0.038
PSYCHOPHYSICAL VARIABLES						
RPE (local)	6.32	0.483	7.10	0.738	10.64	1.578
RPE (central)	6.32	0.483	6.75	0.675	8.33	1.567

TABLE XV: mean data as recorded for the short subjects when running speeds were expressed in absolute terms.

	SLOW		MEDIUM		FAST	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.	$\bar{X}$	Sd.
PHYSIOLOGICAL VARIABLES						
V̇O2	32.61	3.193	39.10	3.186	47.24	3.508
V̇CO2	29.52	2.603	36.01	2.769	43.63	3.797
R-value	0.91	0.038	0.92	0.039	0.92	0.033
V̇I	39.55	5.124	48.41	6.899	60.90	10.320
V̇f	35.22	6.989	38.43	7.720	43.28	8.297
Vt	1.14	0.087	1.28	0.139	1.43	0.189
HR	144.02	11.972	156.62	11.167	176.11	11.328
V̇O2/step	0.20	0.023	0.23	0.024	0.27	0.023
LEC	4.49	0.418	4.41	0.348	4.52	0.343
KINEMATIC VARIABLES						
Cadence	166.32	8.718	171.02	7.789	177.20	8.430
Cycle Time	0.72	0.039	0.70	0.031	0.68	0.029
Stride Length	1.81	0.097	2.15	0.098	2.44	0.143
RSL	1.09	0.057	1.30	0.061	1.47	0.075
Swing Time	0.45	0.030	0.47	0.028	0.47	0.024
Support Time	0.27	0.027	0.24	0.020	0.21	0.019
Support:Swing	0.61	0.076	0.52	0.059	0.45	0.049
PSYCHOPHYSICAL VARIABLES						
RPE (local)	9.30	1.252	10.22	1.229	12.54	2.014
RPE (central)	8.64	1.350	9.76	1.252	11.33	1.829

TABLE XVI: mean data as recorded for the tall subjects when walking speeds were expressed in absolute terms.

	SLOW		MEDIUM		FAST	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.	$\bar{X}$	Sd.
PHYSIOLOGICAL VARIABLES						
$\dot{V}$O2	9.73	0.840	13.65	0.758	19.81	1.233
$\dot{V}$CO2	8.11	0.662	10.97	0.657	17.20	1.298
R-value	0.83	0.041	0.81	0.057	0.86	0.032
$\dot{V}$I	16.44	2.713	21.47	3.844	29.43	2.474
$\dot{V}$f	24.33	4.900	22.77	4.057	26.11	3.247
Vt	0.69	0.128	0.91	0.188	1.14	0.127
HR	78.23	4.566	84.89	4.725	109.83	5.750
VO2/step	0.12	0.016	0.12	0.011	0.16	0.011
LEC	3.95	0.323	3.27	0.163	3.46	0.213
KINEMATIC VARIABLES						
Cadence	84.89	7.233	109.81	4.211	125.75	4.945
Cycle Time	1.38	0.051	1.10	0.041	0.95	0.039
Stride Length	1.19	0.122	1.52	0.057	1.86	0.073
RSL	0.62	0.066	0.80	0.026	0.98	0.033
Swing Time	0.51	0.027	0.44	0.015	0.40	0.017
Support Time	0.87	0.041	0.66	0.037	0.55	0.033
Support:Swing	1.72	0.112	1.49	0.093	1.38	0.096
PSYCHOPHYSICAL VARIABLES						
RPE (local)	6.33	0.483	6.92	0.943	9.29	1.703
RPE (central)	6.33	0.483	6.70	0.675	8.41	1.578

TABLE XVII: mean data as recorded for the tall subjects when running speeds were expressed in absolute terms.

	SLOW		MEDIUM		FAST	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.	$\bar{X}$	Sd.
PHYSIOLOGICAL VARIABLES						
$\dot{V}O2$	29.83	1.741	34.59	2.146	41.71	1.722
$\dot{V}CO2$	26.79	1.928	32.54	2.857	38.33	2.417
R-value	0.90	0.055	0.93	0.066	0.93	0.053
$\dot{V}I$	44.64	3.957	53.10	5.971	68.22	11.489
$\dot{V}f$	31.91	4.175	35.39	6.433	39.42	5.441
Vt	1.41	0.150	1.54	0.255	1.72	0.160
HR	131.22	7.036	140.70	6.019	149.55	5.986
$\dot{V}O2$/step	0.20	0.018	0.22	0.018	0.25	0.013
LEC	4.11	0.231	3.89	0.246	4.00	0.159
KINEMATIC VARIABLES						
Cadence	153.57	7.152	159.70	5.122	164.78	6.052
Cycle Time	0.79	0.034	0.75	0.025	0.73	0.029
Stride Length	1.96	0.091	2.30	0.074	2.63	0.098
RSL	1.02	0.058	1.21	0.047	1.38	0.057
Swing Time	0.48	0.036	0.49	0.028	0.49	0.033
Support Time	0.31	0.029	0.27	0.024	0.24	0.023
Support:Swing	0.65	0.086	0.56	0.068	0.50	0.067
PSYCHOPHYSICAL VARIABLES						
RPE (local)	9.00	1.054	9.79	0.919	12.11	1.300
RPE (central)	8.30	1.160	8.89	1.197	10.90	1.524

TABLE XVIII: mean data as recorded for walking speeds expressed in absolute terms.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}$O2	10.64	0.925	9.72	0.840
Cadence	94.54	6.570	84.89	7.233
Stride Length	1.06	0.093	1.19	0.122
RSL	0.64	0.046	0.62	0.066
MEDIUM				
$\dot{V}$O2	14.70	1.446	13.61	0.758
Cadence	117.92	4.886	109.83	4.211
Stride Length	1.42	0.060	1.52	0.057
RSL	0.86	0.034	0.80	0.026
FAST				
$\dot{V}$O2	22.58	1.647	19.83	1.233
Cadence	137.43	6.569	125.70	4.945
Stride Length	1.70	0.081	1.86	0.073
RSL	1.03	0.031	0.98	0.033

TABLE XIX: mean data as recorded for running speeds expressed in absolute terms.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}$O2	32.61	3.193	29.82	1.741
Cadence	166.32	8.718	153.64	7.152
Stride Length	1.81	0.097	1.96	0.091
RSL	1.09	0.057	1.02	0.058
MEDIUM				
$\dot{V}$O2	39.11	3.186	34.58	2.146
Cadence	171.00	7.789	159.74	5.122
Stride Length	2.15	0.098	2.30	0.074
RSL	1.30	0.061	1.21	0.047
FAST				
$\dot{V}$O2	47.22	3.508	41.70	1.722
Cadence	177.25	8.430	164.78	6.052
Stride Length	2.44	0.143	2.63	0.098
RSL	1.47	0.075	1.38	0.057

TABLE XX: mean data as predicted for walking speeds expressed relative to stature.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}O_2$	10.32	0.822	10.46	0.747
Cadence	94.12	6.557	91.00	5.498
Stride Length	1.06	0.075	1.25	0.091
RSL	0.64	0.045	0.66	0.048
MEDIUM				
$\dot{V}O_2$	14.69	1.069	15.22	0.805
Cadence	115.40	4.926	113.11	2.846
Stride Length	1.38	0.079	1.61	0.064
RSL	0.83	0.038	0.85	0.025
FAST				
$\dot{V}O_2$	20.33	1.146	20.81	1.102
Cadence	132.73	4.473	130.77	6.038
Stride Length	1.65	0.092	1.94	0.118
RSL	0.99	0.035	1.02	0.053

TABLE XXI: mean data as predicted for running speeds expressed relative to stature.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}O2$	30.00	2.877	31.22	1.608
Cadence	161.70	6.684	156.63	6.257
Stride Length	1.73	0.113	2.06	0.087
RSL	1.03	0.055	1.08	0.044
MEDIUM				
$\dot{V}O2$	36.48	3.303	37.12	1.791
Cadence	167.83	6.125	162.47	4.672
Stride Length	2.00	0.119	2.40	0.087
RSL	1.21	0.059	1.26	0.042
FAST				
$\dot{V}O2$	42.91	3.593	43.69	1.812
Cadence	174.10	6.658	167.73	5.313
Stride Length	2.26	0.141	2.75	0.122
RSL	1.38	0.067	1.45	0.059

TABLE XXII: mean data as predicted for walking speeds expressed relative to leg length.

	SHORT		TALL	
	$\overline{X}$	Sd.	$\overline{X}$	Sd.
SLOW				
$\dot{V}$O2	10.54	0.895	10.83	0.923
Cadence	95.44	5.910	93.32	5.775
Stride Length	1.08	0.192	1.30	0.083
RSL	0.65	0.052	0.68	0.043
MEDIUM				
$\dot{V}$O2	14.50	1.228	15.33	0.986
Cadence	114.52	4.577	113.44	4.088
Stride Length	1.37	0.101	1.62	0.066
RSL	0.83	0.051	0.85	0.024
FAST				
$\dot{V}$O2	19.53	1.538	20.89	1.196
Cadence	130.44	3.806	129.56	5.339
Stride Length	1.61	0.114	1.94	0.132
RSL	0.97	0.051	1.02	0.060

TABLE XXIII: mean data as predicted for running speeds expressed relative to leg length.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}$O2	28.64	3.111	30.47	1.180
Cadence	162.11	8.252	154.59	7.412
Stride Length	1.62	0.165	2.02	0.115
RSL	0.98	0.087	1.06	0.057
MEDIUM				
$\dot{V}$O2	34.47	3.599	36.00	1.398
Cadence	167.34	7.289	160.22	5.884
Stride Length	1.90	0.161	2.34	0.133
RSL	1.15	0.082	1.23	0.065
FAST				
$\dot{V}$O2	40.14	4.064	42.09	1.777
Cadence	172.22	7.177	165.20	5.846
Stride Length	2.16	0.180	2.67	0.171
RSL	1.31	0.091	1.40	0.084

TABLE XXIV: mean data as predicted for walking speeds expressed relative to lower-limb length.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}O2$	11.18	0.920	11.63	0.830
Cadence	99.23	6.321	97.88	4.459
Stride Length	1.13	0.078	1.36	0.077
RSL	0.69	0.045	0.72	0.038
MEDIUM				
$\dot{V}O2$	15.11	1.150	16.00	0.893
Cadence	116.82	5.007	116.14	3.143
Stride Length	1.40	0.083	1.67	0.070
RSL	0.85	0.040	0.88	0.025
FAST				
$\dot{V}O2$	19.89	1.322	21.11	1.088
Cadence	131.74	4.270	131.35	5.775
Stride Length	1.63	0.100	1.96	0.141
RSL	0.98	0.041	1.03	0.065

TABLE XXV: mean data as predicted for running speeds expressed relative to lower-limb length.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}O2$	28.74	3.012	30.80	1.385
Cadence	162.21	8.741	155.00	7.040
Stride Length	1.63	0.121	2.04	0.100
RSL	0.98	0.060	1.07	0.048
MEDIUM				
$\dot{V}O2$	34.33	3.376	36.00	1.556
Cadence	167.25	8.311	160.50	5.503
Stride Length	1.89	0.119	2.35	0.112
RSL	1.14	0.057	1.24	0.052
FAST				
$\dot{V}O2$	39.75	3.761	41.70	1.629
Cadence	171.73	7.945	165.11	5.685
Stride Length	2.14	0.134	2.65	0.142
RSL	1.30	0.063	1.40	0.066

TABLE XXVI: mean data as predicted for walking speeds expressed relative to bi-acromial diameter.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}$O2	10.48	0.951	10.20	0.820
Cadence	94.73	5.851	89.68	6.881
Stride Length	1.07	0.088	1.24	0.087
RSL	0.65	0.054	0.65	0.048
MEDIUM				
$\dot{V}$O2	14.59	1.467	14.44	0.731
Cadence	115.23	4.022	110.35	4.668
Stride Length	1.37	0.085	1.57	0.046
RSL	0.83	0.047	0.83	0.018
FAST				
$\dot{V}$O2	19.92	1.850	19.80	0.935
Cadence	132.23	5.116	126.78	5.750
Stride Length	1.62	0.090	1.88	0.117
RSL	0.98	0.040	0.99	0.056

TABLE XXVII: mean data as predicted for running speeds expressed relative to bi-acromial diameter.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}O2$	29.23	3.487	29.40	1.890
Cadence	163.00	8.138	153.55	7.397
Stride Length	1.67	0.121	1.95	0.120
RSL	1.01	0.069	1.03	0.066
MEDIUM				
$\dot{V}O2$	35.44	3.586	34.66	1.961
Cadence	168.42	7.397	159.23	5.865
Stride Length	1.96	0.132	2.27	0.136
RSL	1.18	0.078	1.19	0.074
FAST				
$\dot{V}O2$	41.58	3.856	40.63	2.319
Cadence	173.40	7.321	164.33	6.019
Stride Length	2.23	0.152	2.59	0.164
RSL	1.35	0.087	1.36	0.087

TABLE XXVIII: mean data as predicted for walking speeds expressed relative to bi-iliac diameter.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}O2$	10.91	0.943	10.57	0.764
Cadence	97.44	7.152	92.11	5.087
Stride Length	1.11	0.079	1.27	0.091
RSL	0.67	0.045	0.67	0.050
MEDIUM				
$\dot{V}O2$	15.43	1.065	15.09	0.683
Cadence	118.24	5.633	113.00	4.163
Stride Length	1.42	0.088	1.61	0.056
RSL	0.86	0.041	0.85	0.028
FAST				
$\dot{V}O2$	21.38	1.356	20.55	1.011
Cadence	135.83	6.893	129.73	6.848
Stride Length	1.69	0.103	1.93	0.126
RSL	1.02	0.040	1.02	0.058

TABLE XXIX: mean data as predicted for running speeds expressed relative to bi-iliac diameter.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}O2$	31.00	3.296	30.64	1.906
Cadence	164.44	9.312	154.81	7.436
Stride Length	1.75	0.094	1.89	0.176
RSL	1.06	0.035	1.07	0.069
MEDIUM				
$\dot{V}O2$	37.58	3.605	36.22	2.019
Cadence	170.00	9.177	160.43	5.680
Stride Length	2.06	0.108	2.36	0.140
RSL	1.24	0.045	1.24	0.079
FAST				
$\dot{V}O2$	44.27	3.995	42.55	2.498
Cadence	175.45	9.009	165.64	6.004
Stride Length	2.34	0.147	2.70	0.189
RSL	1.42	0.065	1.42	0.105

TABLE XXX: mean data as predicted for walking speeds expressed relative to the product of an androgyny index and stature.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}$O2	10.80	1.027	11.71	0.881
Cadence	96.91	5.405	98.14	5.763
Stride Length	1.10	0.096	1.37	0.068
RSL	0.66	0.056	0.72	0.033
MEDIUM				
$\dot{V}$O2	14.01	1.525	15.64	0.942
Cadence	112.73	4.270	114.99	4.546
Stride Length	1.33	0.098	1.66	0.073
RSL	0.81	0.053	0.87	0.027
FAST				
$\dot{V}$O2	17.93	1.881	20.69	1.177
Cadence	126.35	4.165	129.63	6.022
Stride Length	1.54	0.105	1.94	0.165
RSL	0.93	0.051	1.02	0.078

TABLE XXXI: mean data as predicted for running speeds expressed relative to the product of an androgyny index and stature.

	SHORT		TALL	
	$\overline{X}$	Sd.	$\overline{X}$	Sd.
SLOW				
$\dot{V}O2$	25.57	4.012	29.91	1.904
Cadence	159.73	8.407	154.00	7.483
Stride Length	1.48	0.162	1.98	0.132
RSL	0.90	0.090	1.04	0.067
MEDIUM				
$\dot{V}O2$	30.63	3.735	34.66	2.216
Cadence	164.00	7.645	159.24	6.339
Stride Length	1.73	0.157	2.27	0.155
RSL	1.04	0.088	1.19	0.077
FAST				
$\dot{V}O2$	35.44	4.044	40.00	2.733
Cadence	168.32	7.025	163.82	6.033
Stride Length	1.96	0.166	2.56	0.182
RSL	1.18	0.094	1.34	0.089

TABLE XXXII: mean data as predicted for walking speeds expressed relative to a Froude number in which stature is used as the characteristic measure of size.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}O2$	10.22	0.823	10.00	0.346
Cadence	93.25	6.563	86.98	6.360
Stride Length	1.04	0.073	1.20	0.100
RSL	0.63	0.045	0.63	0.055
MEDIUM				
$\dot{V}O2$	15.21	1.143	14.69	0.735
Cadence	117.00	4.874	111.10	3.071
Stride Length	1.40	0.070	1.58	0.059
RSL	0.85	0.036	0.83	0.025
FAST				
$\dot{V}O2$	21.88	1.325	20.83	1.031
Cadence	136.87	5.801	130.44	6.168
Stride Length	1.70	0.086	1.93	0.106
RSL	1.03	0.032	1.02	0.048

TABLE XXXIII: mean data as predicted for running speeds expressed relative to a Froude number in which stature is used as the characteristic measure of size.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}O2$	31.36	2.159	31.33	1.706
Cadence	165.64	8.276	155.69	6.413
Stride Length	1.81	0.099	2.07	0.085
RSL	1.10	0.054	1.09	0.047
MEDIUM				
$\dot{V}O2$	39.74	3.327	37.56	1.698
Cadence	171.83	7.642	162.10	5.466
Stride Length	2.14	0.114	2.43	0.082
RSL	1.30	0.054	1.28	0.044
FAST				
$\dot{V}O2$	47.11	3.339	44.80	1.677
Cadence	178.55	6.835	167.73	6.668
Stride Length	2.46	0.152	2.80	0.124
RSL	1.48	0.075	1.47	0.066

TABLE XXXIV: mean data as predicted for walking speeds expressed relative to a Froude number in which lower-limb length is used as the characteristic measure of size.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}O2$	10.24	0.847	9.90	0.763
Cadence	93.22	6.763	87.75	6.056
Stride Length	1.05	0.075	1.21	0.096
RSL	0.63	0.045	0.64	0.036
MEDIUM				
$\dot{V}O2$	15.00	1.149	14.73	0.756
Cadence	116.82	5.051	111.64	3.169
Stride Length	1.40	0.075	1.59	0.058
RSL	0.84	0.038	0.83	0.024
FAST				
$\dot{V}O2$	21.55	1.393	20.71	0.959
Cadence	136.00	5.228	130.44	5.777
Stride Length	1.69	0.091	1.94	0.116
RSL	1.02	0.036	1.02	0.054

TABLE XXXV: mean data as predicted for running speeds expressed relative to a Froude number in which lower-limb length is used as the characteristic measure of size.

	SHORT		TALL	
	$\overline{X}$	Sd.	$\overline{X}$	Sd.
SLOW				
$\dot{V}O2$	31.93	2.948	31.27	1.526
Cadence	165.11	8.386	155.58	6.653
Stride Length	1.79	0.100	2.07	0.088
RSL	1.08	0.052	1.09	0.047
MEDIUM				
$\dot{V}O2$	39.00	3.403	37.55	1.518
Cadence	171.33	7.973	161.83	5.432
Stride Length	2.11	0.113	2.43	0.094
RSL	1.28	0.058	1.28	0.049
FAST				
$\dot{V}O2$	46.11	3.499	44.58	1.457
Cadence	177.32	7.824	167.40	6.415
Stride Length	2.42	0.149	2.80	0.137
RSL	1.46	0.072	1.47	0.070

TABLE XXXVI: mean data as predicted for walking speeds expressed relative to a Froude number in which the cube of stature divided by body surface area is used as the characteristic measure of size.

	SHORT		TALL	
	$\overline{X}$	Sd.	$\overline{X}$	Sd.
SLOW				
$\dot{V}$02	10.42	0.850	10.22	0.639
Cadence	94.30	6.516	89.53	5.603
Stride Length	1.06	0.075	1.24	0.096
RSL	0.64	0.045	0.65	0.052
MEDIUM				
$\dot{V}$02	14.95	1.133	14.94	0.764
Cadence	116.11	4.677	112.34	2.869
Stride Length	1.39	0.073	1.59	0.068
RSL	0.84	0.035	0.84	0.030
FAST				
$\dot{V}$02	20.90	1.300	20.54	0.977
Cadence	134.48	4.995	130.22	7.005
Stride Length	1.67	0.088	1.92	1.027
RSL	1.01	0.032	1.01	0.046

TABLE XXXVII: mean data as predicted for running speeds expressed relative to a Froude number in which the cube of stature divided by body surface area was used as the characteristic measure of size.

	SHORT		TALL	
	$\bar{X}$	Sd.	$\bar{X}$	Sd.
SLOW				
$\dot{V}$O2	30.90	3.042	31.00	1.604
Cadence	164.36	8.003	155.22	6.877
Stride Length	1.74	0.119	2.04	0.074
RSL	1.05	0.063	1.08	0.040
MEDIUM				
$\dot{V}$O2	37.64	3.499	36.95	1.724
Cadence	170.22	7.627	161.33	5.964
Stride Length	2.05	0.125	2.40	0.072
RSL	1.24	0.065	1.26	0.038
FAST				
$\dot{V}$O2	44.30	3.720	43.55	1.689
Cadence	175.82	7.569	166.77	6.233
Stride Length	2.34	0.148	2.75	0.125
RSL	1.42	0.073	1.45	0.066

APPENDIX 5

Equations as used in this Research

A summary of the more useful equations as they were used for the purposes of this investigation.

SOME USEFUL EQUATIONS

BODY SURFACE AREA (BSA)

$$BSA = 71.84 * (BM^{0.425} * St^{0.725})$$

ANDROGYNY INDEX (AI)

$$AI = (3 * BA) - BI$$

RECIPROCAL OF PONDERAL INDEX (RPI)

$$RPI = St \div \sqrt[3]{BM}$$

RELATIVE STRIDE LENGTH (RSL)

$$RSL = SL \div St$$

LOCOMOTOR ENERGY COST (LEC)

$$LEC = \dot{V}O2 * \text{R-value} * \text{time to walk/run 1km}$$

OXYGEN COST PER STEP ($\dot{V}O2.STEP^{-1}$)

$$\dot{V}O2.step^{-1} = VO2 \div Cadence$$

ENERGY EXPENDITURE/OXYGEN CONSUMED

1 kilocalorie = 4.186 kiloJoules = $\frac{1}{5}$ liters of oxygen