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# ASSESSMENT OF PHYSIOLOGICAL, BIOMECHANICAL AND STRUCTURAL CORRELATES OF AGE-RELATED DIFFERENCES IN THE AEROBIC DEMAND OF WALKING OF YOUNG FEMALES

by

Mitchell Wells Craib

A Dissertation Submitted to
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Approved by

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# APPROVAL PAGE

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The purpose of this study was to assess the collective influence of selected metabolic, gait, and morphological variables on age-related differences in the submaximal aerobic demand ($\dot{V}O_2$) of walking. Four age groups of seven females (ages 6, 10, 13 and 18 or 19) comprised the sample. Measurements of walking $\dot{V}O_2$, ventilatory equivalent, and step frequency at 1.56 $m \cdot sec^{-1}$ and 0% grade, were obtained at 10-min intervals during three treadmill testing sessions totaling 70 minutes. Sitting metabolic rate was assessed over a 10-min time period following 10 min of seated rest. Limb morphology (thigh to shank ratio) was determined from measurements of limb volume using a water fill plethysmograph. Average vertical ground reaction forces and ground contact time were measured as participants walked across a force platform at 1.56 $m \cdot sec^{-1}$. Body surface area to mass ratio was predicted from knowledge of body height and mass. Analysis of variance (ANOVA) and Tukey post-hoc multiple comparison procedures were used to assess whether mean values of the dependent (walking $\dot{V}O_2$) and independent variables (ventilatory equivalent, step frequency, resting metabolic rate, limb morphology, average vertical ground reaction force, ground contact time and body surface area to mass ratio) were significantly different across age groups. Residual analysis was used to ensure that the simplest function (line) was fit to each association between the dependent and independent variables and to ensure that the entire data set was characterized accurately prior to multiple regression analyses. Multiple regression procedures were used to select a small set of the most predictive variables associated with age-related differences in mass-specific walking economy. Results indicated that with the exception of average vertical ground reaction force, all variables changed significantly with age. Resting metabolic rate, body surface area to mass ratio, and step frequency emerged as the strongest predictors of walking $\dot{V}O_2$. Within the constraints of this investigation, it is concluded that young female children exhibit a higher aerobic demand than older children and adults and that age-related differences in $\dot{V}O_2$ can best be explained by a small cluster of physiological, structural and biomechanical variables.

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# CHAPTER I
# INTRODUCTION

## Statement of the Problem

Numerous investigations have examined the submaximal aerobic demand of walking and running, otherwise known as locomotor economy (Bransford & Howley, 1977; Conley & Krahenbuhl, 1980; Costill, Thomason, & Roberts, 1973; Daniels, 1985; Inman, Ralston, & Todd, 1981; Morgan & Martin, 1986; Morgan, Martin, & Krahenbuhl, 1989). One of the fundamental principles to emerge from this body of work is the fact that, relative to body mass, children are metabolically less economical than adults (Astrand, 1952; Cassels & Morse, 1962; Daniels & Oldridge, 1971; Daniels, Oldridge, Nagle, & White, 1978; Ebbeling, Hamill, Freedson, & Rowland, 1992; Krahenbuhl, Morgan, & Pangrazi, 1989; MacDougall, Roche, Bar-Or, & Moroz, 1983; Robinson, 1938; Rowland & Green, 1988; Silverman & Anderson, 1972; Thorstensson, 1986; Unnithan & Eston, 1990). When compared to adults at identical walking or running speeds or per unit distance covered, children expend more energy. This phenomenon appears to be age-related, as cross-sectional and longitudinal investigations have demonstrated a decreased metabolic cost of locomotion with increased age and stature (Anderson, Seliger, Rutenfranz, & Messel, 1974; Åstrand, 1952; Cassels & Morse, 1962; Cavanagh & Williams, 1982; Krahenbuhl & Williams, 1992; MacDougall et al., 1983; Rowland, Auchinachie, Keenan, & Green, 1987; Rowland & Green, 1988; Thorstensson, 1986; Unnithan & Eston, 1990).

Proposed explanatory variables for changes in economy with age are numerous. While a number of variables have been associated with changes in economy with age, only a few appear credible, and among these, the relative importance of individual predictor variables remains to be quantified (Krahenbuhl & Williams, 1992). Hence, there is a need for a comprehensive study of the most promising predictor variables to illuminate the primary mechanisms responsible for age-related changes in economy with maturation (Krahenbuhl & Williams, 1992; Morgan, 1993).

In a recent comprehensive review, Krahenbuhl & Williams (1992) examined published explanations for the phenomenon mentioned above and concluded that sufficient evidence exists to support three age-related differences in physiology and gait as possible determinants of differences in locomotor economy. They are (a) resting metabolism, (b) the oxygen cost of ventilation, and (c) step frequency. No study has examined these factors simultaneously. The variance in locomotor economy explained by each of these factors, therefore, has yet to be quantified.

## Resting Metabolism and Surface Area to Mass Ratio

Over a century ago, physiologists made observations that may be relevant to the issue of age-related changes in economy. They found that decreases in mass-specific daily metabolism occurred with increasing animal body size and growth, and that such changes in relative metabolism paralleled alterations in the ratio of body surface area to mass (Kleiber, 1975a; Rubner, 1883; VonBertalanffy, 1957). This discovery led them to speculate that metabolism may be influenced by surface area (VonBertalanffy, 1957). To test this concept, daily metabolic measures, from animals of varying sizes, were normalized to surface area. Differences in size-related metabolism were removed when this calculation was performed, thereby lending support to their hypothesis (VonBertalanffy, 1957).

Contemporary physiologists have observed similar decreases in resting metabolic rates and surface area to mass ratios of growing humans (Cassels & Morse, 1962; MacDougall et al., 1983; Robinson, 1938; Rowland et al., 1987; Rowland & Green, 1988), and have related these changes to reductions in transport cost. MacDougall and associates (1983) found that the relatively higher resting metabolic rates of younger children accounted for a portion, but not all, of the differences observed in locomotor economy. When exercise metabolism was normalized to surface area by these and other researchers, however, differences in aerobic demand across age groups were removed (Cassels & Morse, 1962; MacDougall et al., 1983; Rowland et al., 1987;

Rowland & Green, 1988). Therefore, in growing humans as well as animals, changes in metabolism and surface area appear to be indicative of alterations in metabolism normalized to body mass.

## The Oxygen Cost of Ventilation

Several investigators have observed that children extract oxygen from ambient air less efficiently than adults (Anderson et al., 1974; Krahenbuhl et al., 1989). For each liter of oxygen children removed from the air, greater volumes of air pass through their lungs. For example, Anderson & associates (1974) reported substantial differences in ventilation rates between 8- and 16-year old girls (n=33 and n=9 respectively) exercising at an intensity eliciting an oxygen consumption of 1.0 liter per minute. Eight-year olds required approximately 10 more liters of air per minute than 16-year olds, a difference which amounted to approximately 31%. Findings such as these have led several researchers to propose that this factor may be partly responsible for differences in locomotor economy. Ventilation requires muscular activity, and logic suggests that the increased respiratory costs experienced by children must raise their mass-specific locomotion costs (Bar-Or, 1983; Krahenbuhl & Williams, 1992; Rowland, 1989). Although authorities on the subject of age-related economy agree that the oxygen cost of ventilation is a likely determinant of variance in locomotor economy, the relative importance of this factor has yet to be determined.

## Step Frequency and The Time Course of Force Generation

One factor that changes in parallel with decreases in mass-specific aerobic demand with growth is a reduction in step frequency (Kram & Taylor, 1990; MacDougall et al., 1983; Rowland, 1989). As children grow, they require a less rapid step rate to maintain a given speed and fewer steps to traverse a given distance. Similarly, they expend less energy per kilogram of body mass during locomotion (Krahenbuhl & Williams, 1992). Investigators have noted this association and have theorized that step rate may be linked to locomotor economy, i.e. a decrease in step frequency leads to a reduction in aerobic demand (Krahenbuhl & Williams, 1992; MacDougall et al., 1983; Rowland, 1989; Rowland & Green, 1988). In support of this contention is the consistent observation that when aerobic demand is normalized to step frequency, in either humans or animals, differences in locomotor economy disappear (Baudinette, 1991; Cavagna, Franzetti, & Fuchimoto, 1983; Heglund, Fedak, Taylor, & Cavagna, 1982; Kram & Taylor, 1990; MacDougall et al., 1983; Rowland et al., 1987; Rowland & Green, 1988). Such a finding suggests that step rate may be a determinant of age-related differences in economy.

Muscular efficiency studies conducted by Heglund & Cavagna (1987) and biomechanical analyses performed by Kram & Taylor (1990) suggest that rate of muscle force generation may be a mechanism by which step frequency seems to explain age-related differences in economy. In-vitro peak muscle efficiency appears to occur at contraction rates of approximately one per second (Heglund & Cavagna, 1987). Faster rates, such as those used by children when walking and running at velocities identical with adults, are more expensive metabolically and could partially account for the relatively poor locomotor economy of children (Waters, Lunsford, Perry & Byrd, 1988; Alexander & Ker, 1990; Ebbeling, et al. 1992; Frost, Bar-Or, Dowling & White, 1995).

Other theoretical step frequency-related mechanisms should also be considered when addressing the phenomenon of age-related differences in locomotor economy and step frequency. It is possible that at faster walking step rates, but similar walking speeds, children use a larger fraction of their motor units compared to adults. A proportionally larger use of motor units should be metabolically more expensive and could explain age-related differences in locomotor economy. This hypothesis has yet to be investigated. It is also possible that at faster step rates children use different eccentric to concentric muscle contraction ratios than adults. Concentric muscle contractions are understood to require a higher aerobic demand than eccentric contractions (Pivarnik & Sherman, 1990) which suggests that if a greater proportion of children's contractions were concentric, walking would be less economical for children. This theory also remains to be examined.

Other links (those easier to assess) between age-related differences in step frequency and economy may be found in stance time (foot-contact time with the ground) and average vertical ground reaction forces normalized to body mass (Alexander & Ker, 1990; Kram & Taylor, 1990). Animal cross-species investigations of stance times, which represent the time of external force application during locomotion demonstrate that more economical, larger animals have longer stance times and, therefore, apply force more slowly than less economical animals (Kram & Taylor, 1990). A study by Morgan et al. (1988) reported similar findings (Morgan, Martin, Baldini, & Krahenbuhl, 1988) insofar as stance times were longer in economical versus uneconomical adult human runners. Given that force application takes place over a longer period of time with longer stance times, it is not surprising that ground reaction forces per kilogram of body mass at standard speeds are also lower (Alexander & Ker, 1990; Kram & Taylor, 1990). Alexander & Ker (1990) and Kram & Taylor (1990) hypothesize that these reduced forces are associated with smaller muscle workloads and improved metabolic economy. Taken together, the observations made by these researchers suggest that stance time and average vertical ground reaction forces normalized to body mass, two variables associated with step frequency, may partially account for age-related changes in the aerobic cost of transport.

## Another Potential Predictor of Economy

Although Krahenbuhl & William's review (1992) of published mechanisms for variance in economy is authoritative, the fact remains that other variables may exist which are also capable of explaining age-related variance in economy, but which have yet to be considered and tested. A review of pertinent factors, either known or thought to affect economy, suggests that one additional variable should be examined in relation the issue of age-related changes in economy. This factor is a change in limb mass distribution with growth.

## Limb Mass Distribution

Investigators interested in locomotor economy have long suspected that a significant proportion of the energy required for locomotion is directed towards the task of overcoming inertia during acceleration and deceleration of the limbs. This thought has led functional morphologists to speculate that animals and humans with limb structures that minimize inertia may reduce limb muscle workload and consequently aerobic demand during locomotion (Alexander, 1977; Elliott & Blanksby, 1979; Hildebrand, 1988; Steudel, 1990). Indirect support for this concept can be found in animal models (e.g., deer, horses, and dogs) wherein limb structure appears to be designed to minimize the inertial and metabolic costs of movement. In these quick-moving aerobic animals, the majority of the limb muscle and bone mass is located more proximally to the joint axis of rotation (e.g. hip, shoulder), and far from the point of ground contact. This morphological minimization of inertia is thought to provide a cost advantage for transport over other mammals. Human studies also supply indirect evidence for the concept that limb morphology may affect economy. For instance, in studies where similar masses have been added to the lower or upper segments of the lower limbs in separate measurements, the aerobic demand of locomotion was highest in those carrying mass on the lower segments (Bhambhani, Burnham, Singh, & Gomes, 1989; Claremont & Hall, 1988; Frederick, Daniels, & Hayes, 1984; Inman et al., 1981; Martin, 1985; Myers & Steudel, 1985).

Recently, Jensen and associates (1978-1989) used an elliptical zone photographic procedure (stereo-photogrammetric method) to accurately determine human structural changes in the limbs and trunk with growth (Jensen, 1978; Jensen, 1981; Jensen, 1986; Jensen, 1988; Jensen, 1989). In their cross-sectional and longitudinal assessments of young subjects, this technique demonstrated that child limb morphology (legs and arms) was measurably different from that of adults. Limb mass distribution shifted proximally with growth in subjects between the ages of 6 and 20 (Jensen, 1989). This observation suggests that younger children have a greater proportion of their limb mass located farther from the axis of rotation in a manner likely to increase limb inertia. If overcoming inertia during acceleration and deceleration of the limbs is important to locomotor economy, then proximal shifts in morphology with growth could partially explain variance in economy due to physical growth.

## Chapter Summary

Age-related differences in the economy of locomotion have been reported consistently in the literature. While several plausible hypotheses have been proposed to explain this phenomenon, no single study has examined the importance of more than a single predictor variable at a time. The relative importance of each hypothesized factor, therefore, has yet to be determined. Until such a study is conducted, a clearer understanding of the mechanisms underlying age-related changes in the aerobic demand of locomotion will remain elusive.

## Purpose of the Study

The purpose of this study was to assess the collective influence of selected metabolic, gait, and morphological variables in an attempt to explain age-related differences in locomotor economy. To achieve this goal, physiological and biomechanical test procedures were completed by 28 female participants (varying in age from 6 to 19 years). Females, rather than males, were chosen for study because of limitations in subject number which suggested the testing of one gender or the other, females are typically understudied, and females proved easier to work with during pilot testing. Using multiple regression analyses, the proportion of non-redundant variation in age-related changes in economy accounted for by each predictor variable was determined.

## Hypotheses

This study is based upon the principle that age-related differences in locomotor economy exist. Thus, Hypothesis #1 states that:

*Submaximal mass-specific aerobic demand will decrease with age.*

Mass-specific resting metabolic rates have been shown to decrease in both animals and humans with increasing body size. Thus, Hypothesis #2 states that:

> *Mass-specific resting metabolic rate will decrease with age.*

Body surface area to mass ratios have been shown to decrease in both animals and humans with increasing body size. Thus, Hypothesis #3 states that:

> *Body surface area to mass ratio will decrease with age.*

Children are reported to ventilate larger volumes of air than adults for each liter of oxygen they extract during locomotion. Thus, Hypothesis #4 states that:

> *Ventilatory equivalent will decrease with age.*

Step frequency has been shown to decrease with increasing body stature. Thus, Hypothesis #5 states that:

> *Step frequency will decrease with age.*

Stance time, which is influenced by step frequency, reportedly increases with increasing body size. Thus, Hypothesis #6 states that:

> *Stance time will lengthen with age.*

Mass-specific average vertical ground reaction forces are believed to be lower with reduced step frequency and increased stance times. Thus Hypothesis #7 states that:

> *Mass-specific average vertical ground reaction force will decrease with age.*

Limb mass distribution is thought to shift more proximal to the axis of joint rotation (e.g. hip) with age. Thus, Hypothesis #8 states that:

> *Thigh to shank lower-limb ratio will increase measurably with age.*

## Assumptions and Limitations

The validity of this study rested upon a number of assumptions and limitations having to do with physical growth, age and the cross-sectional nature of the investigation. It was assumed that physical growth between the ages of 6,10,13 and 18/19 years would be substantial enough to affect locomotor economy and the mechanisms hypothesized to explain it. It was assumed that children as young as 6 would exhibit the cognitive, proprioceptive and physical ability to perform the various test procedures in this investigation. It was assumed that 60 minutes of treadmill and 30 minutes of metabolic equipment accommodation would be adequate to derive accurate and stable assessments of step frequency and locomotor economy. It was also assumed that plethysmographic limb volume assessments would result in accurate estimates of limb structure. It was recognized that a limitation of the study was the small sample size (n=7) in each age group, a factor dictated by the labor-intensive nature of the investigation. Another limitation of the investigation was its cross-sectional design. The cross-sectional nature of this study reduced the strength of generalizations that could be made concerning age and developmental factors associated with economy. With these considerations in mind, it was still believed that the investigation could produce information relevant to the issue of changes in economy with age through careful data collection procedures and appropriate statistical control.

## Significance of the Study

Up to the present date no single study has illuminated the proportion of non-redundant variation in age(physical growth)-related changes in walking aerobic demand accounted for by structural, physiological and biomechanical variables. This investigation is the first to do so. Hence, findings from this study can enhance our understanding of physical growth-related changes in the aerobic demand of walking. Results from this study should aid in establishing normative metabolic and gait profiles that can serve as a basis for comparisons with physically challenged young females with health conditions (e.g. cerebral palsy) typified by an elevated aerobic demand of locomotion. In summary, although this study is limited by its cross-sectional nature, it should expand our understanding of metabolism and mechanics of walking in young females.

# CHAPTER II
# LITERATURE REVIEW

## Introduction

The purpose of this chapter is to broaden understanding of metabolic and gait-related issues relevant to the aerobic demand of walking prior to discussion of experimental design, study results and discussion of findings. Child and adult differences in economy are first explained, followed by elucidation of the factors likely to affect the submaximal aerobic demand of walking. At the end of the chapter an argument is made for multivariate analysis of factors thought to impact age-related changes in walking economy.

## Child and Adult Differences in Locomotor Economy

Over the last six decades, cross-sectional and longitudinal walking and running studies have demonstrated that the submaximal aerobic demand of locomotion, expressed per kilogram of body mass and otherwise termed locomotor economy, is higher for children than adults (Astrand, 1952; Cassels & Morse, 1962; Daniels & Oldridge, 1971; Daniels et al., 1978; Ebbeling et al., 1992; Krahenbuhl et al., 1989; MacDougall et al., 1983; Robinson, 1938; Rowland & Green, 1988; Silverman & Anderson, 1972; Thorstensson, 1986; Unnithan & Eston, 1990). As shown in Tables 1 & 2, the metabolic cost of movement is highest in very young children and decreases progressively with growth.

In general, walking economy studies have examined a large number of subjects in a wide range of age groups, most often at constant speeds and at uphill grades of 3 to 20%. Investigators have found that differences in walking economy between children and the most mature participants are approximately 16% (range ~7 to 25%). Similar results have been reported in running economy studies where subject samples and age ranges have been slightly smaller. In these investigations, participants generally ran at 0% grade over a range of speeds while aerobic demand was assessed. Observed differences in running economy averaged ~18% (range ~14 to 21%). Where a spectrum of age groups was examined, in both walking and running studies, submaximal aerobic demand normalized to body mass declined with increased age until maturity.

Table 1. Difference in walking economy between children and more mature participants

| Researchers & Date | Subj. | Ages | Groups | Protocol | % Diff in Economy |
|---|---|---|---|---|---|
| **Robinson** 1938 | n=93<br>M | 6-91 | 11 (n=3-12 subj) | 8.6% Grade<br>1.56 $m \cdot s^{-1}$ | ~20%<br>$O_2$ uptake inversely related to growth |
| **Cassels & Morse** 1962 | n=57<br>M&F | 6-33 | 7 (n=4-13 subj) | 3.0% Grade<br>0.89 $m \cdot s^{-1}$ | ~14%<br>$O_2$ uptake inversely related to growth |
|  | n=85<br>M&F | 7-37 | 7 (n=4-18 subj) | 5.0% Grade<br>1.33 $m \cdot s^{-1}$ | ~13%<br>$O_2$ uptake inversely related to growth |
|  | n=105<br>M&F | 9-17 | 8 (n=4-23 subj) | 8.6% Grade<br>1.56 $m \cdot s^{-1}$ | ~7%<br>$O_2$ uptake inversely related to growth |
| **Skinner et al.** 1971 | n=144<br>M&F | 6-15 | 4 (n=?) | 10-20% Grade<br>1.56 $m \cdot s^{-1}$ | ~17% for M&F<br>$O_2$ Uptake inversely related to growth |
| **Ebbeling et al.** 1992 | n=20<br>M | 9&20 | 2 (2x n=10 subj) | 0% Grade<br>0.94-2.06 $m \cdot s^{-1}$ | ~25%<br>$O_2$ uptake inversely related to age |

M = male, F = female, subj = subject

Why locomotor economy improves with age is a matter still open to debate. Recognized experts in the field suggest that this phenomenon occurs primarily because of age-related changes in resting metabolism, ventilatory efficiency and step frequency (Rowland, 1989; Krahenbuhl & Williams, 1992). Findings in the economy literature also suggest that changes in limb morphology with age may affect submaximal aerobic demand.

Table 2. Difference in running economy between children and more mature participants

| **Researchers & Date** | **Subj** | **Ages** | **Groups** | **Protocol** | **% Diff in Economy** |
|---|---|---|---|---|---|
| **Astrand**<br>1952 | n=69<br>F | 4-17 | 6 (n=8-13 subj) | 0% Grade<br>2.2-4.4 $\text{m·s}^{-1}$ | ~20%:<br>$O_2$ uptake inversely related to age |
| | n=73<br>M | 4-18 | 6 (n=10-19 subj) | 0% Grade<br>2.2-3.9 $\text{m·s}^{-1}$ | ~20%:<br>$O_2$ uptake inversely related to age |
| **Daniels & Oldridge**<br>1971 | n=14<br>M | 10-15 | 1 (n=14 subj) | 0% Grade<br>3.3 $\text{m·s}^{-1}$ | Oxygen uptake decreased Over 22 months |
| **Daniels et al.**<br>1978 | n=20<br>M | 10-18 | 1 (n=20 subj) | 0% Grade<br>3.3 $\text{m·s}^{-1}$ | ~21% between 10 & 18 yr olds<br>$O_2$ uptake inversely related to age |
| **MacDougall et al.**<br>1983 | n=134<br>M&F | 7-16 | 4 (n=? subj) | 0% Grade<br>Variable Vel. | ~14%:<br>$O_2$ uptake inversely related to age |
| **Krahenbuhl et al.**<br>1989 | n=6<br>M | 10&17 | 1 (n=6 subj) | 0% Grade<br>Variable Vel. | ~17% decline in oxygen uptake between 10 and 17 yrs |

M = male, F = female, subj. = subject, vel. = velocity

## Resting Metabolic Rate and Body Surface Area to Mass Ratio

Several investigators have suggested that age-related differences in resting metabolic rate, which may be related to the ratio of surface area to body mass, could be partially responsible for age-associated differences in aerobic demand during walking and running (Cassels & Morse, 1962; Rowland et al., 1987; Rowland & Green, 1988; Thorstensson, 1986). This argument is based upon observations that resting metabolism, surface area to mass ratios, and aerobic demand normalized to body mass all decrease simultaneously with increases in body size.

Over a century ago, size-related differences in mammalian resting metabolism were recognized (VonBertalanffy, 1957). Smaller mammals exhibit higher mass-specific resting metabolic rates than larger mammals (VonBertalanffy, 1957). Rubner (1883) attempted to explain this finding by studying the surface areas of small and large fasting dogs (Kleiber, 1975a). In earlier work (VonBertalanffy, 1957), physiologists had proposed that mammalian heat production (metabolism) was dependent upon surface area, and Rubner's work resulted in support for their contention (Kleiber, 1975a). His data and calculations demonstrated that dogs produced approximately 1000 kcal of heat daily for each square meter of surface area, regardless of body mass (Rubner, 1883). Rubner's calculations also showed that as surface area to mass ratios decreased, so too did resting metabolic rates (Rubner, 1883). These findings led Rubner and others to conclude that surface area is the mechanism responsible for size-related differences in heat loss and metabolism (VonBertalanffy, 1957). Investigators interested in human age- and size-related differences in locomotor metabolism appear to agree with this point of view as surface area remains a prominent variable examined in their investigations (Cassels & Morse, 1962; MacDougall et al., 1983; Rowland et al., 1987; Rowland & Green, 1988). Animal physiologists, however, no longer believe there is more than a simple association between surface area and metabolism (Kleiber, 1975b).

Results from human studies exploring the possible connection between metabolism and surface area demonstrated that differences in economy were removed when locomotor oxygen consumption was normalized to surface area (Cassels & Morse, 1962; MacDougall et al., 1983; Rowland et al., 1987; Rowland & Green, 1988). Such findings appear to lend support to a connection between surface area and metabolism and to the concept that surface area may be indirectly related to variation in locomotor economy. MacDougall and associates (1983), however, present an argument which casts some doubt upon the latter hypothesis. They noted that while resting oxygen consumption (metabolism) was higher in children than adults and did decrease with age (and growth), the largest difference reported amounted to only 1-2 $ml \cdot kg^{-1} \cdot min^{-1}$. Such a difference is not large enough to explain the disparity in the metabolic expense of walking and running exhibited between children and adults, although corrections for differences in resting metabolism narrowed the contrast.

To summarize, physiologists have long been aware that changes in resting metabolism with growth are reflected by changes in body surface area. Investigators of age-related changes in locomotor economy have taken note of this reported association and have explored it in the context of their work. They reported that when aerobic demand was normalized to surface area, age-related differences in economy disappear. Whether or not surface area was responsible for variance in resting metabolism, and ultimately locomotion economy, has yet to be determined. Nevertheless, surface area, and to some degree resting metabolic rate, do appear to be associated with changes in economy with age.

## Ventilatory Equivalent

Various investigators have considered the possibility that ventilatory factors may explain a portion of age-related differences in locomotion economy (Bar-Or, 1983; Krahenbuhl & Williams, 1992; Rowland, 1989). Examination of ventilation ($\dot{V}_E$)values, collected at standard exercise intensities or workloads, have shown that younger children ventilate larger volumes of air than older children, relative to the amount of oxygen consumed ($\dot{V}O_2$) (Anderson et al., 1974; Krahenbuhl et al., 1989). Anderson and colleagues (1974) collected cross-sectional respiratory data on 171 boys (n=83) and girls (n=88) between the ages of 8 and 16 and found that 8-year olds of both genders ventilated between 20 and 30% more air through the lungs for each liter of oxygen they extracted. These marked differences in ventilatory equivalent ($\dot{V}_E \cdot \dot{V}O_2^{-1}$) were less noticeable with increasing age, particularly between the ages of 12 and 16.

Because ventilation occurs at some metabolic expense, Bar-Or (1983), Rowland (1989) and Krahenbuhl and Williams (1992) have suggested that ventilatory inefficiency in children may be partially responsible for their greater mass-specific $\dot{V}O_2$ requirements during walking and running. While this hypothesis appears plausible, no study has explored the importance of this factor in relation to age-associated changes in locomotor economy. Therefore, this age-related difference, which appears to gradually diminish with physical growth, could explain some of the variance in locomotor economy observed in childhood.

## Step Frequency and the Time Course of Force Generation

Evidence in the human, animal, biomechanical and physiological literature suggest that the rate or length of time at which children and larger, more mature individuals apply force to the ground affects locomotor economy (Beck, Andriacchi, Kuo, Fermier, & Galante, 1981; Cavagna et al., 1983; Heglund & Taylor, 1988; Kram & Taylor, 1990; MacDougall et al., 1983; Rowland et al., 1987; Sutherland, Olshen, Cooper, & Woo, 1980; Thorstensson, 1986). Children and small animals have relatively short limbs which require them to employ higher step rates. As size increases, either by growth or across species of animals, step frequency decreases (Heglund & Taylor, 1988; Kram & Taylor, 1990; MacDougall et al., 1983; Rowland, 1989). This reduction in step rate with size is paralleled by a reduction in submaximal $\dot{V}O_2$, a finding which has led several investigators to speculate that step rate may be a basic determinant of aerobic demand (Cavagna et al., 1983; Heglund & Taylor, 1988; Kram & Taylor, 1990; MacDougall et al., 1983; Morgan, 1993; Rowland et al., 1987; Thorstensson, 1986).

Support for this concept is provided by calculations of aerobic demand normalized to body mass and to individual steps (Cavagna et al., 1983; Heglund & Taylor, 1988; Kram & Taylor, 1990; MacDougall et al., 1983; Rowland et al., 1987). These data show that the mass-specific metabolic cost per step is nearly the same for all mammals and is independent of body size (Heglund & Taylor, 1988; Kram & Taylor, 1990). This finding implies that some mechanism(s) associated with step frequency may partially account for the relatively poor walking and running economy of children.

Likely step frequency- and economy-related mechanism(s) are several including possible differences in muscle contraction rates, motor unit recruitment patterns, and eccentric to concentric contraction ratios. Muscle contraction rates may be affected by stride frequency with children requiring higher muscle contraction speeds than adults at similar walking velocities.

Mammalian muscle experiments conducted by Heglund and Cavagna (1987) suggest that muscle has an optimal contraction rate of approximately one per second. Contraction rates either slower or faster than that were found to increase the metabolic cost of work. Children reportedly maintain stride rates faster than one per second when keeping similar pace with adults (Waters, Lunsford, Perry & Byrd, 1988; Ebbeling, et al. 1992; Frost, Bar-Or, Dowling & White, 1995). Adults tend to utilize stride rates approximating one per second (Waters, et al., 1988; Ebbeling, et al., 1992).

It is possible, however, that walking muscle contraction rates may not be the only difference between the gait of children and adults. Increased speed of limb movement may also result from different limb inertial properties (ratio of shank to thigh volumes) rather than muscle contraction rates. Differences in gait-related economy may also be due to differences in motor unit recruitment patterns during walking at similar speeds. Children may engage more motor units in their leg muscles to keep pace with adults and consequently incur a greater metabolic cost of locomotion. Unfortunately, this mechanism remains speculative as deep muscle electromyographic analysis of age-related gait has yet to be performed.

Another variable, the ratio of eccentric to concentric muscle contraction ratios, may also explain step frequency-related differences in economy. A walking study conducted by Pivarnik and Sherman (1990), used uphill, level and downhill grades to demonstrate that reliance upon greater or lesser amounts of concentric or eccentric muscle contractions can affect the metabolic cost of locomotion. A predominant use of concentric muscle contractions (level and uphill walking) appearing to be less economical than predominant use of eccentric contractions (downhill walking) . Given this finding, it is possible that children may rely on concentric contractions to a greater extent than adults when walking at similar speeds, thereby elevating aerobic demand.

Other likely connections between step frequency and locomotor economy exist. In a recent article, Kram & Taylor (1990) related step frequency to force application during stance time. They reasoned that external force generation during locomotion occurs only during the time interval when the feet (of humans and animals) make contact with the ground and that this time period could be a specific marker for differentiating small uneconomical individuals (those with a fast step frequency) from large economical individuals (with a slow step frequency). To test this hypothesis, Kram and Taylor used respiratory gas analysis equipment and either high-speed cinematography or a force platform to measure stance time (e.g. the time one foot is on the ground) over a range of aerobic running speeds for five mammals of varying size (kangaroo rat, ground squirrel, spring hare, dog and pony). As anticipated, an inverse relationship was observed between the aerobic demand of running and the time in which the foot applied force to the ground during each step. In essence, their study showed that more economical large animals used longer time periods to apply force. These results advanced the possibility that stance time may be an effective, non-invasive method for examining the time course of force generation and its involvement on locomotor economy.

Correlational evidence provided by Morgan and associates (1988) lends further support to the concept that stance time, defined by them as stance time, may be indicative of locomotor economy (Morgan et al., 1988). Temporal and kinematic variables were measured on 16 adult male runners at a standard velocity of 3.33 m·sec$^{-1}$. When differences between the six least and the six most economical runners were assessed, longer absolute and relative stance times were observed in the more economical runners. These findings suggest that the time period of external force generation can differentiate economical from uneconomical humans and therefore its assessment might be used to understand better growth-related differences in locomotor economy.

Alexander & Ker (1990) have stated that shorter stance times used by smaller mammals should require them to exert larger forces on the ground relative to their body mass than larger mammals at similar speeds (Alexander & Ker, 1990). If true, this size-related difference in force generation has ramifications for locomotor economy. Taylor and colleagues (1980) have conducted loading experiments on rats, dogs, humans and horses which indicate that differences in force generation can affect locomotor economy. They observed that when weights were added to the backs of animals and humans in a systematic manner, submaximal aerobic demand increased in direct proportion to the relative increases in body mass. Given that the gait patterns remained unchanged, the increase in metabolic cost was attributed primarily to increased forces placed upon the working muscles. Their findings imply that if smaller mammals do generate higher forces relative to body mass (because of their rapid step rates), then their transport costs should be higher than for larger mammals. Their findings also suggest that as mammals increase in size and exert smaller mass-specific forces with each step (because of longer stance times), locomotor economy should improve. Assuming the validity of this argument and considering the evidence that human locomotor economy improves with physical growth and age, changes in mass-specific force generation with each step should parallel changes in economy with growth and age. Therefore, ground reaction forces may help to account for changes in economy with growth and age.

In summary, differences in stature between children and adults require children to walk and run at relatively faster step rates. This difference in step frequency appears to be related to differences in the mass-specific metabolic cost of locomotion. Step frequency-related mechanisms which could explain differences in locomotor economy are speculative, but include different muscle contraction velocities, motor unit recruitment patterns, eccentric and concentric muscle contraction ratios, stance time and, indirectly, muscle forces. Collectively, these findings suggest that easily measured factors such as step rate, stance time and ground reaction force may underlie age-related differences in locomotor economy.

## Limb Mass Distribution

A factor which has received little attention in the context of age-related differences in economy is the effect of changes in limb structure on aerobic demand. Recent morphological data published by Jensen and colleagues (1978-1989) suggest that young children (e.g., 4-year olds) and more mature individuals (e.g., 16-year olds) have limb structures that are measurably different. Photogrammetric structural assessment methods have revealed that a larger proportion of lower limb mass is distributed distal to the hip joint in young children (Jensen, 1978; Jensen, 1981; Jensen, 1986; Jensen, 1989). For example, the feet and lower legs of 4-year olds comprise 43% of the total lower limb mass, whereas in 16-year olds they make up only 37% the total lower limb mass (Jensen, 1989). As discussed below, animal morphology and limb mass perturbation findings imply that this structural difference may contribute to the higher submaximal aerobic demand observed in young children.

Functional anatomists hypothesize that a significant proportion of the energy required for locomotion is used to overcome inertia during acceleration and deceleration of the limbs (Alexander, 1977; Elliott & Blanksby, 1979; Hildebrand, 1988; Steudel, 1990) and that morphological differences in limb structure may affect the metabolic cost of exercise. To support their view, they point to animal models that require speed of movement or the ability to cover large distances (e.g. deer, horses, dogs, camels) (Elliott & Blanksby, 1979; Hildebrand, 1988). In these models, the bulk of limb mass is located proximal to the hip or shoulder joint, and distal portions of the limb are relatively lightweight and narrow. Such low-mass extremity limb design is thought to provide these mammals with an advantage over their heavier-limbed counterparts (who have the same total body mass, travel at the same speed and use the same locomotor patterns) because it would place a smaller inertial load on the musculature during limb acceleration and deceleration and therefore require less energy for movement (Martin & Morgan, 1992). Unfortunately, metabolic data supporting this notion have yet to be collected.

Various investigators of human locomotor economy have been intrigued by the possibility that differences in animal limb structure could influence locomotor economy (Bhambhani et al., 1989; Claremont & Hall, 1988; Frederick et al., 1984; Inman et al., 1981; Myers & Steudel, 1985). To test indirectly the validity of this concept, researchers have manipulated limb structure by adding mass to thighs, shanks, and ankles of humans and compared the aerobic demand of walking and running with and without added weights. As shown in Table 3, a universal finding in studies of this kind has been a significant increase in the metabolic cost of locomotion with added mass, particularly if the mass was added to the distal portion of the limbs, such as the ankles and feet. Although the mass-manipulations performed in these studies were often extreme and highly localized, results supported the notion that limb morphology could alter economy. Observations of this kind suggest that human children who have a greater proportion of their limb mass distributed distally may experience relatively higher metabolic demands.

Table 3. Limb mass manipulation studies

| Researchers Date | Subjects | Protocol | Results |
|---|---|---|---|
| **Inman et al.**<br>1981 | Subject char. and numbers not provided | Walking Velocity ? Treadmill grade 0%. Loads added to each shank 0, 1, 2, 3, 4 kg | Up to a 30% increase in energy expenditure |
| **Frederick et al.**<br>1984 | n=8 | Running Velocities at 0% grade<br>3.83, 4.13, 4.47 & 4.88 $m \cdot sec^{-1}$<br>Weights added to shoes<br>0, 75, 150, 150 & 225 g/shoe | Every 100 g of weight added to each foot raised the aerobic demand of running by about 1% |
| **Myers & Steudel**<br>1985 | n=3 M<br>n=1 F<br>Ages 18-24 yrs | Running Velocity at 0% grade<br>2.68 $m \cdot sec^{-1}$<br>1.8 kg loads added to thigh, shank and ankle in separate conditions | Increases in aerobic demand:<br>5.8% for thigh<br>8.8% for shank<br>20.7% for ankle |
| **Martin**<br>1985 | n=15 M<br>Mean age=29 ± 8 yrs | Running Velocity at 0% grade<br>3.33 $m \cdot sec^{-1}$<br>0.25 or 0.50 kg loads added to each thigh or foot | Increases in aerobic demand<br>Thighs 0.5 kg = 1.6%<br>Thighs 1.0 kg = 3.4%<br>Feet 0.5 kg = 3.2%<br>Feet 1.0 kg = 6.7% |
| **Claremont & Hall**<br>1988 | n=5 M<br>n=3 F<br>Mean age=42 ± 8 yrs | Constant self-selected running pace. 0% grade.<br>Loads added to ankles<br>For M 1.35 kg on each leg<br>For F 0.45 kg on each leg | 6.2% elevation in energy expenditure for each kilogram of weight added |
| **Bhambhani et al.**<br>1989 | n=8 M<br>Mean age=24 ± 5 yrs | Constant self-selected running pace. 0% grade.<br>Loads added to ankles<br>0.8, 1.6 or 2.4 kg on each leg | Increases in aerobic demand:<br>6.4, 12.2 and 17.1% for respective increases in load |

Although limb mass alteration studies demonstrate that limb morphology can affect the metabolic cost of movement, the critical question of whether or not natural human lower-limb morphology varies enough to affect detectably locomotor economy remains unanswered. Studies which have attempted to explore this hypothesized link have thus far proven discouraging. Simple anthropometric measures of limb structure (circumference and length) in adults correlate very weakly with the metabolic cost of locomotion (Cavanagh & Kram, 1989; Pate, Macera, Bailey, Bartoli, & Powell, 1992). It is important to note, however, that these results are limited by the crude nature of limb structure measurement and by the homogeneity of the subject samples. Accuracy of water displacement methodology promoted by Katch and associates (considered the gold standard for limb volume assessment) (Katch, 1974; Katch, Michael, & Amuchie, 1973) and a contrast of morphologically-different subject samples (young children vs. older children or adults) could produce different results. With the advent of morphological findings demonstrating significant mass shifts with growth (Jensen et al. 1989), this topic becomes worthy of further evaluation. Quite possibly, differences in limb morphology with growth could explain a portion of the variance noted in walking and running aerobic demand with growth.

Katch & coworkers (1973 &1974) have pioneered the development of hydrostatic procedures for body and limb volume assessment. They have stated that water displacement techniques are generally considered more accurate than anthropometric, segment-zone or stereo-photogrammetric methods for determining body segment volumes (Katch et al., 1974). If their statement is tenable, then researchers can be confident that hydrostatic procedures will result in the collection of precise data, particularly because small error rates (always < 4%) have been observed for one of the highly respected alternative methods mentioned (Jensen, 1986). Jensen & colleagues (1981, 1986, 1988, 1989) used photogrammetric procedures to predict body segment volumes and masses for child and adult subjects. They found that when predictions of total body segment masses were summed and compared to measured body mass, mean errors ranged between -0.87% and 0.203% (S.D. = 2.63% and 2.30% respectively) (Jensen, 1986). Considering the accuracy of this less precise technique, hydrostatic methodology should satisfactorily detect structural differences in lower-limb volume with increasing age.

In summary, Jensen and associates have introduced photogrammetric evidence to suggest that limb morphology changes measurably with growth. Functional anatomists and findings from limb mass perturbation studies suggest that such differences could affect the metabolic cost of locomotion. Accurate analyses of limb mass distribution in conjunction with locomotor economy measurements would be helpful in testing the validity of this concept.

## Chapter Summary

Children are less economical at walking than adults. An explanation of this phenomenon has yet to be established, although a number of viable hypotheses exist. Age-related differences in step frequency, stance time, average vertical ground reaction forces, resting metabolic rate, body surface area to mass ratio, ventilatory equivalent, and limb mass distribution are factors that could be responsible for age-related variance in submaximal walking aerobic demand. Simultaneous evaluation and analyses of all these factors over a range of age groups would help to assess collectively the relative contribution of these variables in explaining changes in locomotor economy with age.

# CHAPTER III
# PROCEDURES

## Introduction

This chapter details participation criteria for the subjects and describes the physiological and biomechanical methodologies used in the study. The majority of the chapter is devoted to illumination of the procedures used to assess each of the seven variables most likely to impact walking economy. Finally, a description of statistical methods used to examine data collected during the study closes the chapter.

## Subjects

Twenty-eight female prepubescent (n=7 6-year-olds, n=7 10-year-olds), pubescent (n=7 13-year-olds) and postpubescent (n=7 18- and 19-year-olds) subjects were recruited from the University of North Carolina at Greensboro Exercise and Sport Science YES PE (e.g. yes to physical education) program and the local university community to participate in this investigation. To ensure that extremes of body stature, mass and composition did not obscure average age-related metabolic and structural findings, mass and height were required to fall between the 10th and 90th percentiles for age, based upon data collected by the National Center for Health Statistics (NCHS), and predicted percent fat measures were required to fall within the low, optimal and moderately high ranges established for young females by Lohman and colleagues (Tables 4 & 5) (Lohman, 1987; Lohman, Roche, & Martorell, 1988; NCHS, 1982; Slaughter, Lohman, Boileau, Horswill, Stillman, Loan, et al., 1988).

Prior to data collection, written informed consent was provided by the subjects (and parents for participants under the age of 18) and medical history forms were completed and reviewed. The medical evaluation sought to identify

Table 4. NCHS 10th to 90th percentile norms for mass and height

| Age | Mass (kg) | Height (cm) |
|---|---|---|
| 6 | 17-24 | 108-121 |
| 10 | 26-44 | 130-147 |
| 13 | 36-61 | 148-165 |
| 18 | 47-72 | 156-171 |

Table 5. Triceps + calf skinfold and % Body Fat norms (6-17 yrs) Lohman (1987)

| Range | Skinfolds (mm) | Body Fat (%) |
|---|---|---|
| Low | 11-17 | 12-15 |
| Optimal | 17-30 | 15-25 |
| Mod. High | 30-37 | 25-30 |

physical, structural, and orthopedic contraindications to submaximal treadmill walking exercise and/or measurement of limb volume via hydrostatic methods. Contraindicated factors included a congenital cardiac or pulmonary condition which could have affected aerobic exercise, a recent lower-limb fracture (within the last 12 months) or cartilage injury, active treatment for a medical condition or injury, and presence of a lower-limb congenital deformity (including deformities "corrected" by surgery).

## Test Sessions

Three test sessions were completed by each subject. An overview and a detailed description of each session are provided in the following section: (Note: listed times for assessments included time for subject instruction and equipment setup and adjustment.)

### Session 1

| Assessment time | Variable |
|---|---|
| 5 min | Height |
| 2 min | Body mass |
| 20 min | Leg length and segment measures |
| 5 min | Percent body fat |
| 40 min | 1st 30-minute treadmill session<br>• mouth-piece and nose-clip engaged from min 6-10, 16-20, 26-30<br>• Metabolic, heart rate and gait measures obtained from min 8-10, 18-20, 28-30 |
| 15 min | Leg segment volume determinations |

### Session 2

| Assessment time | Variable |
|---|---|
| 35 min | 2nd 30-minute treadmill session<br>• mouth-piece and nose-clip engaged from min 6-10, 16-20, 26-30<br>• Metabolic, heart rate and gait measures obtained from min 8-10, 18-20, 28-30 |

### Session 3

| Assessment time | Variable |
|---|---|
| 25 min | Sitting resting metabolic rate |
| 20 min | Final treadmill walking session (10-minute)<br>• metabolic, heart rate, gait and film assessments conducted |
| 15 min | Force plate assessment of foot strike force generation |

## Height, Body Mass, Leg Length & Segment Measures, Percent Body Fat, Body Surface Area (Session 1)

Following an introduction to the laboratory and a description of the procedures involved in the study, participants had their body mass determined on a standard medical scale and their height measured with a GPM anthropometric kit. Using the same anthropometric kit, right and left leg-lengths were measured from the superior border of the greater trochanter to the floor as participants stood barefoot (Lohman et al., 1988; Ross, Brown, Hebbelinck, &

Falkner, 1978). Subjects with noticeable leg length discrepancies (age 6 > 0.5 cm, age 10 > 1.0 cm, age 13 & 18 > 1.5 cm) were excluded from further study (Recommendations made by Dr. Karl B. Fields, a Family Practice and Sports Medicine physician). Percent body fat was predicted from triceps and medial calf skinfold measures obtained using Harpenden skinfold calipers according to procedures recommended by Lohman (1992) and Slaughter et al (1988) (Lohman, 1992; Slaughter et al., 1988). Percent body fat for the oldest age group (18-year olds) was predicted from skinfold measures taken at the chest, mid axilla, triceps, sub-scapula, navel, supra-iliac, and thigh according to procedures recommended by Jackson and Pollock (1978).

The following formulas were used to determine percent body fat.

*Slaughter et al. (1988) tricep and calf skinfold formulas for females:*

Ages 6, 10 & 13 yrs: $\%fat = 1.33(triceps + calf) - 0.013(triceps + calf)^2 - 2.5$

*Jackson & Pollock (1978) seven site skinfold formula for adult females:*

$$\text{body density} = 1.0970 - 0.00046971(\Sigma 7 \text{ skinfolds}) + 0.000000056(\Sigma 7 \text{ skinfolds})^2 - 0.00012828(\text{age})$$

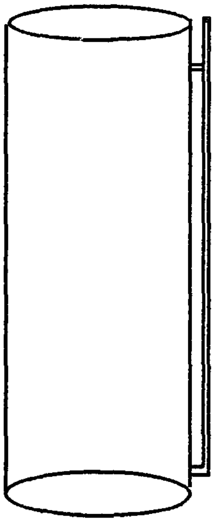
$$\%fat = (\{4.95/\text{body density}\}-4.5) \times 100$$

Body surface area was estimated from knowledge of subject mass and height and use of this formula developed by Haycock, Schwartz & Wisotsky (1978): Surface area ($m^2$) = Mass (kg) $^{0.5378}$ x Height (cm) $^{0.3964}$ x 0.024265. This formula has been validated for prediction of this parameter on children and adults (Haycock, Chir, Schwartz, & Wisotsky, 1978).

## Limb Volume/Morphology (Session 1)

Participants changed into bathing suits for measurement of lower limb mass distribution with a PVC plethysmograph measuring 30.3 centimeters in diameter and 82.0 centimeters in height (Figure 1). The plethysmograph was a water container fabricated from a large section of plastic drainage pipe cut to the desired length and capped at one end. A small clear plastic measuring tube, connected through the base of the container and paralleling the side of the container, showed changes in water level within the plythysmograph. This apparatus measured limb volume by determining the volume of water displaced by any portion of the body located in it.

Figure 1. Limb volume plethysmograph.



Participants had each leg volume assessed separately. To achieve this end, subjects straddled the rim of the unit, submerging one limb to the gluteal furrow. Katch & associates (1973, 1974) recommended the gluteal furrow as a land-mark which differentiates lower-limb mass from trunk mass. Next, by using steps, located next to the cylinder, subjects raised themselves above the apparatus to the anthropometric points (knee, ankle, and complete limb withdrawal) of interest. As they did so, limb segment volumes were obtained from the drop in water within the apparatus. Knowledge of the plethysmograph radius and the distance of the drop in water at each point made calculation of the volume of the limb, or portion thereof, possible ($V = \pi r^2 h$).

On both the younger and older participants, pre-marked limb-segment points were made in the following manner. Horizontal indelible ink marks, approximately 1 cm in length, were placed on the lateral side of the legs level with the gluteal furrow, the knee at the point of articulation (crease) and the inferior border of the lateral maleolus.

Three separate and complete sets of limb volume measurements were made on each participant. The two closest sets of measures were used to generate a mean value for each subject's segmental limb volumes. Mean values were then used to observe hypothesized shifts in limb structure with growth from one age group to the next. Thigh to shank leg volume ratios were used to examine age-related differences in limb morphology.

### Step Frequency and Length (Sessions 1, 2 & 3)

Step frequency and length were determined for 2-min time periods at 10-min intervals throughout the 70 minutes of treadmill walking. To familiarize participants with walking on the treadmill, a demonstration of treadmill walking was provided by the investigator. Immediately thereafter, subjects mounted the treadmill and walked for approximately 2 to 3 minutes until a moderately stable gait was observed. During this time span, walking speed was adjusted gradually up to the test velocity of 1.56 $m \cdot sec^{-1}$, a speed commonly used in walking economy studies involving similar samples of participants (Robinson, 1938; Cassels & Morse, 1962; Skinner, et al., 1971).

Walking accommodation studies conducted on adults suggest that 10 to15 minutes of treadmill walking is too brief a time period to achieve truly stable gait patterns (Charteris & Taves, 1978; Wall & Charteris, 1980) and pilot work on 6- and 7-year old children in our lab tended to support this finding. Therefore, to insure adequate familiarization with the treadmill, participants were required to complete a total of 60 minutes of treadmill walking at 1.56 $m \cdot sec^{-1}$ (two 30-min time periods over two days) before criterion measures of step frequency and length were obtained. To measure the progress and adequacy of accommodation, step frequency and length assessments were made during the last 2 minutes of each of the six 10-min treadmill walking accommodation segments.

Previous investigators found that a walking velocity of 1.56 $m \cdot sec^{-1}$ is submaximal and suitable for the range of age groups involved in this investigation (Kanaley, Boileau, Massey, & Misner, 1989; Skinner, Bar-Or, Bergsteinova, Bell, Royer, & Buskirk, 1971). $\dot{V}O_2$ max values between 43 and 53 $ml \cdot kg^{-1} \cdot min^{-1}$ have been reported for girls ages 6 to 10 (Krahenbuhl, Skinner, & Kohrt, 1985; Skinner et al., 1971). Given that the test pace at 0% grade elicited a submaximal aerobic demand of $< 21$ $ml \cdot kg^{-1} \cdot min^{-1}$ (Skinner et al., 1971), participants in this study were likely to have exercised at an intensity below 50% of $\dot{V}O_2$ max. Although this aerobic demand may appear moderate, the walking pace was brisk for very young participants. Therefore, to ensure that fatigue did not significantly affect gait, 30-minute walking sessions were divided into three 10-min walking bouts, each separated by 5 minutes of rest.

Pilot work revealed that boredom is a significant problem for children walking for an extended period of time. To remove the likelihood of boredom and its possible affects on performance, all participants watched videos (of which Aladdin and Dennis the Menace are representative) as they walked. This form of entertainment was highly effective at reducing the tedium and perception of fatigue during the testing process. What remains unknown is the affect of watching the videos on physiological arousal (increased or decreased). It can be said that pilot work showed gait patterns and metabolism in the youngest participants to be more stable with audio-visual distraction.

Step frequency and step length were measured using a photocell-computer interface and knowledge of treadmill belt velocity. The photocell reflected light off markers placed on the lateral or medial midsoles of participant's shoes. Every time a participant placed a foot into the narrow pathway of the photocell light beam, a digital pulse was sent to the computer. Mean step time, or time between heel contacts of successive steps, was derived by the computer from measurements of the average time interval between digital pulses, and this value, in turn, was multiplied by treadmill velocity to derive mean step length, defined as the distance between successive heel contacts. Step frequency was determined by dividing the average time interval between pulses into 60 seconds. Each participant's freely chosen step length and step frequency was defined as the mean step length and frequency measured from minutes 8 to 10 during a given 10-min period.

## Resting Metabolic Rate (Session 3)

Participants came to the lab 3 to 4 hours postprandial for an assessment of resting metabolic rate (RMR) just prior to assessment of walking economy, stance time, and ground reaction forces. The purpose of this measurement was to determine if mass-specific net aerobic demand during walking (exercise $\dot{V}O_2$ – resting $\dot{V}O_2$) was significantly different across the four age groups. Measurement of resting metabolic rate entailed collection of a 10-minute expired gas sample in a meteorological balloon as participants sat in a resting state. This measurement was preceded by 10 min of sitting quietly during which metabolism was expected to stabilize. At minute 8 of this stabilization period, a nose-clip was placed on each participants nose and a mouth-piece (attached to a respiratory valve, hoses and a meteorological balloon) was inserted into their mouth. Expired gas collection began promptly at the 10-min time mark and continued until the 10-minute gas sample was obtained. Thus, participants were expected to remain seated and as still as possible for a total of 20 minutes. To ensure that participants sat quietly, they were shown a video (one of the seven mentioned above) during the metabolic stabilization and assessment periods.

## Walking Economy (Sessions 1, 2, & 3)

Walking economy was determined during the last two minutes of each 10-min segment of the accommodation and criterion measurement periods while walking at 1.56 $m \cdot sec^{-1}$. During minutes five to eight of these time periods, subjects were connected to expired gas collection equipment. During minutes 8 to 10 of each period, a 2-min expired gas sample was collected in a meteorological balloon. The contents of these balloons were analyzed for oxygen ($O_2$) and carbon dioxide ($CO_2$) using AMETEK electro-chemical gas analyzers (S-3A/1 and CD-3A analyzers, respectively) calibrated against primary standard gases. The micro-Scholander technique (Scholander, 1947) was used to determine the $O_2$ and $CO_2$ content of the primary gases. Expired ventilation was measured by passing the contents of the meteorological balloons through a Rayfield dry-gas meter calibrated previously against a 120-L Tissot. The oxygen consumption value from the balloons provided a measure of walking aerobic demand (e.g., walking economy). Walking oxygen consumption was expressed relative to body mass ($ml \cdot kg^{-1} \cdot min^{-1}$). To ensure that participants utilized aerobic metabolic pathways for energy production, only those subjects whose respiratory exchange ratio values ($CO_2/O_2$) did not exceed 1.00 were included in the study.

### Heart Rate (Sessions 1, 2 & 3)

To determine if aerobic demand was reflected by cardiac function, heart rate was assessed with a Polar Pacer heart rate monitor during the last two minutes of each of the 10-min treadmill accommodation and criterion measurement periods. This heart rate monitoring system involved a small cardiac electrical-pulse-sensor radio-transmitter mounted to a chest strap and a radio-signal receiver-watch unit. The receiver-watch unit was mounted on the treadmill handrail in front of the walking subjects (turned out of view) and checked simultaneously with measurement of aerobic demand. Heart rate was measured in beats per minute.

### Ventilatory Equivalent (Session 1,2 & 3)

Ventilatory equivalent (e.g. breathing efficiency) was determined from exercise oxygen consumption and ventilation values ($\dot{V}_E \cdot \dot{V}O_2^{-1}$) obtained from an average of expired gas samples collected in meteorological balloons during the last two minutes of each of the 10-min walking economy accommodation and assessment periods.

## Stance time and Relative Average Vertical Ground Reaction Force (Session 3)

Stance time is a measure of the time each foot is placed on the ground during a stride cycle, and mass-specific average vertical ground reaction force is a measure of the vertical force generated (normalized to body mass) while the foot is in contact with the ground. These biomechanical parameters were measured using a Kistler force platform placed in the middle of a 10-m walk way. Force platform sampling was set at a rate of 100 Hz per second (e.g., 100 times per second). Following practice of natural walking over the platform, each participant completed a total of five acceptable trials at 1.56 $m \cdot sec^{-1}$. Qualification for appropriate completion of a trial was no visual adjustment of right or left foot placement on the force platform and maintenance of a walking velocity ±5% of the goal test speed (Williams & Cavanagh, 1987). Trials that did not meet these specifications were repeated. At completion of testing, data from the three trials closest to the criterion velocity were used for statistical analysis.

Overground walking velocity was determined from photocells placed two meters apart along the 10-meter walk-way and on either side of the force platform. As each participant passed by the first photocell, a timer was triggered which started collection of ground contact data, ground force reaction data and measurement of walking speed. Then, as the subject passed the second photocell, data collection and time assessment were completed.

## Statistics

Analysis of variance (ANOVA) was used to assess whether mean values of the dependent (walking economy) and independent variables (step rate, stance time, average vertical ground reaction force, body surface area, resting metabolic rate, respiratory equivalent, and limb mass distribution) were significantly different ($p<0.05$) across age groups. Application of the HSD Tukey post-hoc multiple comparison procedure revealed the location of mean differences between groups.

Coefficients of variation ($(\{SD/\overline{X}\} * 100)$) were calculated for each of the dependent and independent variables within an age group. ANOVA was used to determine the significance of differences. As before, the HSD Tukey post-hoc multiple comparison procedure were used to reveal the location of differences.

Residual plots and partial regression plots were used to relate differences in walking economy with age to differences in step rate, stance time, average vertical ground reaction force, body surface area, resting metabolic rate, respiratory equivalent, and limb mass distribution with age. The specific purpose of these plots was to assess assumptions of linearity and homogeneity of variance, in other words to ensure fit of the simplest function (line) to associations between variables (Keppel, 1973). When a straight-line fit appeared inappropriate, orthogonal polynomials were used to fit curvilinear lines to the data. Ultimately, this process of fitting the best line to each association between the dependent and independent variables ensured that the entire data set was characterized accurately prior to further analysis using multiple regression procedures.

Following residual and partial regression plot analysis, multiple regression analysis was used to determine the relative order of importance of the relationship between differences in mass-specific aerobic demand (dependent variable) and changes in selected predictor (or independent) variables. All predictor variable data were standardized to z-scores (mean of 0 and standard deviation of 1) prior to calculation of a general prediction equation. The magnitude the beta coefficients for each predictor variable in the resulting least squares solution indicated the rank order of importance of each of the predictor factors. Larger beta-coefficients indicated a higher correlation with the criterion variable than smaller coefficients when all other concomitantly measured variables were held constant.

The all-regressions analytical method was used to select a small set of the most predictive variables associated with age-related changes in mass-specific walking economy. This statistical procedure involved consideration of every possible regression equation that could be derived from the set of predictor variables (Kachigan, 1982). The equations which provided the largest squared multiple correlation coefficient ($R^2$) using the smallest number of *justifiable* predictor variables were then accepted. Justifiable variables were determined using the following criteria: examination of empirical results from previous research, partial F analysis, and the strength of linear associations between walking aerobic demand and each predictor variable.

# CHAPTER IV
# RESULTS

## Introduction

The objective of this study was to evaluate the unique contributions of selected metabolic, gait, and morphological variables relative to age-related differences in walking $\dot{V}O_2$. To achieve this overall goal, 28 participants (n=7 in each of four age groups ranging from 6 to 19 years) were assessed on submaximal aerobic demand, resting metabolic rate, body surface area to mass ratio, ventilatory equivalent, step frequency, stance time, mass-specific vertical ground reaction forces, and limb mass distribution. With the aid of multiple regression analysis, the proportion of non-redundant variation in age-related differences in metabolic economy associated with selected predictor variables was determined. Results from data analyses are presented below. Descriptive data are presented first, followed by age group walking data, then simple associations between age and each of the primary variables and simple correlations between each predictor variable and walking $\dot{V}O_2$. Finally, multiple regression findings are presented.

## Subject Descriptive Data

Twenty-eight young females were tested during a period of five months in 1994. Subjects conformed to entry criteria fairly closely, with the exception of slight height (n=3), weight (n=1) and age (n=2) deviations in six of the participants. Deviations are described below in Table 6. These participant's data were included in the analyses because it was believed that their physiological and chronological data would not alter significantly the design of the study and because qualified volunteers for the study were scarce.

Table 6. Deviations from predetermined entry criteria.

| Subject | Age | Deviation from predetermined entry criteria |
|---|---|---|
| A | 6 | +0.5 cm or 0.4% above 90th percentile for height |
| B | 6 | +2.1 kg or 8.2% above 90th percentile for weight |
| C | 13 | +0.8 cm or 0.4% above 90th percentile for height |
| D | 19 | 19- rather than 18-years old |
| E | 19 | 19- rather than 18-years old |
| F | 18 | +0.8 cm or 0.5% above 90th percentile for height |

Descriptive data are presented in Table 7. Using Tukey post-hoc procedures, it was determined that all four groups tested were significantly different from each other in age. Six-, 10-, and 13-year olds were also different from each other in height, body mass and body surface area, but not percent body fat. No significant differences in height, body mass, and body surface area were observed across age groups 13 and 18/19. When 18/19-year olds were assessed for body fat from tricep and calf skinfold values (using a formula appropriate for youth ages 6-17), results indicated that these individuals had a

Table 7. Subject characteristics.

| Variable | 6-year olds | 10-year olds | 13-year olds | 18/19-year olds |
|---|---|---|---|---|
| Age (months) | *76.0 ± 4.1 | *123.3 ± 4.2 | *161.5 ± 4.4 | *227.2 ± 2.4 |
| (years) | 6.3 ± 0.3 | 10.3 ± 0.3 | 13.5 ± 0.3 | 18.9 ± 0.2 |
| Height (cm) | *118.1 ± 3.7 | *137.9 ± 5.4 | *159.4 ± 5.6 | 164.6 ± 4.5 |
| Mass (kg) | *22.3 ± 2.2 | *32.5 ± 4.8 | *50.1 ± 6.8 | 57.5 ± 6.9 |
| Body surface area ($m^2$) | *0.85 ± 0.05 | *1.11 ± 0.10 | *1.48 ± 0.12 | 1.62 ± 0.12 |
| Body fat (%) | 18.1 ± 1.8<br>triceps & calf | 19.5 ± 3.4<br>triceps & calf | 20.2 ± 4.1<br>triceps & calf | 22.0 ± 4.6<br>7-site formula |

Values are mean ± standard deviation. * $p \leq 0.05$ different from the value next to it (right or left).

a greater percent body fat than those in all the other age groups. Group differences in body fat were removed when a 7-site adult skinfold formula was used on the oldest age group. With the exception of percent body fat measures in the oldest age group (as discussed above), identical assessment procedures were used on all measures shown.

## Age Group Differences in the Primary Variables

Some discussion of variable calculation is a prerequisite to discussion of age-group differences. Repeated-measures ANOVA indicated that all of the metabolic- and gait-related variables studied during treadmill walking were basically stable across the seven time periods selected for measurement on participants (e.g. Day 1: min 8-10, 18-20, 28-30; Day 2: min 8-10, 18-20, 28-30; Day 3: min 8-10). Slight age group variance (in the 6-year olds) was observed in several of the measures, but when statistical controls were applied for the multitude of pairwise comparisons, no significant differences were found across time periods and age groups. Therefore, accommodation to the treadmill and metabolic equipment was not the concern that had been expected. Frost and colleagues (1995) reported similar results (Frost, Bar-Or, Dowling, & White, 1995). When they tested 24 boys and girls between the ages of seven and 11 "many trials and more than one day of testing" did "not appear to improve the stability of the metabolic or kinematic variables" measured (p. 162). Given findings in the present study and those from Frost and coworker's investigation, it was decided that averages of all seven measures obtained should be generated for each subject prior to further statistical analysis. The intention of this procedure was to minimize unwanted variability and to uncover metabolic- and gait-related values closer to the norm for each variable. It was hoped that by further stabilizing the data in this manner, conclusions drawn from data gathered on the small sample sizes in each group would provide greater generalizability to the population. Tables 8 through 14 show group data by the time period in which variables were assessed.

Table 8. Submaximal oxygen consumption ($ml\cdot kg^{-1}\cdot min^{-1}$) at 1.56 $m\cdot sec^{-1}$ and 0% grade by age group and at each of the seven time periods it was assessed.

| | 6-year olds | | 10-year olds | | 13-year olds | | 18 & 19-year olds | |
|---|---|---|---|---|---|---|---|---|
| Time | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| 1 | 22.1 | 0.9 | 17.9 | 1.6 | 14.9 | 2.0 | 13.8 | 1.0 |
| 2 | 21.4 | 1.3 | 17.7 | 1.5 | 14.4 | 2.0 | 13.5 | 1.1 |
| 3 | 21.4 | 1.6 | 17.4 | 1.8 | 14.5 | 2.0 | 13.3 | 0.9 |
| 4 | 21.0 | 0.8 | 18.0 | 1.0 | 15.1 | 1.1 | 13.6 | 0.9 |
| 5 | 20.9 | 0.7 | 17.6 | 1.0 | 14.9 | 0.9 | 13.2 | 1.2 |
| 6 | 20.9 | 1.0 | 17.9 | 1.1 | 14.9 | 1.1 | 13.1 | 1.2 |
| 7 | 20.9 | 0.8 | 17.4 | 1.7 | 15.1 | 1.0 | 13.4 | 1.4 |

Table 9. Submaximal oxygen consumption ($ml\cdot min^{-1}$) at 1.56 $m\cdot sec^{-1}$ and 0% grade by age group and at each of the seven time periods it was assessed.

| | 6-year olds | | 10-year olds | | 13-year olds | | 18 & 19-year olds | |
|---|---|---|---|---|---|---|---|---|
| Time | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| 1 | 500 | 50 | 590 | 80 | 740 | 80 | 800 | 70 |
| 2 | 480 | 60 | 580 | 70 | 720 | 100 | 760 | 120 |
| 3 | 480 | 50 | 570 | 60 | 720 | 100 | 770 | 110 |
| 4 | 470 | 50 | 600 | 80 | 760 | 90 | 780 | 110 |
| 5 | 470 | 50 | 580 | 80 | 750 | 100 | 770 | 100 |
| 6 | 470 | 40 | 590 | 70 | 750 | 80 | 760 | 100 |
| 7 | 470 | 40 | 570 | 80 | 760 | 90 | 770 | 100 |

Table 10. Submaximal ventilation ($L\cdot min^{-1}{}_{BTPS}$) at 1.56 $m\cdot sec^{-1}$ and 0% grade by age group and at each of the seven time periods it was assessed.

| | 6-year olds | | 10-year olds | | 13-year olds | | 18 & 19-year olds | |
|---|---|---|---|---|---|---|---|---|
| Time | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| 1 | 35.4 | 4.5 | 34.4 | 3.8 | 43.8 | 8.8 | 39.8 | 3.2 |
| 2 | 34.3 | 8.6 | 33.5 | 3.8 | 39.7 | 10.0 | 37.3 | 3.7 |
| 3 | 33.5 | 8.8 | 32.3 | 3.8 | 41.3 | 8.7 | 37.0 | 1.7 |
| 4 | 32.9 | 4.5 | 34.1 | 3.7 | 41.1 | 6.6 | 38.4 | 4.3 |
| 5 | 32.1 | 4.0 | 33.1 | 3.3 | 41.3 | 5.7 | 38.0 | 3.0 |
| 6 | 31.4 | 4.1 | 33.6 | 3.8 | 42.3 | 5.3 | 37.5 | 2.2 |
| 7 | 30.5 | 3.3 | 32.2 | 3.2 | 41.3 | 4.4 | 39.5 | 3.1 |

Table 11. Ventilatory equivalent ($L_{air\ STPD} \cdot min^{-1}/LO_2 \cdot min^{-1}$) at 1.56 m·sec$^{-1}$ and 0% grade by age group and at each of the seven time periods it was assessed.

| | 6-year olds | | 10-year olds | | 13-year olds | | 18 & 19-year olds | |
|---|---|---|---|---|---|---|---|---|
| **Time** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| 1 | 40.1 | 3.9 | 33.4 | 3.7 | 33.1 | 5.0 | 28.2 | 3.4 |
| 2 | 39.8 | 6.3 | 33.0 | 2.8 | 30.9 | 4.4 | 28.0 | 3.2 |
| 3 | 39.0 | 7.0 | 32.5 | 2.3 | 31.8 | 3.1 | 27.3 | 3.6 |
| 4 | 39.5 | 4.6 | 31.1 | 3.6 | 30.4 | 3.5 | 27.8 | 4.3 |
| 5 | 38.9 | 3.9 | 31.6 | 3.4 | 31.0 | 3.0 | 27.9 | 3.5 |
| 6 | 38.2 | 3.9 | 31.3 | 3.1 | 31.9 | 3.0 | 28.0 | 2.2 |
| 7 | 36.9 | 3.0 | 31.9 | 2.2 | 31.0 | 2.2 | 28.9 | 3.7 |

Table 12. Step frequency (steps·min$^{-1}$) at 1.56 m·sec$^{-1}$ and 0% grade by age group and at each of the seven time periods it was assessed.

| | 6-year olds | | 10-year olds | | 13-year olds | | 18 & 19-year olds | |
|---|---|---|---|---|---|---|---|---|
| **Time** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| 1 | 155 | 6 | 136 | 5 | 122 | 4 | 125 | 5 |
| 2 | 153 | 8 | 134 | 5 | 121 | 4 | 126 | 5 |
| 3 | 153 | 7 | 134 | 5 | 121 | 4 | 125 | 5 |
| 4 | 154 | 5 | 135 | 4 | 123 | 3 | 124 | 5 |
| 5 | 154 | 7 | 136 | 4 | 123 | 4 | 124 | 5 |
| 6 | 154 | 8 | 136 | 5 | 122 | 4 | 124 | 5 |
| 7 | 154 | 5 | 136 | 6 | 121 | 6 | 124 | 5 |

Table 13. Step length (cm) at 1.56 m·sec$^{-1}$ and 0% grade by age group and at each of the seven time periods it was assessed.

| | 6-year olds | | 10-year olds | | 13-year olds | | 18 & 19-year olds | |
|---|---|---|---|---|---|---|---|---|
| **Time** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| 1 | 60.5 | 2.2 | 69.2 | 2.5 | 76.0 | 2.2 | 74.7 | 2.6 |
| 2 | 61.3 | 3.1 | 70.0 | 2.3 | 77.3 | 2.4 | 74.7 | 3.0 |
| 3 | 61.4 | 2.9 | 70.1 | 2.7 | 77.3 | 2.8 | 75.3 | 2.8 |
| 4 | 60.9 | 2.0 | 69.5 | 2.3 | 76.4 | 2.0 | 75.3 | 2.9 |
| 5 | 60.8 | 2.9 | 68.7 | 2.2 | 76.5 | 2.3 | 75.6 | 2.8 |
| 6 | 61.1 | 3.2 | 69.0 | 2.6 | 76.6 | 2.6 | 75.5 | 2.8 |
| 7 | 60.8 | 2.0 | 69.1 | 2.8 | 77.2 | 3.8 | 75.2 | 3.0 |

Table 14. Heart rate (beats·min$^{-1}$) at 1.56 m·sec$^{-1}$ and 0% grade by age group and at each of the seven time periods it was assessed.

| | 6-year olds | | 10-year olds | | 13-year olds | | 18 & 19-year olds | |
|---|---|---|---|---|---|---|---|---|
| Time | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| 1 | 144 | 9 | 121 | 8 | 117 | 10 | 119 | 25 |
| 2 | 145 | 11 | 122 | 8 | 116 | 10 | 119 | 23 |
| 3 | 146 | 12 | 123 | 9 | 116 | 9 | 120 | 22 |
| 4 | 145 | 9 | 127 | 8 | 123 | 7 | 119 | 15 |
| 5 | 146 | 10 | 127 | 10 | 126 | 7 | 118 | 15 |
| 6 | 144 | 11 | 125 | 11 | 124 | 8 | 116 | 15 |
| 7 | 142 | 12 | 117 | 9 | 111 | 8 | 113 | 15 |

## Submaximal Aerobic Demand

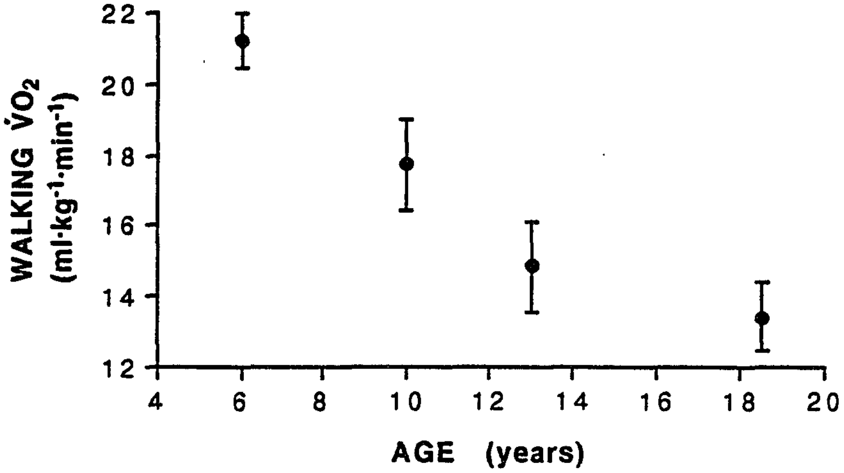
As theorized in Hypothesis #1, submaximal mass-specific oxygen consumption, at a walking speed of 1.56 m·sec$^{-1}$ and 0% grade, was highest in the 6-year old age group and lowest in the 18/19-year old age group. Measured values decreased linearly from ages six to 13, and then remained essentially stable from ages 13 to 18/19 (Table 15, Figure 2).

Table 15. Submaximal oxygen consumption (ml·kg$^{-1}$·min$^{-1}$) by age group at 1.56 m·sec$^{-1}$ and 0% grade.

| | Tukey Grouping | Mean | Standard Deviation | Coefficient of Variation |
|---|---|---|---|---|
| 6-year olds | A | 21.2 | 0.8 | 3.5 |
| 10-year olds | B | 17.7 | 1.3 | 7.1 |
| 13-year olds | C | 14.8 | 1.3 | 8.8 |
| 18/19-year olds | C | 13.4 | 1.0 | 7.1 |

Means with the same letter are not significantly different.

Figure 2. Submaximal oxygen consumption (ml·kg$^{-1}$·min$^{-1}$) by age group at 1.56 m·sec$^{-1}$ and 0% grade. Values shown are means ± 1 standard deviation.



Heart Rate

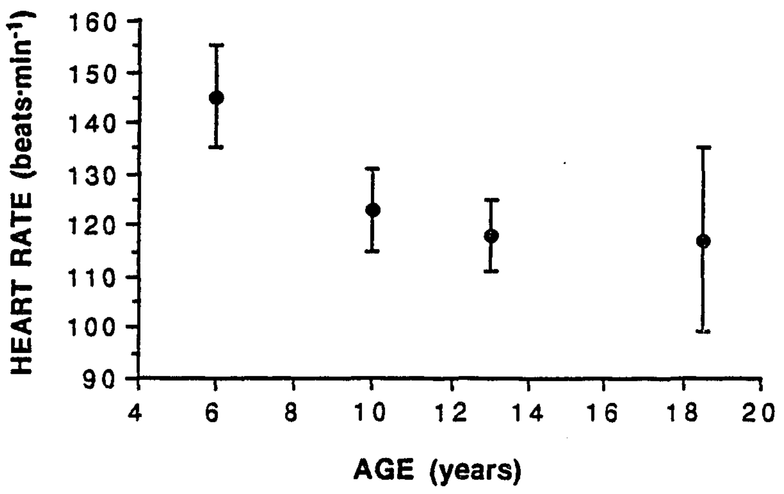
Heart rate data at 1.56 m·sec$^{-1}$ and 0% grade was significantly lower in the 10-, 13- and 18/19-year olds than it was in the 6-year olds (Table 16, Figure 3). Heart rate was not different across age groups 10, 13, and 18/19.

Table 16. Heart rate (bpm) by age group at 1.56 m·sec$^{-1}$ and 0% grade.

| | Tukey Grouping | Mean | Standard Deviation | Coefficient of Variation |
|---|---|---|---|---|
| 6-year olds | A | 145 | 10 | 6.9 |
| 10-year olds | B | 123 | 8 | 6.5 |
| 13-year olds | B | 118 | 7 | 5.9 |
| 18/19-year olds | B | 117 | 18 | 15.4 |

Means with the same letter are not significantly different.

Figure 3. Heart rate by age group at 1.56 m·sec$^{-1}$ and 0% grade. Values shown are means ± 1 standard deviation.



## Resting Metabolism

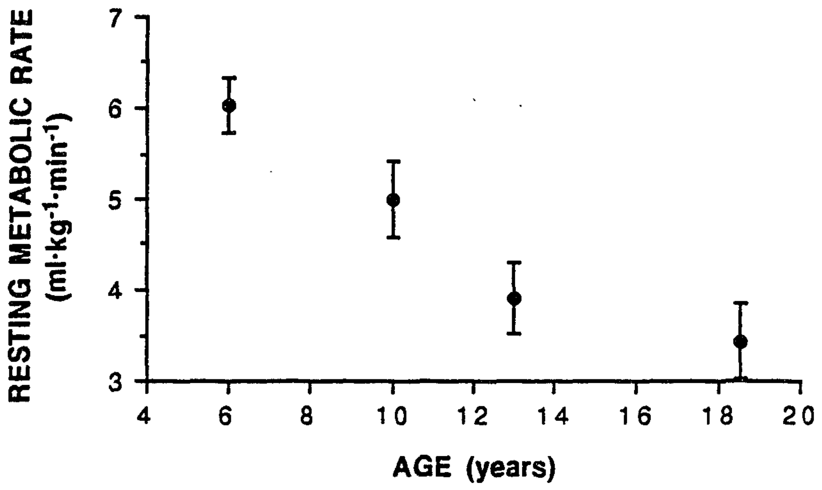
Resting (sitting) mass-specific metabolism decreased across the age groups, as theorized in Hypothesis #2 (Table 17, Figure 4). Significant differences in resting metabolism were evident across the 6-, 10-, & 13-year old age groups. However, significant differences were not evident between 13-year olds and 18/19-year olds.

Table 17. Resting (sitting) oxygen consumption (ml·kg$^{-1}$·min$^{-1}$) by age group.

| | Tukey Grouping | Mean | Standard Deviation | Coefficient of Variation |
|---|---|---|---|---|
| 6-year olds | A | 6.0 | 0.3 | 5.0 |
| 10-year olds | B | 5.0 | 0.4 | 8.7 |
| 13-year olds | C | 3.9 | 0.4 | 10.1 |
| 18/19-year olds | C | 3.4 | 0.4 | 11.6 |

Means with the same letter are not significantly different.

Figure 4. Resting (sitting) oxygen consumption (ml·kg$^{-1}$·min$^{-1}$) by age group. Values shown are means ± 1 standard deviation.



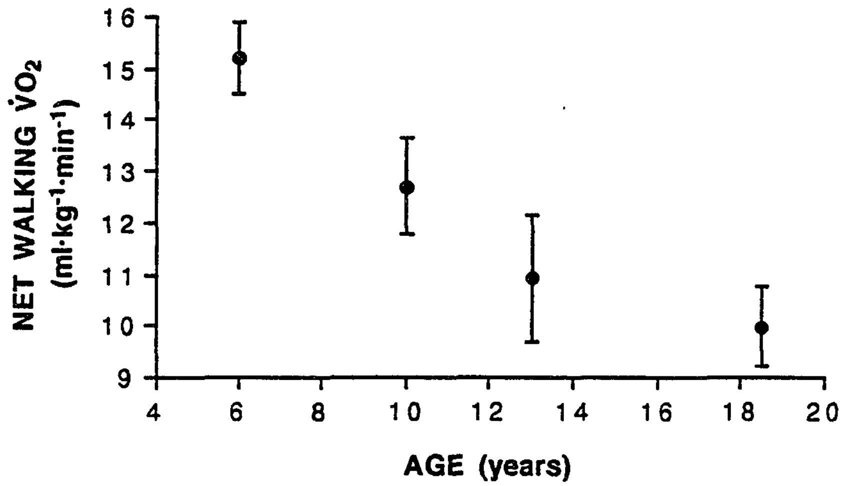
Given that some researchers have suggested that age-related differences in resting metabolism may explain age-related differences in economy, walking minus resting oxygen consumption (e.g., net oxygen consumption) was calculated. Results from this procedure indicated that net walking oxygen consumption still decreased significantly across age groups six, 10, and 13, although not across age groups 13 and 18/19 (Table 18, Figure 5).

Table 18. Net oxygen consumption (ml·kg$^{-1}$·min$^{-1}$) by age group at 1.56 m·sec$^{-1}$ and 0% grade.

| | Tukey Grouping | Mean | Standard Deviation | Coefficient of Variation |
|---|---|---|---|---|
| 6-year olds | A | 15.2 | 0.7 | 4.6 |
| 10-year olds | B | 12.7 | 0.9 | 7.1 |
| 13-year olds | C | 10.9 | 1.2 | 11.0 |
| 18/19-year olds | C | 10.0 | 0.8 | 8.0 |

Means with the same letter are not significantly different.

Figure 5. Net oxygen consumption (ml·kg$^{-1}$·min$^{-1}$) by age group at 1.56 m·sec$^{-1}$ and 0% grade. Values shown are means ± 1 standard deviation.



Body Surface Area to Mass Ratio

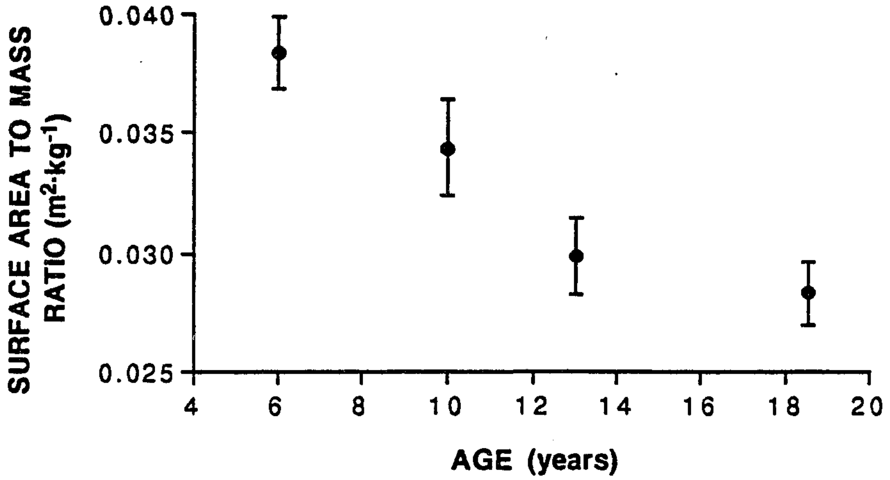
Decreases in surface area relative to body mass were anticipated with advancing age across the four groups tested (Hypothesis #3). Substantial decreases in the ratio of surface area to mass were observed across age groups six through 13 ($p < 0.05$) but not across age groups 13 and 18 & 19 (Table 19, Figure 6).

Table 19. Surface area (m$^2$) to body mass (kg) ratio by age group.

| | Tukey Grouping | Mean | Standard Deviation | Coefficient of Variation |
|---|---|---|---|---|
| 6-year olds | A | 3.8 x 10$^2$ | 0.1 x 10$^2$ | 3.8 |
| 10-year olds | B | 3.4 x 10$^2$ | 0.2 x 10$^2$ | 5.9 |
| 13-year olds | C | 3.0 x 10$^2$ | 0.2 x 10$^2$ | 5.5 |
| 18/19-year olds | C | 2.8 x 10$^2$ | 0.1 x 10$^2$ | 4.7 |

Means with the same letter are not significantly different.

Figure 6. Surface area ($m^2$) to body mass (kg) ratio by age group. Values shown are means ± 1 standard deviation.



## Ventilatory Equivalent

Ventilatory equivalent, or the volume of air moved through the lungs in order to extract one liter of oxygen, was expected to decrease with increasing age across the four groups measured (Hypothesis #4). A significant decrease

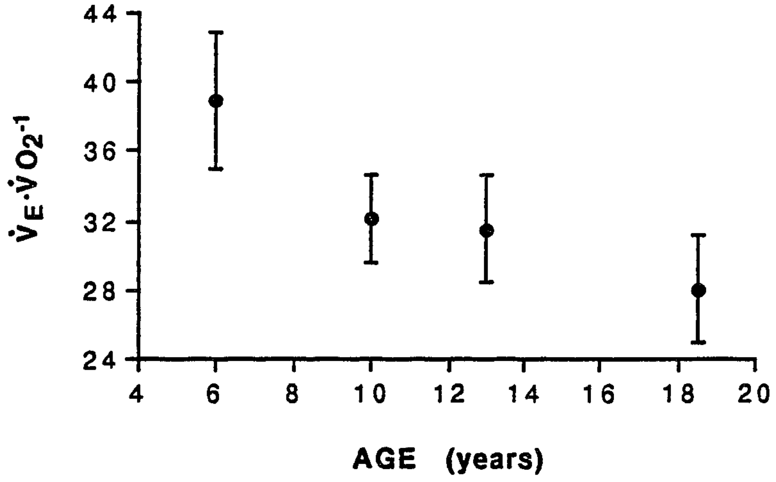
Table 20. Ventilatory equivalent ($\dot{V}_E \cdot \dot{V}O_2^{-1}$) by age group at 1.56 $m \cdot sec^{-1}$ and 0% grade.

| | Tukey Grouping | Mean | Standard Deviation | Coefficient of Variation |
|---|---|---|---|---|
| 6-year olds | A | 38.9 | 4.0 | 10.3 |
| 10-year olds | B | 32.1 | 2.5 | 7.8 |
| 13-year olds | B | 31.5 | 3.2 | 10.2 |
| 18/19-year olds | B | 28.0 | 3.1 | 11.1 |

Means with the same letter are not significantly different.

in ventilatory equivalent was observed from ages six to 10, but not thereafter (Table 20, Figure 7). Substantial variance in the measures obtained may explain this finding.

Figure 7. Ventilatory equivalent ($\dot{V}_E \cdot \dot{V}O_2^{-1}$) by age group at 1.56 m·sec$^{-1}$ and 0% grade. Values shown are means ± 1 standard deviation.



## Step Frequency

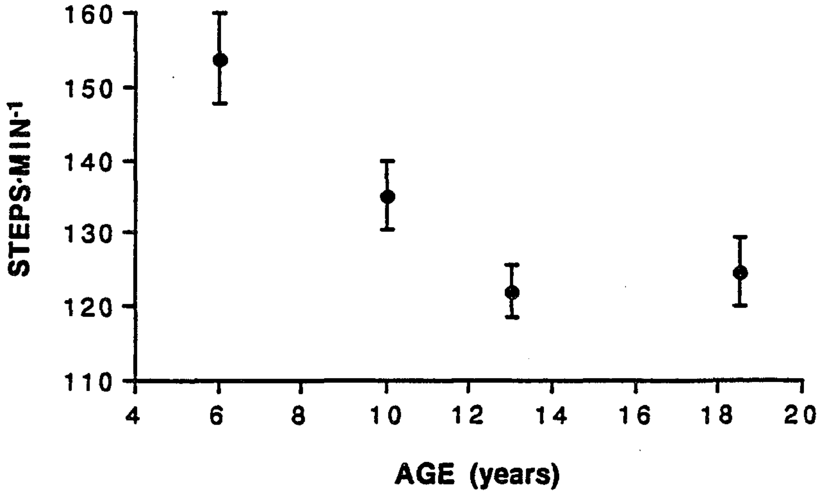
Step frequency (e.g. the number of steps taken per minute) was anticipated to decrease across the four age groups assessed (Hypothesis #5). Participants in this study did indeed demonstrate statistically significant and linear decreases in step number per minute from ages six through 13 (Table 21, Figure 8). No differences were observed in step frequency from ages 13 to 18- or 19 where a plateau in this gait variable appeared to occur.

Table 21. Steps per minute (steps·min$^{-1}$) by age group at 1.56 m·sec$^{-1}$ and 0% grade.

| | Tukey Grouping | Mean | Standard Deviation | Coefficient of Variation |
|---|---|---|---|---|
| 6-year olds | A | 153.8 | 6.2 | 4.0 |
| 10-year olds | B | 135.1 | 4.6 | 3.4 |
| 13-year olds | C | 122.1 | 3.5 | 2.8 |
| 18/19-year olds | C | 124.6 | 4.6 | 3.7 |

Means with the same letter are not significantly different.

Figure 8. Steps per minute by age group at 1.56 m·sec$^{-1}$ and 0% grade. Values shown are means ± 1 standard deviation.



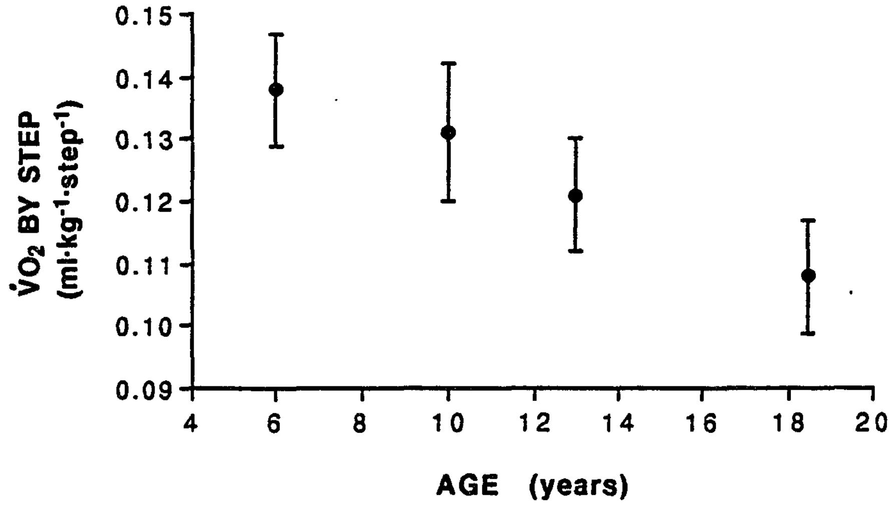
Of equal interest relative to the issue of step frequency was oxygen consumption normalized to each step. It had been theorized that when oxygen consumption was analyzed in this manner, differences in the cost of locomotion across age groups would disappear (Cavagna et al., 1983; Heglund & Taylor, 1988; Kram & Taylor, 1990; MacDougall et al., 1983; Morgan, 1993; Rowland et al., 1987; Thorstensson, 1986). Tukey post-hoc procedures from the present investigation (shown in Table 22) did not support this concept as oxygen consumption values were found to decrease across the four age groups tested, regardless of the "normalizing" procedure (Table 22, Figure 9).

Table 22. Submaximal oxygen consumption relative to each step (ml·kg$^{-1}$·step$^{-1}$) by age group at 1.56 m·sec$^{-1}$ and 0% grade.

| | Tukey Grouping | Mean | Standard Deviation | Coefficient of Variation |
|---|---|---|---|---|
| 6-year olds | A | 0.138 | 0.009 | 6.5 |
| 10-year olds | B A | 0.131 | 0.011 | 8.4 |
| 13-year olds | B C | 0.121 | 0.009 | 7.8 |
| 18/19-year olds | C | 0.108 | 0.009 | 8.3 |

Means with the same letter are not significantly different.

Figure 9. Submaximal oxygen consumption (ml·kg$^{-1}$·min$^{-1}$) relative to each step by age group at 1.56 m·sec$^{-1}$ and 0% grade. Values shown are means ± 1 standard deviation.



Stance time

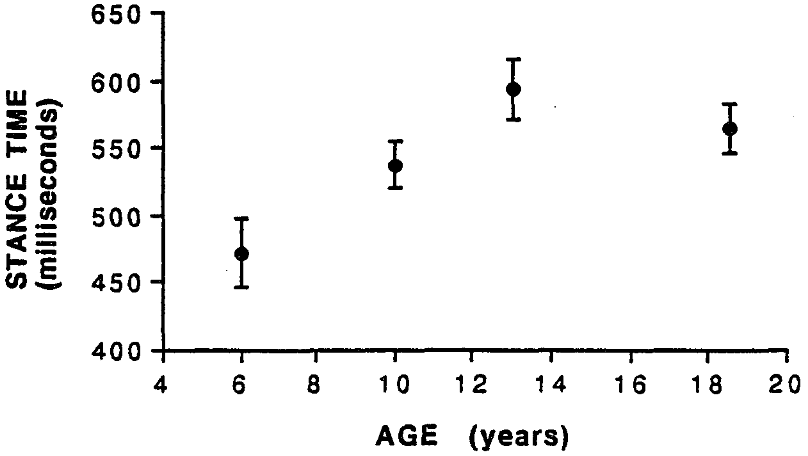
Stance time, which is influenced by step frequency, was hypothesized to increase with growth and age across the four age groups tested (Hypothesis #6). Indeed, increases in stance time were observed across age groups six through 13, but not 13 through 18/19 (Table 23, Figure 10). Tukey post-hoc

Table 23. Stance time (milliseconds) by age group at 1.56 m·sec$^{-1}$ and 0% grade.

| | Tukey Grouping | | Mean | Standard Deviation | Coefficient of Variation |
|---|---|---|---|---|---|
| 6-year olds | | A | 471.9 | 25.8 | 5.5 |
| 10-year olds | B | | 536.7 | 17.6 | 3.3 |
| 18 to19-year olds | B | C | 593.3 | 22.4 | 3.2 |
| 13-year olds | | C | 564.8 | 18.2 | 3.7 |

Means with the same letter are not significantly different. Note that the 13 and 18/19-year old age groups in the table have been reversed from their usual positions for purposes of Tukey grouping.

Figure 10. Stance time (milliseconds) by age group at 1.56 m·sec$^{-1}$ and 0% grade. Values shown are means ± 1 standard deviation.



procedures showed that 6-year olds exhibited shorter stance times than the 10, 13, and 18/19-year olds and that 10-year olds had shorter stance times than 13-year olds. Results also suggested that 10- and 18/19-year olds were similar on this variable and that 13- and 18/19-year olds displayed similar stance times. Table 23 and Figure 10 clarify where differences in this variable appeared.

## Mass-Specific Vertical Ground Reaction Forces

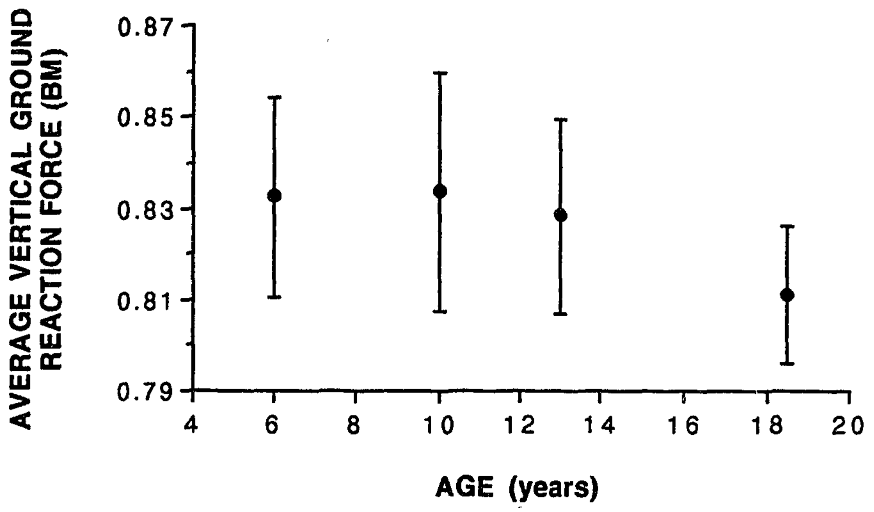
Due to expected reductions in step frequency and increased stance times with age (and growth), Hypothesis #7 stated that mass-specific average vertical ground reaction forces should decrease across the age groups studied. Such changes in mass-specific vertical ground reaction forces were not observed across the four age groups tested. This finding is apparent from examination of the means and standard deviations shown in Table 24 and plotted in Figure 11. No differences between groups were found in spite of low coefficients of variation.

Table 24. Average vertical ground reaction force relative to body mass (BM) by age group at 1.56 m·sec$^{-1}$ and 0% grade.

| | Tukey Grouping | Mean | Standard Deviation | Coefficient of Variation |
|---|---|---|---|---|
| 6-year olds | A | 0.83 | 0.02 | 2.6 |
| 10-year olds | A | 0.83 | 0.03 | 3.1 |
| 13-year olds | A | 0.83 | 0.02 | 2.6 |
| 18/19-year olds | A | 0.81 | 0.02 | 1.9 |

Means with the same letter are not significantly different.

Figure 11. Average vertical ground reaction force (N) relative to body mass (N) at 1.56 m·sec$^{-1}$ and 0% grade. Values shown are means ± 1 standard deviation.



## Lower Limb Mass Distribution

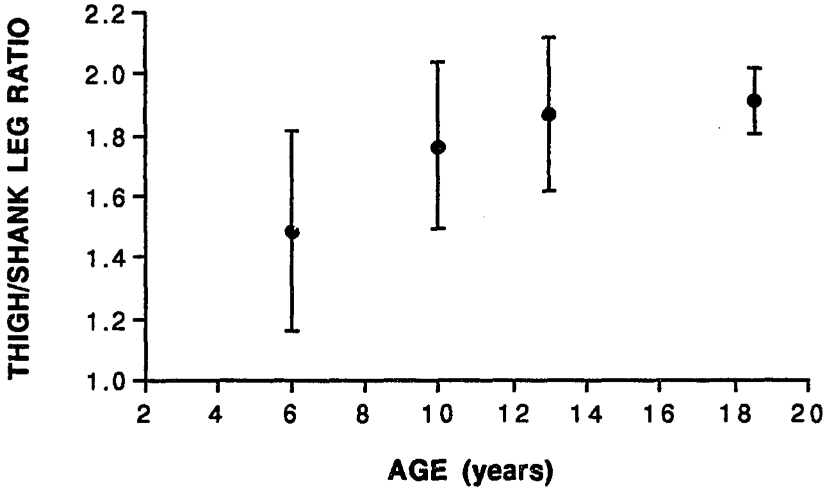
In Hypothesis #8, it was theorized that lower-limb mass distribution would shift measurably from distal to proximal relative the hip joint axis of rotation across the four age groups tested. When a ratio of thigh to shank volume was calculated for each individual and the data analyzed via ANOVA and Tukey post-hoc procedures, only one significant difference in limb mass distribution was observed (Table 25, Figure 12). Thigh to shank ratios increased from the 6- to 10-year old age groups, suggesting that a substantial shift toward a proportionally larger thigh mass occurred. Thereafter, changes in limb mass distribution were insignificant. Taken together, these findings suggest that an adult-like distribution of leg mass occurs as early as age 10. It should be noted that variability in thigh to shank leg ratios was large, particularly in the 6-year old age group. High variability reduced the likelihood of detecting true age-related differences in this measure.

Table 25. Thigh to shank volume ratio by age group.

| | Tukey Grouping | Mean | Standard Deviation | Coefficient of Variation |
|---|---|---|---|---|
| 6-year olds | A | 1.5 | 0.3 | 22.2 |
| 10-year olds | B A | 1.8 | 0.3 | 15.7 |
| 13-year olds | B | 1.9 | 0.2 | 13.3 |
| 18/19-year olds | B | 1.9 | 0.1 | 5.6 |

Means with the same letter are not significantly different.

Figure 12. Thigh to shank leg volume ratio by age group. Values shown are ± 1 standard deviation.



## Correlation Matrix for Dependent and Independent Variables

A correlation matrix (Table 26) for the dependent and independent variables was calculated to demonstrate the strength of linear associations between walking $\dot{V}O_2$ (ml·kg$^{-1}$·min$^{-1}$) and each of the other variables. All associations were deemed first-order, rather than second- or third-order as determined by visual observation and examination of residual and normality plots (normal probability plots, stem and leaf plots, boxplots, and Shapiro-Wilks plots (normal probability plots, stem and leaf plots, boxplots, and Shapiro-Wilks tests). Submaximal walking $\dot{V}O_2$ correlated strongly ($r > \pm 0.75$) with all variables except mass-specific ground reaction forces ($r = 0.36$) and lower limb mass distribution ($r = -0.52$). Variables related directly to metabolism (resting and walking $\dot{V}O_2$ $\{ml \cdot kg^{-1} \cdot min^{-1}\}$, ventilatory equivalent, and surface area to mass ratio) were highly correlated ($r > \pm 0.75$) as were those most closely associated with gait (step frequency, stance time $r = 0.88$). The presence of strong linear associations among the aforementioned variables is not desirable because they can hinder assessment of the assumptions in multivariate ANOVA and decrease the chances of finding linear effects of a single predictor variable using multiple linear regression. There were outliers present among the data for ventilatory equivalent and relative average vertical ground reaction force. A review of the data indicated no data entry error. While these values could be a problematic, they were not considered serious because normal probability plots, measures of skewness and Shapiro-Wilks tests did not indicate a need for concern.

Table 26. Correlation matrix for dependent and independent variables.

| | Walking $VO_2$ | Sitting resting $VO_2$ | Surface area/mass | Vent. equiv. | Step freq. | Stance time | Ground react. force/mass | Thigh to shank volume |
|---|---|---|---|---|---|---|---|---|
| Walking $VO_2$ | 1.00 | | | | | | | |
| Sitting resting $VO_2$ | 0.95** | 1.00 | | | | | | |
| Surface area/mass | -0.93** | 0.92** | 1.00 | | | | | |
| Vent. equiv. | -0.76** | 0.80** | 0.78** | 1.00 | | | | |
| Step freq. | 0.85** | 0.84** | 0.89** | 0.67** | 1.00 | | | |
| Stance time | -0.81** | -0.81** | -0.81** | -0.64** | -0.88** | 1.00 | | |
| Ground react. force/mass | 0.36 | 0.36 | 0.32 | 0.33 | 0.18 | -0.30 | 1.00 | |
| Thigh to shank volume | -0.52** | -0.51** | -0.49** | -0.43* | -0.52** | 0.61** | -0.31 | 1.00 |

(* = $p < 0.05$, ** = $p < 0.01$)

## Simple Correlations Between Walking $\dot{V}O_2$ and the Independent Variables

The purpose of this section is to discuss individual correlations between the dependent variable, submaximal aerobic demand, and the independent variables (e.g., resting metabolic rate, body surface area to mass ratio, ventilatory equivalent, step frequency, stance time, mass-specific vertical ground reaction forces, and limb mass distribution). This section will serve as a preface to the discussion of multiple linear regression, wherein the relative importance of each independent predictor of walking $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$) is evaluated.

Resting (sitting) $\dot{V}O_2$ correlated highly with walking $\dot{V}O_2$ ($r = 0.95$, $r^2 = 0.90$). Therefore, participants with higher resting oxygen consumption values tended to demonstrate higher walking oxygen consumption values while those with lower resting oxygen consumption values tended to demonstrate lower walking oxygen consumption values. Recall that younger females used more oxygen relative to body mass than older females at rest and during walking. The strength of the correlation, when examined in isolation from the other variables assessed, suggests that variance in resting metabolism may explain as much as 90% of the variance observed in walking economy.

Surface area to body mass ratio also correlated highly with submaximal walking $\dot{V}O_2$ ($r = 0.92$, $r^2 = 0.86$). This finding suggests that walking $\dot{V}O_2$ decreased in close association with a drop in the surface area to body mass ratio. Thus, larger (and older) individuals, with smaller surface areas relative to their body mass, exhibited a lower walking $\dot{V}O_2$ compared to smaller (younger) individuals. A simple linear fit of the data suggests that calculation of surface area relative to body mass alone may explain 86% of the variation observed in walking economy.

The simple correlation between ventilatory equivalent ($\dot{V}_E \cdot \dot{V}O_2^{-1}$) and walking $\dot{V}O_2$ was found to be moderately strong ($r = 0.76$, $r^2 = 0.58$). These findings suggest that participants who ventilated fewer liters of air through the lungs to extract one liter of oxygen used less oxygen relative to body mass while walking. Therefore, when the effects of variance of ventilatory equivalent on walking $\dot{V}O_2$ are examined alone, ventilatory equivalent appeared to account for 58% of the variation observed in walking economy.

The simple correlation between step frequency and walking $\dot{V}O_2$ was quite high ($r = 0.85$, $r^2 = 0.73$). Thus, as participants took fewer steps per minute at the specified walking pace (due to longer legs in the older age groups), their walking oxygen consumption decreased. This association between the two variables was sufficiently strong to suggest that variance in step rate could explain 73% of the variance observed in walking $\dot{V}O_2$.

When walking $\dot{V}O_2$ and stance time were examined in isolation, stance time appeared to explain 65% of the variance observed in walking $\dot{V}O_2$ ($r = -0.81$, $r^2 = 0.65$). Therefore, the longer a participant had her foot on the ground during a stride cycle, the less oxygen they consumed relative to body mass.

The simple correlation between walking $\dot{V}O_2$ and ground reaction forces relative to body mass proved to be weak ($r = 0.36$, $r^2 = 0.13$). Therefore, little of the variation observed in walking economy could be explained by this variable. Only a slight trend in the data suggested that lower mass-specific forces with each step were associated with reduced walking $\dot{V}O_2$.

The simple correlation between lower limb thigh to shank volume ratios and walking $\dot{V}O_2$ was moderate at best ($r = -0.52$, $r^2 = 0.27$). Only a quarter of the variance observed in walking $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$) could be explained by mass distribution differences in lower limb structure. This fragile association lends weak support to the notion that as the bulk of lower limb mass moves closer to the hip with age (e.g., the thigh becomes larger relative to the shank), the $\dot{V}O_2$ cost of walking decreases.

Overall, correlation statistics suggest that separate and linear associations exist between measures of walking $\dot{V}O_2$ and resting $\dot{V}O_2$, body surface area to mass ratio, ventilatory equivalent, step frequency, stance time, mass-specific vertical ground reaction forces, and lower limb thigh to shank volume ratios. With the exception of the latter two independent variables, all linear associations between walking $\dot{V}O_2$ and the independent variables were moderate to strong.

## Multiple Regression

Multiple regression analysis was used to determine the relative order of importance of the relationship between changes in walking economy and changes in all selected predictor variables (resting $\dot{V}O_2$, body surface area to mass ratio, ventilatory equivalent, step frequency, stance time, mass-specific vertical ground reaction forces, and lower limb thigh to shank volume ratios) that occur with age. The magnitudes of standardized beta coefficients (STB) for each predictor variable were used to indicate the rank order of importance of each of the predictor factors. As shown in Table 27, results from this procedure suggest that sitting resting metabolic rate ($ml \cdot kg^{-1} \cdot min^{-1}$) accounted for almost all of the changes in walking $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$) observed across age groups (STB = 0.6224, $p \leq 0.0015$) when all other concomitantly measured variables were held constant. Surface area to body mass ratio also exhibited a relatively

Table 27. Regression analysis; submaximal oxygen consumption ($ml \cdot kg^{-1} \cdot min^{-1}$) at 1.56 $m \cdot sec^{-1}$ and 0% grade as the dependent variable.

| | Beta Weight | Standardized Beta Weight | P-Value |
|---|---|---|---|
| Sitting resting metabolic rate ($ml \cdot kg^{-1} \cdot min^{-1}$) | 1.8446 | 0.6224 | 0.0015 |
| Surface area to body mass ratio ($m^2 \cdot kg^{-1}$) | 263.7942 | 0.3544 | 0.1141 |
| Ventilatory equivalent ($\dot{V}_E \cdot \dot{V}O_2^{-1}$) | -0.0173 | -0.0469 | 0.6561 |
| Steps per minute ($steps \cdot min^{-1}$) | 0.0110 | 0.0462 | 0.8119 |
| Thigh to shank leg ratio | -0.4972 | -0.0452 | 0.5681 |
| Stance time (ms) | 1.2886 | 0.0201 | 0.8916 |
| Peak ground reaction force (BM) | -1.8306 | -0.0127 | 0.8770 |

large standardized beta weight (STB = 0.3544). With resting metabolic rate included in the model, however, surface area to body mass ratio as a possible determinant of walking economy was non-significant ($p \leq 0.1141$). The remaining variables in the model produced small and non-significant beta weights. Thus, these variables were less strongly correlated with the criterion variable than surface area to body mass ratio, when holding other variables constant.

## Multiple Regression Predictor Models With Fewer Variables

It can be argued that the small subject (28) to variable (7) ratio inherent in this study does not allow for justifiable inclusion of all variables in the linear multiple regression model at one time (Neter, Wasserman, & Kutner, 1990). Therefore, to minimize error and maximize generalizability of the resulting multiple regression parameter estimates to a similar population, the number of variables used in multiple regression was limited to two or three. Selection of the "best" two or three variable predictor models was determined by computing all possible two- and three-variable models using the magnitude of the adjusted $R^2$ as the criterion for variable selection. The first-order models that resulted using these criteria are shown in Tables 28, 29, and 30.

Table 28. Best two- and three-variable multiple regression models selected from a choice of all seven predictor variables.

| | Intercept | Variable 1 | Variable 2 | Variable 3 | $R^2$ | Adj. $R^2$ |
|---|---|---|---|---|---|---|
| | | Resting metabolism | Surface area/ body mass | | 0.925 | 0.919 |
| Parameter Estimate | -0.480 | 1.824 | 272.146 | | | |
| Standardized Estimate | 0.000 | 0.615 | 0.365 | | | |
| | | Resting metabolism | Surface area/ body mass | Thigh/shank leg ratio | 0.926 | 0.917 |
| Parameter Estimate | 0.689 | 1.775 | 268.097 | -0.463 | | |
| Standardized Estimate | 0.000 | 0.599 | 0.360 | -0.042 | | |

Table 28 shows that when all seven independent variables were used to generate the best two- and three-variable multiple regression models, resting metabolism and surface area to body mass ratio produced the best two-predictor model (Adj. $R^2 = 0.919$), and resting metabolism, surface area to body mass ratio, and thigh to shank leg ratio produced the best three-variable predictor model (Adj. $R^2 = 0.917$). These results suggest that these two- and three-variable models appear to account for more than 90% of the variance observed in walking $\dot{V}O_2$.

Because resting metabolism and surface area to body mass ratio were closely interrelated (and therefore potentially redundant as predictors of walking $\dot{V}O_2$), multiple regression analyses were performed excluding one variable or the other. Table 29 presents parameter and standardized estimates for two- and three-variable models in which surface area to body mass ratio was removed from the seven-variable predictor set used in the multiple regression procedures. Data presented in this table show that resting metabolism and step frequency produced the best two-predictor model (Adj. $R^2 = 0.907$), while resting metabolism, step frequency, and average vertical ground reaction force produced the best three-variable predictor model (Adj. $R^2 = 0.906$). These calculations suggest that the combinations of resting metabolism, step frequency, and average vertical ground reaction force account for more than 90% the variance observed in walking $\dot{V}O_2$.

Table 29. Best two- and three-variable multiple regression models excluding surface area to body mass ratio.

| | Intercept | Variable 1 | Variable 2 | Variable 3 | $R^2$ | Adj. $R^2$ |
|---|---|---|---|---|---|---|
| | | Resting metabolism | Steps·min$^{-1}$ | | 0.914 | 0.907 |
| Parameter Estimate | -0.076 | 2.338 | 0.046 | | | |
| Standardized Estimate | 0.000 | 0.789 | 0.193 | | | |
| | | Resting metabolism | Steps·min$^{-1}$ | Ground reaction force | 0.917 | 0.906 |
| Parameter Estimate | -6.744 | 2.226 | 0.051 | 7.845 | | |
| Standardized Estimate | 0.000 | 0.751 | 0.215 | 0.054 | | |

Table 30 presents estimates for models in which resting metabolic rate was removed from the predictor variable set. It shows that surface area to body mass ratio and stance time (milliseconds) produced the best two-predictor model (Adj. $R^2 = 0.861$), while the same variables and ventilatory equivalent produced the best three-predictor model (Adj. $R^2 = 0.860$). As with the previous multiple regression models discussed above, the models containing these variables accounted for a large proportion (86%) of the variance observed in walking $\dot{V}O_2$.

Table 30. Best two and three variable multiple regression models excluding resting metabolic rate.

| | Intercept | Variable 1 | Variable 2 | Variable 3 | $R^2$ | Adj. $R^2$ |
|---|---|---|---|---|---|---|
| | | Surface area/ body mass | Stance time | | 0.872 | 0.861 |
| Parameter Estimate | 2.324 | 601.145 | -9.607 | | | |
| Standardized Estimate | 0.000 | 0.808 | -0.150 | | | |
| | | Surface area/ body mass | Stance time | Ventilatory Equivalent | 0.875 | 0.860 |
| Parameter Estimate | 2.043 | 544.427 | -9.564 | 0.036 | | |
| Standardized Estimate | 0.000 | 0.731 | -0.149 | 0.099 | | |

Examination of the two- and three-variable models shown in Tables 28, 29, and 30 reveals several principles: (1) models with three-predictor variables do not estimate variance in walking $\dot{V}O_2$ more effectively than models with two predictor variables, (2) when either resting metabolism or surface area to body mass ratio were excluded from the multiple regression equation, models which included resting metabolism produced the largest $R^2$s, and (3) all two- and three-variable model estimates presented in Tables 27 through 29 account for a large amount of the variance observed in walking $\dot{V}O_2$. These findings suggest that measurements of resting metabolism and surface area to body mass ratio, or resting metabolism and step frequency (steps·min$^{-1}$) produce the best estimates (> 90% of the variance explained) of walking $\dot{V}O_2$.

## Chapter Summary

To summarize, with the exception of minor deviations in physiological and chronological characteristics, the subject sample selected conformed closely to predetermined participation criteria. Expected differences in age, height, body mass, and body surface area were observed across age groups six through 13, but not across age groups 13 to 18/19. As anticipated, body composition was similar across all groups. The majority of the eight primary variables measured (excluding mass-specific vertical ground reaction forces) changed as hypothesized across age groups. As with the descriptive data, however, significant differences in the primary variables across age groups 13 and 18/19 were generally not observed.

Strong first-order linear associations were noted between the majority of the independent variables and the mass-specific aerobic demand of walking. Only lower limb thigh to shank ratios and mass-specific vertical ground reaction forces produced $R^2$ values less than 0.60. When the primary variables were entered into a multiple regression model, standardized beta weights suggested that resting metabolic rate was the most effective predictor of walking $\dot{V}O_2$, followed closely by surface area to body mass ratio. Other variables accounted for little variation in walking $\dot{V}O_2$ when all variables were examined simultaneously. When two- and three-variable predictor models were developed to estimate walking $\dot{V}O_2$, adjusted $R^2$ values revealed that two-predictor models were just as effective as three-predictor models. Combinations of resting metabolism and surface area to body mass ratio, or resting metabolism and step frequency were able to explain more than 90% of the variance observed in walking $\dot{V}O_2$.

In conclusion, this study met the main objective set forth in Chapter 1; to shed light on the most important determinants of age-related differences in walking $\dot{V}O_2$ that occur with age. From the data gathered in this investigation, it appears that resting metabolic rate, body surface area to mass ratio and step frequency may be the primary determinants of age-associated variation in walking $\dot{V}O_2$ with age.

# CHAPTER V
# DISCUSSION

## Introduction

The primary purpose of this chapter is to compare and contrast results found in the present study with those reported in the literature. A secondary focus of this chapter is to explain why aerobic demand data used for statistical analyses was corrected for body mass ($ml \cdot kg^{-1} \cdot min^{-1}$) rather than resting metabolism, step frequency, body surface area or the 3/4 power of body mass. In closing, the final goal of the chapter is to determine the most appropriate regression model for prediction of age-related changes in walking $\dot{V}O_2$. Fulfillment of the three objectives provides a foundation on which to base the overall study conclusions presented in chapter six.

## Walking $\dot{V}O_2$

Seven walking studies (Cassels & Morse, 1962; Ebbeling et al., 1992; Forster, Hunter, & Hester, 1994; Robinson, 1938; Skinner et al., 1971; Spurr & Reina, 1986; Waters, Lunsford, Perry, & Byrd, 1988) have reported submaximal $\dot{V}O_2$ cross-sectional data on children, adolescents and adults. Without exception, all studies demonstrated that young children exhibit a higher mass-related submaximal aerobic demand than adolescents, and that adolescents in turn consume more oxygen, per kilogram of body mass, than adults. Nearly identical results were found in the present investigation. Six-year olds exhibited a higher aerobic demand than 10-year olds, and 10-year olds demonstrated higher aerobic demands than 13- and 18/19-year olds.

Comparison of metabolic values in the present investigation with those of earlier studies is possible with data from three studies referenced in Table 31. These particular studies (Ebbeling et al., 1992; Spurr & Reina, 1986; Waters et al., 1988) used walking velocities (1.33 to 1.67 $m \cdot sec^{-1}$) and grades (0%)

similar to those employed in the present investigation. Participants demonstrated walking $\dot{V}O_2$ values comparable to those observed in the present investigation. The youngest participants (6- to 9-year olds) in the previous and present investigations exhibited a walking $\dot{V}O_2$ of approximately 20 $ml\cdot kg^{-1}\cdot min^{-1}$ whereas the oldest participants (15- to 30-year olds) exhibited $\dot{V}O_2$ values roughly 5 $ml\cdot kg^{-1}\cdot min^{-1}$ less than children. Such similarities in the metabolic findings suggest that measurements obtained in the present investigation are within normal limits.

Table 31. Cross sectional studies reporting submaximal walking $\dot{V}O_2$ ($ml\cdot kg^{-1}\cdot min^{-1}$)

| Researchers | Subjects | Age | Velocity | Grade | $\dot{V}O_2$ $ml\cdot kg^{-1}\cdot min^{-1}$ |
|---|---|---|---|---|---|
| Level Treadmill Tests | | | | | |
| Spurr & Reina (1986) | M (n=25) | 6-8 | ~1.33 $m\cdot sec^{-1}$ | 0.0% | ~21.7 |
| " | M (n=41) | 10-12 | " | " | ~18.1 |
| " | M (n=27) | 14-16 | " | " | ~15.5 |
| " | M (n=10) | 28.3 ± 3.8 | " | " | ~12.6 |
| Waters et al. (1988) | F (n=27) | 8.9 ± 2.0 | ~1.45 $m\cdot sec^{-1}$ | 0.0% | 19.3 ± 3.7 |
| " | M (n=34) | 8.9 ± 2.0 | " | " | 19.9 ± 3.3 |
| " | F (n=28) | 15.6 ± 1.9 | ~1.67 $m\cdot sec^{-1}$ | " | 18.5 ± 3.3 |
| " | M (n=25) | 16.3 ± 2.1 | " | " | 20.0 ± 4.7 |
| Ebbeling et al. (1992) | M (n=10) | 9.5 ± 0.7 | ~1.40 $m\cdot sec^{-1}$ | 0.0% | 19.7 ± 2.7 |
| " | M (n=10) | 20.0 ± 2.0 | ~1.54 $m\cdot sec^{-1}$ | " | 15.0 ± 1.2 |
| **Craib (1995)** | F (n=7) | 6.3 ± 0.3 | 1.56 $m\cdot sec^{-1}$ | 0.0% | 21.2 ± 0.8 |
| " | F (n=7) | 10.3 ± 0.3 | " | " | 17.7 ± 1.3 |
| " | F (n=7) | 13.5 ± 0.3 | " | " | 14.8 ± 1.3 |
| " | F (n=7) | 18.9 ± 0.2 | " | " | 13.4 ± 1.0 |

M = male, F = female

## Walking Heart Rate

Few investigators have reported cross sectional heart rate data on subjects tested at similar walking velocities to the one used in this study (1.56 $m\cdot sec^{-1}$). Waters and colleagues (1988) examined pre- and post-pubescent males and females tested at walking velocities averaging between 1.45 and 1.67 $m\cdot sec^{-1}$ (Table 32). Pre-pubescent subjects appeared to exhibit higher heart rates than post-pubescent subjects at these paces. Ebbeling and coworkers (1992) also tested pre- and post-pubescent subjects (males). Heart rates were distinctly higher in the younger versus the older age groups. Such age-related findings are similar to those observed in the present investigation wherein six-year olds demonstrated higher heart rates than older study participants (10, 13-, 18/19-year olds). Measured heart rate values were also akin to those noted by Waters et al. (1988) and Ebbeling et al (1992). These observations suggest that heart rate responses found in the present study are within normal limits.

Interestingly, although a decrease in heart rate across age-groups was noted, the drop did not parallel decreases in submaximal aerobic demand across age-groups as closely as anticipated. Whereas aerobic demand decreased significantly across age groups six, 10 and 13, heart rate decreased only across age groups six and 10. Heart rates were similar across age groups 10, 13 and 18/19. A simple correlation between heart rate and walking economy also appeared weak (r=0.54) Taken together, these findings suggest that heart rate may not directly reflect metabolic (aerobic) demand during walking in young females at a velocity of 1.56 m·sec$^{-1}$. Researchers,

Table 32. Cross sectional studies reporting heart rate (beats·min$^{-1}$)

| Researchers | Subjects | Age | Velocity | Grade | Heart Rate (bpm) |
|---|---|---|---|---|---|
| Waters et al. (1988) | F (n=27) | 8.9 ± 2.0 | ~1.45 m·sec$^{-1}$ | 0.0% | 132 ± 14 |
| " | M (n=34) | 8.9 ± 2.0 | " | " | 123 ± 12 |
| " | F (n=28) | 15.6 ± 1.9 | ~1.67 m·sec$^{-1}$ | " | 124 ± 19 |
| " | M (n=25) | 16.3 ± 2.1 | " | " | 107 ± 14 |
| Ebbeling et al. (1992) | M (n=10) | 9.5 ± 0.7 | ~1.40 m·sec$^{-1}$ | 0.0% | 125 ± 9 |
| " | M (n=10) | 20.0 ± 2.0 | ~1.54 m·sec$^{-1}$ | " | 97 ± 9 |
| **Craib (1995)** | F (n=7) | 6.3 ± 0.3 | 1.56 m·sec$^{-1}$ | 0.0% | 145 ± 10 |
| " | F (n=7) | 10.3 ± 0.3 | " | " | 123 ± 8 |
| " | F (n=7) | 13.5 ± 0.3 | " | " | 118 ± 7 |
| " | F (n=7) | 18.9 ± 0.2 | " | " | 117 ± 18 |

M = male, F = female

therefore, should consider caution when using heart rate as a possible indicator of age-related differences in walking aerobic demand. (Note: Heart rate was not intended as a primary variable in the present investigation)

## Resting Metabolism

The few studies which have examined resting metabolic rates in children and adults have demonstrated that small children have values 30 to 50% higher than older children and adults (Cassels & Morse, 1962; MacDougall et al., 1983; Robinson, 1938) (Table 33). Robinson (1938), Cassels and Morse (1969), and MacDougall and colleagues (1983) reported values ranging from 5.5 to 7.4 $ml \cdot kg^{-1} \cdot min^{-1}$ for 6- and 7-year olds compared to values of approximately 3.5 $ml \cdot kg^{-1} \cdot min^{-1}$ for adults. These findings are compatible with those in the present investigation where 6-year olds exhibited oxygen uptake

Table 33. Cross sectional studies reporting resting metabolic rate ($ml \cdot kg^{-1} \cdot min^{-1}$).

| Researchers | Subjects | Age | $\dot{V}O_2$ $ml \cdot kg^{-1} \cdot min^{-1}$ |
|---|---|---|---|
| Robinson (1938) | M (n=8) | 6.0 | 7.4 |
| " | M (n=10) | 10.5 | 6.2 |
| " | M (n=11) | 14.1 | 4.5 |
| " | M (n=12) | 17.4 | 4.1 |
| " | M (n=11) | 24.5 | 3.6 |
| Cassels and Morse (1969) | F (n=12) | 7.3 | 6.0 |
| " | F (n=21) | 11.2 | 4.9 |
| " | F (n=17) | 14.1 | 3.6 |
| " | F (n=23) | 25.0 | 3.3 |
| " | M (n=13) | 10.3 | 5.3 |
| " | M (n=11) | 14.2 | 4.2 |
| " | M (n=17) | 26.6 | 3.6 |
| MacDougall et al. (1983) | MF (n=27) | 7-37 | RMR of Children 1-2 $ml \cdot kg^{-1} \cdot min^{-1}$ higher than adults |
| **Craib (1995)** | F (n=7) | 6.3 ± 0.3 | 6.0 ± 0.3 |
| " | F (n=7) | 10.3 ± 0.3 | 5.0 ± 0.4 |
| " | F (n=7) | 13.5 ± 0.3 | 3.9 ± 0.4 |
| " | F (n=7) | 18.9 ± 0.2 | 3.4 ± 0.4 |

M = male, F = female, RMR = resting metabolic rate values of 6.0 ± 0.3 $ml \cdot kg^{-1} \cdot min^{-1}$, and adults (18/19-year olds) exhibited values of 3.4 ± 0.4 $ml \cdot kg^{-1} \cdot min^{-1}$. The similar nature of the past and present findings suggest that resting metabolism was measured comparably to previous studies.

## Surface Area to Body Mass Ratio

Researchers have long understood that decreases in body surface area relative to body mass occur as children grow to maturity (Cassels & Morse, 1962; MacDougall et al., 1983; Rowland et al., 1987; Rowland & Green, 1988). Calculations of this ratio from cross-sectional data supplied in numerous studies substantiate this size-related phenomenon (Cassels & Morse, 1962; Ebbeling et al., 1992; Forster et al., 1994; Robinson, 1938; Rowland et al., 1987; Rowland & Green, 1988; Spurr & Reina, 1986) (Table 34). Robinson (1938) and Spurr and Reina (1969), for example, reported data which indicate that 6-year olds have surface area to body mass ratios of $4.0 \times 10^2$, whereas physically mature individuals exhibited ratios ranging closer to $2.5 \times 10^2$ (a difference of at least 30%). Such data suggest that children have larger body surface areas relative to their mass compared to adults. Similar results were obtained in the present investigation. The youngest age group tested (e.g. 6-year olds) exhibited a mean ratio of $3.8 \times 10^2$ whereas the 18/19-year olds exhibited a mean ratio of $2.8 \times 10^2$. Ratios gradually decreased across the four age groups tested. The calculations presented in this study are comparable to those generated from data presented in previous investigations.

Table 34. Cross sectional studies reporting data from which surface area ($m^2$) to body mass (kg) ratio was calculated.

| Researchers | Subjects | Age | Surface area $m^2/BM_{kg}$ |
|---|---|---|---|
| Robinson (1938) | M (n=8) | 6.0 | 4.0 x $10^2$ |
| " | M (n=10) | 10.5 | 3.6 x $10^2$ |
| " | M (n=11) | 14.1 | 2.9 x $10^2$ |
| " | M (n=12) | 17.4 | 2.7 x $10^2$ |
| " | M (n=11) | 24.5 | 2.6 x $10^2$ |
| Cassels and Morse (1969) | F (n=12) | 7.3 | 3.7 x $10^2$ |
| " | F (n=21) | 11.2 | 3.3 x $10^2$ |
| " | F (n=17) | 14.1 | 2.9 x $10^2$ |
| " | F (n=23) | 25.0 | 2.8 x $10^2$ |
| " | M (n=13) | 10.3 | 3.4 x $10^2$ |
| " | M (n=11) | 14.2 | 2.9 x $10^2$ |
| " | M (n=17) | 26.6 | 2.7 x $10^2$ |
| Spurr & Reina (1986) | M (n=25) | 6-8 | 4.0 x $10^2$ |
| " | M (n=41) | 10-12 | 3.6 x $10^2$ |
| " | M (n=27) | 14-16 | 3.2 x $10^2$ |
| " | M (n=10) | 28.3 ± 3.8 | 2.5 x $10^2$ |
| Rowland et al. (1987) | M (n=20) | 9-13 | 3.2 x $10^2$ |
| " | M (n=20) | 23-33 | 2.5 x $10^2$ |
| Rowland et al. (1988) | M (n=18) | 11.3 ± 1.1 | 3.2 x $10^2$ |
| " | M (n=18) | 28.7 ± 3.6 | 2.8 x $10^2$ |
| Ebbeling et al. (1992) | M (n=10) | 9.5 ± 0.7 | 3.3 x $10^2$ |
| " | M (n=10) | 20.0 ± 2.0 | 2.6 x $10^2$ |
| Forster et al. (1994) | MF (n=19) | 5.2 ± 0.9 | 4.0 x $10^2$ |
| longitudinal study | MF (n=19) | 9.3 ± 1.0 | 3.4 x $10^2$ |
| Rogers et al. (1995) | M (n=21) | 9.0 ± 0.7 | 3.5 x $10^2$ |
|  | F (n=21) | 8.8 ± 0.7 | 3.4 x $10^2$ |
| **Craib (1995)** | F (n=7) | 6.3 ± 0.3 | 3.8 x $10^2$ ± 0.1 x $10^2$ |
| " | F (n=7) | 10.3 ± 0.3 | 3.4 x $10^2$ ± 0.2 x $10^2$ |
| " | F (n=7) | 13.5 ± 0.3 | 3.0 x $10^2$ ± 0.2 x $10^2$ |
| " | F (n=7) | 18.9 ± 0.2 | 2.8 x $10^2$ ± 0.1 x $10^2$ |

M = male, F = female

## Ventilatory Equivalent

Few age-related ventilatory equivalent data exist on walking subjects (Ebbeling et al., 1992; Maffeis et al., 1993) (Table 35). Ebbeling and colleagues (1992) tested male children (age ~9.5) and adults (age ~20.0) at similar, but not identical speeds. Ventilatory equivalents for children obtained in their study appeared to be slightly higher than those of men in spite of the fact that boys walked at a pace 9% slower than men. Mafeis and coworkers (1993) assessed ventilatory equivalents on a sample of boys and girls similar in age (age ~9.2) to those tested by Ebbeling et al. (1992). Ventilatory equivalents of boys and girls in Mafeis et al.'s study were substantially higher than those exhibited by the adults in Ebbeling and colleague's study. When considered together, these findings suggest that children had to ventilate more air in order to extract one liter of oxygen. Similar results were obtained in the present investigation. Six-year olds exhibited larger ventilatory equivalents than the older age groups, and 10-year olds demonstrated larger values than 13- or 18/19-year olds. The fact that age-related differences in ventilatory equivalent occurred in a manner similar with those of previous studies lends support to the comparability of the data.

Table 35. Studies reporting walking ventilatory equivalents ($\dot{V}E \cdot \dot{V}O_2^{-1}$) for children

| Researchers | Subjects | Age | Velocity | Grade | $\dot{V}_E \cdot \dot{V}O_2^{-1}$ |
|---|---|---|---|---|---|
| Ebbeling et al. (1992) | M (n=10) | 9.5 ± 0.7 | ~1.40 $m \cdot sec^{-1}$ | 0.0% | 20.8 |
| " | M (n=10) | 20.0 ± 2.0 | ~1.54 $m \cdot sec^{-1}$ | " | 20.7 |
| Maffeis et al. (1993) | MF (n=17) | 9.2 ± 0.6 | 1.50 $m \cdot sec^{-1}$ | 0.0% | ~37.7 |
| **Craib (1995)** | F (n=7) | 6.3 ± 0.3 | 1.56 $m \cdot sec^{-1}$ | 0.0% | 38.9 ± 7.2 |
| " | F (n=7) | 10.3 ± 0.3 | " | " | 32.1 ± 3.6 |
| " | F (n=7) | 13.5 ± 0.3 | " | " | 31.5 ± 5.8 |
| " | F (n=7) | 18.9 ± 0.2 | " | " | 28.0 ± 5.4 |

M = male, F = female

More detailed generalizations and comparisons of mean ventilatory equivalent values obtained in this and previous investigations are hard to form due to variance in study testing protocols and the lack of age-related $\dot{V}E \cdot \dot{V}O_2^{-1}$ data. Nevertheless, it appears that when available walking data are considered, ventilatory equivalents fall within a range of 20 to 40, with adults on the low end of the ventilatory equivalent spectrum and children on the higher end.

## Step Frequency

Several walking studies have demonstrated that children use more steps than adults to maintain a given speed (Ebbeling et al., 1992; Waters et al., 1988; Frost et al.,1995) (Table 36). Waters and colleagues (1988), Ebbeling and coworkers (1992), and Frost et al. (1995) tested age groups that fell within the range investigated in the present study. All three groups reported higher step rates in children compared to step rates observed from adolescents and adults, regardless of the fact that younger children were generally tested at slightly slower velocities than the older participants. These results compare nicely with those obtained in the present investigation. As noted in the previous chapter, walking step rates decreased from childhood to adolescence

Table 36. Studies reporting walking step frequency (steps·min$^{-1}$) for children

| Researchers | Subjects | Age | Velocity | Grade | Steps·min$^{-1}$ |
|---|---|---|---|---|---|
| Waters et al. (1988) | MF (n=61) | 6-12 | ~1.45 m·sec$^{-1}$ | 0.0% | 135.2 ± 6.5 |
| " | MF (n=53) | 13-19 | ~1.67 m·sec$^{-1}$ | " | 123.6 ± 15.2 |
| Ebbeling et al. (1992) | M (n=10) | 9.5 ± 0.7 | ~1.40 m·sec$^{-1}$ | 0.0% | 132.4 ± 5.0 |
| " | M (n=10) | 20.0 ± 2.0 | ~1.54 m·sec$^{-1}$ | " | 118.8 ± 4.6 |
| Frost et al. (1995) | MF (n=24) | 9.1 ± 1.4 | 1.52 ± 0.2 m·sec$^{-1}$ | 0.0% | 145.5 ± 0.5 |
| **Craib (1995)** | F (n=7) | 6.3 ± 0.3 | 1.56 m·sec$^{-1}$ | 0.0% | 153.8 ± 6.2 |
| " | F (n=7) | 10.3 ± 0.3 | " | " | 135.1 ± 4.6 |
| " | F (n=7) | 13.5 ± 0.3 | " | " | 122.1 ± 3.5 |
| " | F (n=7) | 18.9 ± 0.2 | " | " | 124.6 ± 4.6 |

M = male, F = female

and adulthood. The present findings differed from those reported previously only in the detail of the age- and height-related changes in step frequency. Step frequency decreased linearly and significantly across age groups until adolescence. Thereafter, step frequency leveled off. Earlier studies did not illuminate the age at which females appear to achieve adult-step rates. Overall, similarities in test results between the present and past investigations suggest that the step frequency data collected in this study are within normal limits.

## Stance time

Very little information has been published on the stance time of each step while walking or running relative to the aerobic demand of locomotion (Kram & Taylor, 1990; Morgan et al., 1988). Kram and Taylor (1990) reported that large animals exhibited longer stance times than small animals while running. They also reported that large animals required less oxygen per unit of body mass (kg) than small animals to maintain a given running speed. Unfortunately, the physiology and gait patterns of the animals assessed were vastly different from those of the subjects in the present investigation, thereby making comparisons of stance time data inappropriate. Morgan and coworkers (1988), however, also assessed human subjects. Biomechanical variables were measured on two groups of adult male (human) runners tested at a velocity of 3.33 $m \cdot sec^{-1}$. Morgan and colleagues (1988) found that runners who exhibited longer stance times with each step also used less oxygen relative to body mass. When considered together, findings from Kram and Taylor (1990) and Morgan et al. (1988) suggest a relationship between stance time and mass-specific $\dot{V}O_2$. Data gathered in the present investigation support this potential relationship. Older participants, who tended to used less oxygen per kilogram of body mass, exhibited longer stance times while walking than younger participants. Unfortunately, since stance times during walking have not been collected and published on similar populations, there are no data with which to compare the present findings.

## Average Vertical Ground Reaction Forces Relative to Body Mass

Few walking average vertical ground reaction force data exist for humans, let alone humans of different age groups. Inman (1966) and Winter (1987) both reported vertical ground reaction forces for adults corrected to body mass during walking stance time. Estimates of average vertical ground reaction forces from plots of their data suggest that walking adults exerted forces close to those observed in the present investigation. On average, the men in their studies appeared to generate average vertical ground reaction forces between 80 and 90% of body mass. In the present study, participants generated forces ranging between 81 and 83% of body mass. The similarity of these findings suggest that average vertical ground reaction forces were measured comparably. Unfortunately, the previous and present data are too limited for speculation of cross-sectional trends of ground reaction forces normalized to body weight.

## Limb Mass Distribution

Numerous investigators have examined lower limb morphology using a variety of assessment procedures (Cavanagh & Kram, 1989; Jensen, 1978; Jensen, 1989; Katch, 1974; Katch et al., 1973; Zatsiorsky & Seluyanov, 1983). These included volumetric (via water displacement) (Katch, 1974; Katch et al., 1973), photogrammetric (Jensen, 1978; Jensen, 1989), and gamma scanning methodologies (Zatsiorsky & Seluyanov, 1983) which resulted in thigh, shank and foot segmental volume or mass data. Transformations of the data into thigh to shank volume or mass ratios demonstrated changes in limb morphology across age groups during the maturation process (Table 37). In general, smaller ratios were found in the children (1.9 to 2.1) compared to adults (2.1 to 3.3). This finding suggested that the thighs of children are not as well developed as those of adults and therefore children's thighs make up a smaller proportion of overall limb volume or mass. Similar results were found in the present investigation. Thigh to shank volume

Table 37. Studies reporting thigh to shank volume or mass ratios.

| Researchers | Subjects | Age | Method | Thigh/shank ratio |
|---|---|---|---|---|
| Katch et al. (1973) | F (n=70) | 20.7 ± 1.6 | Volume | 2.1 |
| Katch et al. (1974) | F (n=24) | 20.2 ± 1.6 | Volume | 1.9 |
| Jensen (1979) | M (n=3) | 9.9 ± 1.2 | Volume | 1.9 |
| Zatsiorsky & Seluyanov (1983) | M (n=100) | 23.8 ± 6.2 | Mass | 3.3 |
| Jensen (1989) | M (n=?) | 6.0 | Mass | 2.0 |
| • from regression equations | " | 10.0 | " | 2.1 |
| " | " | 13.0 | " | 2.3 |
| " | " | 18.0 | " | 2.5 |
| Cavanagh & Kram (1989) | M (n=21) | 18-40 | Mass | 2.2 ± 0.2 |
| " | M (n=16) | " | " | 2.1 ± 0.2 |
| **Craib (1995)** | F (n=7) | 6.3 ± 0.3 | Volume | 1.5 ± 0.3 |
| " | F (n=7) | 10.3 ± 0.3 | " | 1.8 ± 0.3 |
| " | F (n=7) | 13.5 ± 0.3 | " | 1.9 ± 0.2 |
| " | F (n=7) | 18.9 ± 0.2 | " | 1.9 ± 0.1 |

M = male, F = female

ratios shifted from small to large (1.5 to 1.9) across age groups nine through 13 and older. Ratio values in the present investigation, however, were slightly smaller than those calculated from data reported previously. This difference may be attributed to differences in the way thigh volume and masses were assessed. Gamma scanning and photogrammetric measurement procedures ascertained thigh volume and mass from a point higher up on the leg. This methodological difference resulted in larger thigh volumes and masses and therefore larger thigh/shank ratios. In summary, since the thigh to shank ratios in the present investigation are similar to those observed by Katch et al. (1973, 1974) and Jensen (1979, 1989), and since age-related ratios are comparable given differences in measurement procedures (Jensen, 1989), it appears that lower limb volume data reflect trends found in the literature.

### Alternative Methods of Expressing Walking $\dot{V}O_2$

To compare the aerobic demand of locomotion in individuals with different body sizes, physiologists have traditionally normalized oxygen uptake ($\dot{V}O_2$) to body mass ($ml \cdot kg^{-1} \cdot min^{-1}$). Rogers and colleagues (1995) suggest, however, that use of this simple ratio standard may be invalid. With this possibility in mind, the following section addresses alternative methods for expressing walking $\dot{V}O_2$.

### The Problem

Normalizing oxygen consumption to body mass ($ml \cdot kg^{-1} \cdot min^{-1}$) does not remove age-related differences in oxygen consumption (Cassels & Morse, 1962; Ebbeling et al., 1992; Forster et al., 1994; Maffeis et al., 1993; Robinson, 1938; Skinner et al., 1971; Spurr & Reina, 1986; Waters et al., 1988). This finding suggests that some factor(s) other than body mass may determine age-related variance in $\dot{V}O_2$. Although it seems logical that more than one variable is responsible for age-related changes in locomotor $\dot{V}O_2$, researchers have sought one central factor, or mathematical expression, which explains variance in locomotor economy (Astrand, 1952; Kleiber, 1975b; MacDougall et al., 1983; Rowland et al., 1987; Rowland & Green, 1988; Unnithan & Eston, 1990). Thus far, the chief normalizing variables proposed by these investigators are calculation of locomotor $\dot{V}O_2$ minus resting metabolic rate (e.g. net locomotor metabolism), assessment of $\dot{V}O_2$ relative to body surface area, $\dot{V}O_2$ normalized to step frequency, and use of allometric equations. Each of these normalizing variables and their efficacy are discussed below.

### Net Locomotor Metabolism

Both Åstrand (1952) and MacDougall and colleagues (1983) investigated the possibility that removal of resting $\dot{V}O_2$ from locomotor $\dot{V}O_2$ can eliminate age-related differences in locomotor metabolism. In both studies, researchers found that differences in resting metabolic rate (~1-3 ml·kg$^{-1}$·min$^{-1}$) between children and adults were not large enough to erase age-related differences in metabolism during locomotion. Findings in the present study corroborate Åstrand (1952) and MacDougall and colleague's (1983) observations. Mean age-related differences in resting metabolic rate did not exceed 3 ml·kg$^{-1}$·min$^{-1}$. and a negative linear association between age and walking $\dot{V}O_2$ remained evident following calculation of net locomotor $\dot{V}O_2$. Thus, computation of net locomotor $\dot{V}O_2$ does not appear to totally explain age-related differences in locomotor economy.

## Oxygen Consumption Relative To Surface Area

Previous researchers reported that when oxygen consumption during running locomotion was normalized to body surface area, age-related differences in the cost of locomotion disappeared (Rowland et al., 1987; Rowland & Green, 1988; Unnithan & Eston, 1990). Such a conclusion was appropriate given examination of the mean data presented in their publications. In contrast, two of three studies, which measured oxygen consumption during walking locomotion reported results which appear to contradict these findings. In considering this point, Ebbeling and coworkers (1992) found that this calculation removed age-related economy differences between children and adults. Robinson (1938) and Cassels and Morse (1969), on the other hand, tested numerous individuals from a variety of age groups ranging from 6-year olds to adults (Table 38). Calculations derived from their walking data suggest that oxygen consumption may actually increase moderately relative to surface area from childhood to physical maturity. Unfortunately, since no analyses of variance were conducted by Robinson (1938) and Cassels and Morse (1969) on this variable, it is unclear if significant age- and surface area-related differences existed.

Table 38. Cross-sectional studies reporting walking oxygen consumption relative to surface area (ml·min$^{-1}$·m$^2$).

| Researchers | Subjects | Age | Velocity | Grade | $\dot{V}$O2 (ml·min$^{-1}$·m$^2$) |
|---|---|---|---|---|---|
| Robinson (1938) | M (n=8) | 6.0 | 1.56 m·sec$^{-1}$ | 8.6% | 837.5 |
| " | M (n=10) | 10.5 | " | " | 897.9 |
| " | M (n=11) | 14.1 | " | " | 962.5 |
| " | M (n=12) | 17.4 | " | " | 1026.6 |
| " | M (n=11) | 24.5 | " | " | 1027.3 |
| Cassels and Morse (1969) | M (n=4) | 10.1 | 1.56 m·sec$^{-1}$ | 8.6% | 804 ± 44 |
| " | M (n=5) | 11.3 | " | " | 742 ± 55 |
| " | M (n=12) | 12.1 | " | " | 825 ± 58 |
| " | M (n=17) | 12.9 | " | " | 834 ± 81 |
| " | M (n=20) | 14.1 | " | " | 870 ± 72 |
| " | M (n=23) | 15.0 | " | " | 882 ± 65 |
| " | M (n=18) | 16.1 | " | " | 897 ± 79 |
| " | M (n=6) | 16.8 | " | " | 915 ± 73 |
| Ebbeling et al. (1995) | M (n=10) | 9.5 ± 0.7 | 1.40 m·sec$^{-1}$ | 0% | 573 ± 80 |
| | M (n=10) | 20.0 ± 2.0 | 1.54 m·sec$^{-1}$ | 0% | 584 ± 38 |
| **Craib (1995)** | F (n=7) | 6.3 ± 0.3 | 1.56 m·sec$^{-1}$ | 0% | 559.5 ± 20.4 |
| " | F (n=7) | 10.3 ± 0.3 | " | " | 523.3 ± 35.3 |
| " | F (n=7) | 13.5 ± 0.3 | " | " | 501.7 ± 40.4 |
| " | F (n=7) | 18.9 ± 0.2 | " | " | 476.9 ± 38.2 |

M = male, F = female

Findings in the present investigation disagree with results reported in all previous surface area-related studies. Oxygen consumption appeared to decrease relative to surface area from childhood to maturity which suggests that surface area alone cannot explain age-related changes in walking $\dot{V}O_2$. Six-year olds, for example, exhibited significantly higher oxygen consumption values, relative to body surface area, than 13- and 18/19-year olds. An explanation for the variable findings presented in this section may lie in the use of different predictive equations for surface area. Previous investigators used a surface area formula derived by Dubois and Dubois (1916). In contrast, a formula generated by Haycock and coworkers (1978), that has been validated on infants, children and adults, was used in the current study. In summary, the diversity of findings discussed in this section do not illuminate a clear relationship between body surface area and the metabolism of walking locomotion.

## $\dot{V}O_2$ Normalized To Step Frequency

Three groups of investigators have explored oxygen consumption relative to each step as a method for removing age-related differences in locomotion economy (Astrand, 1952; Rowland & Green, 1988; Unnithan & Eston, 1990). Results from these studies indicated that differences in submaximal aerobic demand between children and adults were eliminated when an adjustment for step frequency was made. Such was not the case in the present investigation. As shown in the Results chapter, the aerobic demand of each step decreased significantly from age six to age 18/19. This finding reiterates the point that age-related changes in gross $\dot{V}O_2$ are not influenced by changes in a single factor.

Why $\dot{V}O_2$ adjustments for step frequency were helpful in previous investigations, but not the present study, is unclear. Divergent results are not likely due to measurement error since both step frequency and $\dot{V}O_2$ data in the present investigation appear to be comparable to previously reported values in walking studies using similar subject samples. The only fundamental difference in methodology between the past and present studies was choice of mode of locomotion. All three previous studies used treadmill running to test subjects, whereas this study used treadmill walking. Running and walking gaits differ from each other in that running has a flight phase whereas walking does not (during walking one or both feet are in contact with the ground at any point in time). Given the disparity in findings between earlier work and those of the present investigation and paucity of walking step frequency data, substantial conclusions about the efficacy of this normalizing method remain elusive. At this point in time, findings from the present study do not justify normalizing mass-related oxygen consumption to step rate.

## Allometric Equations

Numerous animal and human physiologists have questioned the value of normalizing $\dot{V}O_2$ to body mass because of statistical artifacts and errors introduced by the procedure (Brody, 1945; Kleiber, 1947; Kleiber, 1961; McMahon, 1973; Rogers, Turley, Kujawa, Harper, & Wilmore, 1995; Schmidt-Nielsen, 1975; Schmidt-Nielsen, 1984; Sjodin & Svedenhag, 1992; Tanner, 1949; Wilke, 1977; Winter, 1992). Several investigators have demonstrated, for example, that such a simple ratio can inappropriately skew the results, causing larger individuals to appear to use less oxygen relative to body mass than smaller individuals at rest and during exercise (Rogers et al., 1995; Tanner, 1949; Winter, 1992). A more appropriate alternative, they propose, is normalization of oxygen uptake to an exponential power of body mass. This procedure controls for variance in body mass in both linear and non-linear models (Rogers et al., 1995). The exponent for this calculation is derived from a transformation of body size and metabolic data into logarithmic values that are then plotted and fit with a regression line (Rogers et al., 1995). The slope of the regression line provides the appropriate exponent (Rogers et al., 1995).

Findings in the animal literature relative to allometric scaling suggest that an exponent of 0.75 is most appropriate for normalization of metabolism in resting adult animals ranging in size from mice to elephants (Brody, 1945; Kleiber, 1947; Kleiber, 1961; McMahon, 1973; Schmidt-Nielsen, 1975; Schmidt-Nielsen, 1984; Wilke, 1977). The variety of human studies available are less settled on this value (McMiken, 1976; Morgan & Craib, 1995; Ross, Bailey, Mirwald, Faulker, Rasmussen, Key, et al., 1991; Sjodin & Svedenhag, 1992; Sprynarova, Parizkova, & Bunc, 1987). When subject data from six different groups of athletes and seven endurance-trained men were combined into one sample (n=134), however, an exponent of 0.76 was derived for submaximal exercise (Bergh, Sjodin, Forsberg, & Svedenhag, 1991). This latter finding, considered in conjunction with those from the animal studies, suggests that normalization of oxygen uptake by this scaling procedure may be more appropriate than normalization of $\dot{V}O_2$ relative to body mass.

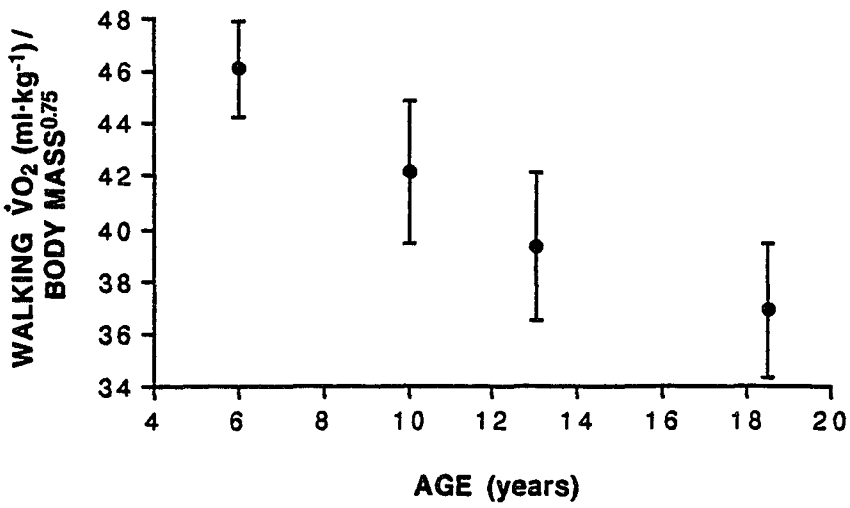
To examine this possibility, the $\dot{V}O_2$ data obtained in this study were transformed using an exponential power of 0.75 of body mass. Results from this analysis indicated that allometric scaling did not remove age-related differences in walking aerobic demand (Table 39, Figure 13). Six- and 10-year olds, for example, still utilized more oxygen at 1.56 $m{\cdot}sec^{-1}$ than 18/19-year olds. The gradual decrease in relative aerobic demand across age groups appeared linear and quite similar to decreases observed in the simple $\dot{V}O_2$ to body mass ratio used in this investigation.

Table 39. Submaximal walking $\dot{V}O_2$ relative to body mass$^{-0.75}$ by age group at 1.56 m·sec$^{-1}$ and 0% grade.

| | Tukey Grouping | Mean | Standard Deviation | Coefficient of Variation |
|---|---|---|---|---|
| 6-year olds | A | 46.1 | 1.8 | 3.9 |
| 10-year olds | A B | 42.2 | 2.7 | 6.4 |
| 13-year olds | C B | 39.3 | 2.8 | 7.2 |
| 18/19-year olds | C | 36.2 | 2.5 | 7.0 |

Means with the same letter are not significantly different.

Figure 13. Submaximal walking $\dot{V}O_2$ relative to body mass$^{-0.75}$ by age group at 1.56 m·sec$^{-1}$ and 0% grade. Values shown are means ± 1 standard deviation.



To evaluate the effect of normalizing walking $\dot{V}O_2$ to an exponent of body mass on multiple regression analyses, oxygen uptake to the 0.75 power of body mass (ml·min$^{-1}$·kg$^{-0.75}$) was used as the dependent variable (Note: resting metabolic rate was normalized in a similar manner for these regression analyses). This model, unlike regression analyses which used $\dot{V}O_2$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$) for the dependent variable, produced regression equations with three or more independent variables (Table 40). No two-variable models resulted. A comparison of the three variable equations produced by both models show remarkable similarities (Table 41). Resting metabolic rate, surface area to mass ratio and step frequency were important variables in both regression models which used all seven predictors and adjusted $R^2$ values larger than 0.90.

Table 40. Variables in regression models using either $\dot{V}O_2$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$) or $\dot{V}O_2$ ($ml{\cdot}kg^{-.75}{\cdot}min^{-1}$) as the dependent variables.

| Dependent Variable | Variable 1 | Variable 2 | Variable 3 | Adj. $R^2$ | $R^2$ |
|---|---|---|---|---|---|
| $\dot{V}O_2$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$) | RMR | Surface/mass | Thigh/shank | 0.919 | 0.925 |
| " | RMR | Surface/mass | Step Frequency | 0.916 | 0.926 |
| $\dot{V}O_2$ ($ml{\cdot}kg^{-0.75}{\cdot}min^{-1}$) | RMR ($kg^{-0.75}$) | Surface/mass | Step Frequency | 0.964 | 0.968 |

RMR = resting (sitting) metabolic rate, RMR ($kg^{-.75}$) = resting metabolic rate ($ml{\cdot}kg^{-.75}{\cdot}min^{-1}$), Surface/mass = Surface area ($m^2$) to mass (kg) ratio, Thigh/shank = Thigh/shank leg volume ratio.

Table 41. Variables in regression models using either $\dot{V}O_2$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$) or $\dot{V}O_2$ ($ml{\cdot}kg^{-0.75}{\cdot}min^{-1}$) as the dependent variables. Surface area removed from the set of seven predictor variables.

| Dependent Variable | Variable 1 | Variable 2 | Variable 3 | Adj. $R^2$ | $R^2$ |
|---|---|---|---|---|---|
| $\dot{V}O_2$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$) | RMR | Step Frequency | Gr. Reac. Force | 0.906 | 0.917 |
| $\dot{V}O_2$ ($ml{\cdot}kg^{-0.75}{\cdot}min^{-1}$) | RMR ($kg^{-.75}$) | Step Frequency | Gr. Reac. Force | 0.908 | 0.918 |

RMR = resting (sitting) metabolic rate, RMR ($kg^{-0.75}$) = resting metabolic rate ($ml{\cdot}kg^{-0.75}{\cdot}min^{-1}$), Gr. Reac. Force = Average vertical ground reaction forces normalized to body mass.

When surface area to mass ratio was removed from regression models, resting metabolic rate, step frequency and normalized average vertical ground reaction forces remained in the model with adjusted $R^2$ values were larger than 0.90. Taken together, these findings indicate the same predictor variables with roughly the same ability to explain age-related changes resulted from regression models using either $\dot{V}O_2$ divided by the 0.75 power of body mass or $\dot{V}O_2$ divided by body mass as the dependent variable. Thus, normalization of $\dot{V}O_2$ to the 3/4 power of body mass appeared to do little to enhance understanding of age-related changes in walking economy. Consequently, use of allometric procedures were not deemed applicable in this study.

Note: Calculations were performed to determine the allometric scaling factor for the subject sample examined in this study. $\dot{V}O_2$ ($L \cdot min^{-1}$) and body mass (kg) data were transformed into logarithmic values ($Log_{10}$), plotted against each other and then fit with a regression line. The slope of the line was 0.54. For this sample, therefore, an exponent of 0.54 was the adjustment factor for body mass. This value is reasonably close to exponents reported in the human physiology literature (range 0.60 to 0.86) (Schmidt-Nielsen, 1975; Bergh, et al., 1991). Using the exponent derived from this investigation, it is possible to normalize this sample's oxygen uptake values across age groups with the following calculation:

$$\dot{V}O_2 = ml \cdot min^{-1} \cdot kg^{-0.54}$$

## Selection of the Best Multiple Regression Model

Answering the question of which variables best predicted age-related changes in walking economy requires a multi-faceted answer. Beta weights suggested that sitting resting metabolic rate and possibly surface area to body mass ratio were the only variables of sufficient magnitude to warrant consideration. Given this approach, a two-factor multiple regression model, employing these variables, resulted in a prediction equation accounting for 92% of the variance observed in walking $\dot{V}O_2$. That is a high degree of predictive ability from two variables. The best three-factor model, which included the variable thigh to shank leg ratio, did little to increase predictive ability.

One can argue, however, that sitting resting metabolic rate and surface area to body mass ratio are variables too closely related to be used in the same multiple regression equation. VonBertalanffy (1957), among others (Kleiber, 1961; Rubner, 1883), suggested that there is a link between body surface area and resting metabolism. If these two variables are indeed related, then their predictive ability should be partially redundant in a regression equation. Such a conclusion implies that either sitting resting metabolic rate or surface area to body mass ratio should be removed from regression analyses so that other non-redundant variable(s) might enter the equation. When regression analyses were performed excluding either variable, higher $R^2$ values were produced when surface area to body mass ratio was removed and sitting resting metabolic rate was retained in the model. In such a model, resting metabolism and step frequency were the two variables which best predicted age-related changes in walking economy. The next most significant variable, average vertical ground reaction force, did not enhance the predictive ability of the regression equation substantially.

When considering either a model including resting metabolic rate and surface area to body mass ratio, or resting metabolic rate and step rate, the latter appears more desirable. Resting metabolic rate and surface area to body mass ratio are arguably related and therefore redundant, while resting metabolic rate and step rate are clearly independent. Consequently, it is suggested that the model including resting metabolic rate and step rate accounted for the greatest amount of true non-redundant variance in walking aerobic demand. As suggested in Chapters 1 and 2, both resting metabolic rate and step frequency have a theoretical link to age-related differences in walking $\dot{V}O_2$.

## Chapter Summary

The primary goal of this chapter was met insofar as comparisons and contrasts were made between the values obtained in the present study and those observed in other studies. In general, findings compared closely with those reported in the literature. This outcome suggests that the methodologies used in the present study were suitable. The secondary goal of this chapter was also met insofar as alternative methods of expressing the walking $\dot{V}O_2$ data were considered. Examination of the present data set showed that the traditional method of normalizing oxygen consumption to body mass remained the simplest choice for further analyses. Finally, the last goal of this chapter was met because the most viable independent variables (e.g., resting metabolic rate and step frequency) were selected for prediction of walking $\dot{V}O_2$. The information presented within this chapter establishes a foundation for overall study conclusions in chapter six.

# CHAPTER VI
# SUMMARY AND CONCLUSIONS

## Introduction

Many researchers have attempted to explain decreases in the mass-specific aerobic demand of locomotion which occurs during childhood (Astrand, 1952; Krahenbuhl et al., 1989; MacDougall et al., 1983; Morgan, 1993; Rowland, 1989; Rowland & Green, 1988; Unnithan & Eston, 1990). Through their efforts, numerous predictor variables have surfaced, including resting metabolic rate (MacDougall et al., 1983), body surface area to mass ratio (Cassels & Morse, 1962; MacDougall et al., 1983; Rowland, 1989; Rowland & Green, 1988), ventilatory equivalent (Bar-Or, 1983; Krahenbuhl & Williams, 1992; Rowland, 1989), and step frequency (Cavagna et al., 1983; Heglund & Taylor, 1988; Kram & Taylor, 1990; MacDougall et al., 1983; Morgan, 1993; Rowland et al., 1987; Thorstensson, 1986). A limitation of this body of work, however, is that it focused on only one or two explanatory variables at a time. This approach left unclear the true predictive ability of single variables given the fact that a number of variables appear to influence locomotor economy. To remedy the situation, seven variables were measured on a sample of 28 females to determine which single variable, or cluster of variables, resulted in the best predictive regression equation explaining age-related changes in mass-specific walking $\dot{V}O_2$.

## Summary of Procedures

Using normal ranges (10th to 90th percentile) for height, mass and body fat, four age-groups of seven healthy females were selected for assessment of age-related changes of walking $\dot{V}O_2$. Repeated measurements of limb structure (volume) were obtained with a plythysmograph on the first day of testing as were repeated measurements of walking aerobic demand, ventilatory equivalent, and step frequency at a velocity of 1.56 $m \cdot sec^{-1}$and 0% grade.

Participants returned on a second day for identical repeated assessments of the latter three variables. Finally, on a third day, participants visited the laboratory for measurement of resting metabolism, 10 additional minutes of treadmill walking and assessment of gait-related stance time and average vertical ground reaction forces. Resting metabolism was obtained in a seated position from a 10-min expired gas sample, and stance time and ground reaction forces were acquired from a force platform as participants walked across it at a velocity of 1.56 $m \cdot sec^{-1}$. A ratio of body surface area to body mass was calculated for each participant from knowledge of height and weight. Statistical analyses of data gathered during the study included assessment of data reliability, determination of age-related differences in all the variables measured, and regression analyses for estimation of the best predictors of age-related changes in walking aerobic demand.

## Summary of Results

Metabolic and gait-related data obtained in this study appeared to be reliable as indicated by repeated measures analysis of variance (ANOVA) and use of Tukey post-hoc multiple comparison procedures. With the exception of average vertical ground reaction forces expressed relative to body mass, all variables measured changed significantly with age as hypothesized. Submaximal aerobic demand, resting metabolic rates, body surface area to mass ratios, ventilatory equivalent and step frequencies decreased with age. Stance time and thigh to shank volume ratio increased with age.

Multiple regression analyses, using walking submaximal aerobic demand as the dependent variable and resting metabolism, body surface area to mass ratio, step frequency, ventilatory equivalent, stance time, average vertical ground reaction force, and thigh to shank volume ratio as independent variables, indicated that the first three independent variables listed were the best predictors of economy. Other variables proved to be non-significant predictors of aerobic demand when all factors were considered simultaneously.

## Summary of Discussion

Detailed comparisons of the present data set with those published in previous studies led to the conclusion that measures obtained in the present study are similar. This portion of the discussion was then followed by consideration of alternative methods for expressing aerobic demand. It was concluded that correction of oxygen consumption for differences in resting metabolism, body surface area, step frequency or an exponent of body mass did not enhance understanding of age-related differences in walking aerobic demand. Thus, normalization of $\dot{V}O_2$ to body mass in the traditional manner was considered the adjustment procedure most appropriate for comparing the participants in this study. Finally, numerous two- and three-factor multiple regression predictor models were evaluated to determine which appeared to best explain age-related changes in walking $\dot{V}O_2$. A two-factor predictor model emerged consisting of resting aerobic demand and step frequency.

## Directions for Future Study

Research avenues which emerge from the present study are numerous. Several methodological suggestions are offered below, with the understanding that they are by no means comprehensive. They simply provide a possible foundation from which to design future investigations.

**Longitudinal compared to cross-sectional study:** Although this study has served to illuminate resting metabolism, surface area to body mass ratio, and step frequency as the primary variables apparently associated with age-related changes in walking economy, the study cannot be considered definitive because its design was cross-sectional in nature and limited to small age-group samples of a single gender. Future investigations would benefit from longitudinal design involving larger samples.

**Age versus size phenomenon:** If longitudinal studies with larger samples (exhibiting greater height and mass variability) were conducted and similar findings observed, the next direction of inquiry could be to separate age-related from size-related differences in locomotor economy. A sample of individuals similar in age (adults), but diverse in body size, could be tested on the same variables examined in this study. If the same factors were still associated with differences in walking economy, then size and not age may be the more important factor contributing to walking economy. Likewise, a sample of individuals diverse in age (children and adults), but similar in body size, could be tested on the same variables examined in this study. If age-related differences in the same factors were still associated with differences in walking economy, then age and not size may be the more important factor contributing to walking economy.

**Ventilatory equivalent:** Previous investigators noted larger ventilatory equivalents in children compared to adults, yet did not specify the nature of the relationship (linear or curvilinear) across age groups. The present study also found higher ventilatory equivalents in children, but only in 6-year olds compared to the 10-year and older age-groups. Why the change in ventilatory equivalents occurred only between ages six and 10 needs to be clarified. Was this abrupt change an artifact of sample size or a phenomenon that occurs early in child development?

**Gender differences:** Close examination of walking $\dot{V}O_2$ data obtained in this study suggests that economy improves with age in females until puberty. Thereafter it did not change. The same connection between walking $\dot{V}O_2$ and puberty may be found in males, however at a slightly later age. Such a finding would be intriguing since it would demonstrate that male and female walking economy change at different rates during childhood and that there may be a hormonal link to age-related improvements in economy. With these thoughts in mind, future studies may want examine the association between economy and puberty in males as well as females.

**Ground reaction forces:** As reported in chapter 4, average vertical ground reaction forces relative to body mass were not significantly different across the four age groups studied. This finding was unanticipated. In light of this finding, researchers may want examine ground reaction forces with greater scrutiny. It is quite possible that more specific measures of vertical ground reaction forces are important to economy, while averaged vertical ground reaction forces are not. To give examples, loading rate (the rate one applies force to the ground with a step), magnitude of impact peak with each step, and thrust maximum (force of push-off with the forefoot) could differ across age groups while average vertical ground reaction forces may not. It is also possible that horizontal forces may differ across age groups although evidence to support this hypothesis has yet to be collected. With these considerations in mind, future age-related walking economy studies may want to examine ground reaction force data more broadly.

**Limb morphology:** Arguments were provided for examination of limb structure in connection with age-related changes in economy and yet only weak age-related differences in limb structure (volume) were found in the present investigation. While efforts were made to assess accurately changes in limb morphology with growth, the methodology used may not have been refined enough for this measure. Future investigators may want adopt other limb structure assessment methodologies, with a variety of age groups, to determine if possible age-related changes in limb morphology deserves further attention.

## Overall Conclusions

As anticipated, this study clearly demonstrated that young children exhibit a higher aerobic demand than older children and adults. Through selection of promising predictor variables from the literature, tight methodological control, and measurement of generally large age-related effect sizes, strong prediction of age-related changes in walking economy was achieved. This outcome occurred despite the small sample size. As a consequence, this study was able to establish that the best predictors of age-related changes in economy appear to be resting metabolic rate, surface area to body mass ratio, and step frequency.

In addition to helping narrow the focus of future research, this study presents data beneficial to physicians and researchers who work with physically challenged children insofar as excellent normative data are provided for purposes of evaluation and rehabilitation.

Directions for future research are plentiful. Longitudinal designs, assessing larger sample sizes (with greater height and mass variability) of both genders, are needed to examine the same variables tested in this study.

Attempts need to be made to separate age- from size-related differences in walking $\dot{V}O_2$. The time course of age-related changes in ventilatory equivalent needs to be explored in greater detail in other samples. Additionally, the time course of age(puberty)-related changes in economy needs to be carefully plotted in males as well as females. Ground reaction forces relative to body mass and walking $\dot{V}O_2$ warrant closer examination. And finally, enhanced accuracy in limb morphology assessment may lead to a stronger association between walking $\dot{V}O_2$ and limb structure in future studies.

In conclusion, this study achieved its main purpose, to elucidate the primary variables associated with age-related differences in walking economy and the relative importance of these variables.

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