ADIPOSITY AND ENERGY COST OF WALKING IN ADOLESCENT BOYS

ENERGY COST OF WALKING IN ADOLESCENT BOYS WHO DIFFER IN ADIPOSITY BUT ARE MATCHED FOR TOTAL BODY MASS: METABOLIC AND MECHANICAL APPROACHES

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ABSTRACT

Energy cost of walking at any given speed is higher for heavier people than for lighter ones. We compared adolescents that were matched for total body mass but had different body composition. Nine pairs of boys (16.37 ± 1.57 years in the lean group and 12.90 ± 1.49 years in the obese group) participated. Metabolic energy expenditure (EE) was compared at three walking speeds and moments and powers at the hip and ankle at push off were analyzed. Assessment of fat mass and distribution was performed using whole body dual-energy x-ray absorptiometry. A repeated measure ANOVA was performed when matched pairs were compared. Based on multiple regression, pooling all subjects together, body mass was the main predictor of EE. Variance explained by adiposity increased with increasing speed. Obese subjects tended to expend more energy than their lean pairs at the two fastest walking speeds (5 and 6kph). There was a significant difference between the pairs in EE (kJ/min) at 6kph ($p<0.05$). Ventilation showed the same pattern as $\dot{V}O_{2net}$ (exercise $\dot{V}O_2$ minus resting $\dot{V}O_2$), increasing with increasing speed and showing differences between the pairs at the fastest speed. Heart rate was consistently higher in the obese subjects. Stride length, stride rate, progression velocity and moments and powers at the hip and ankle at push off were not correlated with body fat. No relationship between $\dot{V}O_{2net}$, total amount of body fat, or segment fat content was found. Total amount of fat in the body and the amount of fat in the legs had no influence on gait parameters. In conclusion, excess body fat does not influence the energy cost of walking at low speeds but does so at 6kph. Obese subjects demonstrated higher effort at all speeds. Amount of fat distributed in body segments does not influence either energy cost of walking or mechanical gait parameters.

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1. INTRODUCTION

1.1 Background and Rationale

Sedentary lifestyles are associated with obesity and the rate of obesity in children has been increasing at a fast pace in recent years (Kuczmarski et al., 1991; Troiano et al., 1995). This is a major concern among health professionals, since childhood obesity is strongly associated with adulthood obesity and several other related diseases (Williams, 1985; Kuczmarski et al., 1991; Bar-Or et al., 1998). As with adults, body weight control is also an important health concern for children and adolescents. Almost one-quarter of U.S. children are now obese, a dramatic increase of over 20% in the past decade (Troiano et al., 1995). There seems to be an influence of genetic factors on body mass and composition, but the hereditary factors related to juvenile obesity are unknown. Obese children and adolescents are identified as having low physical activity level, and this may be one important cause of juvenile obesity.

Walking is the most common form of exercise. For most individuals, walking represents the major type of physical activity that falls outside the realm of sedentary living. Various studies have been conducted to measure energy cost of locomotion among different populations, using various intensities and different ergometers, such as cycle ergometer and treadmill. However, investigations concerned with variations in energy expenditure (EE) occuring within the obese population do not exist. It is not clear whether differences exist in energy expenditure when one compares children/adolescents of different levels of body fat, while they perform physical activity, and how much of this energy is expended due to the amount and distribution of body fat.

Some attempts have been made to explain energy cost of locomotion using mechanical factors (Cavanagh, Kram, 1985). Obese individuals have been observed to experience increased loading on major joints during normal locomotion (LeVeau, Bernhardt, 1984). Therefore, larger forces and moments are applied to the ground and larger internal joints forces, moments and powers are produced compared to lighter individuals (Hills, 1994). At the same time, obese people demonstrate an increased energy expenditure for the same weight-bearing activity, when compared to their lighter counterparts (Bar-Or, 1983; Pate et al., 1989; Rowland, 1991; Pate et al., 1992; Maffeis et al., 1993; Murray et al., 1993; Rowland, 1996). Subjective observations highlight the difficulty that obese individuals experience in executing what are considered simple daily tasks. Moreover, the walking gait of obese prepubertal children has been suggested to be more compromised than that of normal-weight individuals when the obese attempt to move at speeds other than their comfortable walking speed (Hills, Parker, 1991). A mechanical gait assessment would then provide comprehensive identification of possible differences in energy cost of walking between obese and non-obese subjects.

Knowledge of a person's energy expenditure when performing different activities might explain some of the limitations demonstrated by obese children and adolescents when they perform physical tasks. It can be very useful to know the caloric expenditure of an individual, and the differences in energy expenditure among individuals with various body compositions, while they perform physical activity. Using this information will help health professionals to design therapeutic exercise programs for obese individuals.

1.2 Objectives

This study was intended to determine the contribution of adiposity to energy expenditure in male adolescents varying in the amount of body fat but matched for total body mass, while walking at several velocities on a motorized treadmill. We also wished to determine whether differences exist in the kinetics (joint moments and powers) of walking between the lean and the obese groups and if these differences could explain expected differences in energy expenditure. The amount and distribution of fat in the body and its effect on energy expenditure and mechanical gait parameters was a third objective of this study.

1.3 Hypothesis

We hypothesized that adiposity would contribute to the energy cost of walking so that obese boys would require more energy to perform the exercise than would their lean counterparts. We also expected the obese to demonstrate a mechanically disadvantageous gait compared to the lean subjects: lower stride length, higher stride rate, slower walking speed, and increased loading on major joints of lower limbs resulting in increased moments and powers generated in the joints. These hypotheses were based on the fact that the obese individuals need to move excessive fat, which is an inert load during weight-bearing activities.

2. REVIEW OF THE LITERATURE

In the following section I shall describe some aspects that have been reported to influence the energy expenditure during rest and physical activity. In most cases there is controversy in the literature on how these aspects affect the energy cost of locomotion. Definitions of variables being used in the current study and how the measurements are done are presented in section 2.2. Mechanical considerations relevant to the present study are presented as well as a description of the method used for body composition assessment.

2.1 Energy cost of movement

Measurement of an individual's energy expenditure (EE) at rest or during a particular type of exercise has many practical applications. One direct practice applies to exercise-assisted weight loss programs. Knowledge of the energy cost of walking at different speeds is useful for individuals who use this mode of exercise as a method for weight loss.

Effects of body mass and adiposity on energy expenditure

It is often observed when children play or perform physical activities that the obese child finds it difficult to carry on at par with the leaner peers. One reason for this deficient performance is a greater metabolic cost for executing a physical activity. In physiologic terms, obese children require a higher oxygen uptake

($\dot{V}O_2$) to perform a given task than non-obese children due to a greater total body mass (McArdle et al., 1986a). Because their maximal oxygen uptake ($\dot{V}O_2$ max) is often lower than that of leaner children (Dempsey et al., 1966)(Salvadori et al., 1992) at any given level of exercise obese children operate at a higher percentage of their maximal aerobic power (Davies et al., 1975).

Maffeis et al. (1993) found energy expenditure to be significantly greater in the obese when compared to non-obese children at the same speed of exercise; i.e., when walking at 5 km/h, the obese children expended approximately 50% more energy than did the non-obese children. However, when $\dot{V}O_2$ was expressed per kilogram of body weight or per kilogram of fat-free mass, the rate of energy expenditure did not differ between the two groups. Obesity in that study was defined as body weight >20% of predicted weight for height, which does not necessarily represent obesity. Another study (Rowland, 1991) considered that obesity did not affect submaximal walking economy in a group of adolescent girls with a wide range of body fat. In agreement with Maffeis and co-workers (1993), absolute values of submaximal $\dot{V}O_2$ were greater among obese subjects but the oxygen cost of moving body mass ($\dot{V}O_2$/kg) was not affected by increased body fat. Both studies had similar findings but they were interpreted differently by the authors.

In three studies with adolescents, it was found that body fat as measured by the sum of triceps and medial calf skinfolds contribute to the weight-relative energy cost of walking and running (Pate et al., 1989; Murray et al., 1993; Walker et al., 1999). It is very likely that those with higher skinfold thickness also weighed more, masking the specific effect of *adiposity* on the energy cost. In a study comparing the energy cost of running on the treadmill in young basketball players (38 boys and 14 girls aged 14.2 ± 0.3 and 12.2 ± 1.9 years, respectively) and middle-distance runners (27 men and 14 women aged 23.7 ± 3.4 and 23.9 ± 4.1 years, respectively), age, gender, body mass and running training were examined and it was concluded that body mass was the most important factor in determining the variation in cost of running (Bourdin et al., 1993).

In a study with adults 18- to 30-years of age (Dempsey et al., 1966), energy expenditure per unit of mechanical power on a cycle ergometer was markedly higher in obese than in lean subjects. In agreement with that data, Cotes (1969) found that the $\dot{V}O_2$ during both steady state and progressive leg exercise on a cycle ergometer was greater in heavy than in light subjects. Even when performing a predominantly weight-supported task, the obese persons had excessive physiologic cost (Whipp, Davis, 1984). When a lean 80-kg subject was compared to a moderately obese 80-kg person for unloaded cycling, the obese showed 60% greater $\dot{V}O_2$ (800ml/min vs. 500ml/min) (Wasserman, Whipp, 1975). Another study has shown that body mass is positively correlated with, and will significantly affect, the determination of cycle ergometer exercise $\dot{V}O_2$ and the calculations of gross and net efficiency (Berry et al., 1993).

Williams et al. (1966) demonstrated a significant positive relationship between $\dot{V}O_2$ and body mass at low work rates of cycling.

Kuchly et al. (1984) explained the fact that, even when the obese do not have to support their body weight, they expend more energy than lean people. They found that approximately 70% of the increased energy cost during cycling in obese subjects, as compared with normal subjects, was due to the work of moving the legs. Subjective observation of markedly obese people exercising on a cycle ergometer demonstrates the difficulty encountered in moving the legs and accommodating an abdomen that is impeding the natural movement of the legs. This, in part, may also reflect a lower fitness level among the obese.

According to Bergh and co-workers (1991), neither submaximal nor maximal $\dot{V}O_2$ increased in proportion to body mass during running in six groups of endurance athletes and one group of very active men (age range 17 to 44 years). In a study by Pate et al. (1992), an inverse relationship between body mass and submaximal $\dot{V}O_2$ (expressed in ml/kg.min) was observed. It was suggested that heavy runners were more economical than lighter runners. Total body mass (kg) in those subjects was 67.8 ± 12.4 and total body fat (%) was 22.3 ± 6.4 (mean ± SD). The authors implied that this inverse relationship might exist because of weight-related inter-subject differences in segmental mass distribution. It has been shown that a lighter individual, as compared with a heavier counterpart, tends to possess a greater percentage of body mass in the extremities (Zatsiorskii, Selvyanov, 1983). It should be pointed out, though, that when dividing $\dot{V}O_2$ by body mass the heavier people obtain lower values, which does not necessarily imply better economy of locomotion.

Body mass is a major determinant of the gross energy cost of weight-bearing activities like walking and running. The correlation between $\dot{V}O_2$ and total body mass is reported to be approximately $r = 0.7$ (Katch, 1973). In a study from our laboratory (Ayub, Bar-Or, 1999) this correlation was found to vary from 0.83 to 0.98 when boys 8- to 13- years of age, of a wide range of percent body fat, walked at five different speeds on the treadmill. Adiposity *per se* could explain only a small variance of the energy cost of walking, indicating that total body mass was the main factor determining O_2 cost of locomotion in those children.

The design of the present study enables us to isolate the effect of body mass since subjects are matched for total mass but have different levels of adiposity thereby answering the question of whether body fat affects the energy cost of walking, independent of body mass. To our knowledge this is the only study in which the effects of adiposity on the energy cost of walking were observed when total body mass was matched in lean and obese subjects.

Effects of walking speeds on energy expenditure

It is known that walking speed influences metabolic cost of walking (Fellingham et al., 1978; Ebbeling et al., 1992). Studies have shown that the metabolic cost is directly related to the speed of running (Dill, 1965; Costill, Fox, 1969; Costill et al., 1973; McMiken, Daniels, 1976; Bransford, Howley, 1977; Daniels et al., 1977; Cavagna, Kaneko, 1977; Jones, Lindstedt, 1993; Svedenhag, 1995). There is a curvilinear relationship between $\dot{V}O_2$ and walking speed and a linear relationship between $\dot{V}O_2$ and running speed (Dill, 1965; Van Der Walt, Wyndham, 1973; Falls, Humphrey, 1976; Bransford, Howley, 1977; Leger, Mercier, 1984; Walker et al., 1999). For example, in young adult male subjects, the relationship between $\dot{V}O_2$ and walking speed is nearly linear between speeds of 3.0 and 5.0 kilometers per hour but at faster speeds walking becomes less economical and the $\dot{V}O_2$ increases curvilinearly indicating a greater caloric cost per unit of distance walked at faster speeds (Fellingham et al., 1978).

The energy expended during walking has been shown to occur in a “U” shape in relation to the walking speed: at slow and fast speeds the individual spends more energy than when walking at their preferred walking speed (Martin, Morgan, 1992). Increases in cost per unit distance are most apparent at low and high speeds of walking. Ralston (1958) reported that energy expenditure was lowest at 1.23 m/s (4.43 km/h) but between approximately 1.1 m/s (3.96 km/h) and 1.4 m/s (5.04 km/h) the energy expenditure curve did not increase.

Some studies have used relative speeds (Krahenbuhl, Pangrazi, 1983; Frost, 1995); e.g., 50, 75, 100% of the preferred walking speed during a one-mile walk test, while others have used absolute velocities (Rowland, Green, 1988; Maffeis et al., 1993; Bouchard et al., 1993; Unnithan, 1993); e.g., 4, 5, 6, 7 km/h. In the present study, we used absolute speeds, three of which overlap for the two groups. One additional speed used was a comfortable walking speed (CWS), which has been used in previous research (Frost et al., 1995; Maltais, 1997; Frost et al., 1997a).

Age-related differences in energy expenditure

The oxygen cost (expressed per kilogram body weight) of walking and running is higher in children as compared to adolescents and adults (Skinner et al., 1971; Krahenbuhl et al., 1979; MacDougall et al., 1983; Frost, 1995; Frost, 1995). According to Ebbeling et al. (1992) the age of children influences the energy cost of locomotion: economy of the children ages 8.2 to 10.6 years ranged from 15 to 22% of that of young adults 17.9 to 23.7 years. The oxygen cost of locomotion (walking and running on a treadmill) per kg body mass decreased with age when a group of 7-8 year old children was compared with a 10-12 year old group and both were compared with 15-16 years old (Frost, 1995). Frost and co-workers concluded that the best single predictor of $\dot{V}O_{2net}$

was age, and that the higher levels of co-contraction of antagonist muscles at the thigh and leg in the younger children was responsible for the higher metabolic cost in that group (Frost et al., 1997b). Longitudinal studies (Daniels et al., 1978; Krahenbuhl et al., 1989) have shown that, with age, maximum $\dot{V}O_2$ (expressed in ml/kg.min) remains essentially unchanged while the O_2 cost of running is less per kg body mass and time of endurance tests improves. The mean aerobic demands of submaximal running decreased 13% over time in young males, tested at 9.9 years of age and again at 16.8 years (Krahenbuhl et al., 1989).

Cross-sectional studies examining running economy in children indicate that older children are more economical than younger children and therefore utilize a smaller percentage of their $\dot{V}O_2max$ to run at a given speed (Daniels, Oldridge, 1971; Daniels et al., 1978; MacDougall et al., 1983; Frost et al., 1997b). In a study with youth, an age-related improvement was reported in running economy in children/adolescents 7- to 17-years of age: older subjects spent less energy and had a greater performance in the 1-mile run/walk test (Cureton et al., 1997). Daniels and associates (1978) suggested that age affects submaximal $\dot{V}O_2$ in well-trained 12-18 year old boys; however, a test for an age effect was not performed, and the ages at which the largest differences occurred were not reported. In another recently reported study, no age differences were found in the relationship between speed and relative energy cost when 12 to 18 year old males and females were tested (Walker et al., 1999). The authors suggested that the onset of puberty may affect the walking and running energy cost of children more than age alone.

Walking economy and aerobic fitness

Studies of groups of children of similar age have failed to provide convincing evidence that walking and running economy relates to either endurance performance or $\dot{V}O_2$max.

Economy has not been found to differ among nonathletic and endurance-trained children, and little or no change in economy has been observed with aerobic training (Rowland, 1996). Supporting these findings is the fact that economy may be equal among men and women, even though men have a decided advantage in $\dot{V}O_2$max (Daniels et al., 1977). Unnithan (1993) found no differences between a group of trained runners and control boys who ran at submaximal speeds (8 and 9.6 km/h). When energy cost of running was studied in groups of athletes trained in various sports (i.e. adult middle-distance runners, adult long-distance runners, adult canoeists, young middle-distance runners, and young long-distance runners), no differences were found in the net energy cost expressed in J/kg/m. A negative relationship was found between the energy cost of running and maximal oxygen uptake when $\dot{V}O_2$max was expressed relative to body mass (Bunc, Heller, 1989).

According to Pate et al. (1992), running economy tended to be lower in the subjects with higher maximal aerobic power, while running at 161 m/min (188 subjects were tested). Lake and Cavanagh (1996) also found $\dot{V}O_2$ to be higher (41.0 +/- 4.5 vs. 42.4 +/- 4.3 ml/kg.min) after a 6-week training period, even though a significant increase in $\dot{V}O_2max$ was seen.

In contrast, it was demonstrated by Daniels et al (1978) that training, together with growth, contributes to the decrease in the aerobic demands of submaximal running so that a linear decrease in $\dot{V}O_2$ can be expected to occur with training.

These controversial findings may be explained by Daniels (1985) who suggested that there might be a threshold of training or a particular type of training necessary to induce a significant increase in running economy. A variation in economy of locomotion among individuals of similar performance seems to exist, explaining the poor correlation sometimes found between economy and performance. An example of this variation was demonstrated by the same author (Daniels, 1974) when he studied two experienced and well-trained, equally performing runners who varied by 30% in $\dot{V}O_2$ at a common submaximal running speed.

Run-trained subjects exhibited a greater change in economy as compared to active but non-run-trained boys. This indicates that specific training might influence the aerobic demands of running (Krahenbuhl et al., 1989).

2.2 Measurement of metabolic cost

Oxygen uptake measurement has generally been accepted as an accurate method of assessing metabolic energy cost when the task calls for primarily aerobic energy sources. Different studies have demonstrated that it is possible to estimate the energy expended during physical activity with reasonable precision (Blessey, 1978; Freedson et al., 1981; Anton-Kuchly et al., 1984; Daniels, 1985; Bandini et al., 1990; Ebbeling et al., 1992; Bunc, Dlouha, 1997). During steady state submaximal exercise the body derives its energy through aerobic metabolism and thus reflects energy expenditure (Rowland, 1996). Energy expenditure during walking can be expressed in different ways according to the questions being asked and the variables that need to be accounted for in the measure. Total body mass, fat-free mass, distance or speed of locomotion, and mechanical energy produced are just a few examples of variables that can be accounted for when measuring energy expenditure.

The net oxygen cost of walking is the $\dot{V}O_2$ during a period of steady state walking minus the $\dot{V}O_2$ during rest, which can be expressed as the total or absolute $\dot{V}O_2$, measured in L/min or ml/kg.min (relative to body mass). It has been assumed that dividing by body mass will remove differences in metabolic cost that are due to the subject's size. Even though it is a commonly used tool when comparing people of different body mass, there is some controversy as to the appropriate scaling factor when normalizing for body mass (Rowland, 1996). Initially, several scaling models were developed using animals of various sizes. Later, human models have been developed and many studies have investigated different allometric scaling strategies, but no final conclusion has emerged as to what the best normalizing factor is when comparing individuals of different body sizes (Bergh et al., 1991; Winter, 1992; Welsman et al., 1996; Nevill, 1997; Janz et al., 1998). There is a possibility for distorted results (giving small people advantage while penalizing large people) which could be obtained when physiological functions, such as $\dot{V}O_2$, are expressed per body mass or per body surface area. In this study, because we are comparing pairs of lean and obese subjects that are matched for total body mass, the normalization for this factor was not relevant. When subjects were not compared using the matched pair design, body mass was accounted for (per kg body mass).

Oxygen consumption

Oxygen consumption is an expression of the product of cardiac output and arteriovenous oxygen difference, but several factors, including pulmonary and hematologic factors and muscle disease can limit maximal oxygen uptake (Bar-Or, 1983). Functional aerobic fitness is the maximal oxygen uptake relative to body mass ($\dot{V}O_2$max/kg of body weight), a critical determinant of exercise capacity or performance, which refers to capabilities in physical activities.

Physical activity affects oxygen consumption and carbon dioxide production more than any other form of physiologic stress (McArdle et al., 1986).

Ventilation

Pulmonary ventilation ($\dot{V}E$) is the product of tidal volume and breathing frequency. Although during treadmill walking at the same absolute speed, there is a curvilinear increase in tidal volume with age, breathing frequency decreases linearly (Rowland, Cunningham, 1997).

Ventilation was found to be positively correlated with oxygen consumption while subjects (ages from 20 to 60 years) were walking at 6.12 km/h and running at 9.66 km/h (Pate et al., 1992).

Submaximal ventilation per kilogram is higher in children than in adults, diminishing linearly with age. Rutenfranz and associates (1981) presented longitudinal findings in 8- to 17-year-old subjects where submaximal ventilatory responses were described while subjects exercised at the same relative intensity (65-70% $\dot{V}O_2max$). From ages 12 to 17 years, values for absolute $\dot{V}E$ increased in males from 52.2 to 68.1 L/min. Respiratory rate declined from 39 to 28 breaths/min while tidal volume rose from 1.58 to 2.48 L. Cross-sectional data reported similar findings (Andersen et al., 1974). When 8- to 16-year-old adolescents were cycling at 50 and 75% of their $\dot{V}O_2max$, a steady decline of about 10 breaths per minute over the age span (for the males) was observed in breathing rate related to age. With increasing age, tidal volume at a relative workload of 50-60% of $\dot{V}O_2max$ increased from 530 to 1760 ml in the boys.

Energy cost of breathing

At rest and in light exercise in healthy subjects, the oxygen requirement of breathing is small, averaging 1.9 to 3.1 ml of oxygen per liter of air breathed, or about 2% of the total energy expenditure. As the rate and depth of breathing increase, the cost of breathing rises to about 4 ml of oxygen per liter of ventilation, and may rise to as high as 9 ml of oxygen when ventilation exceeds 100 L/min (Martin, Stager, 1981; Wilmore, Costill, 1994). The contribution of the oxygen cost of ventilation to the oxygen deficit and recovery oxygen consumption has been estimated during steady-state exercise. Ventilatory work has been shown to account for 7-8% of the overall energy cost of exercise (Millic-Emilli et al., 1962).

Wearing respiratory apparatus does not seem to affect running style and economy in actively trained men (Siler, 1993). In that study, running using either a mouth piece or a respiratory face mask were compared to running without using a respiratory apparatus and it was concluded that neither of them generally affect running style of individuals running at comfortable, submaximal running speeds.

Ventilatory equivalent for oxygen

The ratio between the volume of air ventilated and the amount of oxygen consumed by the tissues ($\dot{V}O_2$) indicates breathing efficiency. This ratio is the ventilatory equivalent for oxygen. The ventilatory "inefficiency" is indicated by a high $\dot{V}E/\dot{V}O_2$. At the same submaximal relative workrate, $\dot{V}E/\dot{V}O_2$ declined with age in a group of 8- to 16-years old subjects (Andersen et al., 1974).

During light and moderate steady-state exercise, ventilation increases linearly with oxygen consumption and carbon dioxide production and averages between 20 and 30 litres of air for each litre of oxygen consumed. Under these conditions, ventilation is mainly increased by increasing tidal volume whereas at higher exercise levels breathing frequency takes on a more important role (Grimby, 1969).

Respiratory exchange ratio

The RER is the ratio of carbon dioxide output to oxygen consumption at the mouth and is used in place of the same ratio, called respiratory quotient (RQ) which refers to the cellular level. The RER is used to indirectly indicate substrate utilization, since the ratio of carbon dioxide production to oxygen consumption varies for different fuel sources. The contribution of protein is ignored as it is considered to be minimal during exercise (McArdle et al., 1986a). Since fuel sources will vary in the amount of biochemical energy needed to "burn" them, the biochemical energy expenditure can be estimated knowing the O_2 requirements and the RER. The RER however, being an indirect estimation of RQ, is also influenced by such things as hyperventilation. Increased ventilation and therefore an increase in RER, also occurs when there is a need to remove excessive CO_2, as is produced during high intensity exercise, secondary to bicarbonate production for buffering. The RER ranges from 0.70 with pure fat utilization to 1.0 for pure carbohydrate utilization. The RER can be greater than one with hyperventilation or during intense exercise (McArdle et al., 1986b).

Resting metabolic rate and baseline subtractions

Metabolic energy expenditure measured as $\dot{V}O_2$ during physical activity reflects not only the cost of the exercise, but also the cost of energy used during rest, which can be also called 'physiological maintenance work'. This includes the energy needed to power the muscles of respiration and posture as well as all organs' activities, transport ions against electrochemical gradients, synthesize and mobilize substrates and circulate blood (Stainsby et al., 1980). Energy expenditure can be expressed accounting for differences in resting metabolic rate (RMR), by subtracting the resting value from the total metabolic cost measured during exercise ($\dot{V}O_{2net}$).

Calculating walking $\dot{V}O_{2net}$ gives an indication of the O_2 cost of walking that is incurred over and above the O_2 cost of maintaining homeostasis at rest.

However, to imply that $\dot{V}O_{2net}$ reflects exclusively the O_2 cost of walking may be untrue as there is no conclusive evidence that $\dot{V}O_2$ at rest reflects the O_2 cost of these same basal metabolic functions during exercise (Alexander, 1991). For practical purposes, $\dot{V}O_{2net}$ has generally been accepted as an accurate method of accounting for differences in RMR.

In absolute terms, obese individuals normally have greater RMR than lean ones (Segal et al., 1989). Obese people have higher fat mass, but also more lean mass, which accounts for their higher RMR (Ferrannini, 1995). In the present study, since the pairs of boys are of similar total body mass and one group is more muscular than the other, we could assume the obese group would have less fat-free mass than the lean group and, therefore, a lower RMR.

Thermic effects of food

The metabolic rate increases after food intake and requires several hours to return towards baseline. The increase in metabolic rate is associated with the digestion, absorption, transport, metabolism and storage of ingested food. During this process, the increase in energy expenditure can approximate 10-15% of the total energy value of the ingested food (Ziegler, Filer, 1996). It accounts for 10% of the total energy expended each day (Wilmore, Costill, 1994; Ziegler, Filer, 1996). Thermic effect of food has been shown to be lower in obese individuals compared with lean ones (Ferrannini, 1995). These facts were considered when testing the subjects in this study: they were asked to fast for 12 hours before measurements of resting metabolic rate were taken.

Habituation to the treadmill

Sufficient treadmill exposure for the individual to achieve a stable and consistent gait pattern with minimal stride-to-stride variability is important when $\dot{V}O_2$ is being measured. When within-day or between-day differences from stride-to-stride do not take place, it is recognized that habituation to the treadmill has occurred.

A study from our laboratory (Frost et al., 1995) examined between-trial (on the same day) and between-day differences in metabolic, cardiovascular, and kinematic variables of twenty-four children, 7 to 11 years of age, who were walking and running at various speeds on the treadmill. While subjects did not show difficulties in learning the task, the great variability in individual responses led the authors to suggest that monitoring subjects' habituation individually is important – in that study some subjects fulfilled the criteria for habituation while others showed different response patterns. In another study from our laboratory (Ayub, Bar-Or, 1999) 8-13 years old lean and obese children were tested, and less than 3 minutes of treadmill walking/running were necessary for the investigator to feel that subjects were confident and stable on the treadmill.

Efficiency vs. Economy

Efficiency of movement is defined as the ratio of the mechanical work performed to the metabolic cost of performing the work (Winter, 1979; Stainsby et al., 1980; Williams, Cavanagh, 1983; Kaneko, 1990; Fetters, Holt, 1990; Ebbeling et al., 1992; Berry et al., 1993). It is often difficult to compute how much mechanical work is performed during sports events. Calculation of the work performed while a subject walks on a treadmill is not generally possible when the treadmill is horizontal since the vertical displacement of the body's centre of gravity is not easily measured. According to Winter (1979),

$$\text{efficiency} = \frac{\text{external + internal mechanical work}}{\text{metabolic cost}} \times 100\%$$

The difficulty, therefore, is to calculate internal mechanical work, which is the work involved in walking horizontally.

Economy is defined as the submaximal oxygen uptake per unit body mass required to perform a given task (Cavanagh, Kram, 1985). Thus, $\dot{V}O_{2net}$ represents the amount of energy being used to execute the task. Economy has been expressed as the $\dot{V}O_2$ demand of moving the body mass a given distance at a given treadmill slope. An individual is less economical at higher $\dot{V}O_{2net}$. This method assumes that at a constant speed the mechanical cost of an activity is constant (Fetters, Holt, 1990).

2.3 Mechanical considerations

There is a tendency for biological systems to attain the ultimate in performance at a minimal cost to the system. Anatomical structure and function have ensured that vertical displacement of the body's centre of mass and inertial changes have been minimized to reduce metabolic energy requirements during walking (Fisher, Gullickson, 1978).

Gait development

Gait describes the manner or style of walking, rather than the walking process itself (Whittle, 1991). Developmental changes in gait continue up to 14- to 16-years of age but are most intense during the first 8 to 10 years of life. Thereafter, only minor changes in spatial-temporal components of gait take place (Norlin et al., 1981).

The most active period in the development of walking appears to be before 4 to 5 years of age (Sutherland et al., 1980; Beck et al., 1981). Sutherland and co-workers (1980) tested 186 healthy children, ages 1 to 7 using five determinants of mature gait: i) duration of single-limb stance, ii) walking velocity, iii) cadence, iv) step length and v) pelvic span : ankle spread ratio. The children were filmed as they walked along a corridor and over a force plate. Increases in duration of single-limb stance, walking velocity, step length and pelvic span:ankle spread ratio occurred most rapidly up to 2.5 to 3.5 years of age. Cadence decreased from age 1 to age 7. This group concluded that mature gait is well established at the age of three years. In agreement with this study, it has been otherwise suggested that, at approximately 3 years of age, children's gait is relatively mature (Sutherland et al., 1988). Evidently, the neuromuscular control and locomotor function are still developing, and will mature well beyond age 3 (Sutherland et al., 1980; Beck et al., 1981; Sutherland et al., 1988). It has also been suggested that children older than 4 to 5 years walk with a gait pattern similar to that of adults (Norlin et al., 1981).

Time and distance parameters and foot-ground reaction forces were investigated in 51 healthy children ages 1 to 14 years, walking at various speeds (Beck et al., 1981). Velocity, stride length, cadence, support time, swing time and dual-limb support time (normalized for height and total cycle time) were found to be dependent on age, but most differences disappeared after the age of two years. After age 5, adult-like patterns of ground reaction forces were seen.

Although we are confident that the adolescents participating in the present study had developed their mature gait well before participation in the study, we would like to point out that even healthy young adults are thought to have fluctuations in their gait cycle duration (the stride time) from one stride to the next (Pailhous, Bonnard, 1992). The extent of these fluctuations is relatively small in adults with intact neural control and seems to decrease with maturation in healthy children (Hausdorff et al., 1999). The temporal structure of gait fluctuations is not fully developed in 7-yr-old children, whereas in older children

(11- to 14-yr-old) stride dynamics approach the values observed in adults (Hausdorff et al., 1999).

Asymmetry, or the unequal progression of contralateral limbs on the sagittal plane, is common in younger children and usually disappears during prepubertal years, assuming normal development (Scrutton, Robson, 1968; Delacerda, Wickoff, 1982). It was assumed there would be symmetry between the right and left limbs in our cohort since it was presumed they would have intact nervous systems. Therefore, we analyzed the right lower limb of our subjects, as being representative of both sides.

Gait cycle

The gait cycle is comprised of the following points: heel contact, foot flat, mid stance, heel off, toe off, and mid swing. With the exception of swing, all the other points are part of the stance phase. In the present study we decided to analyze variables at the time of toe off, or push off, which is the end of stance. This is when individuals are expected to generate high moments and powers especially at the ankle, to be able to push the foot off the ground, and at the hip, to move the leg forward, for the swing phase. It is a critical time of the gait cycle.

During normal walking, a stride cycle is composed of two consecutive steps such that each step makes up approximately 50% of the stride time. Step time is the duration from ipsilateral heel strike to contralateral heel strike (Jeng et al., 1997).

Gait in the obese

In a study by Hills and Parker (1991), obese prepubertal children showed the following differences when compared to normal-weight subjects: a slower walking speed; a lower relative stride length (corrected for height); a lower relative velocity; lower cadence (100 vs. 118 steps per minute); a tendency to spend more time in stance (support) at slow and fast speeds; greater hip and knee rotations at the normal and fast speeds, respectively; greater external rotation of the foot (out-toeing); and consistently higher double stance period at each walking speed. To this author's knowledge, no others studies have analyzed the gait of obese children/adolescents.

Mechanical factors affecting economy of movement

Many mechanical factors have been suggested to have a direct influence on the economy of movement or show significant association with energetically economical movement: leg length, stride length, body centre of mass excursion, energy transfer between segments, net positive mechanical work rate, impact force, foot strike, foot contact time, arm motion, trunk angle of inclination, shank angle, knee flexion velocity in support, and plantar flexion at toe off (Van Der Walt, Wyndham, 1973; Williams, 1980)

Studies that have attempted to relate metabolic cost of locomotion to specific biomechanical variables have generally found weak relationships, at best. In a study with recreational adult runners, an extensive set of biomechanical variables including three-dimensional angular and translational kinematics, ground reaction forces and centre of pressure patterns, mechanical power and anthropometric measures were correlated with submaximal $\dot{V}O_2$. Although several biomechanical variables were positively correlated with $\dot{V}O_2$, the authors suggested that economical running might be more related to the overall combined effect of a large number of variables rather than the effect of only one or two (Williams, Cavanagh, 1987).

Stride frequency

At each speed there is an optimal stride frequency at which the total (external plus internal) mechanical power, and hence the metabolic cost, is minimal (Saibene, 1990).

A freely chosen stride was found to be the most economical, as measured by $\dot{V}O_2$ during walking (Zarrugh, Radcliffe, 1978; Zarrugh, 1981; Fetters, Holt, 1990; Holt et al., 1991; Minetti et al., 1995; Jeng et al., 1997) and running (Knuttgen, 1961; Unnithan, Eston, 1990; Kaneko, 1990). It has been suggested that there is an increase in mechanical work rate at any deviation from the freely chosen stride frequency (Fetters, Holt, 1990; Minetti et al., 1995). In the present study, stride frequency was not controlled in an attempt to have subjects walking as economically as possible. Adopting a natural walking frequency also minimizes asymmetry and variability of inter- and intra-limb coordination (Holt et al., 1991; Jeng et al., 1997). This pattern of optimization appears to be complete at age seven, as a result of synergistic cooperation of the physiological, neural, and musculoskeletal systems (Jeng et al., 1997).

Stride length

A description of preferred stride length and frequency in healthy children and in children with cerebral palsy was reported in a study where efficiency of movement, and self-optimization, were defined and associated with oxygen consumption (Fetters, Holt, 1990). Stride length increases linearly with age, but the relationship between stride length and age becomes constant after adjusting for height or leg length (Beck et al., 1981).

As with stride frequency, normal individuals appear to minimize O_2 consumption when they walk using their preferred stride length (Fetters, Holt, 1990). It has been reported that an optimum stride length to minimize $\dot{V}O_2$ is seen at any given running speed as well (Knuttgen, 1961; Cavanagh, Williams, 1982).

2.4 Dual-energy x-ray absorptiometry

Whole body dual-energy x-ray absorptiometry (DXA) can provide safe, accurate and precise measurements of bone mass and body composition in the majority of *in vivo* applications (Webber, 1995). This technology has been recommended as a reference technique for assessing changes in body composition in children and adults (Lukaski, 1993).

The fat mass measured by dual photon absorptiometry represents the sum of all fat-like elements while the lean mass is the sum of all fat-free, non-mineral tissue elements. In grossly obese subjects, errors might be present due to difficulties in measuring photon attenuation correctly due to excessive mass and fat. Dual photon absorptiometry should be considered as a first choice technique for the non-invasive measurement of body composition during growth (Webber, 1995). It has been suggested that the precision of DXA for percent body fat estimation is greater than that of the underwater weighing which is currently recognized as a 'gold standard' method (Pritchard et al., 1993). As well as giving a total percent body fat measure, this technique presents regional measures of fat and fat-free mass, and regional percent body fat. DXA has been used as a criterion method to validate bio-electric impedance and skinfolds (Wattanapenpaiboon et al., 1998).

The radiation dose involved in the use of photon absorptiometry is so small that it is considered very difficult to measure. With sophisticated techniques, it can be shown that the absorbed dose to the subject is less than 40μGy (Pye et al., 1990). Such a dose is roughly equivalent to the whole body exposure received from natural radiation and radioactivity during 5 days of normal living. According to Cohen and Lee (1979), the general risk associated with eating a calorie rich dessert could be equivalent to that associated with one person having 34 whole body dual photon scans. This comparison shows that whole body photon scanning is a low risk procedure that can be used for sequential *in vivo* measurements.

In summary, there are many aspects to consider when measuring metabolic cost of walking in children/adolescents. Studies to date have failed to provide evidence regarding the contribution of adiposity *per se* to the energy cost of walking, as well as the mechanical influence on walking economy when comparing lean and obese adolescents. Some studies have shown an association between adiposity and energy expenditure but this observation is not consistent throughout the literature. Different gait patterns between obese and lean children were also observed but no attempt has been made to explain the higher energy expenditure in the obese using mechanical variables. The effect of fat distribution in the body on energy expenditure and mechanical gait output has not been investigated.

3. METHODS

3.1 Subjects

Eighteen males between 11 and 18 years of age participated in the study. Pairs of subjects were matched for total body mass but had a different amount of body fat - each pair included an obese and a lean boy. The range of adiposity level was 26-42% body fat in the obese group and 4-23% body fat in the lean group. Therefore, adiposity in the obese group ranged from slight to marked obesity, whereas the “lean” group ranged from a very lean to lean.

The obese subjects were significantly ($p<0.01$) younger and shorter than the lean ones (16.37 ± 1.57 and 12.90 ± 1.49 years and 172.96 ± 7.92 and 159.00 ± 8.18 cm). Body mass was closely matched with group means ± SD of 71.24 ± 15.25 and 71.84 ± 15.49 kg for lean and obese subjects, respectively.

Most of the subjects in the lean group were wrestlers and practitioners of other sports, and 3 of them did not practice one sport in particular, but they played different sports according to time of year and opportunities. In the obese group, most reported sedentary activities during their spare time but they all participated in physical education classes at school and recorded participation in unstructured physical activity for at least 3 hours per week (minimum reported). The overall level of activity in the lean group was higher than the obese group, as expected (see Appendix A for activity questionnaire).

Some obese participants were former or current patients from the Children's Exercise and Nutrition Centre and others were recruited by contact with coaches. None of the subjects had a major disease of the neuromuscular, musculoskeletal, or cardiopulmonary systems. The following conditions were reported in the medical questionnaire: one subject reported Osgood Schlater, 2 subjects complained of chest pain when they exercise, 3 reported cough and one complained of wheezing when exercising; 3 had asthma (one of the wrestlers used Ventalin every 4 h), 5 reported allergies, one boy reported high blood pressure, one had a heart murmur, one subject takes Zoloft (antidepressant - 25 mg daily), one boy complained of knee pain during exercise, and another complained of ankle and leg pain during exercise (this same boy took Effexor, 75mg/day, for depression), one lean boy reported dizziness during exercise and reported hay fever medicine during summer and also had irregular occurrence of bursitis on the ankle, one obese subject reported non-insulin dependent diabetes mellitus and flat foot. None of the above conditions was considered a contraindication for participation in this study. Indeed, with the exception of one asthmatic boy that wheezed and coughed after the $\dot{V}O_2max$ test, none of the other symptoms were noticed by the subjects during their participation in the study; they were only reported in the medical questionnaires (Appendix B). We believe they do not affect the results of the present study.

The study was approved by the Ethics Committee of the Faculty of Health Sciences, McMaster University, Hamilton, ON, Canada. Prior to each subject's participation in the study, verbal assent was obtained and they subsequently signed an informed consent (Appendix C). In the situations where subjects were under 17 years of age, a parent or guardian also signed a consent form (Appendix D).

For their time and effort, study participants received a T-shirt imprinted with the study logo. Parents were reimbursed for travel expenses.

3.2 Study design

This is a measurement study where adolescent boys were selected according to their total body mass and percent fat. Subjects were matched for total body mass while adiposity level varied significantly within each pair. The protocol included two visits to the Children's Exercise and Nutrition Centre and one visit to the McMaster University Medical Centre.

3.3 Protocol

For all visits, subjects wore shorts and T-shirt. For the treadmill sessions, they wore socks and sneakers, while the mechanical gait analysis was performed in bare feet.

During the *first visit,* parent(s) and subject were given an explanation of the study. Measurements of height with a Harpenden wall-mount Stadiometer 2109 (0.1cm accuracy), and body mass with an Ancaster electro-scale model UMC-600 (20g accuracy) were performed. Daily activity was assessed using the activity questionnaire modified from Bar-Or (1983) (Appendix A). Measurement of aerobic fitness was done using a progressive continuous maximal aerobic test on a motor-driven treadmill. The actual protocol varied according to the subject's activity level and expected fitness (Appendix E). Speeds and slopes were adjusted during each test according to subjects' heart rate. Prior to performing the treadmill test, subjects practiced walking and running on the treadmill for approximately 2-3 minutes, or until the investigator decided that the subject had sufficient treadmill exposure to achieve a stable and consistent gait, with minimal step-to-step variability. Most of the subjects had had treadmill experience prior to participating in this study. Nonetheless, they all practised walking and running before the test began. Practice included a slow and a fast walking speed as well as one or two running speeds. Some subjects required more practice than others but all seemed to achieve a stable gait within less than 3 minutes. Heart rate was monitored during the test and recovery periods using a Polar Sports Tester (Polar Electro Oy, Finland). This telemetry-based system detects electrical signals generated by the heart through a transmitter belt worn on the chest and transmitted and displayed on a wristwatch receiver. It is a valid instrument as compared to heart rate determined from ECG (Karvonen et al., 1989; Treiber et al., 1989; Bar-Or et al., 1996; Karvonen et al., 1989).

Attainment of $\dot{V}O_2max$ occurred when two of the following criteria were fulfilled: 1) heart rate higher than 195 beats/min (Bar-Or, 1983); 2) heart rate plateau (plateau defined as less than a 5 beat increase from the penultimate to the final stage); 3) respiratory exchange ratio value equal or greater than 0.98; 4) plateau for $\dot{V}O_2$ values (defined as an increase in $\dot{V}O_2$ in the last full stage equal or less than 2.1 ml/kg.min) (Krahenbuhl et al., 1989; Rowland, 1996); 5) change in gait style showing that the subject was struggling to keep walking or running. We did not expect to see a plateau for $\dot{V}O_2$ values in all cases, according to what has been reported in the literature (Armstrong et al., 1996). $\dot{V}O_2$ plateau has been shown to occur in only about 65% of adolescents tested on a treadmill (Rivera-Brown, Frontera, 1998). Total time for this visit was around 45 minutes.

The *second visit* was always in the morning with subjects fasting for twelve hours, to avoid thermic effects of food when measuring resting metabolic rate. A medical questionnaire was filled out by the subject or his parent describing the boy's medical history and any current medications used, while the subject was waiting to begin the resting measurements. Each subject sat on a chair for at least 12 minutes, prior to the start of resting data collection. This measurement was taken in a sitting position for 5 minutes, as $\dot{V}O_2$ was monitored using a mouthpiece and a low dead-space (50 ml) valve connected to an open circuit system (VMAX Series/V6200, SensorMedics, Yorba Linda, CA). After the resting measurements were completed, subjects were asked to walk in a corridor to find out their comfortable walking speed (CWS). They began and finished walking 2 meters before and after the stopwatch was started and stopped, respectively. This ensured that they would already be at their selected walking speed when they reached the start line and would not slow down as they approached the finish line. An investigator walked slightly behind the subjects. They walked the 30-meter distance four times: we timed all the walks and chose to average the first and third 30m walks. The subjects were told to walk at their normal pace: "Walk at a comfortable speed, the speed that you normally walk (when you are not in a hurry, of course)". They then walked on the treadmill at five different speeds at zero elevation: the obese adolescents walked at 3, 4, 5 and 6 km/h while the lean group walked at 4, 5, 6, and 7 km/h. Both groups also walked at their CWS. The order of speeds was randomly assigned, to eliminate an order effect. The boys picked 5 pieces of paper with numbers on them, representing the 5 different speeds. The between-bout recovery period was eight minutes or until heart rate was less than 100 beats/min, whichever came first (Frost et al., 1995). Heart rate was monitored during gas collection and recovery periods. Subjects walked 4 minutes at each speed, to ensure achievement of steady state (Montoye, 1975). $\dot{V}O_2$ was measured at each breath and 30-sec averages of the last minute of exercise were used to calculate $\dot{V}O_{2net}$.

Calibration of treadmill speed was performed before and after each test. The length of the treadmill belt was measured and the duration for the belt to go around 10 times was timed, giving an accurate speed of the treadmill in km/h. This procedure was done by the same investigator at all times.

Subjects were always asked to walk naturally without holding on to the handrail. Corrections of posture were seldom made, and only occurred during habituation to the treadmill. Once they passed the habituation period there was no need for adjustments, except for reminders to walk in the centre of the treadmill. A single trial was considered a reliable measure of $\dot{V}O_2$ under these testing conditions and care was taken to have similar settings and procedures for all subjects.

For measurement of resting metabolic rate, room lights were turned off and the surrounding environment was kept quiet while subject rested comfortably on a chair. The temperature in the laboratory varied from 19 to 22°C. Total time for this visit was around 75 minutes. The form used in this section is presented in Appendix F.

The *third visit* was at the McMaster University Medical Centre. First, measurement of body composition and mass distribution, using whole body dual-energy x-ray absorptiometry (DXA - Hologic QDR 4500A) was performed. The dual-energy x-ray absorptiometry gives information on total body mass as well as fat and lean mass distributed in the whole body. DXA operates on the premise that a photon emitted from a beam will interact with body tissues and either be absorbed or scattered (Webber, 1995). The system delivers x-rays through a collimated beam to the subject and the tissue in the path of the beam is measured on the other side by a detector. For a whole body scan, the subject is placed on the bed and the DXA scans the body from head to toe. An example of the data output is shown in Appendix G.

For the mechanical data, 14 male subjects 14.85 ± 2.41 years (age range: 11.42 to 18.75 years), body mass: 73.91 ± 15.35 kg (range: 58.09 to 108.36 kg), body height: 166.39 ± 10.45 cm (range: 148 to 181.4cm), were studied. They were of a wide range of body fat: 4.1 to 41.7%. Twelve of those were part of the whole study.

After body mass and fat distribution assessments, subjects went to the Human Movement Laboratory, where a mechanical gait analysis was performed. The gait laboratory used for this study is a state-of-the-art facility which uses an OptoTrak system (Northern Digital Inc., Waterloo, Ontario). A three dimensional system that records translation along X, Y, and Z axes as well as rotations about these three axes. In addition, a flush-to-the-floor mounted force platform (OR6-5 Biomechanics Platform, AMTI – Advanced Mechanical Technology, Inc., Newton, Massachusetts) was used as well as Intel based personal computers to collect and process gait data. A sampling rate of 50 Hz was used for all kinematic data collection.

Data acquisition:

First, anthropometric measurements were taken on the right side of the body, using an anthropometer (Holtain, Ltd.), measuring tape (for circumferences) and a small ruler (for malleolus height) (Table 7 and Appendix

H). These measurements were used to estimate the segment mass, centre of mass, and moment of inertia of the thigh, calf, and foot.

Second, nine reflective markers were placed on seven sites: pelvis (three ireds), greater trochanter, femoral condyle, tibial tubercle, lateral maleolus, heel and fifth metatarsal head. The markers point towards the camera of the OptoTrak System and must be visible at all times during data collection.

Finally, subjects were instructed to walk at their comfortable walking speed and at their fastest walking speed along a 6 meter walkway, with one step (of the right foot) being on the force plate located on the ground.

After establishing the appropriate starting point so that the subject could cleanly hit the force plate, they walked as many times as it was necessary to have 8 good steps on the force platform, for each speed (Appendix I). Special attention was given to naturalness of walking and to maintenance of a constant walking velocity for each selected speed. In addition to temporal and spatial measurements (stride time, stride length, progression velocity) we recorded external kinetics (ground reaction force) and calculated internal kinetic (joint force, moment and power) as well as kinematics (angles in the sagittal and frontal planes, angles in the transverse plane) of the three major joints in the lower extremity.

The subjects walked with their right hand on the left shoulder, to avoid obstructing the markers. Total time for this visit was approximately 75 minutes.

In four cases the order of the visits was not like the one described above, for scheduling convenience of subjects and/or parents. We do not believe this interfered with our results.

4. CALCULATIONS AND DATA REDUCTION

Metabolic calculations:

The O_2 requirement for walking at each speed was determined by averaging $\dot{V}O_2$ over the final minute of each bout. Since one of the assumptions of indirect calorimetry for the determination of energy expenditure is that the subject be in a steady state (Berry et al., 1993), care was taken to be as consistent as possible when analyzing the data. There was one case where steady state was not maintained towards the end of exercise, we therefore used data between 2:30 and 3:30 instead of 3:00 and 4:00 min for calculation of metabolic variables. With the exception of that one case, $\dot{V}O_2$ and RER during the 4th minute of each trial were used to estimate exercise energy expenditure, using an equation created from the data of Robergs and Roberts (Table 6.4 on page 133) (1997). This same equation was used for calculation of energy expenditure during rest:

$$\text{EE (kJ/min)} = \dot{V}O_2^{*} \text{ (L/min)} \times (\text{RER}^{*} \times 1.232 + 3.815) \times 4.184^{**}$$

* average values over the analysis period

** conversion factor for determining energy in kJ from energy measured in kcal

Net energy expenditure (EE_{net}) for each treadmill walking trial was calculated by subtracting resting energy expenditure (kJ/min) from gross, or exercise, energy expenditure (kJ/min).

RER, ventilation, breathing efficiency, and heart rate values for each trial were determined by averaging the data over the same one minute of steady state exercise.

All the metabolic variables during rest were calculated by averaging the values of the two lowest consecutive 30-s averages. HR average was calculated for the respective time in each trial.

Mechanical calculations:

The moments and powers at the hip and ankle presented in the mechanical analysis were generated at push off (end of stance). No analyses of other stages of the gait cycle were performed.

Individual segment masses are related not only to the subject's total body mass but also to the dimensions of the segment of interest. For prediction of segment masses, a multiple linear regression was used, taking into account the density, length and circumference of the segment. In the case of the foot, density, width, height and length were considered. It is assumed that the segment density among subjects is invariant and the linear dimensions are, therefore, the predictors of the segment masses.

The equations used to predict joint centres used 3-D positions of external landmarks and anthropometric data to predict the 3-D positions of internal skeletal landmarks (i.e., joint centres). Coefficients used to derive equations were based on stereo X-rays of one normal subject (Vaughan, 1983).

Resultant force at a joint is the resultant of all the forces acting across the joint, including bone, ligament, and muscular forces. To calculate this resultant force, several factors were taken into consideration. Taking the ankle as an example, the weight of the foot (mass of the foot times acceleration due to gravity), the ground reaction force obtained from the force plate, the mass of the foot, and acceleration of the foot's centre of gravity (obtained from three-dimensional displacement data of external landmarks) were all used to calculate the resultant force at the ankle joint.

The equations of motion are used to calculate the joint forces and moments. The figure presented in Appendix J is an example of factors that are included in the calculation of moments at the ankle. Some of those variables are obtained directly while others are calculated. The left side of the equation, the rate of change in angular momentum, is calculated using principal centroidal moments of inertia (from anthropometric data using regression equations to calculate body segment paramenters) and segmental angular velocities and accelerations (from anatomical joint angles). The ground reaction torque (T_Z) and the ground reaction force (F_R) are obtained directly from the force plate. The force exerted by the calf on the foot at the ankle joint ($F_{R.Ankle}$) is calculated as explained above (resultant force at the ankle joint). The unknown variable in that equation is the moment of the calf on the foot at the ankle joint ($M_{R.Ankle}$). This equation of motion integrates body segment parameters, linear kinematics, centres of gravity, angular kinematics (i.e., angular velocities and angular accelerations) and ground reaction forces (Vaughan et al., 1992).

Analysis of the force plate vertical force data vector was used to estimate the start of the gait cycle (right heel contact). Temporal events for the starting and ending gait cycle frames were obtained from least squares best fit matching of the vertical component of the kinematic marker data in the vicinity of the start of the gait cycle, with that at the predicted gait cycle end point (40% beyond the end of the vertical force data vector at toe-off).

Estimates of the stride time, length, and velocity, 3D ground reaction force and moment, and the 3D joint angle, force, moment and power at the hip, knee and ankle joints were provided from the anthropometric, kinematic and kinetic data. All the angle, force, moment, and power data were then sampled to provide 51 gait data values at each 2% of the gait cycle. Joint powers were calculated by combining the joint moment with the respective angular velocity data. For each subject we have multiple trials (≤8) for each of the two walking speeds.

A major concern of the gait analyst is personalizing the body segment parameters of the individual subject. The following were used in the present study and are crucial when using gait analysis to compare individuals:

- Mass of each segment (thigh, calf, foot)
- Centre of gravity location of the individual segments relative to some specified anatomical landmarks (proximal and distal joints)

- Moments of inertia of the segments about three orthogonal axes, i.e. axes at right angles to one another, that pass through the segment centre of gravity.

Moment of inertia is a measure of the way in which the mass is distributed about the axis of interest. It varies with the mass and the square of length. Moments of inertia were used to calculate the resultant joint moments. In the stance phase, the contribution from the inertial terms to joint moments are very small because the velocity and acceleration of the limb segments are small.

Velocity normalization

Mechanical data were normalized to one walking velocity. Calculation of the moments and powers was done from the two walking velocities using the following equation:

$$\text{Constant} = \frac{\text{target velocity}^{*} - \text{CWS velocity}}{\text{FWS velocity} - \text{CWS velocity}}$$

*target velocity was 1.30m/s based on the subjects' velocities
CWS velocity = comfortable walking speed
FWS velocity = fast walking speed

After acquiring this constant, the actual variable was normalized for its respective value:

$$\text{XNvel} = \text{XN} + [\text{constant} \times (\text{XN FWS} - \text{XN CWS})]$$

XN = variable normalized for total mass and leg length (see below)

XNvel = variable normalized for total mass and leg length, and to the target velocity

This enabled the comparison of moments and powers between the subjects at a pre-determined velocity (1.3 m/s or 4.68 km/h). Since mechanical variables are directly related to walking velocity, the procedure mentioned above was used as means of standardizing the progression velocity and accounting for differences in the subjects' freely chosen velocities (comfortable and fast).

When problems in data collection were detected in any of the two walking velocities, subjects were completely excluded from this segment of the study.

A scaling strategy from Pierrynowski and Galea (1999) was used to reduce inter-subject variability in gait and account for anthropometric differences among the subjects, which can affect the forces and moments applied to the ground (Chao et al., 1983).

The scaling method used in this study is based on the principles of physical similarity, dimensional analysis and muscle properties. In Table 8 a list of variables that were normalized is presented, as well as to what variables they were normalized for.

Statistical Analysis

A *t-test* for dependent samples (paired *t-test*) was used to analyze subjects' anthropometric and physical characteristics. This statistical procedure was used for all comparisons of means between the two groups; always taking into account the fact that subjects were matched and, therefore, not independent.

A two-factor within-subject repeated measures analysis of variance (ANOVA) was used to detect significant differences between pairs of lean and obese subjects for all the metabolic variables. This statistical analysis allows comparison between dependent samples since it is used for a repeated measures design. Probability of making a Type I error (finding differences just by chance) was set at $p<.05$. We also calculated the Pearson product moment (r) for correlations between lean and obese subjects in some of the variables.

A post-hoc test, Tukey honest significance difference (HSD), was used to locate differences among the three walking speeds.

Multiple regression was used to determine the effects of age, height, mass and adiposity on energy cost of walking, combining all subjects into one group.

The ANOVA and t-test calculations were performed using a statistical analysis software program (STATISTICA for Windows, Version 5.0, StatSoft, Inc.). Correlations were calculated using a graphing analysis program (GraphPad Prism for Windows, Version 2.00, GraphPad Software Inc.).

5. RESULTS

Data in this section are presented as means ± SD, unless stated otherwise. Descriptive data of the two groups of subjects are summarized in Table 1. With the exception of total body mass and comfortable walking speed, the means of all other variables were significantly different between the two groups. Total body mass was closely matched between pairs (Table 2) and percentage of body fat was very different between them (Table 3). These were the two main independent variables in this study. Other individual characteristics are shown in Table 3.

PHYSIOLOGICAL VARIABLES

The difference between the two groups in $\dot{V}O_{2net}$ (ml/kg.min) increased with increasing speed. It did not reach significance but we could see a tendency for the obese subjects to spend more energy, especially at 6 km/h (Figure 1). Evidently, each group spent more energy with increasing speed (Figure 10). HSD post-hoc comparison showed that the higher $\dot{V}O_{2net}$ with increasing speed was significant for all speeds. There was a significant difference in $\dot{V}O_2$ even between the speeds of 3 and 4 km/h in the obese group and between 6 and 7 km/h in the lean.

When age and height were used as covariates for the $\dot{V}O_{2net}$ analysis, there was less variation in the mean squares effect, indicating that part of the difference in $\dot{V}O_{2net}$ between the groups was due to these two variables, especially the difference in height. This is a statistical tool to account for differences in certain variables that might affect the results and cannot be manipulated during data collection. For more detailed information on the effect of those variables on the energy cost of walking we analyzed the two groups together, as a whole.

Multiple regression analysis (Table 5) showed that when subjects walked at 4 km/h the variance in the energy cost of walking (L/min) that was due to body fat was 2.1%. It was 21.61% for age and 21.0% for height. At 5 km/h the variance in energy cost of walking due to adiposity increased to 8.4% while the contribution of the others decreased (8.6% for age and 7.6% for height). When subjects walked at 6 km/h there seemed to be a greater influence of fat, accounting for 16% of the variance in energy cost. The contribution of age and height diminished even more at 6km/h: 1.2 and 0.3%, respectively. The contribution of mass to the energy cost of walking was great at 4 km/h (89.1%) and accounted for less variance with increasing speeds (76.3 and 62.1% at 5 and 6 km/h, respectively). This shows that with increasing speed fat became more important in the determination of energy cost of walking in those subjects.

$\dot{V}O_{2net}$ was analyzed in kJ/min using the formula described in the "Calculations and Data Reduction" section. There was a significant difference ($p<0.05$) between the lean and obese pairs in the amount of energy expended when walking at 6 km/h: the obese subjects spent more energy than did the lean

(Figure 2). The difference disappears when the groups are compared as independent samples, as opposed to the dependent pairs, showing that indeed the difference in $\dot{V}O_{2net}$ is between the matched pairs of subjects.

Resting metabolic rate (ml/kg.min) was significantly different ($p<0.01$) between the two groups: 3.45 ± 0.35 vs. 2.99 ± 0.59, for lean and obese groups, respectively. Data for each pair are shown in Figure 3. Once values were analyzed accounting for fat-free mass (ml/kgFFM.min), the lean subjects demonstrated lower ($p<0.01$) RMR than did the obese: 4.11 ± 0.39 and 5.02 ± 0.65, respectively (Figure 4). When age is used as a covariate, no differences are seen between the pairs in RMR (ml/kg.min) and RMR/FFM (ml/kgFFM.min).

Some boys in the obese group were considered to have below average scores for $\dot{V}O_2$max and others around average scores for their age and gender, when compared to published information. All the lean subjects were considered to have around average $\dot{V}O_2$max, according to the same criteria (Figure 5). A $\dot{V}O_{2max}$ test from one lean subject was not used due to problems in the metabolic data and one obese subject did not reach his maximum according to the criteria used in this study. Therefore, data reported for $\dot{V}O_2$max include 7 pairs of subjects.

The obese subjects walked at a higher percentage of $\dot{V}O_{2max}$ than did the lean at all speeds (Figure 6). Again, the difference between the groups increased with increased walking speed and it was statistically significant at $p<0.01$ at all times.

During rest, ventilation was similar between the matched pairs: 8.06 ± 1.37 and 8.41 ± 1.24, for lean and obese groups, respectively. VE (L/min) was significantly different ($p<0.01$) among the three walking speeds for the obese group and between the speeds of 4 and 6 and 5 and 6 km/h for the lean group. Between-pair differences were found when subjects walked at 6 km/h ($p<0.05$). Walking at 4 km/h, ventilation values were 20.77 ± 2.31 and 20.5 ± 3.17 for lean and obese respectively; at 5 km/h 23.5 ± 3.6 and 25.71 ± 4.01; and at 6 km/h 30.39 ± 3.94 and 34.75 ± 6.85. Figure 7 shows the comparison of ventilation between the pairs of lean and obese subjects walking at the three speeds.

Although ventilation did not differ between the groups at the two lower walking speeds, significant difference was found in respiratory rate and tidal volume. Obese subjects demonstrated higher respiratory rate than their lean pairs at all speeds ($p<0.05$ at 4 km/h and $p<0.01$ at 5 and 6 km/h). Tidal volume was significantly lower in the obese subjects at all walking speeds ($p<0.01$).

Post hoc analysis revealed that among the obese subjects respiratory rate was lower when subjects were walking at 4 than 6 km/h ($p<0.01$). Within the lean subjects respiratory rate was significantly lower at 4 km/h compared to 6 km/h ($p<0.01$), and at 5 km/h compared to 6 km/h ($p<0.05$). With increasing speeds the obese subjects had a significant increase in tidal volume ($p<0.01$). The lean subjects also showed increased tidal volume as walking speed increased ($p<0.05$ when 4 and 5 km/h were compared, and $p<0.01$ when 4 and 6 km/h, and 5 and 6 km/h were compared).

Breathing efficiency (using $\dot{V}E/\dot{V}O_2$) was not different between the two groups. When walking at three speeds on the treadmill the obese and the lean groups values for $\dot{V}E/\dot{V}O_2$ were 28.59 ± 2.11 and 27.95 ± 2.94 at 4 km/h, 27.98 ± 2.04 and 26.09 ± 3.75 at 5 km/h, and 28.03 ± 2.44 and 26.20 ± 2.44 at 6 km/h, respectively. There was no difference in breathing efficiency among the three walking speeds.

There was no within -or between-group pattern for respiratory exchange ratio when lean and obese subjects walked at 4, 5, and 6 km/h. Figure 8 shows the RER values for the pairs at each walking speed. There was no difference between the groups in RER, but Tukey post-hoc showed significant difference in RER between the speeds of 4 and 6 km/h and 5 and 6 km/h in the obese group and between 5 and 6 km/h in the lean subjects.

Comfortable walking speed (km/h) chosen by the subjects prior to the test were 4.32 ± 0.4 and 4.55 ± 1.07 (lean and obese groups, respectively). These means were not different between the groups but the range of comfortable walking speeds in the obese group was much wider than in the lean (Figure 9).

Using DXA we were able to determine the fat distribution in body segments: arms, legs and trunk. The lean and obese subjects had similar amount of fat in the legs as a percentage of total body fat. In the arms and trunk the obese subjects had significantly more fat ($p<0.01$) than did the lean (Figure 11). When the same variable is analyzed in absolute terms (grams of fat per body segment as opposed to a percentage of the total fat) the obese subjects have significantly more fat than the lean group in each body segment (Figure 12).

Figures 13a and 13b show the amount of fat and fat-free mass in each body part, as a percentage of the total mass of the segment, in each group. As expected, the obese subjects had more fat than the lean subjects in each body segment. In absolute terms, the legs, arms and trunk of both groups had similar total mass (g).

When $\dot{V}O_{2net}$ was analyzed taking into account the amount of fat in each segment as a percentage of total body fat, no difference was seen between the lean and the obese subjects. This indicates that the energy expended during walking at the three selected speeds is not related to the amount of fat in each body part in relation to total body fat. Figure 14, 15, and 16 illustrates the relationship between $\dot{V}O_{2net}$ and percentage of total body fat in the legs when subjects walked at 4, 5 and 6 km/h, respectively. The relation between $\dot{V}O_{2net}$ and percentage of total body fat in the arms and trunk was similar to that found in the legs. No relationship was found for any of the body segments and any of the walking speeds.

When the relationship between $\dot{V}O_{2net}$ and the amount of fat in each segment (taking the total mass of the segment as 100%) was examined, there was no difference between the groups, even though there was a significant difference in the amount of fat in each body part. Figure 17 shows $\dot{V}O_{2net}$ and fat percentage in the legs when subjects walked at 4 km/h. The same relationship was found for 5 and 6 km/h (Figures 18 and 19). This pattern of inter-group differences occurred also for the other body segments.

Resting heart rate did not differ significantly between the two groups: 68.25 ± 9.04 vs. 76.63 ± 8.31 for lean and obese groups, respectively.

Heart rate for lean and obese subjects was significantly different at each walking speed ($p<0.01$). Walking at 4 km/h, HR (beats/min) for lean and obese groups was 91.33 ± 9.53 and 107.75 ± 6.84, respectively. At 5 km/h HR values were 96.78 ± 9.99 and 117.89 ± 8.15 and at 6 km/h, 107.11 ± 10.55 and 137.33 ± 15.18 for lean and obese subjects, respectively (Figure 20).

MECHANICAL VARIABLES

Our initial goal was to determine the effect of mechanical variables on the energy cost of walking in adolescents. Due to difficulties in obtaining usable data for all subjects, the pair comparison approach was not used in the analysis of mechanical data. The following results are displayed in relation to a continuum of adiposity, ranging from extremely lean to markedly obese subjects.

Figure 21 shows the two walking velocities used by all subjects when instructed to walk at a comfortable and a fast walking speed. Note that velocity is normalized for leg length to the power of 0.5, accounting for length differences, which were fairly variable in our cohort. From the graph we can see that when walking at a comfortable velocity all subjects, irrespective of adiposity level, chose a similar velocity. The same pattern is not shown while walking at the fast walking velocity. The obese subjects tended to have a wider range in freely chosen velocities when walking fast, i.e. they walked the fastest and the slowest, while the leaner subjects had data points closer together, not ranging as much in velocity.

When stride length was normalized for leg length to the power of 1, and to the velocity of 1.3 m/s (Figure 22) similar findings are seen among all subjects. Stride time was mostly similar among the subjects (Figure 23).

Moments at the hip normalized for total mass and leg length to the power of 1.5 and to the walking velocity of 1.3 m/s ranged in the same way for subjects, irrespective of adiposity (Figure 24). In an attempt to see if the amount of fat in the leg would influence the moments generated at the hip to move the leg forward we plotted the hip moment against the fat percent of total leg mass (Figure 25). No relationship was found.

In Figure 26 we can see that the lowest moments at the ankle are shown for the two most obese subjects at the same time as the highest moments are seen for very lean ones. There seems to be a decrease in moments with increasing adiposity level, at least among the obese subjects. Overall there is no relationship between these two variables. Moments are normalized for total mass and leg length to the power of 1.5 and to a walking velocity of 1.3 m/s.

Powers generated at the hip, normalized for total mass and leg length to the power of 0.5 and to the walking velocity of 1.3 m/s, seem to have identical patterns among all subjects, independent of adiposity level (Figure 27). A similar response is seen when the amount of fat in the legs is taken into consideration (Figure 28).

Ankle powers, normalized for total mass and leg length to the power of 0.5 and to the walking velocity of 1.3 m/s, tended to be higher in the obese subjects. Correlation between ankle power and adiposity was low (r=0.39) (Figure 29).

6. DISCUSSION

Our results show that there was a tendency for the obese subjects to spend more energy than the lean ones when walking on the treadmill, at least at 5 and 6 km/h. Indeed, when expressed in kJ/min, the difference became significant at 6 km/h. Our main goal in the biomechanical gait analysis was to determine if there was any variation in gait of subjects who vary in body fat. We were not able to detect any significant correlation, rejecting our hypothesis that the obese subjects would demonstrate a mechanically disadvantageous gait compared to the lean ones. The amount and distribution of fat did not have an effect on either energy expenditure or gait pattern.

Some tables of energy expenditure during various physical activities have been described in the literature (Lusk, 1976; Bar-Or, 1983; McArdle et al., 1986a; Wilmore, Costill, 1994). These tables present values of energy expended according to the activity performed and the persons' body weight and gender. Our concern was to find out if there is a difference in the energy cost of an activity among adolescents with the same body weight but different body composition. Our hypothesis that the obese would expend more energy due to the excessive fat was not entirely confirmed. We cannot say that the difference between the groups when walking at faster speeds was exclusively due to the difference in adiposity level.

It has been implied that because fat-free mass is more metabolically active than fat mass, there might be a variation in $\dot{V}O_2$ that is due to body composition independent of body mass (Walker et al., 1999). In that study it was suggested that a scaling method that controls for each subject's fat-free mass may be more appropriate for adjusting $\dot{V}O_2$ when comparing groups of varying body sizes and composition. We intuitively agree with this assumption but were not able to confirm it in this study. The fact that the obese were younger and shorter than the lean subjects has partly influenced the results. $\dot{V}O_{2net}$ varies with age, and biomechanics of gait, which influences walking economy, depends on individual height. Tall people have longer stride lengths and slower cadences (Zatsiorskii et al., 1994).

A study by Walker et al (1999) found that skinfolds thickness accounts for a variation in walking and running energy cost in adolescents, supporting the paradigm that body composition is a factor in the metabolic response to exercise in children. However, when energy cost was adjusted for body mass through allometric scaling or analysis of co-variance, there was no additional variation in energy cost due to adiposity. In all studies cited, none have attempted to match the subjects for total body mass, and in most cases adiposity has been studied without partialing out the effects of total body mass: the subjects that are fatter are often heavier than the lean ones and it is total body mass that is being compared between the lean and obese groups, rather than adiposity *per se*.

The main consideration in designing this study was to have pairs of subjects matched for total body mass. Ideally, body height and age should also have been matched between the pairs to avoid any possible confounding factors. That turned to be quite impossible with this age group since lean adolescents are not muscular enough to weigh as much as obese individuals of the same age and height. We tested younger boys in the obese group since our lean subjects were often light, and difficult to match with an obese peer for both body mass and age. Because the obese boys were younger than their lean pair, they were also somewhat shorter in most cases. When $\dot{V}O_{2net}$ (ml/kg.min) was analyzed using age and height as covariates, to account for the differences between the pairs, less variation between groups was revealed, indicating an effect of those variables on the energy cost of walking. However, when we used multiple regression analysis to determine the contribution of independent variables (adiposity, age, height and body mass) to the energy cost of walking (L/min), we found that with increasing speed adiposity accounted for a greater portion of the variance of the energy cost of walking while age and height did not improve its predictive power.

Both age and height have been reported to contribute to the weight-relative energy cost of walking and running (Bonen et al., 1979; Krahenbuhl et al., 1989; Ebbeling et al., 1992; Cureton et al., 1997). In a study where 47 male and 35 female adolescents (7-to 16-years old) were tested walking and running on a treadmill, it was concluded that differences in height accounted for only a small percentage of the variation in submaximal oxygen demands of running (MacDougall et al., 1983). A possible explanation for this variation is that younger, and consequently generally shorter children, have shorter strides lengths and higher stride rates. Neither age nor height, though, significantly improved prediction of energy cost in adolescents (12 to 18 years of age) (Walker et al., 1999). In another study where twenty-eight prepubertal boys with diverse athletic abilities underwent progressive maximal treadmill testing, no relationship between economy of running and height was found (Rowland et al., 1988). In that study economy was measured at 9.6 km/h and increasing running speed by 1.6 km/h. The fact that height and age accounted for a small proportion of the variation in $\dot{V}O_2$ of walking in the present study can be due to a relative great range in both variables in a small sample of the population. We found significant differences between the two groups when $\dot{V}O_{2net}$ was normalized for fat mass and fat-free mass, that is probably due to the large difference between the two groups for these two variables.

Contrary to what Ralston (1958) has suggested, we saw a significant increase in energy expenditure between the speeds of 4 and 5 km/h. Indeed, there was a significant increase in energy cost among all walking speeds in both groups. As mentioned earlier, it is well known that walking speed influences metabolic cost of walking (Fellingham et al., 1978; Ebbeling et al., 1992).

It has been shown that at faster speeds walking becomes less efficient. This finding accounts for the observation that, per unit distance walked, the total calories expended are greater at the faster walking speeds (faster than 5 km/h) (Fellingham et al., 1978). We believe this accounts for the greater differences between the obese and lean as the speeds increased. Since the most economical walking speed is the so called "comfortable walking speed" (Martin, Morgan, 1992; Hills, 1994; Minetti et al., 1995; Jeng et al., 1997) we concluded that the similarity between the pairs in energy cost at 4 km/h was due to that speed being close to their normal, or comfortable, or yet optimal, walking speed. As the challenge increased, so did the energy cost. At a higher intensity the differences between the groups appear, indicating that fatness may play a role when obese subjects have a greater challenge.

As expected, RMR was significantly different between the groups (the lean subjects had higher RMR than the obese ones) and that was by virtue of the great differences in fat-free mass, which is the main factor influencing RMR (Cunningham, 1991; Bar-Or et al., 1998). We verified that RMR tended to decrease with increasing age in our cohort and this might explain the higher RMR values in the obese group once data were normalized for fat-free mass. Therefore, we can say that age plays an important role in RMR although RMR depends on fat-free mass. When data are normalized for fat-free mass it is the subjects' age that determines the results.

In agreement with our findings, resting metabolic rate has been shown to be inversely related to age accounting for a portion of the change that occurs with age in the gross oxygen demands of running (MacDougall et al., 1983). A study on running economy also suggested that children had higher RMR than did older individuals (Krahenbuhl, Williams, 1992). It has been demonstrated that relative resting metabolic rate declines during childhood (6-18 years), no matter whether it is related to body mass or body surface area (Rowland, 1990). The reason for the decline in size-related RMR can be partly explained by a decrease in the relative size of the major organs contributing to resting metabolic expenditure (Rowland, 1996).

Because we tested an obese and a lean group, we expected to see differences in aerobic fitness between the two groups but we did not believe these differences would be responsible for possible differences in energy cost of walking. As predicted, the obese subjects were less fit and consequently had to work harder than the lean individuals to perform the same task. The fact that at each speed the obese subjects were walking at a higher relative intensity than the lean ones (Figure 6) did not seem to interfere with the energy cost of walking, at least when they walked at 4 km/h. Functional changes that result from conditioning of the obese person are accompanied by improvements in maximal aerobic power and decreases in oxygen consumption for a given task.

It has been suggested that better running economy is associated with lower submaximal HR (Pate et al., 1992). Our obese subjects had consistently higher HR than the lean subjects (Figure 20) and a tendency to be less economical (Figures 1 and 2). It has been found that obese individuals exercise at a higher percentage of their maximal heart rate (Berndt et al., 1975) and that HR during exercise increases more rapidly in obese than in non-obese individuals (Barta et al., 1968). It is also known that both resting and submaximal HR decline with age (Ebbeling et al., 1992) and the obese subjects were younger than their lean pairs. There are other reasons for the difference in HR: when walking at the same absolute speed, i.e. 4, 5, and 6 km/h, the obese boys were exercising at a higher relative intensity than the lean ones, always at a higher percentage of their $\dot{V}O_2max$ (Figure 6); and the obese boys were less fit than their lean pairs, and consequently, were expected to show higher HR when exercising, even if they were walking at the same intensity as the other group.

As seen with $\dot{V}O_{2net}$, $\dot{V}E$ increased with increasing walking speed and the difference between the groups became significant at 6 km/h (Figure 7). Although ventilation was not different between the lean and obese subjects walking at 4 and 5 km/h, we found significant differences in the two components of $\dot{V}E$: tidal volume was lower and respiratory rate was higher in the obese subjects. There seems to be a decrease in RR up to 10 breaths/min between the ages of 12 and 25 years (Astrand, 1952), which probably did not influence the results of the present study due to a normal variation within subjects of the same age and a smaller range in age than the one studied by Astrand. The RR is normally balanced in such a way that a certain ventilation takes place with utilization of a minimum of energy by the respiratory muscles (Milic-Emili, Petit, 1960).

It is not surprising that obese, less fit subjects, showed lower tidal volume than did the lean, more fit boys. There is an effect of the untrained respiratory muscles not being able to contract as well as those in more fit individuals. The fact that the obese were shorter than the lean probably affected their vital capacity, and therefore, tidal volume. Obese adults have a somewhat reduced tidal volume, excessive ventilation and respiratory rate, as well as alveolar-arterial O_2 difference during submaximal exercise (Dempsey et al., 1966). Obese subjects have been shown to have increased alveolar-arterial O_2 gradients during intense work, but the magnitude of these gradients was not sufficient to warrant the implication of ineffective pulmonary gas exchange as a major limitation to maximum oxygen transport (Dempsey et al., 1966).

Minute ventilation was significantly higher in obese patients (17-to 42-years old) at rest, at zero resistance, and at 20 W. However, when work rates were higher than 20 W (i.e., 40, 60, 80, 100, and 120 W) the differences between the groups did not reach significance (Salvadori et al., 1992). In contrast, in the present study (Figure 7) with increasing work rates the average values of VE were consistently higher in the obese group, reaching significance at the highest speed. The opposite findings might be due to different ergometers utilized in the two studies (cycle ergometer vs. treadmill).

The carbon dioxide production relative to oxygen consumption is different when fats, carbohydrates and proteins are used as fuels. As a result, the amount of oxygen used during metabolism also depends on the type of fuel being oxidized. Our results show that the lean group had a tendency for lower RER values than did the obese, i.e. metabolizing more fat than carbohydrate, at least when walking at 5 and 6 km/h. It is known that fit people tend to mobilize more fat than non-fit individuals (Wilmore, Costill, 1994). Although fat provides more energy than carbohydrate, more oxygen is needed to oxidize fat than carbohydrate. This would lead to a higher oxygen uptake in the lean group. Since no significant differences between the groups in RER were found, we do not consider RER to have influenced the energy cost of walking in our cohort.

The means for comfortable walking speed measured and used for metabolic data analysis were very similar between the two groups. However, the range of speeds was much wider in the obese group (Figure 9). Data analysis for metabolic variables was not performed using CWS since the speeds varied between and within groups and results in energy expenditure would be related to the walking speed, i.e. whoever walked faster would spend more energy. A study with healthy teenagers reported similar CWS to what we found in our cohort (Waters et al., 1983). In that study the mean CWS of 53 males and females, 13 to 19 years old, was 4.38 km/h, very close to the CWS of the lean group in the present study (4.32 km/h).

After having tested some obese subjects in our pilot study, we decided to have the obese boys walk at 3 km/h as opposed to 7 km/h, one of the speeds used for the lean group. It was hard for the obese subjects in the pilot study to walk at 7 km/h without breaking into a run or to hold on to the railing. In the present study, when walking at 6 km/h, some of the obese subjects were exercising at a fairly high percentage of their $\dot{V}O_2max$ (Figure 6). The lean subjects did not find it difficult to walk at 7 km/h. In contrast, 3 km/h is very slow and seemed inadequate for lean (and active) adolescents from our pilot study. Our lean subjects were also taller than the obese. It was therefore easier for them to walk faster.

Comfortable walking speeds on the ground and treadmill may not be the same (Jeng et al., 1996). Different age groups were tested previously, ranging from 3 to 21 years of age, and for all of the age groups preferred walking speed on the treadmill was significantly lower than the overground speeds (Jeng et al., 1997). One study failed to clearly identify differences between treadmill and overground running styles (Williams, 1985). Treadmill running at a given speed, however, has generally been shown to result in lower $\dot{V}O_2$ than overground running (Morgan et al., 1989; Williams, 1990). Because of air and wind resistance, the aerobic demands of indoor treadmill running significantly underestimate the cost of overground running, especially at higher speeds (Morgan et al., 1989). Therefore, the energy cost of walking measured in the present study might be underestimated when compared to outdoor walking. When different methodologies are used to compare walking at different settings, it is difficult to clearly determine which results are accurate. For instance, should one use the same absolute speed to compare economy in the two different running modes?

A relation between adiposity and an external load can be assumed since fat is considered to be an inert, non-metabolic, load. A study was undertaken to examine the energy cost of prolonged walking while carrying a backpack. Six trained adults were tested while walking for 120 min on a treadmill at a speed of 1.25 m/s and 5% elevation with a well fitted backpack load of 25 and 40 kg alternately. Carrying 40 kg elicited a significantly higher ($p < 0.01$) energy cost than with 25 kg (in absolute values and relative to total body mass). The study implies that increase in load causes physical fatigue, once work intensity is higher than 50% maximal work capacity (Epstein et al., 1988). Because five of the obese subjects in the present study walked in excess of 50% of $\dot{V}O_{2max}$ at 6 km/h while all the lean were walking at a intensity lower than 40% of $\dot{V}O_{2max}$ (Figure 6) we can assume that this is one of the reasons for inter-group difference at 6 km/h. It might happen due to altered gait and disadvantaged biomechanics, which in turn could lead to the increase in energy cost. Unfortunately, we are not able to directly address this question with the present results.

It has been suggested that the energy cost of walking with a load increases proportionally with the load. However, walking at low speed with a load not exceeding 5-10 per cent of the body weight is not more expensive than unloaded walking (Saibene, 1990). Moreover, it has been observed that African women walking at their optimal speed can carry on their heads loads of up to 20 per cent of their body weight without any extra cost (Saibene, 1990). This can help explain the similarity in energy expenditure between our two groups when walking at 4 km/h: because subjects walked at a speed close to their optimal, an increased load (increased amount of fat in this particular case) did not cause a difference in energy cost.

It has been suggested that a potential mechanical source for individual differences in economy is the difference in the distribution of mass among limb segments (Cavanagh, Kram, 1985). Considerable variation can exist in the distribution of segmental mass between individuals with identical total body mass. Persons who have a greater fraction of body mass in the limbs may tend to have a greater $\dot{V}O_2$max because of a greater active muscle mass (Pate et al., 1992). During walking and submaximal running, these same persons would tend to manifest higher $\dot{V}O_2$ and, therefore, expend more energy, because of the increased energy cost of moving the relatively heavier limbs (Myers, Struedel, 1985). Carrying an extra load placed on an extremity has been suggested to increase the oxygen cost as compared to placing the load in the trunk (Cureton, Sparling, 1978). From the DXA measurements we can confirm that our obese subjects had a higher percentage of their total body fat in the arms and in the trunk as compared to their lean pairs (Figure 11). We performed further analysis to investigate the effects of higher percent fat in the arms on the energy cost of walking. As seen in Figures 14-16, there is no influence of the amount of fat in the limbs on the $\dot{V}O_2$ of walking. When $\dot{V}O_2$ was plotted against percent fat of arms, legs and trunk mass, no relationship was found, indicating that the amount of fat and fat-free mass in the limbs does not affect the energy cost of walking. That was true for all walking speeds.

Although the mass of each body segment was very similar between the groups, the obese group has consistently more fat than the lean group, in each of the segments analyzed (arms, legs, trunk) as one would expect (Figures 13a and 13b). When $\dot{V}O_2$ and the amount of fat per segment were analyzed, no relation was found (Figures 17-19). These variables might have somewhat affected the energy expenditure but not enough to detect a difference between the groups.

Buskirk and Taylor (Buskirk, Taylor, 1957) contended that “the presence of excess fat *per se* does not have any important influence on the capacity of the cardiovascular system to deliver oxygen to muscles under maximal performance conditions”. A study with adolescent girls with a wide range of percent body fat failed to identify any evidence of physiological impairment due to obesity during maximal or submaximal treadmill walking (Rowland, 1991). It has also been suggested that the cardiorespiratory-circulatory oxygen delivery system is reasonably normal in the obese (Buskirk, 1969).

Different factors have been documented to influence the energy cost of walking. In addition to all of those mentioned earlier, we should also refer to a few more: state of relaxation, ambient temperature, wind, treadmill slope, circadian rhythms, surface compliance, shoe weight and shoe softness (Frederik, 1985). Although we used a controlled climate and tried to create identical conditions for all subjects at all trials, the intrinsic factors (e.g., state of relaxation, body posture) were not manipulated and many variables were not measured. It is important to note that the metabolic and mechanical variables were collected on different locations and days. One advantage to this is that all instrumentation involved in the mechanical data collection did not interfere in the metabolic responses to exercise, and vice versa.

Other factors that have been suggested to affect energy expenditure are muscle fiber type distribution (Coyle et al., 1992), and training modality of the subjects (Stuart et al., 1981). Six of the nine lean subjects that participated in the present study were wrestlers. Since the task required of our subjects in this study was walking, it is unlikely that sports specialty, or the lack of participation in sports, would bias the results. We have no information on their fiber type distribution, or activation.

It is not unreasonable to suppose that there is variability between individuals, even between those of the same body size, in the distance of the insertions of key muscles from joint centres. The origin and insertion of a muscle defines the angle of pull of the tendon on the bone and therefore the mechanical leverage it has at the joint centre. Each muscle has its unique moment arm length. This moment arm length changes with the joint angle (Winter, 1990). This will change the mechanical advantage of the joint and presumably would affect the energy required to perform a given movement (Cavanagh, Kram, 1985). We were not able to test individuals of similar body height or limb length, which has a great influence on biomechanical variables. Height was accounted for, at least partially, by normalizing data for leg length.

Kinetic analysis allows us to determine the magnitude of the moments and forces on a joint produced by factors such as body weight, muscle action, soft tissue resistance, and externally applied loads in any situation, either static (at rest or at a constant speed) or dynamic (an accelerating or decelerating body). It also allows us to identify those situations that produce excessively high moments or forces (Nordin, Frankel, 1989). The walking velocities utilized might not have been the best approach to allow us to determine the effect of body fat on gait mechanics. Had we challenged the subjects more intensely by having them walk faster at a determined velocity, it may have been possible to confirm the stated hypothesis. We only saw differences in energy expenditure at the 6 km/h and the mechanical variables might have had a similar pattern, and even have influenced the energy cost.

Despite the belief that biomechanical factors help explain energy economy differences between individuals, it is not fully apparent to what extent these differences can be attributed to biomechanics nor how consistently biomechanical variables explain these differences (Martin, Morgan, 1992). As mentioned earlier, running economy has been suggested to be more related to the overall combined effect of a large number of biomechancial variables rather than the effect of only one or two (Williams, Cavanagh, 1987). This author believes that to be true for walking as well.

In the present study we were not able to detect differences in the mechanical gait parameters, among the subjects who varied in the amount of adiposity. We now believe that choosing selected biomechanical variables at one point of the gait cycle at which to compare the two groups might not have been the best approach. No attempt to correlate the gait data with the metabolic variables was made due to different subject representation in each segment of the study and different methodologies used (e.g. controlled walking speed on the treadmill vs. freely chosen walking speed on the ground).

Because of the great intra-subject variability normally seen in any gait analysis, a much bigger sample size would be necessary to identify possible differences among subjects. Different moment patterns of the hip and knee during stance were found for nine repeat trials on the same subject whose lower limb kinematics were extremely consistent (Winter, 1989). Power production on the other hand, showed little individual variation when 25 men and 25 women, ages ranging from 19 to 74 years, walked at a self selected velocity (Iida, Yamamuro, 1987). It has been suggested that assumptions made about energy transfers and the relative metabolic cost of positive vs. negative work normally cause large variations in mechanical power values (Williams, Cavanagh, 1983).

The key to understanding the way in which human beings walk is integration. This means that one should strive to integrate the following components: anthropometry, segment kinematics, ground reaction forces and electromyography.

The ability of the central nervous system to control motor patterns is what influences the mechanical efficiency. The motor patterns that we looked at (joints moments and powers) are neurologically controlled. Only at the joint level can one see the algebraic summation of all muscle forces and therefore be able to identify the final desired pattern of the central nervous system (Winter, 1989). How adiposity influences this gait pattern is yet to be determined.

Examples of individual gait cycle outputs are shown in appendices K and L. There, moments and powers at the hip, knee and ankle are shown. As seen in those graphs, intra-subject variability is different in each case. Each point at the cycle shows the mean and SD for all the walking trials performed (≤8). When the two figures are compared we can see that the moments on Appendix K (a lean subject walking at a fast speed) had much lower between-trial variability than the ones on Appendix L (an obese subject walking at a slow speed). The moment at the ankle joint is largely determined by the ground reaction force.

As seen in Figure 30, two lean subjects demonstrated very low power at the ankle at push off. We suggest that the lower power was due to a different pattern of power generation in those two subjects: they generated more power at the ankle at the beginning of stance as opposed to at push off, when the power generated was much lower. Appendix K exemplifies this for one of the subjects.

As mentioned earlier, both kinematic and kinetic parameters of gait have a significant dependency on subject walking velocity. Hip flexion-extension, stride length, hip resultant force, hip resultant moment, and hip contact force all increase with increasing velocity (Crowinshield et al., 1978). In describing gait ability, velocity is the most important factor to measure because (a) it is the most descriptive variable and (b) all other variables are correlated to velocity, and, therefore, the analysis of each observed variable must be related to the actual velocity (Norlin et al., 1981). Since the walking velocity was not controlled in this study, we normalized the forward velocity to 1.3 m/s, in which moments and powers at the hip and ankle are corrected for, so that all results are presented for all subjects at the same velocity (see "Calculations and data reduction" for details). That velocity was chosen according to the velocities acquired from our cohort.

Leg length may be a means of normalizing walking speed for children and adults (Ebbeling et al., 1992). From comparisons using linear regressions, it has been concluded that for children younger than 8 years velocity and stride length are mainly dependent on age and for older children on leg length (Norlin et al., 1981). The literature provides several conflicting strategies to reduce gait data variability through the use of scaling methods for specific anthropometric measures. The practical application of a reduced inter-subject variation increases the ability of a statistical tool to detect inter-population differences (Pierrynowski, Galea, 1999). Since scaling for body mass and leg length performed much better than leg length alone, that scaling strategy was considered the best method to reduce inter-subject variation for joint force, moment and power outputs and it was used in this study (Pierrynowski, Galea, 1999).

Stride length increases linearly with age, but the relationship between stride length and age becomes constant after adjusting for height or leg length (Beck et al., 1981). As children get older, increase in stride length, at the same time as decreases in stride rate, are both associated with the greater height of older children (MacDougall et al., 1983; Zatsiorskii et al., 1994). In this study, when stride length was normalized for leg length it was not the taller subjects that showed a tendency for higher stride lengths (Figure 23).

Excessive mass and girth of the thighs is likely to change stride length and rate due to morphological limitations. That was not seen in the subjects that participated in this study, probably because they were not sufficiently obese to demonstrate this implication of excessive mass and adiposity.

By having the subjects walk at a freely chosen velocity, and therefore a natural walking frequency, mechanical work was likely reduced as compared to what it would have been if it had been imposed (i.e., when walking on a treadmill).

The effects of stored elastic energy in muscles and ligaments, co-activation of antagonist muscles, muscle fiber type, and isometric work done were not taken into consideration in the present study. It has been found that there is an age-related difference in co-activation in thigh and calf muscles even when adolescents 10-12 and 15-16 years old were compared, contributing to the higher energy cost of walking and running in the younger group (Frost et al., 1997b). Muscle activation in obese people is extremely difficult to measure due excess mass and fat in each body part which makes it hard to find the correct location for placement of electrodes and not to have too much interference due to extra skin movement.

Study Strengths and Limitations

Strengths

This study was unique as it was the first to measure the effects of adiposity *per se* on the energy cost of walking, having the subjects matched for total body mass. As well, having information on the mass and fat distribution and correlating these variables with energy expenditure was another unique aspect of this study. Our findings are relevant in that we were able to compare the energy cost of walking between the lean and obese pairs, and find that fat might indeed play a role when subjects walk faster than their comfortable walking speed (in this case, at 6 km/h).

Limitations

Because our measurements are on dependent samples, i.e. repeated measures, it is not possible to eliminate the influence of age and height. We did see a variation in energy cost of walking due to these variables and that was when the two groups as a whole, as opposed to the matched pairs, were compared. We were not able to use those two variables as co-variates considering the fact that the boys were matched for total mass.

The challenge of getting matched pairs of subjects made it really hard to find a greater number of participants for the study. We believe that a larger sample size was needed to have a higher statistical power for some of the variables. Other variables, though, like $\dot{V}O_{2net}$ (kJ/min) when subjects were walking at 6 km/h, showed high power (0.7), due the greater differences between the pairs. On the other hand, when differences between pairs were small, the statistical power dropped markedly.

When the study was planned, it was intended to include adolescents 15- to 18-years of age. Due the difficulties in finding obese volunteers of a similar body mass to that of the lean volunteers, the age range had to be increased to 11-18 years. In this case, it would have been interesting to know the subjects' Tanner stages since it has been suggested that the stage of maturation may effect energy cost of locomotion more than age itself. However, we did not determine Tanner stage.

The fact that energy cost was measured on the motorized treadmill limits the applicability of these findings to this mode of locomotion, and we cannot extrapolate the results to walking on the ground. The study aimed to determine the effect of adiposity on the energy cost of walking and not the amount of energy expended for a population exercising outdoors. Indeed, this factor limits the application of the results.

Monitoring oxygen consumption during walking ignores the anaerobic aspects of exercise and the excess post-exercise oxygen consumption. This is the energy expended during the recovery period. Therefore, the total cost of an activity will exceed that measured during the activity, increasing the amount of energy expended. The excess post-exercise oxygen consumption was not measured in the present study, therefore, we are not able to calculate the total energy expended due to the physical activity.

Even though wearing a respiratory apparatus does not seem to affect energy cost of locomotion, it might make a difference in the freely chosen walking speed. In the present study subjects were not wearing the gadgets used later for metabolic and cardiovascular data collection, when comfortable walking speed was measured. Since we did not use CWS for comparison between groups, this issue is only acknowledged here for further studies on the topic.

Marker-related sources of error include incorrect placement with respect to the anatomy, skin and soft tissue motion (especially in the obese), marker drop-out due to limb swing, trunk rotation, and marker vibration. The location of the markers with respect to anatomical landmarks is critical to the overall accuracy of the system (Harris, Wertsch, 1994). In the present study there were a few cases of excessive noise that might have been caused by soft tissue motion as well as marker drop-out that we were not able to detect during data collection. In those cases, data could not be used and therefore the number of subjects with usable mechanical data dropped markedly. The result is a major limitation for the study since we were not able to maintain the original design of comparing pairs of subjects matched for total body mass. Due to all difficulties encountered in the data collection of the mechanical segment, 6 subjects had to be excluded from this part of the analysis.

The small yield of mechanical data did not allow to determine whether, in matched pairs, differences in metabolic cost of walking could be explained by mechanical variables. We recognize that some error might have occurred in measurements of body segments due to lack of experience of the investigator taking the measurements and difficulties of finding certain anatomic points especially in the obese subjects.

The fact the mechanical data were analyzed at only one point of the gait cycle has certainly limited the chances of finding possible relationships between moments and powers and adiposity level.

Walking velocity was not controlled for the collection of mechanical data, which poses an important limitation, since the mechanical variables are dependent on velocity. Since we were not able to control the walking velocity at the Human Movement Laboratory, a normalization was performed to account for the differences in walking velocity among all subjects. Ideally, walking velocity should have been dictated by the investigators.

7. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. Obese adolescent boys tend to spend more energy than their lean pairs, matched for total body mass, when walking at speeds faster than their comfortable walking speed. When $\dot{V}O_2$ was expressed in kJ/min, the obese showed significantly higher energy cost of walking at 6 km/h.
2. Both lean and obese groups showed an increased energy cost of locomotion with increasing walking speeds.
3. When subjects were analyzed as a group, body mass was the main predictor of EE. Variance explained by adiposity increased with increasing speeds.
4. Ventilation showed the same pattern as $\dot{V}O_{2net}$. There was an increase with walking speeds and differences between the pairs became greater at the two fastest walking speeds.
5. The obese subjects demonstrated a higher heart rate and exercised at a higher percent of $\dot{V}O_{2max}$ than their respective lean pairs at all walking speeds.
6. The amount of fat in each body segment as a percent of total body fat did not affect the energy cost of walking in either group at any walking speed.
7. The same finding was demonstrated when the amount of fat in each segment was analyzed, as a percent of the total mass of the segment.

8. None of the mechanical variables analyzed, i.e. moments and powers at the hip and ankle at push off, seemed to be affected by the amount of total body fat or body fat in the legs (in the case of hip analysis) in lean and obese subjects when data were normalized for a walking velocity of 1.3 m/s.

RECOMMENDATIONS FOR FUTURE RESEARCH

There are many unanswered questions regarding the energy cost of locomotion in children and adolescents of a wide range of adiposity. The following points represent the interests of the author in this topic:

- Application of biomechanical variables to the energy cost of locomotion

Testing metabolic and mechanical variables simultaneously allows to determine how much variation in energy expenditure is due to mechanical aspects. Using a complete mechanical gait analysis in children/adolescents matched for body mass and/or body height, will permit to identify which point of the gait cycle affects energy expenditure and by how much.

- Comparison of the energy cost of faster walking and running in lean and obese groups

The fact that at faster speeds the difference between the groups was augmented suggests that at faster speeds fat may play a role in the energy cost of walking and maybe even more so during running. Using the same protocol and design as in the present study, but at a wider range and more challenging walking speeds, would help to address this question. Ideally, age, height and fitness level should also be matched between the groups.

- Determine effects of relative walking speeds on the energy cost of walking

It has been well established that energy cost of walking increases with increasing walking and running speeds. It is not known whether it is the absolute speed or the high percentage of the fastest speed, or yet the high percentage of $\dot{V}O_{2max}$ at a certain speed, that triggers the higher metabolic cost of walking.

- Refine methods to determine comfortable walking speed on the treadmill

Although measurements taken on the treadmill cannot be directly applied to the ground, treadmill protocols allow practical and safe data collection for physiological and biomechanical variables during walking and running. Improving methods for determining CWS on the treadmill would increase validity of results.

- Determine mechanical and metabolic changes after weight loss

It would be interesting to determine differences in mechanical variables due to weight loss that consequently may affect energy cost of locomotion and mechanical gait paramenters.

- Identify the most informative point during gait cycle in relation to EE

We hypothesized that obese and lean subject would have greater differences in moments and powers at push off and preparation for swing. Maybe there is another element of the gait cycle that is more relevant when comparing the gait of lean and obese individuals. That has yet to be investigated.

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Table 1: Groups characteristics (mean ± SD)

	Lean	Obese
Age (years)	16.37 ± 1.57*	12.90 ± 1.49
Body mass (kg)	71.24 ± 15.25	71.84 ± 15.49
Body height (cm)	172.96 ± 7.92*	159.00 ± 8.18
Body fat (%)	9.13 ± 5.19*	36.58 ± 5.37
VO_2max (ml/kg.min)	47.49 ± 5.12*	29.65 ± 6.04
Comfortable walking speed (km/h)	4.32 ± 0.40	4.55 ± 1.07

*p<.01

Table 2: Individual total body mass (kg) for pairs of subjects

Pair #	Lean	Obese
01	108.36	109.46
02	63.30	63.70
03	65.34	66.60
04	75.78	77.42
05	58.14	58.09
06	70.60	69.32
07	74.14	76.10
08	58.28	61.00
09	67.26	64.88

Table 3: Individual age, height, body fat, and $\dot{V}O_{2max}$ for pairs of subjects matched for total body mass

	Age (years)		Height (cm)		Body fat (%)		$\dot{V}O_{2max}$ (L/min)	
Pair #	Lean	Obese	Lean	Obese	Lean	Obese	Lean	Obese
1	17.75	16.58	179.6	177.6	15.9	35.3	N/A	2.82
2	14.50	13.00	165.3	159.8	7.6	35.6	3.34	2.33
3	17.25	12.67	167.0	163.6	5.5	25.5	3.09	2.53
4	15.92	12.33	167.3	157.0	14.7	41.0	2.84	2.40
5	14.50	12.33	163.9	148.0	4.9	38.8	2.59	1.59
6	15.08	11.42	169.2	153.8	4.1	41.5	3.28	1.77
7	18.75	12.92	178.3	158.2	17	41.7	3.48	N/A
8	17.83	13.08	181.4	157.7	5.4	38.4	3.58	1.99
9	15.75	11.75	184.6	155.3	7.1	31.4	2.99	1.78

Table 4: VO_2 (ml/kg.min) values for each group, walking at 5 speeds. Mean ± SD

Speed (km/h)	Lean	Obese
3	-	5.35 ± 0.57
4	7.19 ± 0.41	7.11 ± 0.57
5	9.44 ± 0.95	9.96 ± 1.05
6	13.19 ± 1.92	14.43 ± 1.39
7	17.32 ± 1.04	-
CWS	7.98 ± 1.29	8.94 ± 3.34

CWS = Comfortable walking speed

Table 5: Predictive power of adiposity (%), age (years), height (cm) and mass (kg) on the energy cost of walking (L/min), based on multiple regression

Speed (km/h)	Variable	Predictive power (%)
4	Adiposity	**2.1**
	Age	21.6
	Height	21.0
	Mass	89.1
5	Adiposity	**8.4**
	Age	8.6
	Height	7.6
	Mass	76.3
6	Adiposity	**16.0**
	Age	1.2
	Height	0.3
	Mass	62.1

Table 6: Heart rate (beats/min) of lean and obese groups walking at 5 speeds on the treadmill. Values are mean ± SD.

Speed	Lean	Obese	P
3	-	101.75 ± 6.30	-
4	91.33 ± 9.53	107.75 ± 6.84	<0.01
5	96.78 ± 9.99	117.89 ± 8.15	<0.01
6	107.11 ± 10.55	137.33 ± 15.18	<0.01
7	120.50 ± 10.52	-	-
CWS	91.22 ± 7.48	115.78 ± 12.04	<0.01

Table 7: Description of anthropometric parameters and how they were measured

Parameter	Description
Body mass	Measure of mass with subject wearing shorts and T-shirt
Anterior-superior iliac spine breadth	Horizontal distance between the spines
Thigh length	Vertical distance between the superior point of the greater trochanter and the lateral femur condyle
Mid-thigh circumference	With a tape perpendicular to the long axis of the thigh, measure the maximum circumference
Calf length	Vertical distance between the superior margin of the lateral tibia and the lateral malleolus
Calf circumference	With a tape perpendicular to the long axis of the calf, measure the maximum circumference
Knee diameter	Maximum breadth of the knee across the femoral condyles
Foot length	Distance from the posterior margin of the heel to the tip of the longest toe
Malleolus height	Vertical distance from the floor to the lateral malleolus
Malleolus width	Maximum distance between the medial and lateral malleoli
Foot breadth	Breadth across the distal ends of metatarsals I and V

Table 8: Variables obtained from the gait analysis and their normalization factors used in the present study

Variable	Normalize for
Stride time	leg length$^{1/2}$
Stride length	leg length^{1}
Progression velocity	leg length$^{1/2}$
Joint moment	total mass x leg length$^{3/2}$
Joint power	total mass x leg length$^{1/2}$

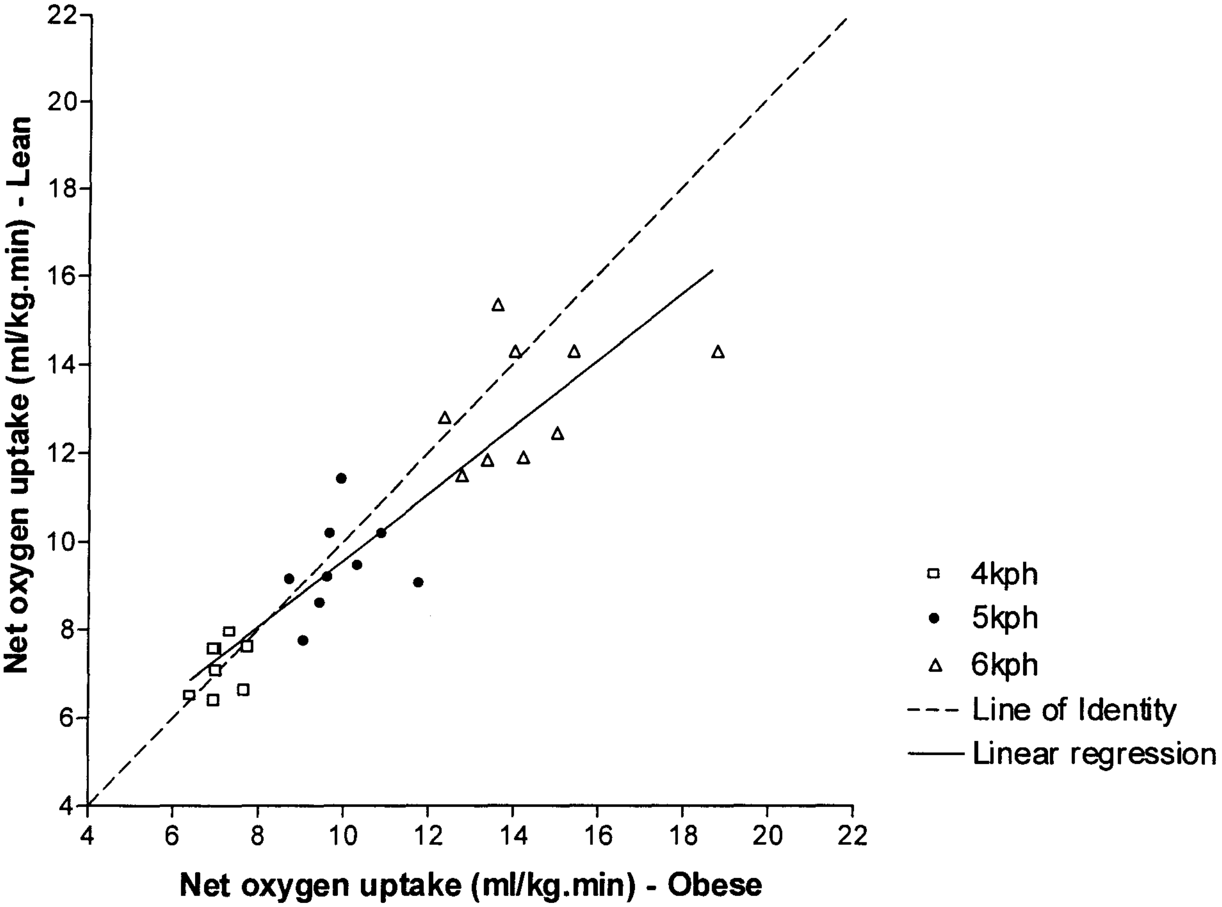


Figure 1: $\dot{V}O_{2net}$ for 9 pairs of lean and obese subjects walking at 3 absolute speeds

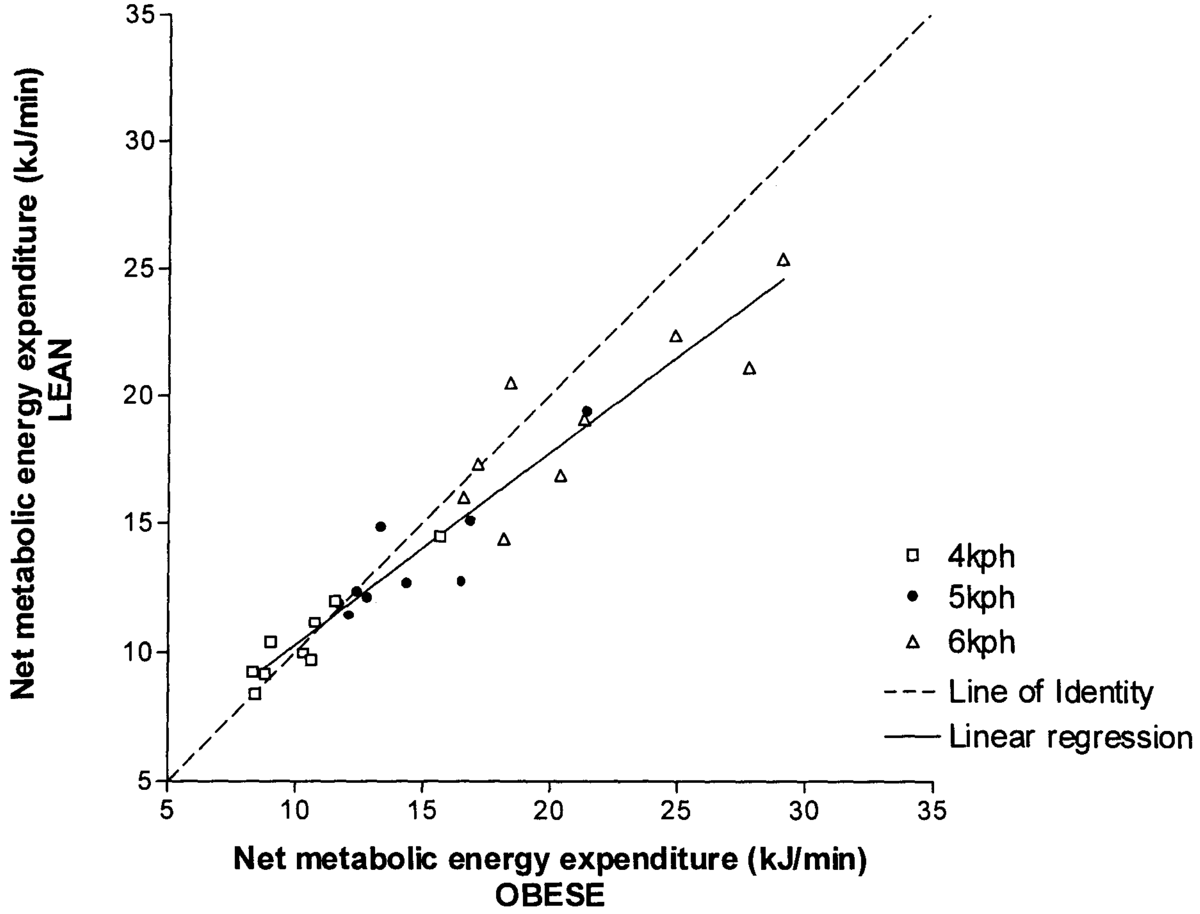


Figure 2: Metabolic energy expenditure for 9 pairs of lean and obese subjects walking at 3 absolute speeds

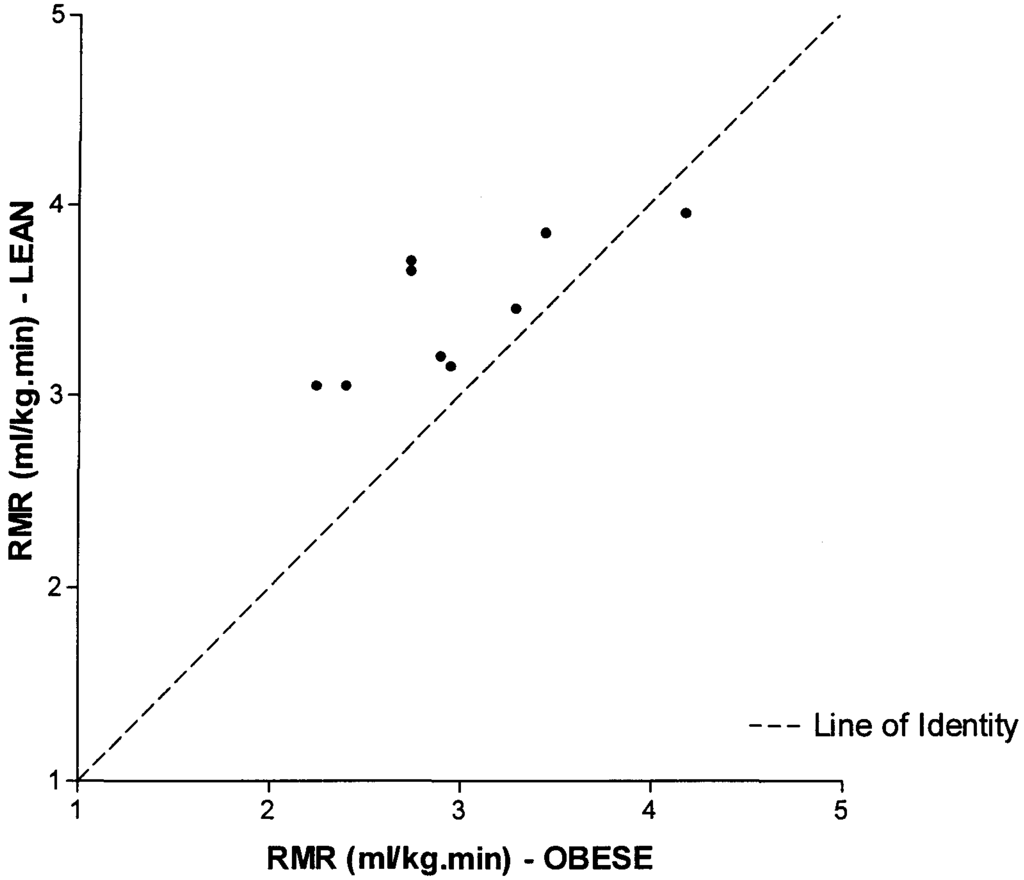


Figure 3: Resting metabolic rate in 9 pairs of lean and obese adolescent boys

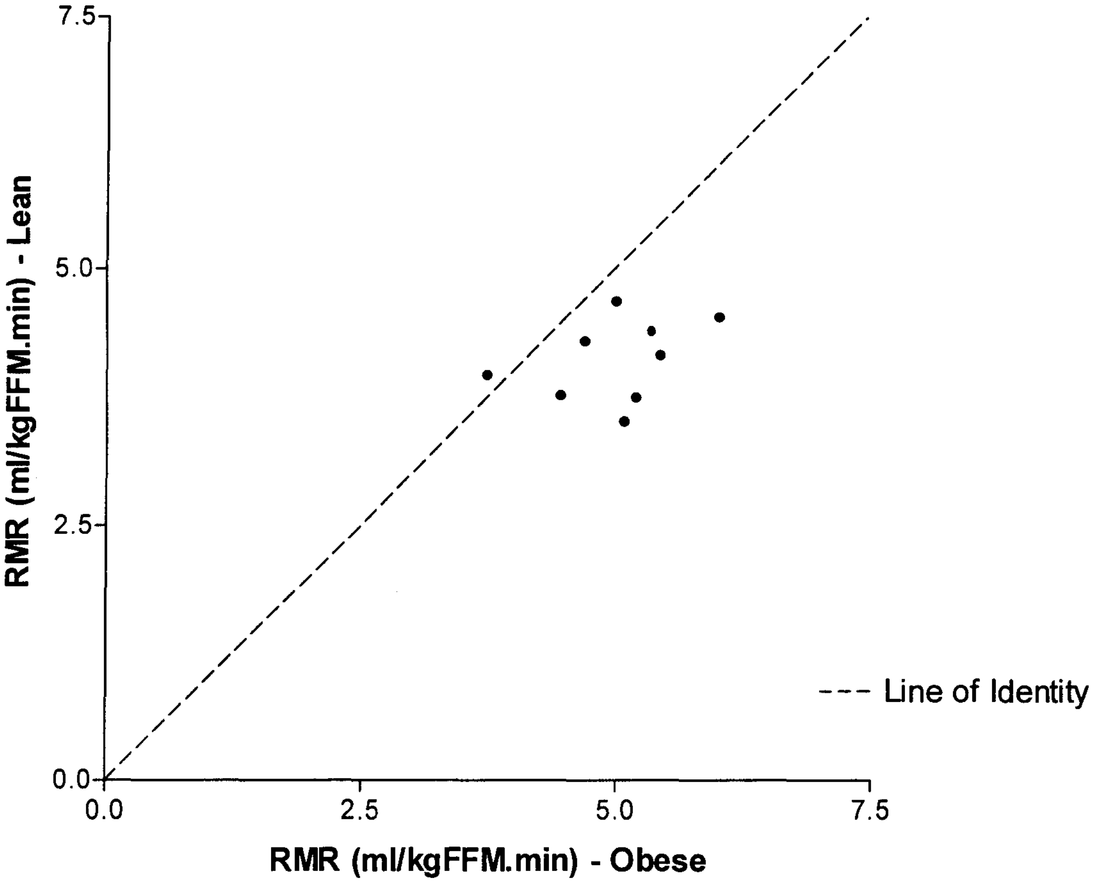


Figure 4: Resting metabolic rate in 9 pairs of lean and obese adolescent boys

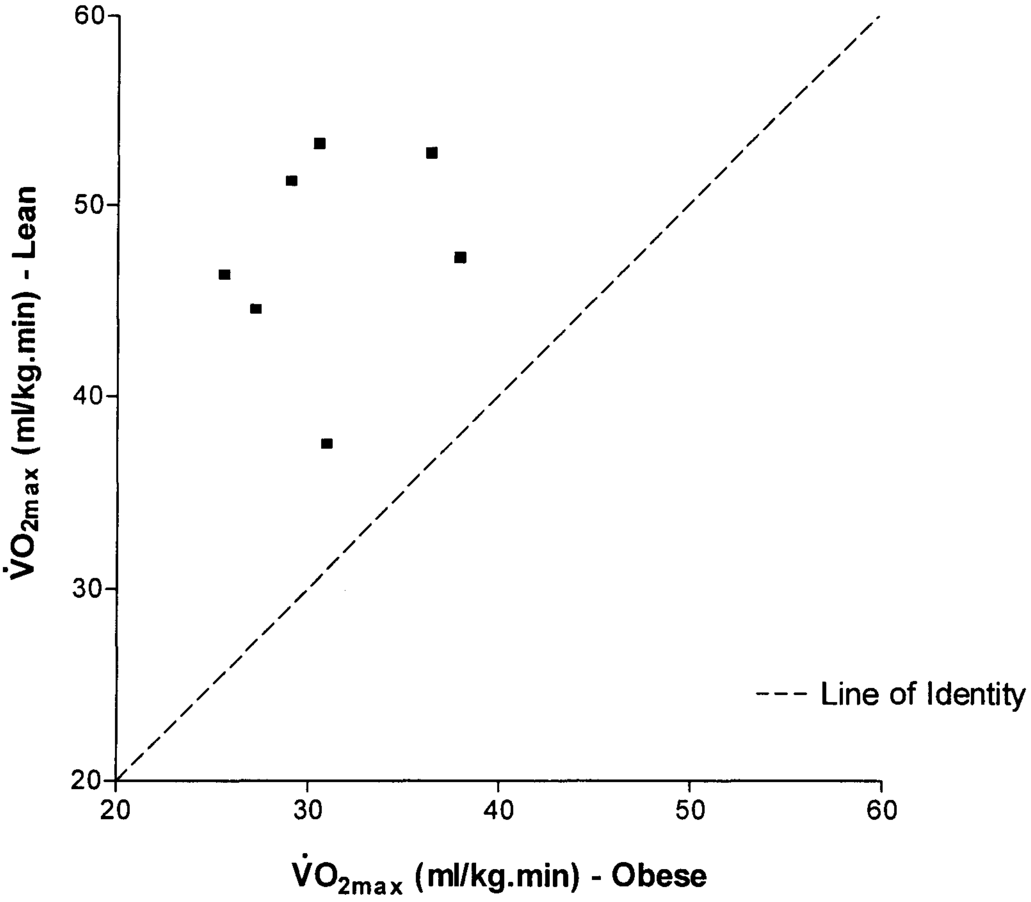


Figure 5: $\dot{V}O_{2max}$ in 7 pairs of lean and obese subject.

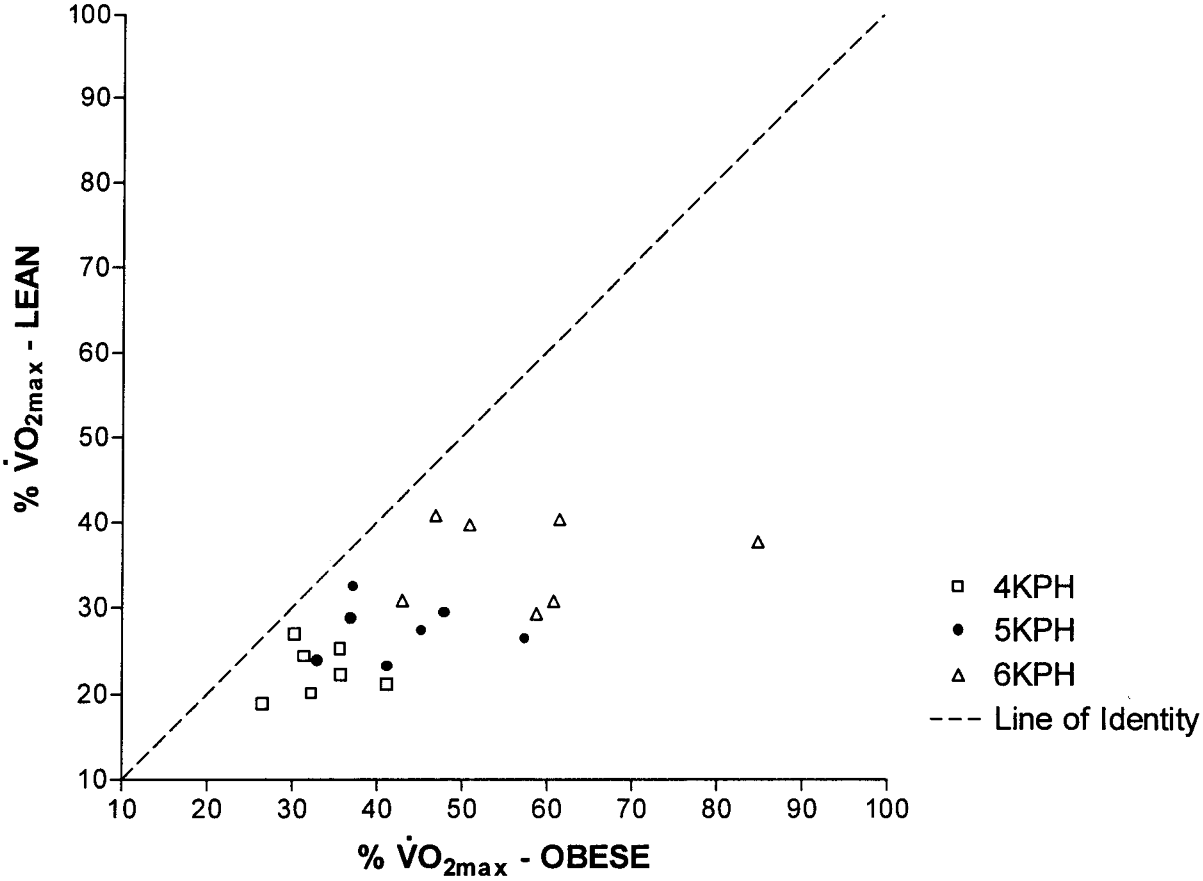


Figure 6: Percent $\dot{V}O_2$max of pairs of lean and obese subjects walking at 3 absolute speeds on the treadmill

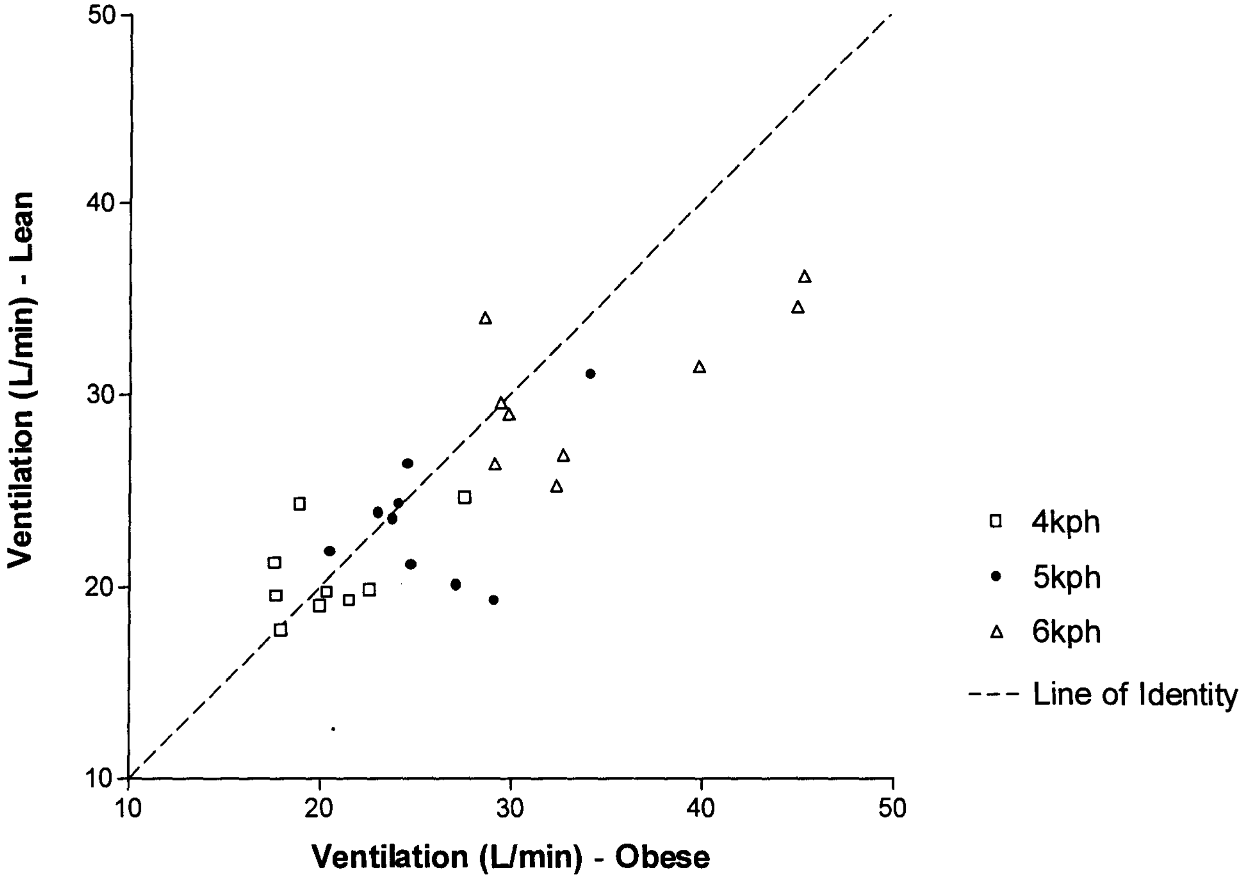


Figure 7: Ventilation for 9 pairs of lean and obese subjects walking at 3 speeds on the treadmill

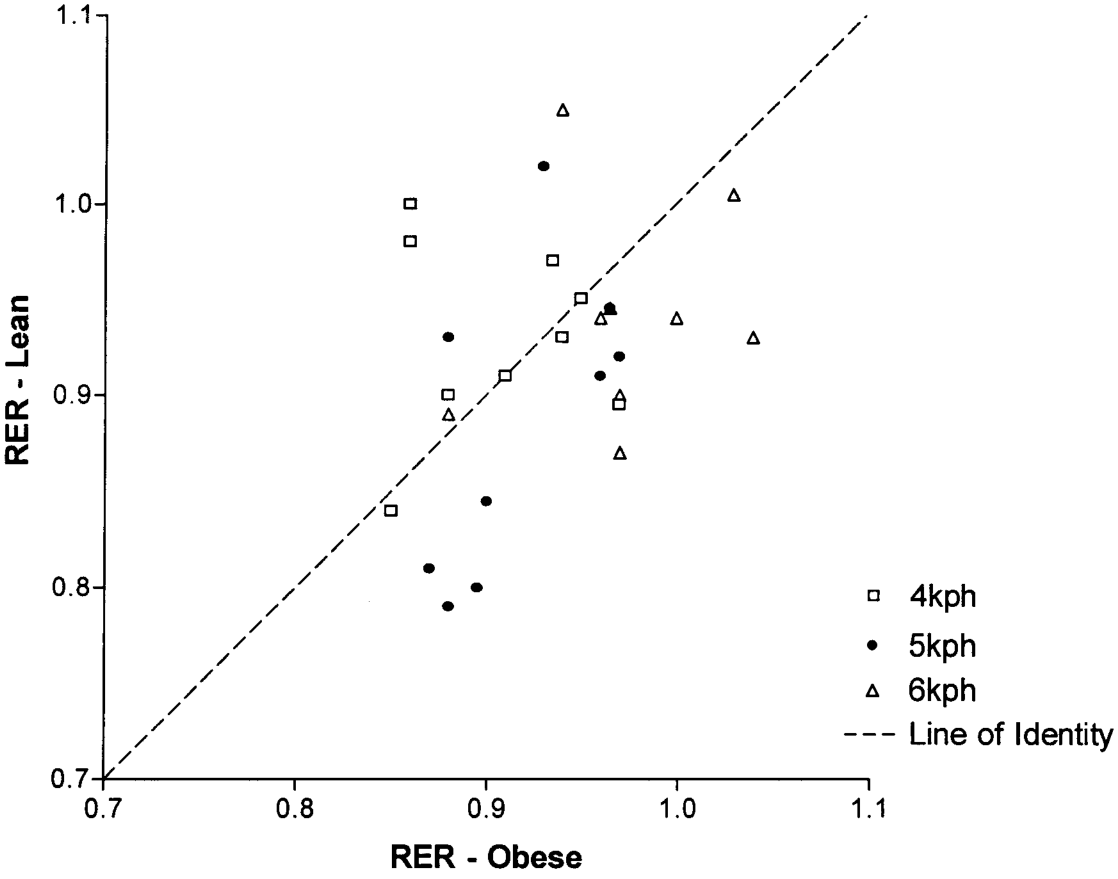


Figure 8: Respiratory exchange ratio (RER) for 9 pairs of lean and obese subjects walking at 3 speeds on the treadmill

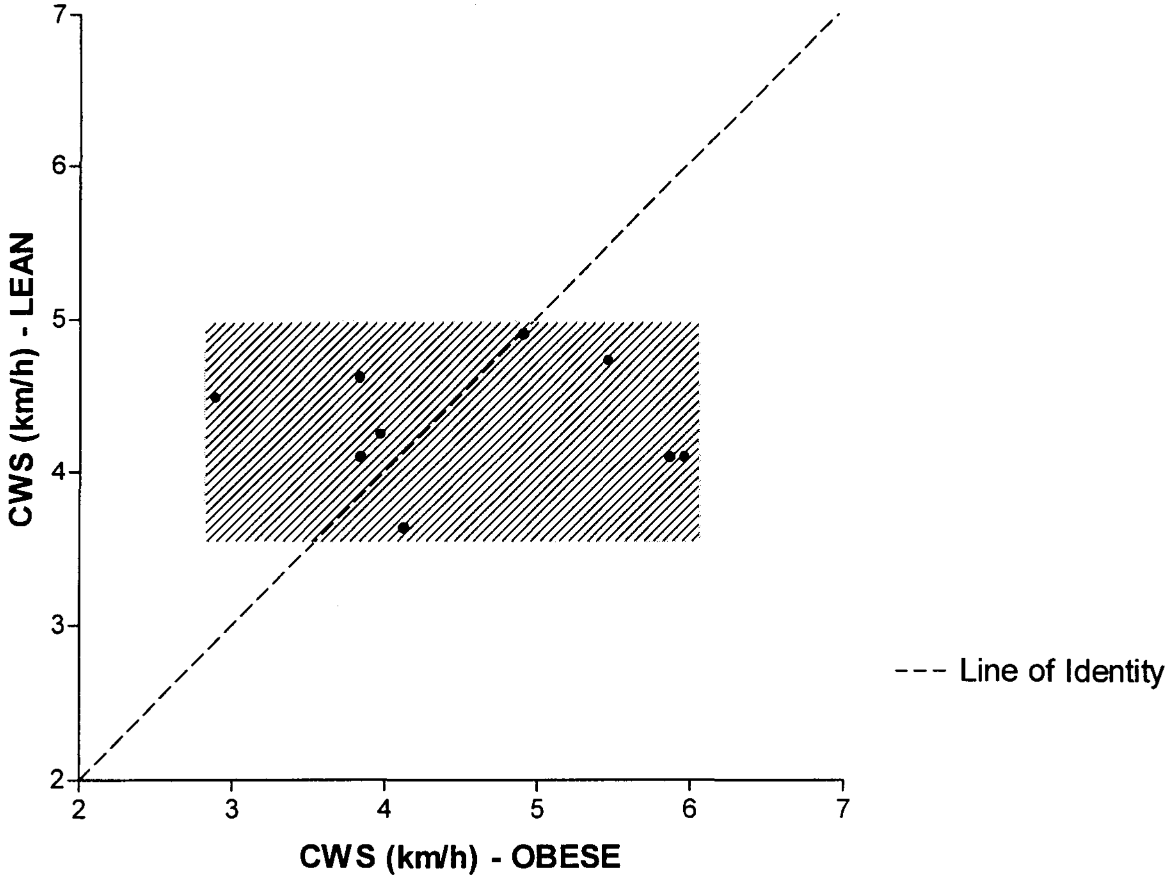


Figure 9: Comfortable walking speed (CWS) of 9 pairs of lean and obese subjects

Shaded area demonstrates the range of speeds in both groups to demonstrate the larger range in the obese group.

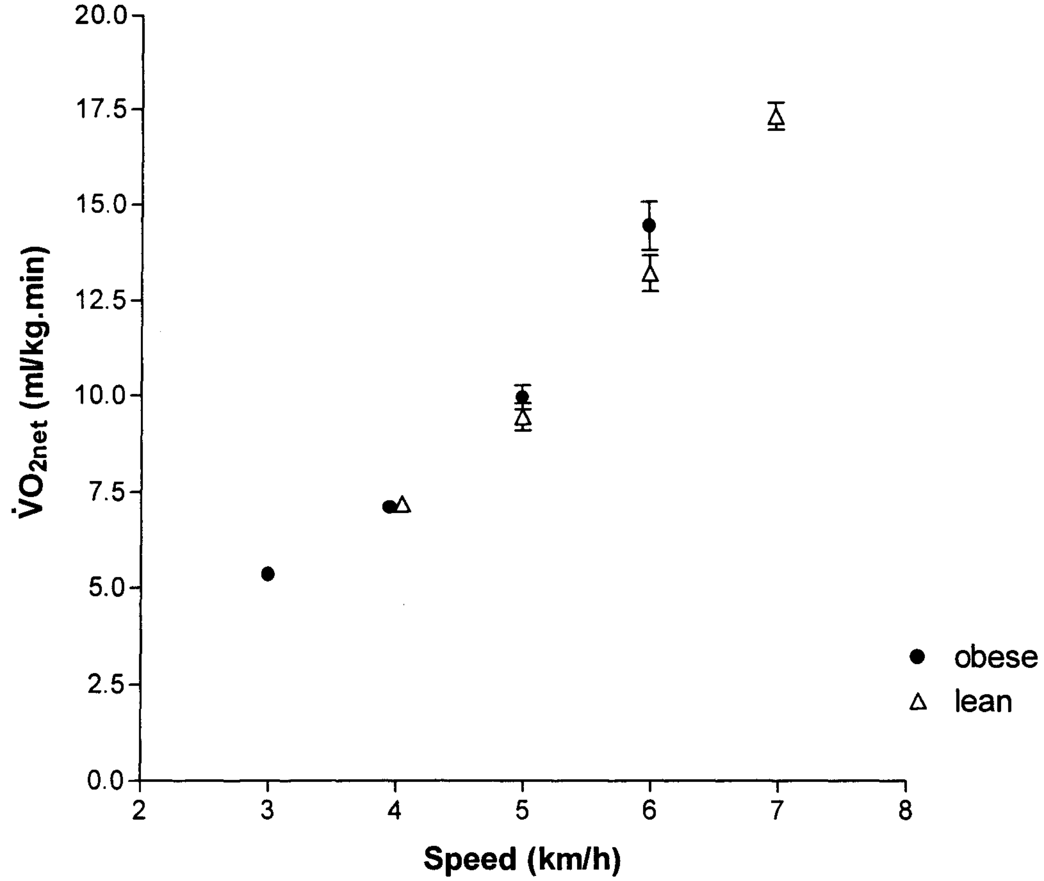


Figure 10: $\dot{V}O_{2net}$ of 9 lean and 9 obese subjects walking at 4, 5, 6, and 7kph and 3, 4, 5, and 6kph, respectively (mean ± SEM).

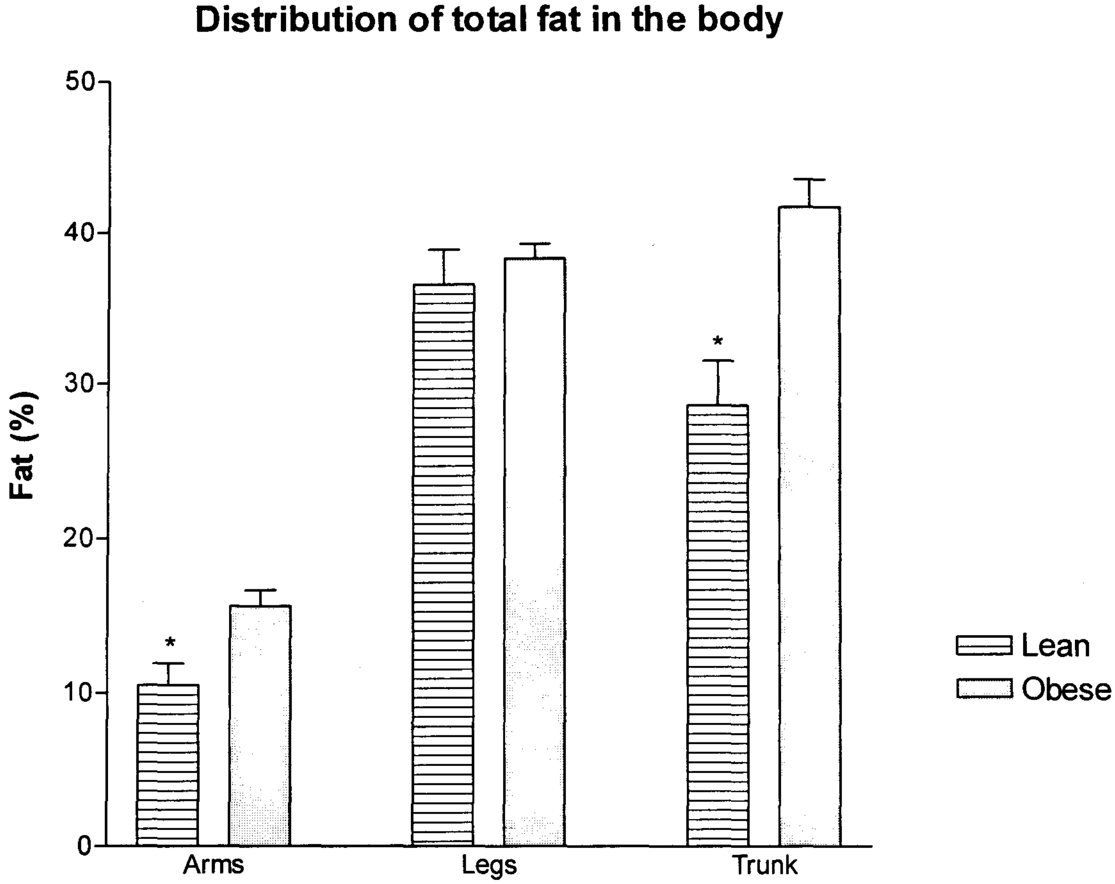


Figure 11: Fat distribution in the arms, legs and trunk in 9 lean and 9 obese adolescent boys (Mean±SEM). 100% = total body (minus head), *$p<0.01$

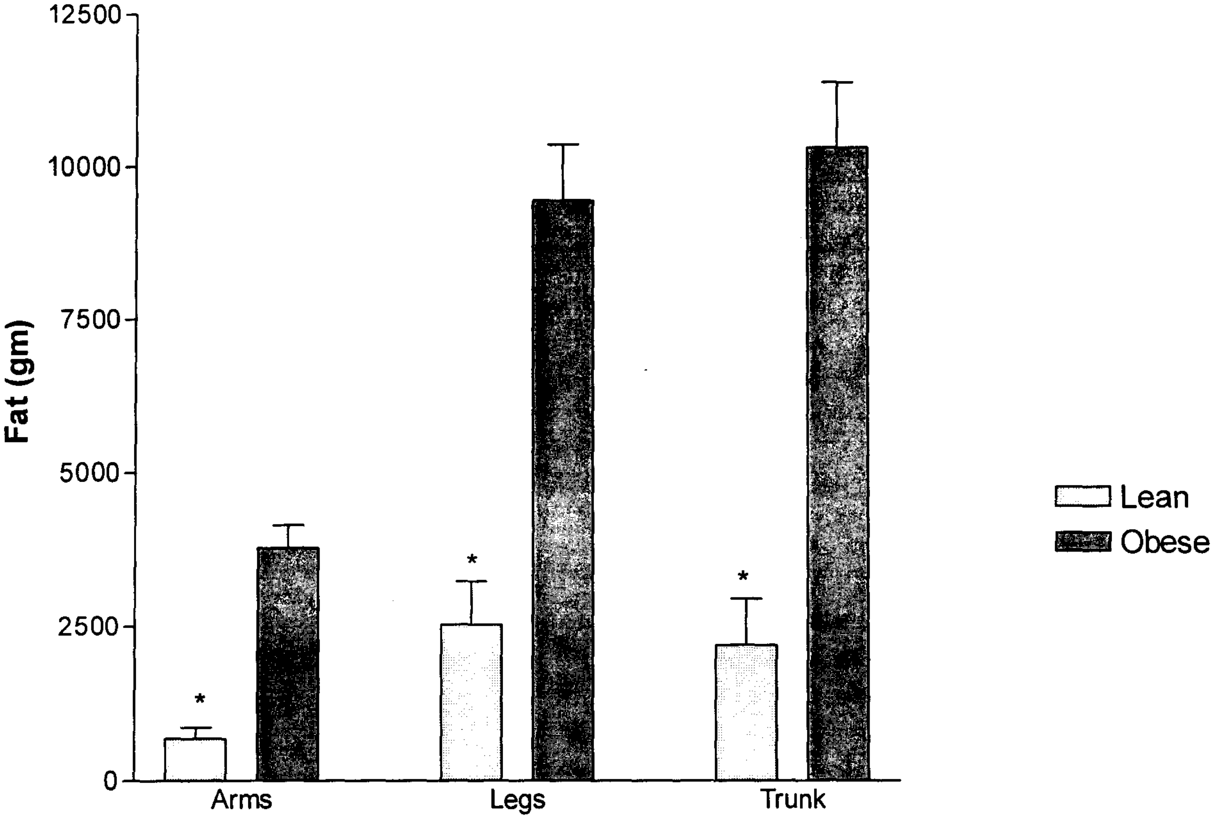


Figure 12: Fat distribution in the arms, leg and trunk in 9 lean and 9 obese adolescent boys (Mean ± SEM), *$p<0.01$

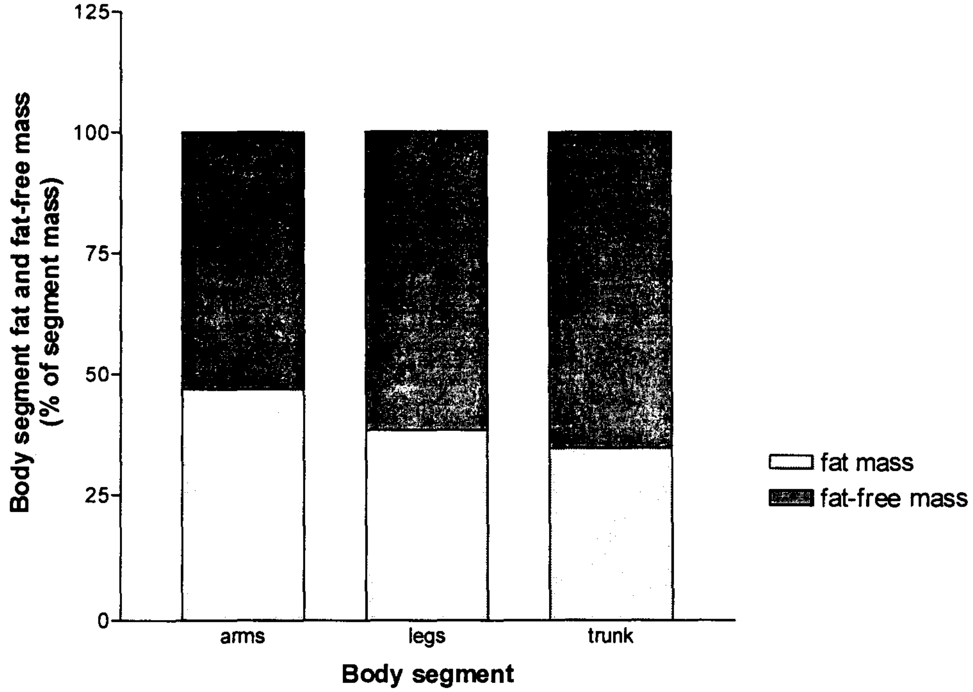


Figure 13a: Fat mass and fat-free mass, as a percentage of total mass, in each body part. Data are for 9 obese adolescent boys

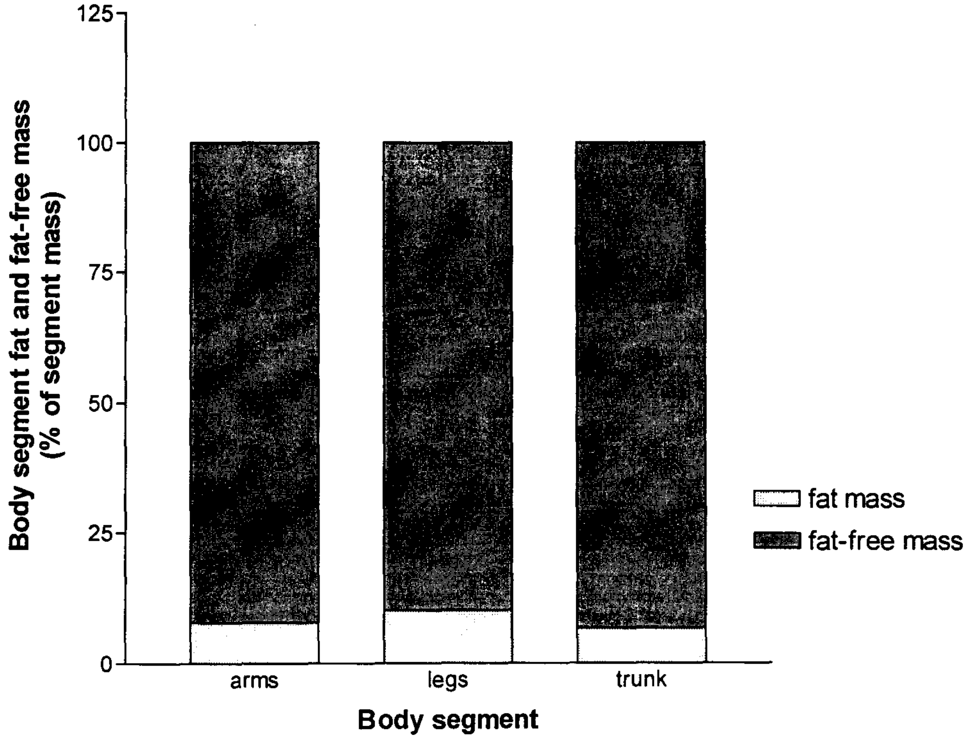


Figure 13b: Fat mass and fat-free mass, as a percentage of total mass, in each body part. Data are for 9 lean adolescent boys

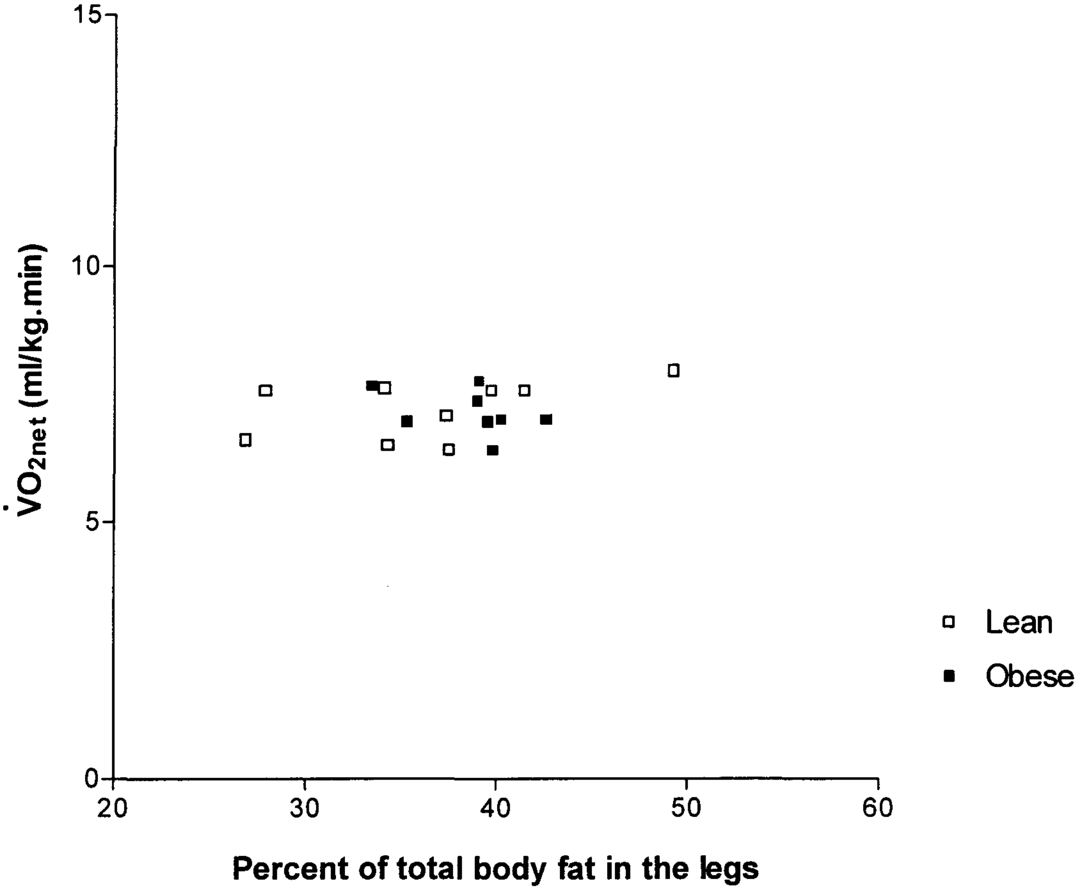


Figure 14: Relationship between $\dot{V}O_{2net}$ and percent of total body fat in the legs in 9 lean and 9 obese subjects walking at 4kph

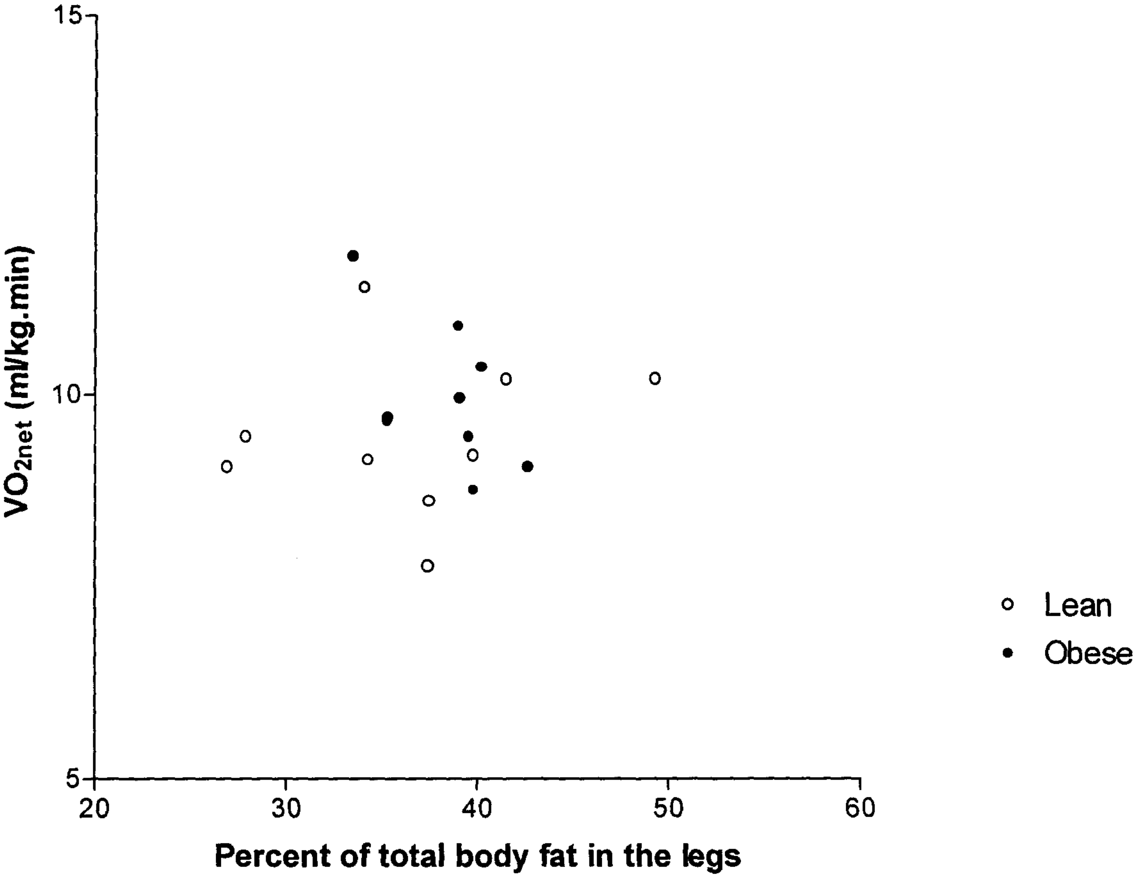


Figure 15: Relationship between $\dot{V}O_{2net}$ and percent of total body fat in the legs in 9 lean and 9 obese subjects walking at 5kph

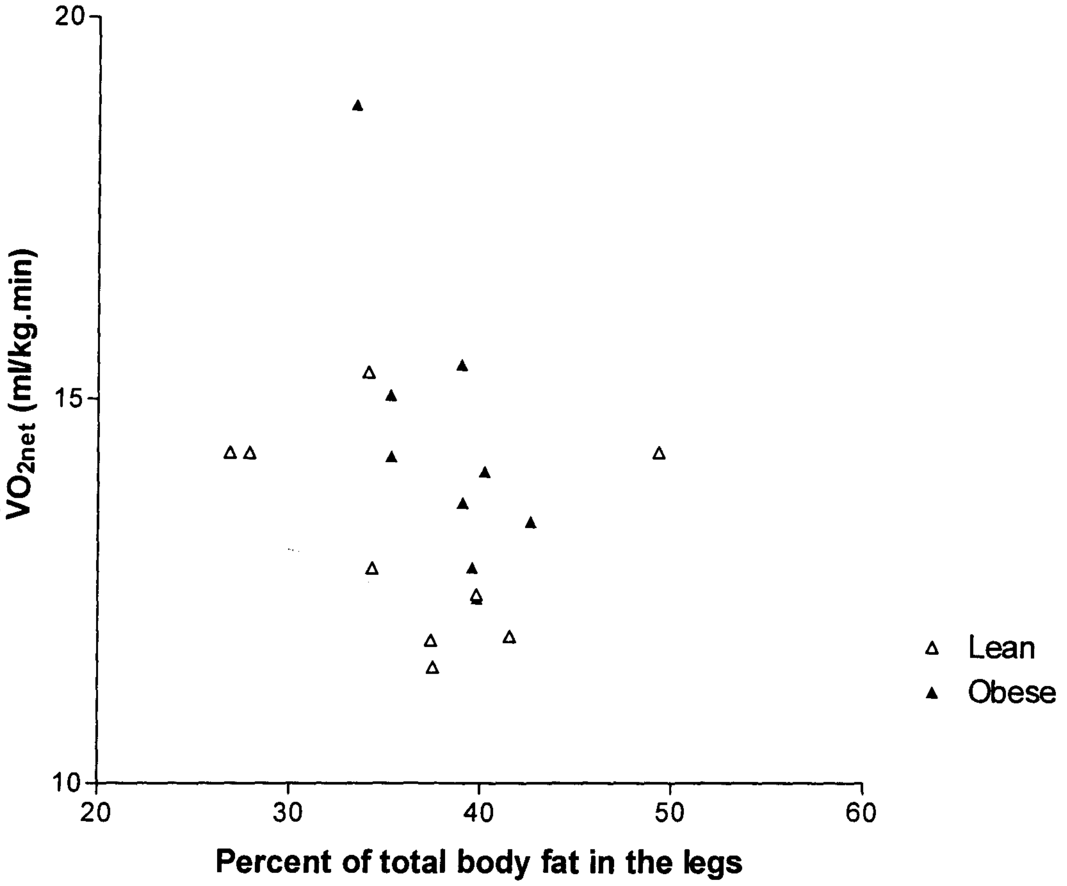


Figure 16: Relationship between $\dot{V}O_{2net}$ and percent of total body fat in the legs in 9 lean and 9 obese subjects walking at 6kph

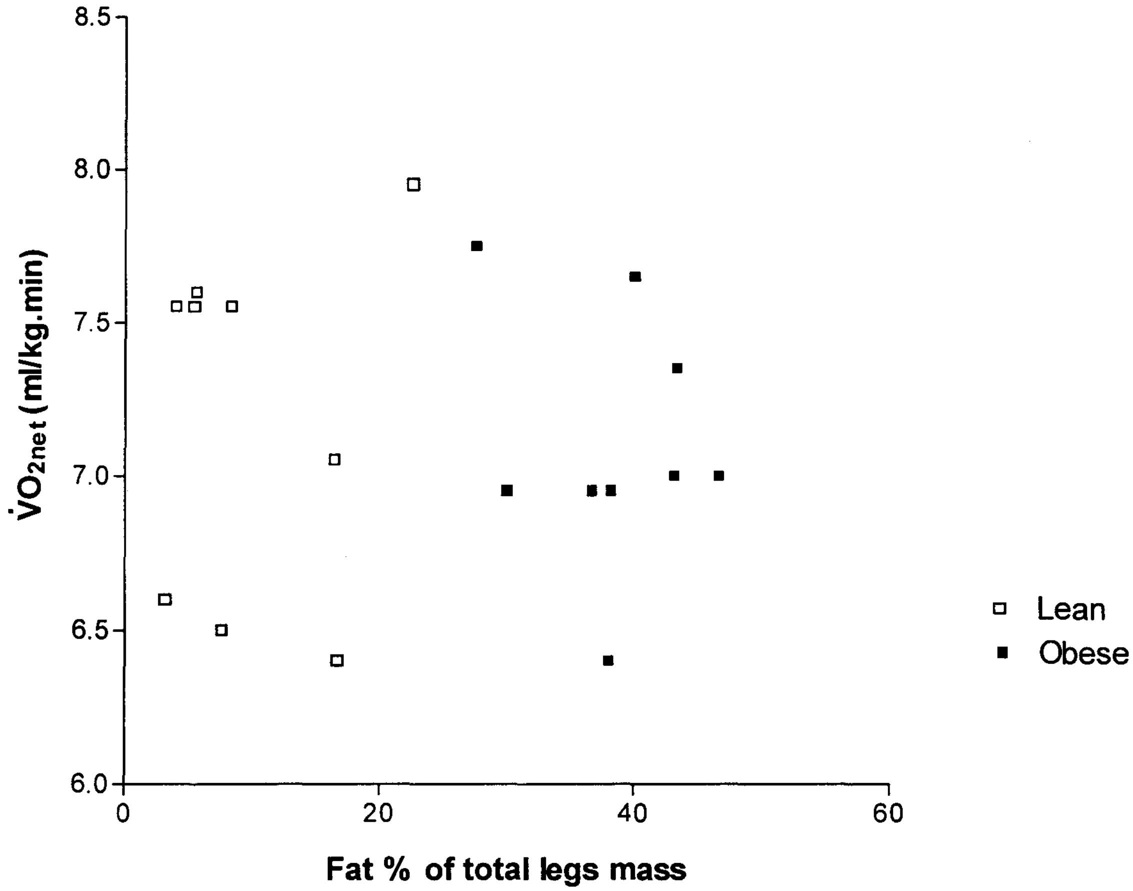


Figure 17: Relationship between $\dot{V}O_{2net}$ and fat % of total leg mass in 9 lean and 9 obese subjects walking at 4kph

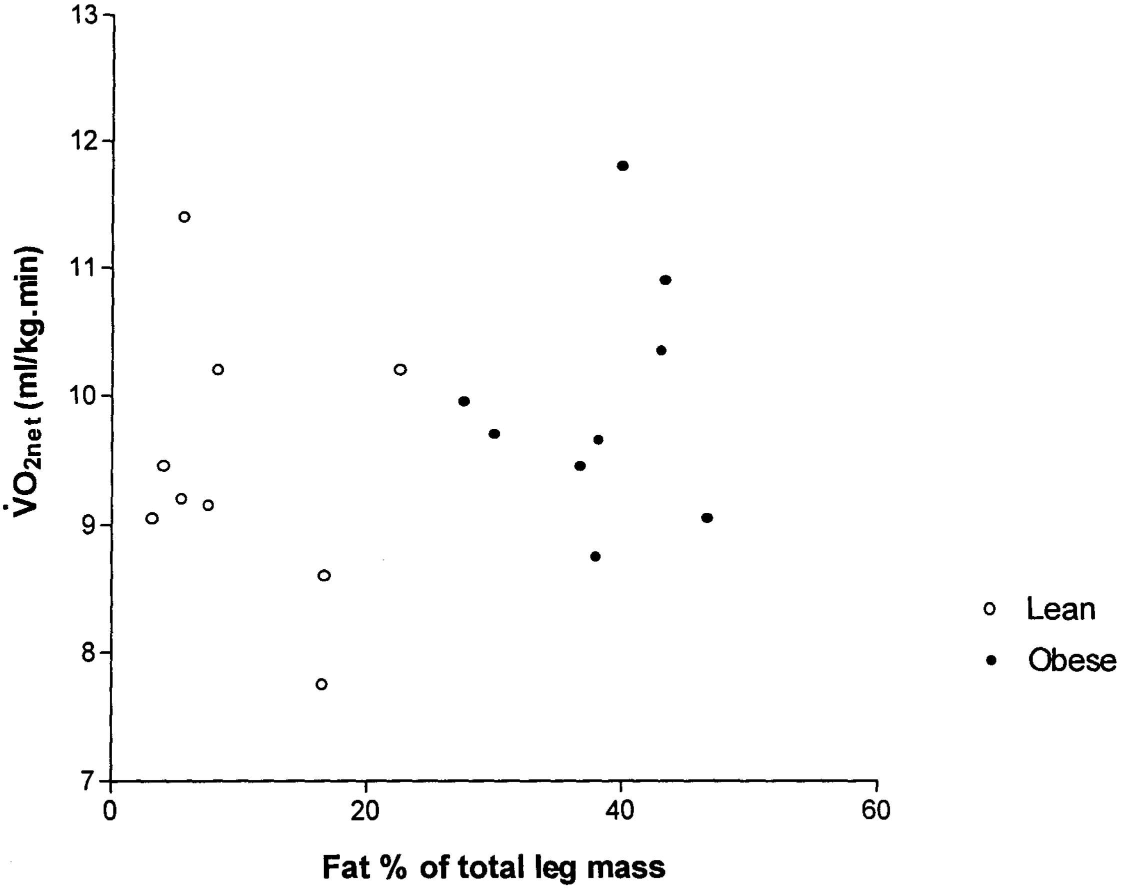


Figure 18: Relationship between $\dot{V}O_{2net}$ and fat % of total leg mass in 9 lean and 9 obese subjects walking at 5kph

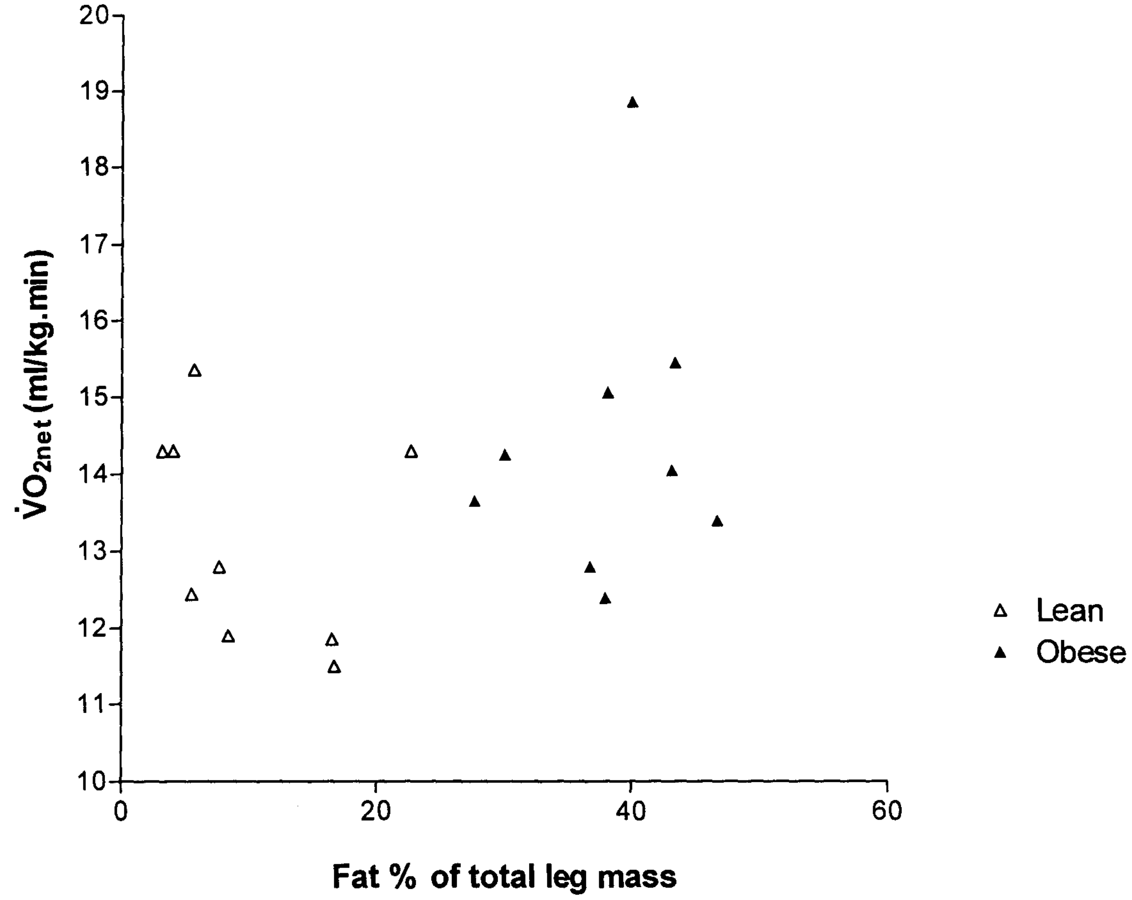


Figure 19: Relationship between $\dot{V}O_{2net}$ and fat % of total leg mass in 9 lean and 9 obese subjects walking at 6kph

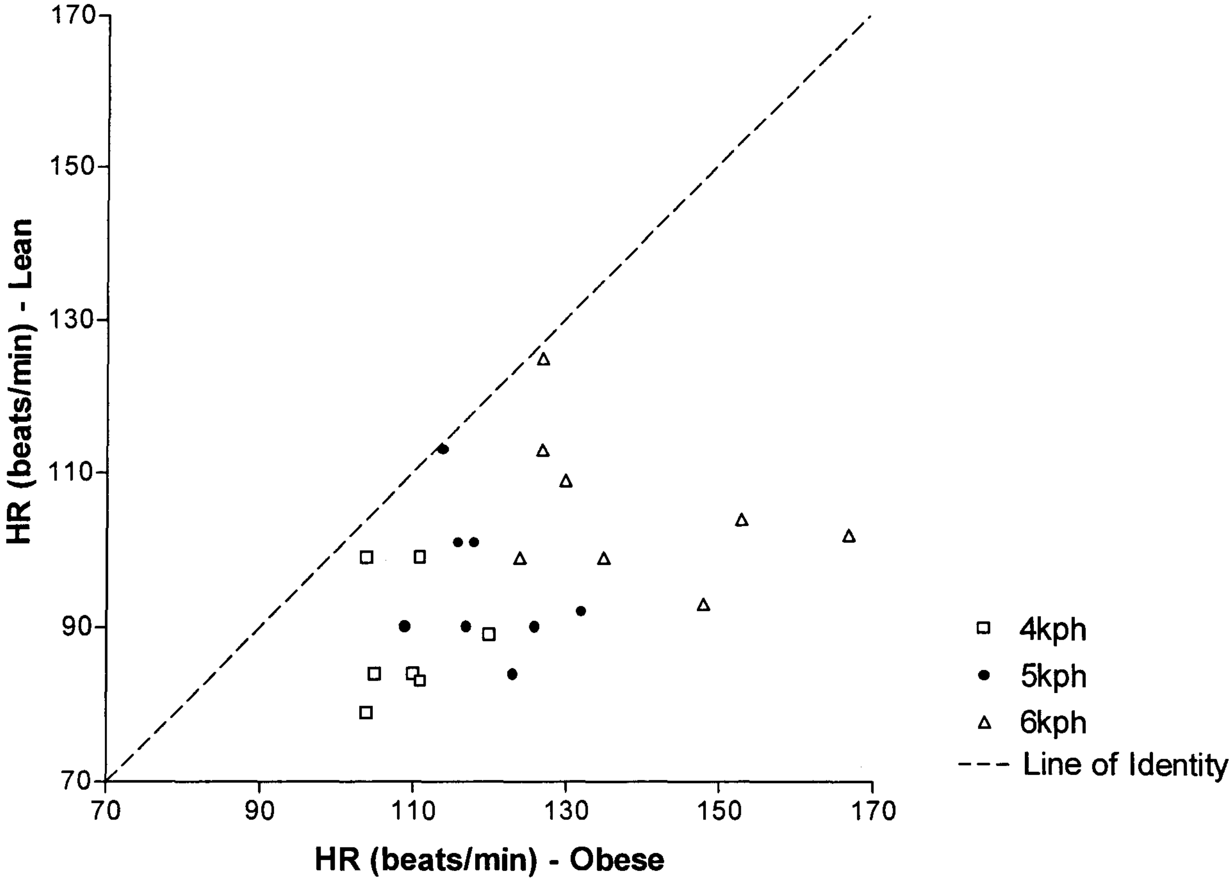


Figure 20: HR (bpm) for pairs of lean and obese subjects, walking at 3 absolute speeds on the treadmill

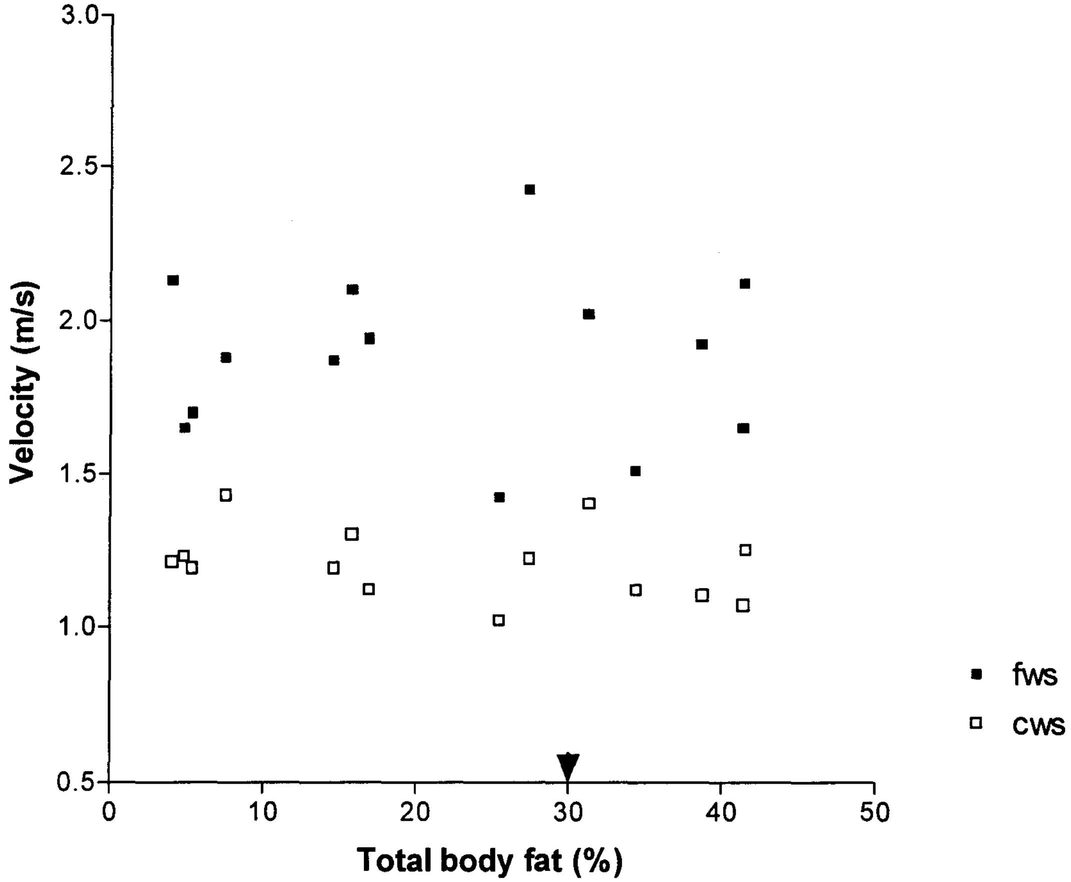


Figure 21: Freely chosen walking velocities for comfortable walking (CWS) and fast walking (FWS) in relation to total body fat (n=14).

Arrow shows where obesity begins (30% body fat)

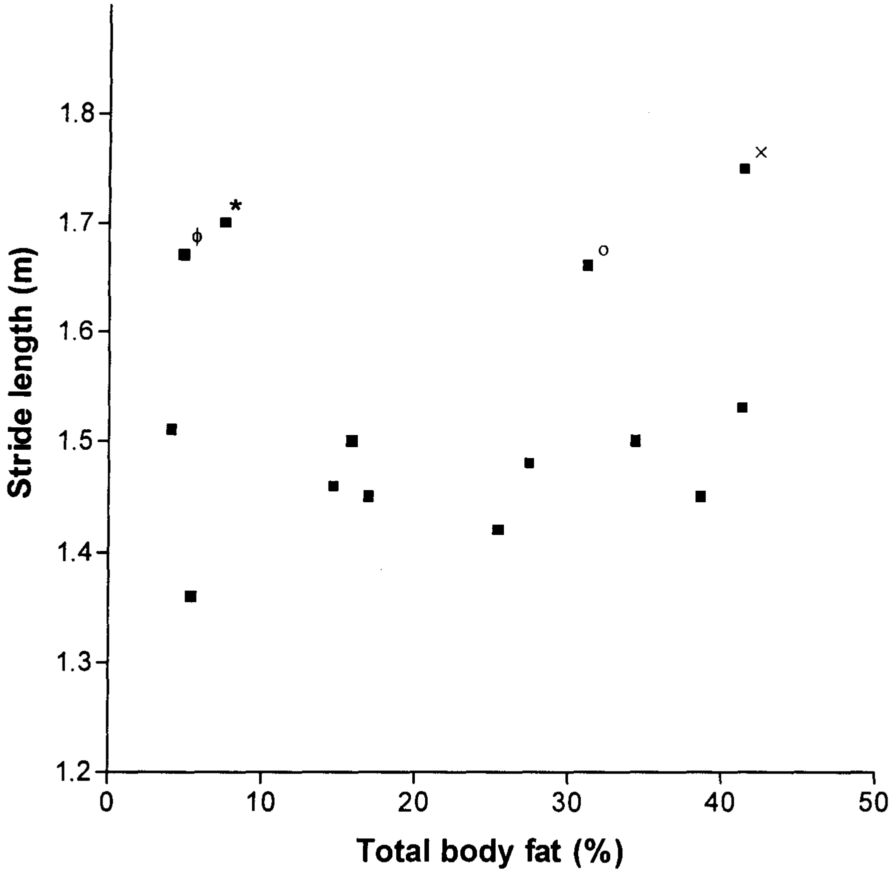


Figure 22: Stride length normalized for leg length[1] and the walking velocity of 1.3m/s, and total body fat in 14 subjects of a wide range of adiposity

Subjects' height ϕ = 163.9cm

* = 165.3cm

o = 155.3cm

× = 158.2cm

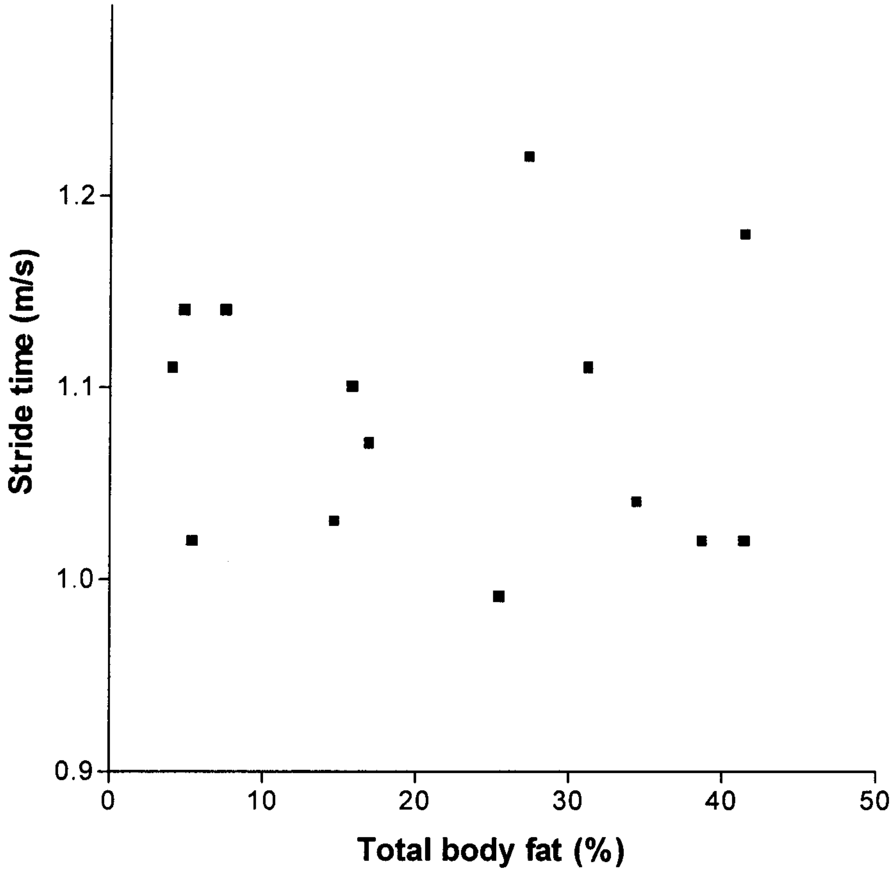


Figure 23: Stride time normalized for leg length$^{1/2}$ and to the walking velocity of 1.3m/s, and total body fat in 14 subjects of a wide range of adiposity

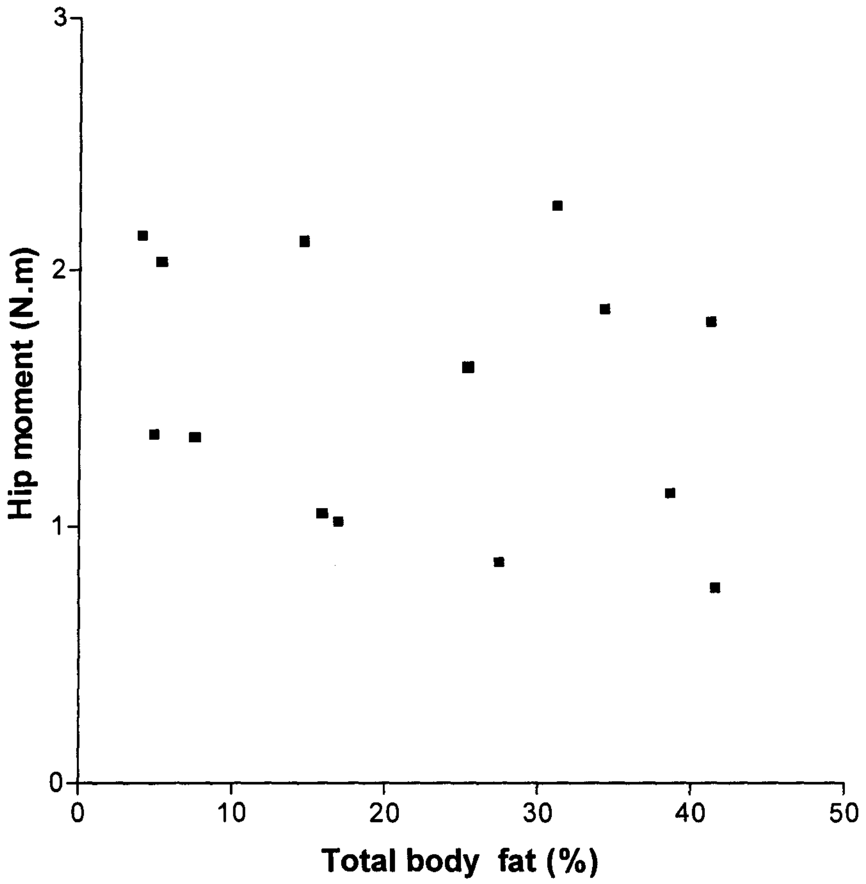


Figure 24: Moments at the hip normalized for body mass and leg length$^{3/2}$ and to the walking velocity of 1.3m/s, at push off, and total body fat in 14 subjects of a wide range of adiposity

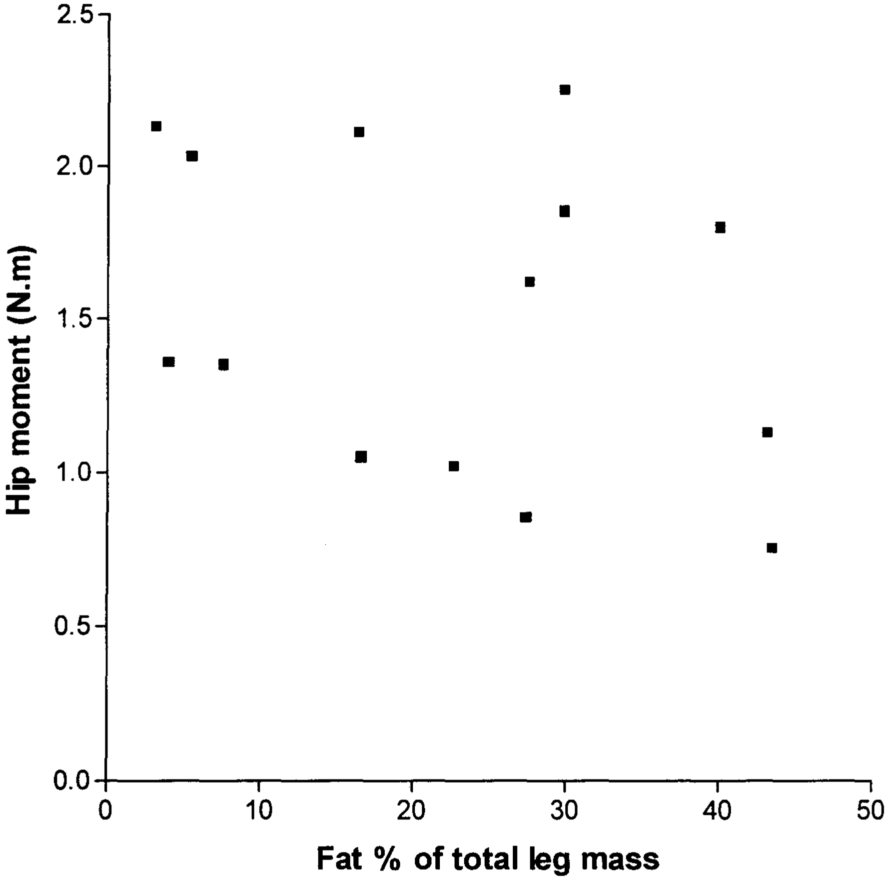


Figure 25: Moments at the hip normalized for body mass and leg length$^{3/2}$ and to the walking velocity of 1.3m/s, at push off, and fat % of total leg mass in 14 subjects of a wide range of adiposity

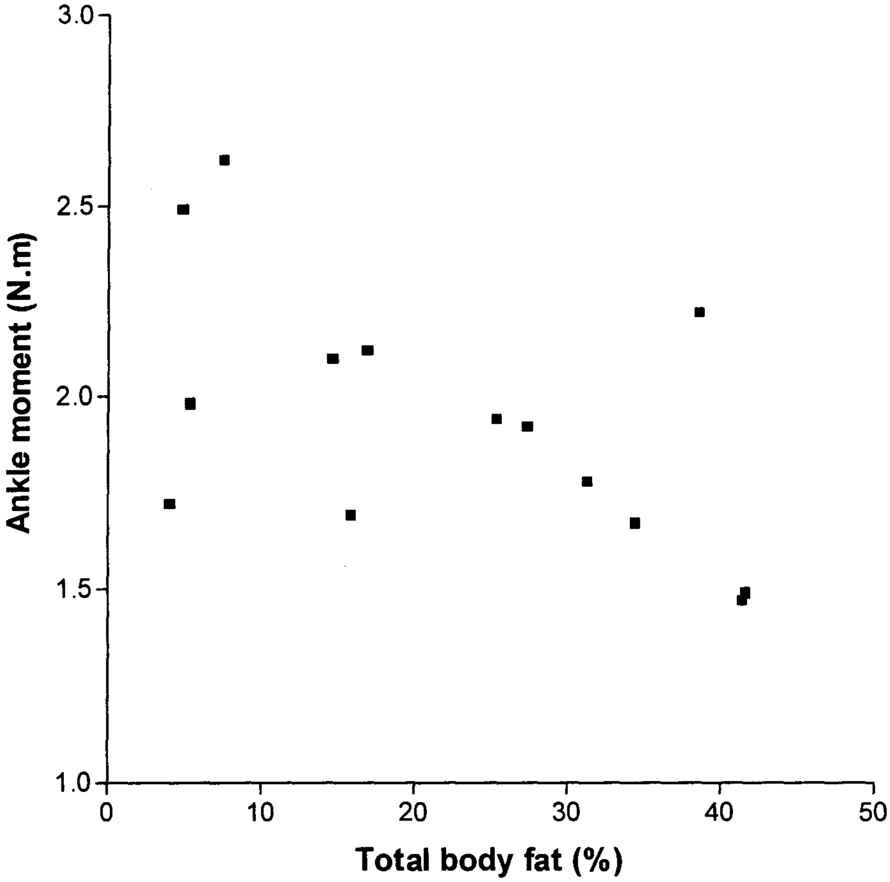


Figure 26: Moments at the ankle normalized for body mass and leg length$^{3/2}$ and to the walking velocity of 1.3m/s, at push off and total body fat in 14 subjects of a wide range of adiposity

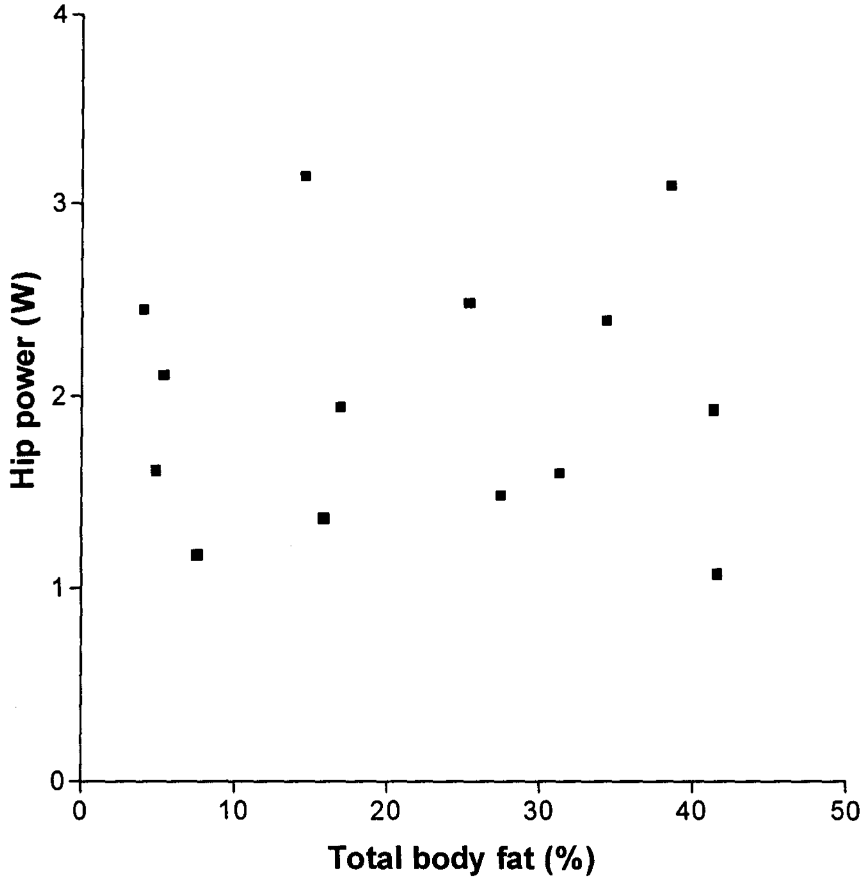


Figure 27: Powers generated at the hip normalized for body mass and leg length$^{1/2}$ and to the walking velocity of 1.3m/s, at push off, and total body fat in 14 subjects of a wide range of adiposity

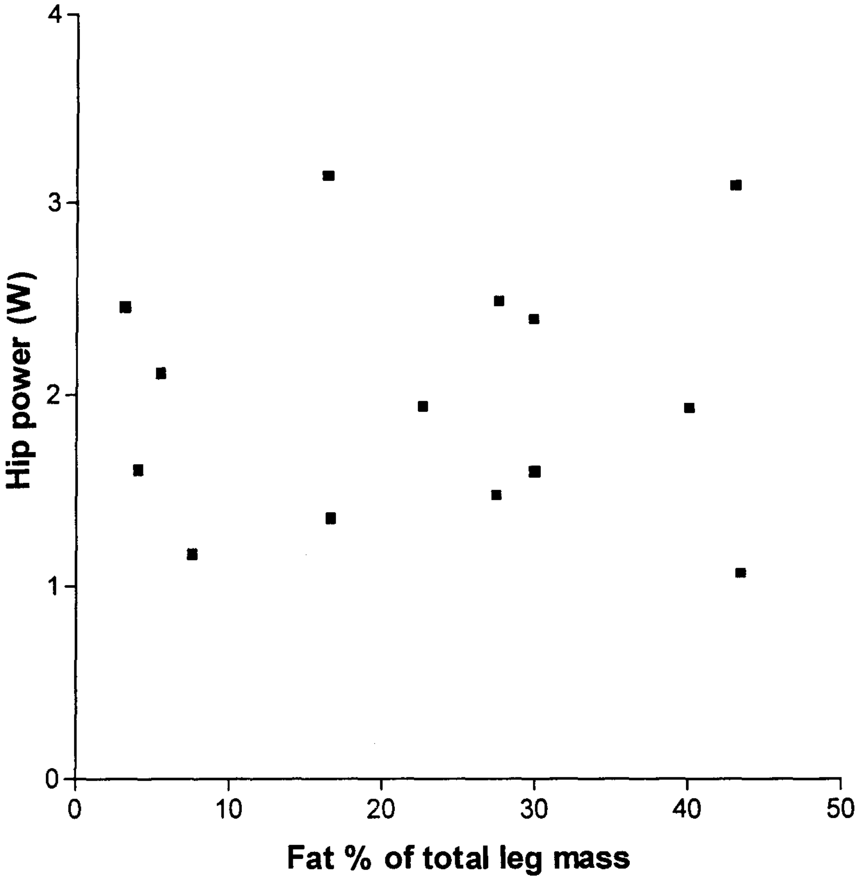


Figure 28: Powers generated at the hip normalized for body mass and leg length$^{1/2}$ and to the walking velocity of 1.3m/s, at push off, and fat % of total leg mass in 14 subjects of a wide range of adiposity

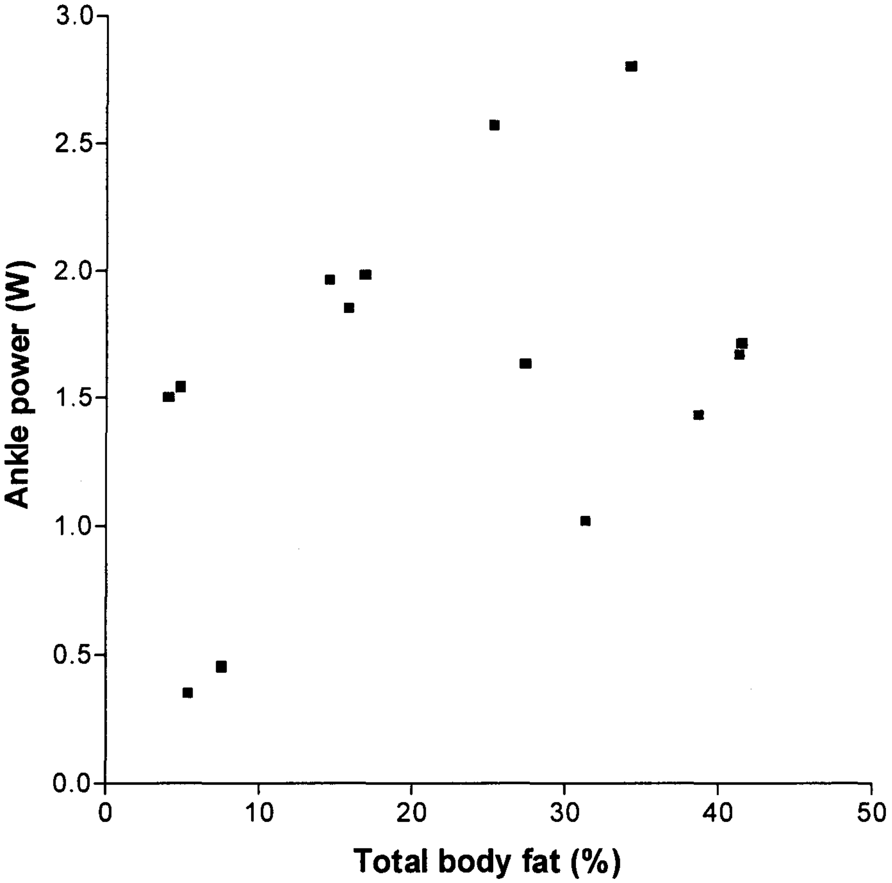


Figure 29: Powers generated at the ankle normalized for body mass and leg length$^{1/2}$ and to the walking velocity of 1.3m/s, at push off, and total body fat in 14 subjects of a wide range of adiposity

APPENDICES

Appendix A Activity Questionnaire

Name...ID#.........Date.................

1. How would you compare your physical activity with that of your friends?

a. as active
b. more active
c. less active
d. hard to compare
Comments..

2. How much spare time do you have each day?..............hours

3. What do you do in your spare time? List in order of most to least time spent, and indicate the average time spent.

a..

b..

c..

d..

e..

4. Do you participate in physical education classes at school?

a. Yes, all activities (hours per week)...........................

b. Yes, some activities (hours per week)........................

c. No (why not?)..

Comments..

5. Are you a member of a school or community sport team? Please specify sport.

a. Yes, intramural team...

b. Yes, school team..

c. Yes, club team..

d. Yes, in the past but not now.....................................

Level reached..................when stopped..................

e. No

6. Do you train regularly? If so, how often?

SPORT	Hours/Week	Time of year	Comments

7. Do you participate in any recreational activity that requires physical effort? (eg. skiing, canoeing, cycling, swimming, running)

ACTIVITY	Hours/Week	Time of year	Comments

8. How do you usually get to school? Please indicate time needed.

METHOD	TIME
Car/Bus	
Bicycle	
Walking	
Rollerblading	

Appendix B Medical Questionnaire

Name.. Date of Birth...........................
Address...
City...Postal Code..........................
Phone #...

Medical history

I. Do you have (have ever had) any of the following conditions? (check those which are appropriate)

- a. heart disease
- b. asthma
- c. allergies
- d. diabetes
- e. high blood pressure
- f. epilepsy
- g. surgery
- h. fractures
- i. Orthopedic problems
    - back
    - hip
    - knee
    - ankle

II. Do you ever complain about the following during or after exercise? (check those which are appropriate)

- a. inability to keep up with other boys
- b. chest pain
- c. fainting
- d. dizziness
- e. irregular heart beat
- f. wheezing
- g. cough
- h. other...........................

III. Have you ever been hospitalized? If so, please list dates and reasons.

IV. Do you use any medications?

Type..Frequency of use.............................

V. Has a physician ever suggested that you should be restricted from physical activity?

VI Do you know of any medical reasons that would prevent you from participating in physical activity?

McMASTER UNIVERSITY
Department of Pediatrics
Chedoke Hospital Division, Evel Bldg., 4th Floor
P.O. Box 2000
Hamilton, Ontario L8N 3Z5
(905) 521-2100 Ext. 7615 • Fax: 1-905-385-5033

Note ext. change to 77615

CHILDREN'S EXERCISE AND NUTRITION CENTRE

Appendix C Consent Form

I, ______________________________, consent to participate in a study designed to measure how much energy adolescents use to walk on a treadmill. Beatriz Volpe Ayub (521-2100, Ext 7615), the investigator, has explained that I will be invited to the laboratory for three visits, as outlined in the information sheet overleaf.

I understand that no known harmful effects occur during or following the above observations, apart from fatigue following the maximal aerobic fitness test. I further understand that there are no direct benefits to me from taking part in this study. I can withdraw at any time from participation in the study, even after I have signed this form. Any information which is collected will be kept confidential, and will not identify me in any way, even if the results are published.

____________________	____________________	____________________
Name (print)	Signature	Date
____________________	____________________	____________________
Witness (print)	Signature	Date

I have explained the nature of this study to the subject and believe he understood it.

____________________	____________________	____________________
Investigator	Signature	Date

McMASTER UNIVERSITY
Department of Pediatrics
Chedoke Hospital Division, Evel Bldg., 4th Floor
P.O. Box 2000
Hamilton, Ontario L8N 3Z5
(905) 521-2100 Ext. 7615 • Fax: 1-905-385-5033

Note ext. change to 77615

CHILDREN'S EXERCISE AND NUTRITION CENTRE

Appendix D Parent Consent Form

I, ________________________________, consent to allow my son ________________________________ to participate in a study designed to measure how much energy adolescent boys use to walk on a treadmill. Beatriz Ayub (521-2100, Ext 7615), the investigator, has explained that my son will be invited to the laboratory for three visits, as outlined in the information sheet overleaf.

I understand that no known harmful effects occur during or following the above observations, apart from fatigue following the maximal aerobic fitness test. I further understand that there are no direct benefits to my son from taking part in this study. My son can withdraw at any time from participation in the study, even after I have signed this form. Any information which is collected will be kept confidential, and will not identify my son in any way, even if the results are published.

________________	________________	________________
Name (print)	Signature	Date
________________	________________	________________
Witness (print)	Signature	Date

I have explained the nature of this study to the boy's parent (guardian) and believe he understood it.

________________	________________	________________
Investigator	Signature	Date

Appendix E $\dot{V}O_{2max}$ Test

NAME: ______________________________ DATE: ________________

Ht _______________ Wt ______________ DOB ________________

TIME Min	SPEED Miles/h Km/h	GRADE %	RPE	HR beats/min
0-2				
2-4				
4-6				
6-8				
8-10				
10-12				
12-14				

$\dot{V}O_2$max ____________________ HR max _________________

Appendix F Data Spreadsheet

ID#__________

$\dot{V}O_2$ max ______________________________

3 km/h (1.7-1.8) timer ____________________dial____________

4 km/h (2.3-2.4) timer ____________________dial____________

5 km/h (3.0-3.1) timer ____________________dial____________

6 km/h (3.5-3.6) timer ____________________dial_____________

7 km/h (4.2) timer _____________________dial____________

CWS = ____________ timer ____________________dial____________

Appendix G

Output of body composition analysis

Chedoke-McMaster Hospitals

```
                                          V04139910    Tue Apr 13 16:14 1999
                                          Name:
 Hologic QDR-4500A (S/N 45048)            Comment:
     Whole Body V8.19a:3                  I.D.:                     Sex:     M
      oApr 13 16:24 1999                  S.S.#:         -  -    Ethnic:
                                          ZIPCode:          Height:        cm
                                          Operator:         Weight:        kg
  TBAR907                                 BirthDate: 06/28/80      Age:    18
  F.S.  68.00%  0(10.00)%                 Physician:

 Region     BMC       Fat       Lean    Lean+BMC    Total     % Fat
          (grams)   (grams)   (grams)   (grams)    (grams)     (%)
 -------- --------- --------- --------- --------- --------- ---------
  L Arm     172.7     630.0    3144.8    3317.5    3947.6     16.0
  R Arm     218.4     439.2    3090.1    3308.5    3747.7     11.7
  Trunk     616.1    3796.5   26266.9   26883.1   30679.6     12.4
  L Leg     472.1    2629.3    9988.1   10460.2   13089.5     20.1
  R Leg     466.1    3260.7    9132.1    9598.1   12858.8     25.4
 SubTot    1945.4   10755.8   51622.0   53567.4   64323.1     16.7
~  Head     435.0    1159.8    4214.7    4649.7    5809.4     20.0
  TOTAL    2380.4   11915.5   55836.7   58217.0   70132.6     17.0

~assumes 17.0% brain fat
 LBM 73.2% water
```

HOLOGIC

ANTHROPOMETRY

Name	
Date	
File Directory	

Anthropometrist	
Gender (M/F)	
Birthdate (DD/MM/YY)	

Height (m)	Floor-vertex length	
Total Body Mass (kg)	All clothes except underwear removed	
ASIS Breadth (m)	Horizontal distance between anterior superior iliac spines	
Thigh Length (m)	Vertical distance between the superior point of the greater trochanter and the superior margin of the lateral tibia	
Mid Thigh Circumference (m)	With a tape perpendicular to the long axis of the thigh and at a level midway between the trochanteric and tibial landmarks	
Calf Length (m)	Vertical distance between the superior margin of the lateral tibia and the lateral malleolus	
Calf Circumference (m)	With a tape perpendicular to the long axis of the lower leg, measure the maximum circumference	
Knee Diameter (m)	Maximum breadth of the knee across the femoral condyles	
Foot Length (m)	Distance from the the posterior margin of the heel to the tip of the longest toe	
Malleolus Height (m)	With the subject standing, measure the vertical distance from the floor to the lateral malleolus	
Malleolus Width (m)	Maximum distance between the medial and lateral malleoli	
Foot Breadth (m)	Breadth across the distal ends of metatarsals I and V	

Anthropometry File Name	

Appendix H

Anthropometric Data Spreadsheet

GAIT COLLECTING & PROCESSING

Name	
Date	
File Directory	

Trial	COLLECT	WIPEND	SEGAIT	RUNGAIT	ACCEPT	Comments
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						

101	RASIS	
102	LASIS	
103	SACRUM	

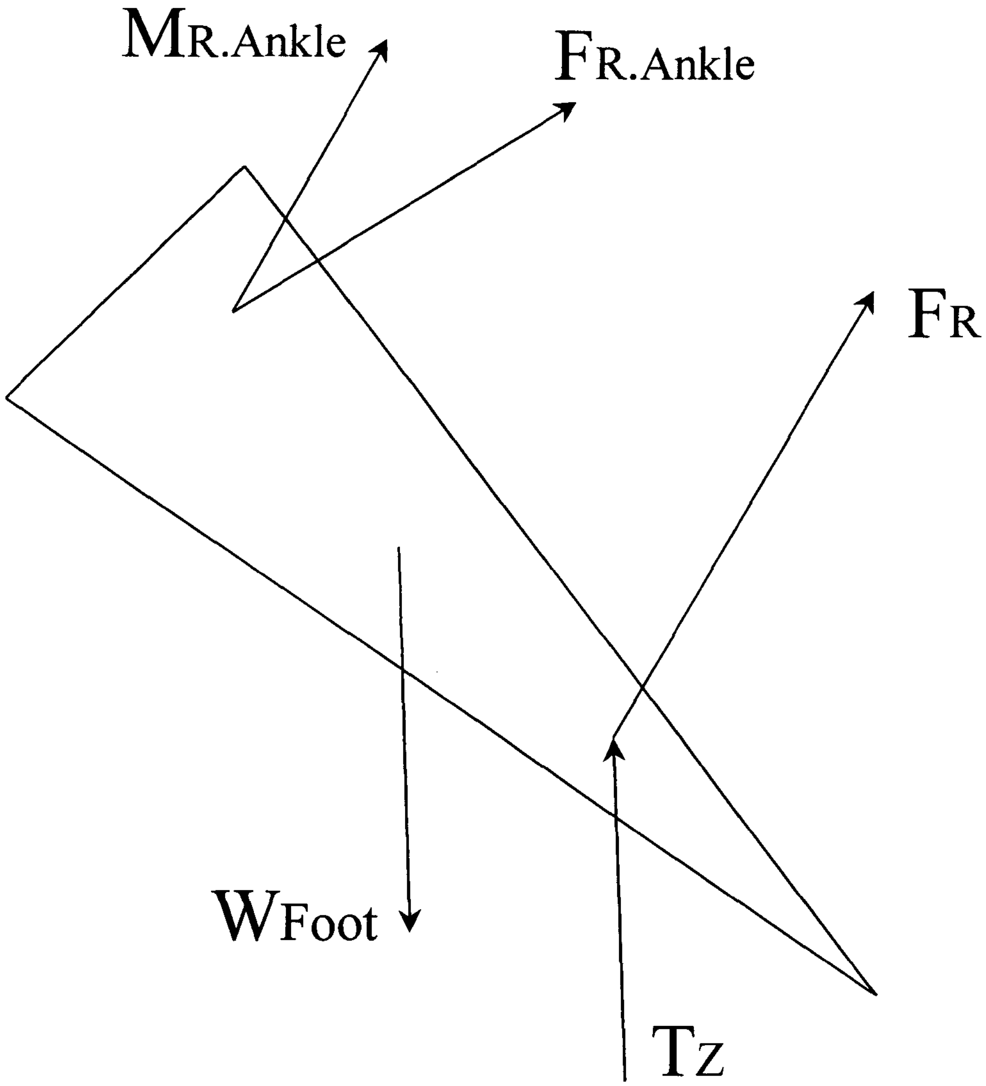
AVERAGE	
HARDCOPY	
HIDEGAIT	

VIDEO			
TAPE	Start	End	Elapsed

EMG		
NAMES	GAINS	A/D

Appendix I Data Spreadsheet

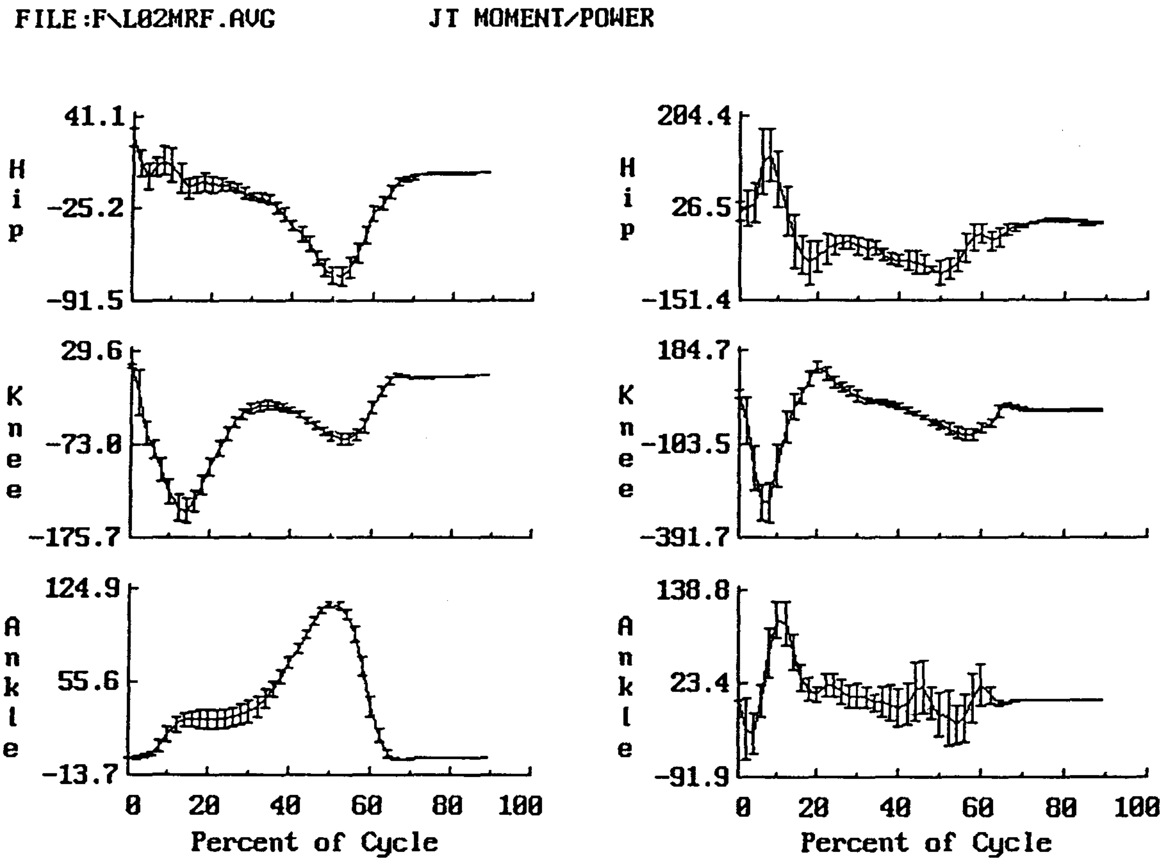
Appendix J Free Body Diagram



Free Body Diagram for the right foot at push off. The *external* forces acting on the foot are its weight W_F, the resultant ground reaction F_R, and the force of the calf on the foot at the ankle joint $F_{R.Ankle.}$ The external moments acting on the foot are the ground reaction torque about the Z axis T_Z, and the moment of the calf on the foot at the ankle joint $M_{R.Ankle}$.

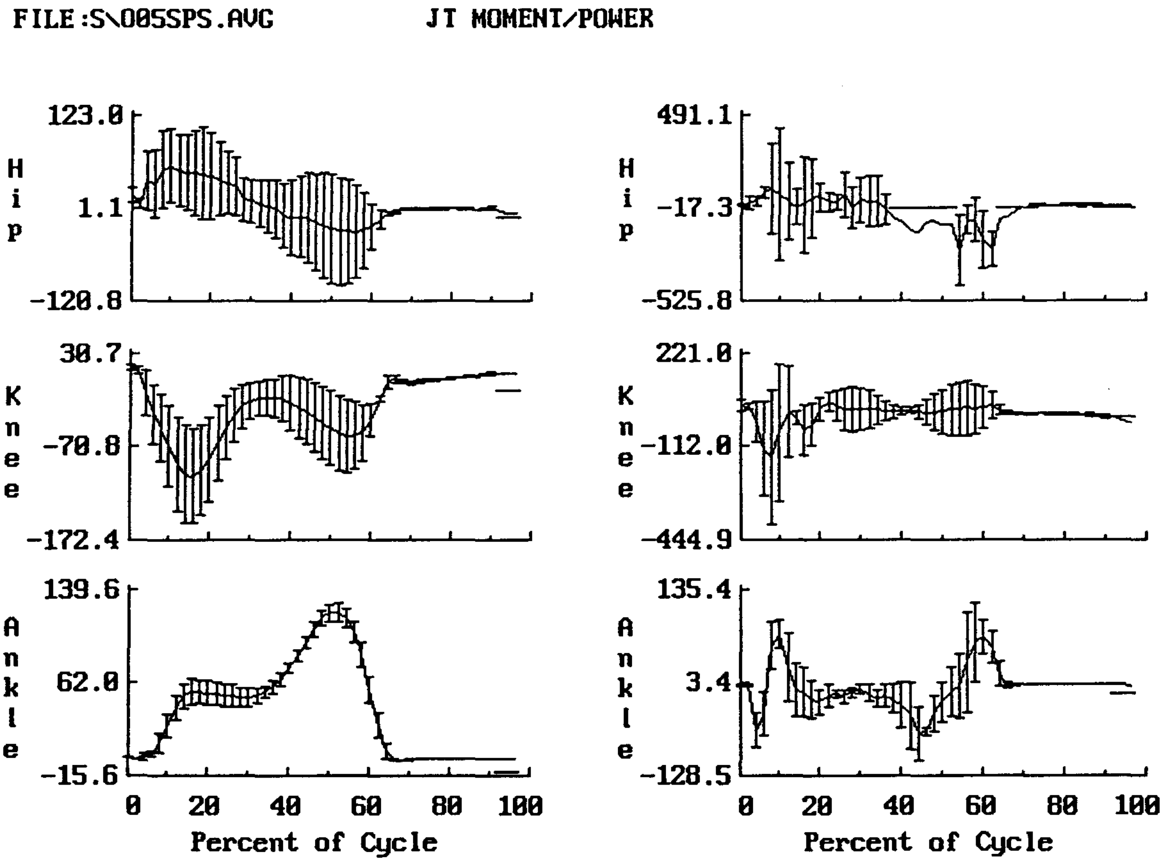
$\sum$ Moments = $M_{R.Ankle}$ + T_Z + Moment due to $F_{R.Ankle}$ + Moment due to F_R

Appendix K Raw mechanical data output



Raw gait cycles for various trials (≤8) of one subject walking at a fast speed. Moments and powers at the hip, knee and ankle are presented

Appendix L Raw mechanical data output



Raw gait cycles for various trials (≤8) of one subject walking at a slow speed. Moments and powers at the hip, knee and ankle are presented