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Effects of obesity and sex on the energetic cost and preferred speed of walking

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Browning, Raymond C., Emily A. Baker, Jessica A. Herron, and Rodger Kram. Effects of obesity and sex on the energetic cost and preferred speed of walking. *J Appl Physiol* 100: 390–398, 2006. First published October 6, 2005; doi:10.1152/japplphysiol.00767.2005.—The metabolic energy cost of walking is determined, to a large degree, by body mass, but it is not clear how body composition and mass distribution influence this cost. We tested the hypothesis that walking would be most expensive for obese women compared with obese men and normal-weight women and men. Furthermore, we hypothesized that for all groups, preferred walking speed would correspond to the speed that minimized the gross energy cost per distance. We measured body composition, maximal oxygen consumption, and preferred walking speed of 39 (19 class II obese, 20 normal weight) women and men. We also measured oxygen consumption and carbon dioxide production while the subjects walked on a level treadmill at six speeds (0.50–1.75 m/s). Both obesity and sex affected the net metabolic rate (W/kg) of walking. Net metabolic rates of obese subjects were only ~10% greater (per kg) than for normal-weight subjects, and net metabolic rates for women were ~10% greater than for men. The increase in net metabolic rate at faster walking speeds was greatest in obese women compared with the other groups. Preferred walking speed was not different across groups (1.42 m/s) and was near the speed that minimized gross energy cost per distance. Surprisingly, mass distribution (thigh mass/body mass) was not related to net metabolic rate, but body composition (% fat) was (r^2 = 0.43). Detailed biomechanical studies of walking are needed to investigate whether obese individuals adopt novel energy saving mechanisms during walking.

locomotion; energy cost per distance; cost of transport; economy; body mass distribution

WALKING IS A POPULAR AND CONVENIENT form of exercise that can play an important role in weight management (24, 26). Effective weight management requires an accurate knowledge of how much metabolic energy is expended during exercise. Obese individuals expend much more metabolic energy during walking than normal-weight individuals (3, 16, 18, 31, 32). However, the energy expended across walking speeds has only recently been established for obese female adults (6, 31, 32), and it is not well understood for obese men. When gross metabolic rate is expressed per kilogram of total body mass, the difference between individuals who are obese vs. normal weight is much reduced (1, 6), which suggests that total body weight is the primary determinant of the cost of walking.

Measuring the net metabolic rate (gross − standing) can give a better measure of the cost of the walking movement itself. Some previous studies of energy expenditure during level walking suggest a 10–15% greater net metabolic rate of walking (per kg of total body mass) for class II obese adults [body mass index (BMI) = 30–40 kg/m^2; Ref. 42] compared with normal-weight adults (6, 31, 32). Other studies suggest that walking may be as much as 50% more expensive for adults with a BMI >35 kg/m^2 (3, 16, 18, 32). The greater net metabolic rate of obese adults may be partly due to heavier and larger legs that require an increase in step width and leg swing circumduction (lateral leg swing) (40). Both factors have been shown to substantially increase net metabolic rate in normal-weight subjects (10, 39).

One might predict that walking would be more expensive for obese women because women carry more of their body fat in the hips and thighs (gynoid adiposity) than men (android adiposity) (4). However, it is not known whether the energy expenditure during walking is different for obese women vs. obese men and whether any difference is due to the distribution of adipose tissue. It seems logical to expect that the net metabolic cost of walking is affected by the distribution of adipose tissue. Experiments on normal-weight individuals show that walking is more expensive when mass is placed on the thighs or lower legs compared with waist loads (41). This increase in net metabolic rate is partly due to the increase in mechanical work required to swing legs that have a greater mass and moment of inertia (38). Women may have relatively heavier legs (thigh mass/body mass) than men due to differences in the distribution of body fat (4), which might result in a greater net metabolic rate. Dual-energy X-ray absorptiometry (DEXA) provides a means of accurately determining leg segment masses and moments of inertia (13), but no leg mass or moment of inertia data have been reported for obese individuals.

Even among normal-weight individuals, sex may affect the net metabolic rate measured during walking. Normal-weight women and men have similar gross energy expenditures during walking (41). However, normal-weight women have smaller standing metabolic rates (per kg body weight) than normal-weight men (37) because of their smaller lean body mass (greater body fat percent) (7). The similar gross and smaller standing metabolic rates of normal-weight women would presumably result in a greater net metabolic rate than normal-weight men during walking.

In normal-weight adults, the gross energy consumed per unit distance vs. walking speed relationship is U-shaped (30, 35). The minimum energy cost required to walk a given distance occurs at ~1.4 m/s (~5 km/h or 3 miles/h) (30, 34, 43), which is also the preferred walking speed of normal-weight adults (37). Class II obese adults prefer to walk more slowly than

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normal-weight adults (1.2 vs. 1.4 m/s) in some studies (31, 32), but our recent study found no difference between young class II obese and normal-weight women (6). Although we reported that young obese women walked slightly faster (1.4 m/s) than the speed that minimized gross energy cost/distance (1.25 m/s), it is important to note that the difference in energy cost between the preferred and energetic minimum speed was small (~3%). Our study suggests that obese adults prefer a walking speed that approximately minimizes the energy cost per distance and that moderate obesity does not affect the gross energy cost per distance metabolic rate vs. walking speed relationship (6, 37). Therefore, we would expect that preferred walking speeds would be similar between class II obese and normal-weight women and men.

The primary purpose of this study was to compare the metabolic rates, energy cost per distance of walking vs. speed relationships, and the preferred walking speed for class II obese vs. normal-weight men and women. A secondary purpose of this study was to determine the effects of adipose tissue distribution on the metabolic cost of walking.

We hypothesized the following. *1*) The net metabolic cost of walking is greatest (per kg total body mass) for obese women, less for obese men and normal-weight women, and least for normal-weight men. *2*) The greater net metabolic cost of walking for the obese women is due, in part, to the greater relative mass and moment of inertia of their legs compared with the obese men and normal-weight women and men. *3*) Preferred walking speed corresponds to the speed that minimizes the gross energy cost per distance for obese and normal-weight adults of both sexes.

METHODS

The experimental protocol as well as the methods used to determine metabolic rate and preferred walking speed have been described in detail in Browning and Kram (6) and will be described only briefly here.

Subjects

Four groups of young adults volunteered for this study: class II obese women ($n = 9$), class II obese men ($n = 10$), normal-weight women ($n = 10$), and normal-weight men ($n = 10$). BMI was used to classify the participants; obese subjects had BMI values of 30–40 kg/m^2, and normal-weight subjects had BMI values of <25 kg/m^2. The female subjects were part of an earlier study (6). All subjects were in good health, not taking medications known to influence metabolism, sedentary to moderately physically active (<90 min/wk), and body mass stable (<2.5 kg net change over the previous 3 mo). Subjects gave written, informed consent to this study that followed the guidelines of the University of Colorado Human Research Committee.

The physical characteristics of the groups were significantly different and are shown in Table 1. The obese groups had a greater body mass, waist-to-hip ratios, BMI, and percent body fat than the normal-weight groups. In addition to differences in fat mass, lean body mass was greater in the obese women compared with normal-weight women, but the difference in lean body mass between the male groups was not significant. The men were taller and had a smaller percent body fat than their female counterparts.

Experimental Protocol

Each subject completed three test sessions. In the first session, 12-h-fasted subjects underwent a physical examination, blood draw and analysis, and body composition measurement. The second session included treadmill familiarization (Track Master 425, Newton, KS) and a maximal oxygen uptake ($\dot{V}O_{2\,max}$) test. In the third session, we measured each subject's preferred overground walking speed and then their metabolic cost during six level treadmill walking trials. The trials began after 5 min of quiet standing on the treadmill, and speeds were 0.50, 0.75, 1.00, 1.25, 1.50, and 1.75 m/s, with 5 min of rest between trials. Trial order progressed from the slowest to the fastest speed.

Assessments

Physical health and activity. Each subject's health and physical activity level were assessed by physical examination and interview. Resting heart rate and blood pressure were recorded, and resting levels of glucose, thyroid-stimulating hormone, and blood cell counts and profiles were determined and confirmed to be within normal ranges. Subjects completed a physical activity-level questionnaire (27). More than 90 min of moderate or vigorous activity per week was an exclusion criterion.

Body and segment measurements and composition. Measuring each subject's waist circumference at the level of the umbilicus and hip circumference at the widest point between the hips and buttocks yielded the waist-to-hip ratio (4). We measured each subject's body composition using a whole body DEXA scanner (DPX-IQ, Lunar, Madison, WI). The DEXA scan measured fat mass, lean tissue mass, and bone mineral content of the total body and of the trunk, arm, and leg regions. The DEXA software allowed us to identify and digitize the thigh and shank segments lengths and cross-sectional areas using the DEXA software (Fig. 1). The thigh segment proximal and distal end points were the superior border of the greater trochanter and a transverse plane running between the femoral condyles and the tibial plateau, respectively. The shank segment proximal end point was the same as the distal end point of the thigh, and the distal end point was the lateral malleolus. Polygons defined the thigh and shank cross-sectional area. After segment cross-sectional areas were defined, the DEXA software calculated segment mass and composition. To determine thigh and shank radius of gyration, we used the regression

Table 1. *Physical characteristics of obese and normal-weight women and men*

Physical Characteristic	Women		Men	
	Obese ($n = 9$)	Normal ($n = 10$)	Obese ($n = 10$)	Normal ($n = 10$)
BMI, kg/m^2	33.8 (3.3)	20.4 (2.1)	33.5 (2.1)	22.3 (1.9)
Body mass, kg	94.8 (15.7)	58.7 (9.5)	104.7 (10.2)	74.7 (7.1)
Height, m	1.67 (0.07)	1.68 (0.06)	1.76 (0.08)†	1.82 (0.03)†
Age, yr	25.3 (7.3)	26.6 (5.5)	25.6 (7.0)	20.6 (1.3)
Waist-to-hip ratio	0.82 (0.08)*	0.73 (0.04)	0.95 (0.06)*†	0.80 (0.04)
Percent body fat, %	45.5 (2.3)*	27.8 (6.2)	34.5 (4.1)*†	16.2 (4.2)†
Lean body mass, kg	51.6 (8.5)*	42.1 (5.9)	67.5 (6.4)†	62.6 (6.1)†

Values are means (SD); *n*, no. of subjects. *$P < 0.05$, obese vs. normal-weight of that sex. †$P < 0.05$, women vs. men of that group (obese or normal weight). BMI, body mass index.

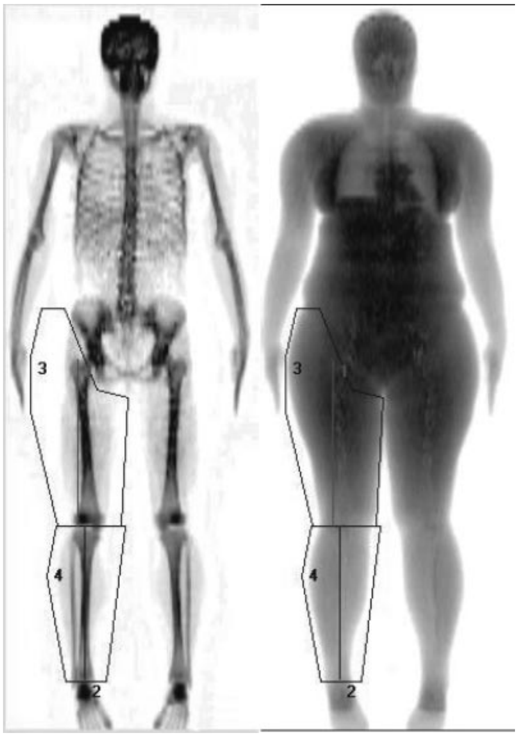

Fig. 1. Dual-energy X-ray absorptiometry scan showing segmentation of thigh (3) and shank (4) segments. The thigh segment was defined from an origin of the soft tissue border of the pubic symphysis to the inferior lateral border of the ilium, along the lateral border of the ilium to the iliac crest, horizontal to the lateral soft tissue border and inferior to the lateral epicondyle, medial to the soft tissue border, and back to the origin. This was done to include the lateral section of the hip without including the pelvis and to avoid including adipose tissue of the waist. The proximal and distal ends of the shank segment were the tibial plateau and the inferior border of the lateral malleolus, respectively. The soft tissue borders of the shank served as the medial and lateral borders.

equations provided by Durkin and Dowling (12) and calculated frontal plane moment of inertia (I_{com}) using the segment mass and radius of gyration. Differences between frontal and sagittal plane segment parameters have been shown to be small (8), so we used the frontal plane values to represent the sagittal plane moments of inertia.

$\dot{V}O_{2\,max}$. Each subject completed a modified Balke treadmill protocol (17) to measure $\dot{V}O_{2\,max}$. Treadmill speed was held constant, and grade was increased by 2% every 2 min. Subjects breathed through an open-circuit respirometry system (CardiO2/CP, MedGraphics, St. Paul, MN), which averaged expired gas data over 30-s intervals.

Preferred walking speed. To determine preferred walking speed, each subject walked 70 m on a level sidewalk (<1° inclination as measured by surveyor's line level). They walked back and forth six times at their "comfortable walking pace." We timed subjects over the middle 50 m during each trial and calculated preferred walking speed as the mean of the last five trials.

Energetic Measurements

To determine metabolic rate during standing and walking, we measured the rates of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) using an open-circuit respirometry system (CardiO2/CP Gas Exchange System, MedGraphics). For each trial, we allowed 3 min for the subjects to reach steady state and then calculated the average $\dot{V}O_2$ (ml O_2/s) and $\dot{V}CO_2$ (ml CO_2/s) for the final 2 min of each trial. We calculated gross metabolic rate (W/kg) from $\dot{V}O_2$ and $\dot{V}CO_2$ using a standard equation (5). Subtracting standing metabolic rate from the walking gross metabolic rate yielded net metabolic rate. Finally, dividing gross metabolic rate (W/kg total body mass) by walking speed (m/s) gave gross metabolic energy cost per distance ($J \cdot kg^{-1} \cdot m^{-1}$). For each walking speed, the time required for 10 strides allowed the calculation of stride frequency and stride length because treadmill speed was known.

Statistical Analysis

A two-factor (obesity and sex) ANOVA identified group differences in physical characteristics. A three-factor ANOVA with repeated measures determined how walking speed, obesity, and sex affected $\dot{V}O_2$, metabolic rate, energy cost per distance, and relative aerobic effort. An analysis of covariance (ANCOVA) procedure was used to determine whether the significant main effects of obesity and sex on net metabolic rate remained when the covariate height, body mass, or body fat was included. An ANCOVA was performed for each covariate with both obesity and sex as the categorical independent variables. When warranted, a Tukey's honestly significant difference post hoc procedure discriminated statistical differences. Bivariate correlations tested for collinerarity of independent variables. Linear regression analysis determined whether adipose tissue distribution (i.e., thigh mass/body mass), leg segment parameters (i.e., thigh and shank moment of inertia), or body composition (% body fat) was correlated to the net metabolic rate. A criterion of $P < 0.05$ defined significance.

RESULTS

Overview

In both sexes, obesity greatly increased the total energy expenditure for walking. Walking was most expensive (net metabolic rate, W/kg) for the obese women, less expensive for the obese men and normal-weight women, and least expensive for the normal-weight men. All groups preferred to walk at similar speeds, which were near the speeds that minimized their gross energy cost per distance traveled. Part of the variance in the metabolic cost of walking across the groups could be explained by differences in the percentage of body fat, but the metabolic cost of walking was not related to distribution of body mass.

Energetics

While standing, obese subjects consumed ~20% less metabolic energy per kilogram body mass than normal-weight subjects. However, when standing $\dot{V}O_2$ was normalized to lean body mass, there were no differences among the groups. Moreover, obese and normal-weight subjects of each sex achieved similar absolute $\dot{V}O_{2\,max}$ (l/min) values (Table 2). When normalized to mass, $\dot{V}O_{2\,max}$ values were lower in the obese subjects. Specifically, the obese women had a 33% lower mass-specific $\dot{V}O_{2\,max}$ compared with the normal-weight women, whereas the obese men had a 28% lower mass-specific $\dot{V}O_{2\,max}$ compared with the normal-weight men.

The gross $\dot{V}O_2$ vs. walking speed relationships was curvilinear for all groups. Differences between the groups were dependent on the normalization method used. Gross $\dot{V}O_2$ (l/min) was greater for the obese vs. normal-weight groups (Fig. 2*A*). The difference in gross $\dot{V}O_2$ between the obese and normal-weight groups increased with walking speed. Gross $\dot{V}O_2$ was 53 and 70% greater for obese vs. normal-weight women at 0.5 and 1.75 m/s, respectively. For the men, the differences in gross $\dot{V}O_2$ were 29 and 47% at those speeds. There were no differences between the groups when $\dot{V}O_2$ was normalized to total body mass ($ml \cdot kg^{-1} \cdot min^{-1}$) (Fig. 2*B*). Normalizing

Table 2. *Standing and maximal metabolic rates for obese and normal-weight men and women*

Metabolic Rate	Women		Men	
	Obese (n = 9)	Normal (n = 10)	Obese (n = 10)	Normal (n = 10)
$\dot{V}O_{2\ Stand}$, ml·kg^{-1}·min^{-1}	3.07 (0.36)*	3.84 (0.50)	3.44 (0.29)*	4.01 (0.49)
$\dot{V}O_{2\ Stand}$, ml·kg$_{lean}^{-1}$·min^{-1}	5.64 (0.55)	5.32 (0.54)	5.28 (0.44)	4.78 (0.48)
Standing metabolic rate, W/kg	1.06 (0.12)*	1.32 (0.17)	1.19 (0.11)*	1.40 (0.17)
$\dot{V}O_{2\ max}$, l/min	2.44 (0.40)	2.27 (0.47)	3.58 (0.63)†	3.64 (0.50)†
$\dot{V}O_{2\ max}$, ml·kg^{-1}·min^{-1}	25.9 (3.3)*	38.6 (4.4)	35.1 (7.5)*†	48.6 (4.4)†

Values are means (±SD); *n,* no. of subjects. $\dot{V}O_{2\ Stand}$: standing oxygen consumption; kg$_{lean}$, lean body mass; $\dot{V}O_{2\text{-}max}$, maximal oxygen consumption. *$P < 0.05$, obese vs. normal weight of that sex. †$P < 0.05$, women vs. men of that group (obese or normal weight).

$\dot{V}O_{2\ max}$ to lean body mass (ml·lean kg^{-1}·min^{-1}) resulted in obese women having the greatest metabolic rate (Fig. 2*C*), due to their smaller relative lean tissue mass (greater percent body fat).

The net metabolic rate (i.e., the cost of the walking movement per kg body mass) was ~10% greater for the obese groups compared with their normal-weight counterparts averaged across all speeds (Fig. 3). ANOVA revealed that there were significant speed × obesity (P = 0.006) and speed × sex (P = 0.020) interactions, but there was no significant interaction between speed, sex and obesity (P = 0.158). In addition, there were significant between group (obese vs. normal weight) and sex main effects (P < 0.01), but the interaction between group and sex was not significant (P = 0.928). ANCOVA revealed that neither height, mass, or percent body fat was responsible for the group or sex differences in the net metabolic rate vs. walking speed relationship. The net metabolic rates (W/kg) for walking were significantly greater for the obese vs. normal-weight women at 1.50 and 1.75 m/s and significantly greater for the obese vs. normal-weight men at 1.00, 1.25, 1.50, and 1.75 m/s. Stride lengths were not different between the groups at any walking speed.

Body Mass Distribution and Net Metabolic Rate

Thigh and shank mass and I_{com} were dramatically different between the obese and normal-weight groups (Table 3). The obese groups had greater thigh mass, thigh I_{com}, and shank mass than the normal-weight groups. The ratio of thigh mass to total body mass was greater in the obese women compared with the other groups, as was the composition of the thigh and shank (% fat). Interestingly, the absolute thigh mass, thigh I_{com}, shank mass, and shank I_{com} did not differ between normal-weight women and men. Also, thigh and shank composition were similar between the obese men and normal-weight women.

Multiple linear regressions of the pooled subject data revealed that body mass distribution (i.e., thigh mass/body mass) did not explain the variance in net metabolic rate (r^2= 0.04, P = 0.54 at 1.5 m/s, similar values at other speeds). In addition, normalized thigh I_{com} did not explain the variance in net metabolic rate (r^2 = 0.004, P = 0.69 at 1.5 m/s, similar values at other speeds). However, overall body composition (% body fat) did explain a significant portion of the variance in net metabolic rate, as shown in Fig. 4 (r^2 = 0.43, P < 0.001 at 1.5 m/s). At slower speeds, body composition explained less of the variance in net metabolic rate. For example, at 0.75 m/s body composition explained only 15% of the variance in net metabolic rate (r^2 = 0.15, P = 0.01).

Gross Energy Cost per Distance and Preferred Walking Speed

Subjects in all groups consumed a similar amount of gross energy per distance traveled (J·kg^{-1}·m^{-1}) at all speeds. Although net metabolic cost was greater in the obese subjects, their lower standing metabolic rates led to similar gross costs (Fig. 5). All groups exhibited similar U-shaped relationships between cost per distance and walking speed. The calculated speeds (from second-order least squares regression) that corresponded to the minimum energy cost per distance were slightly slower for the obese women compared with the other groups (Table 4). Minimum energy cost per distance was 2.95, 2.89, 3.01 and 2.81 J·kg^{-1}·m^{-1} for obese women, obese men, normal-weight women, and normal-weight men, respectively.

Neither obesity nor sex affected the preferred walking speed (Table 4). The obese women walked slightly slower (1.41 m/s) than the normal-weight women (1.47 m/s), but the difference was not statistically significant (P = 0.28). By interpolating the energy cost per distance vs. walking speed relationship to their preferred walking speeds, we found that the gross energy cost per distance was 3.04, 2.92, 3.06, and 2.81 J·kg^{-1}·m^{-1} for obese women, obese men, normal-weight women, and normal-weight men, respectively. Thus the difference in the energy cost per distance at the preferred speed and at the minimum energy cost per distance speed was small, ~3% for the women and <1% for the men.

DISCUSSION

Energetics

We accept our hypothesis that the net metabolic rate of walking would be greatest for obese women and least for normal-weight men. The ~10% greater mass-specific net metabolic rate of obese vs. normal-weight adults reported here is similar to values reported by Mattsson et al. (31) and Melanson et al. (32), but it is lower than values reported by others. Bloom and Marshall (3) reported that the net metabolic rate of walking at speeds ranging from 0.7 to 1.4 m/s was ~45% greater in obese men and women compared with normal-weight adults, but their data are difficult to interpret because mean data for all subjects are not presented. The study of Foster et al. (16) reported net metabolic rates of slight uphill walking for adults with class II obesity (BMI = 39 kg/m^2) that were ~45% greater than the net metabolic rate of normal-weight subjects during level walking. Walking on a slight incline increases net metabolic rate by ~15% (33), so the difference in net metabolic rate between the Foster et al. study and ours is 20%. It

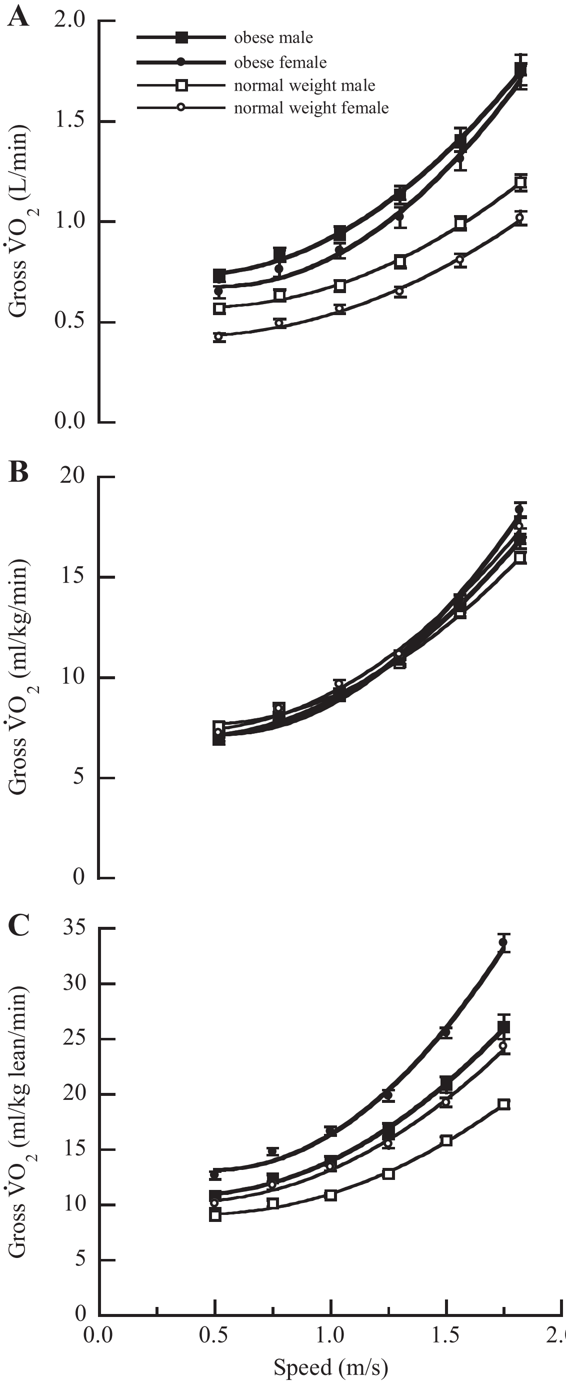

Fig. 2. Gross oxygen consumption ($\dot{V}O_2$) vs. walking speed, *A*: absolute $\dot{V}O_2$ (l/min). *B*: relative $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}). *C*: relative $\dot{V}O_2$ (ml·kg lean^{-1}·min^{-1}). Absolute $\dot{V}O_2$ was greater for the obese vs. normal-weight but relative $\dot{V}O_2$ (per kg total body mass) was similar across groups. Relative to lean body mass, $\dot{V}O_2$ was greatest for the obese women. Values are means ± SE. kg lean, kilograms of lean body mass.

may be that walking up a slight incline increases the metabolic rate disproportionately for obese subjects.

It is intriguing to compare the effects of obesity and external loading on the net metabolic rate of walking. Griffin et al. (22) found that when normal-weight individuals walked with an external load of 30% of body mass carried around the waist, net metabolic rate increased by 47%, whereas lower extremity kinematics were unchanged. Hence, net metabolic rate increased by ~15% when normalized by total mass (body + load). When we account for differences in lean body mass, our obese subjects were carrying ~30% of their "normal" mass (assuming same percent body fat as normal-weight subjects) as extra adipose tissue and net metabolic rate increased by 10%. Thus our net metabolic rate data suggest that external loading and adipose tissue have similar effects on the energetic cost of walking.

However, the situation may not be so simple. Stride lengths were similar between all of the groups, but other biomechanical variables may affect metabolic cost. Although we did not measure step width and leg swing circumduction in our subjects, Spyropoulos et al. (40) report that obese persons walk with a step width that is twice that of normal-weight persons and a midswing hip abduction angle of 19 vs. 9° in obese vs. normal-weight individuals, respectively. In normal-weight adults, doubling step width increases the metabolic cost of walking by 25% (10), and increasing leg swing circumduction increases the metabolic cost of walking by up to 30% (39). These increases are much larger than the 10% differences observed in this study and suggest that obese individuals may be able to walk in a way that minimizes the metabolic penalty associated with their step width and leg swing circumduction.

Supporting body weight and performing work on the center of mass are two important determinants of the net metabolic cost of walking (20). Obese individuals may reduce the cost of supporting body weight by walking with a straighter leg and more erect posture (9). This adaptation would reduce the muscles forces required to support the body (2). Obese individuals may reduce the work performed on the center of mass by a more effective use of the body as an inverted pendulum. An improved "recovery" of mechanical energy has been implicated in mitigating some of the increase in metabolic rate associated with carrying loads (23). In addition, obese individuals may somehow use wider steps to their advantage by utilizing lateral motion to improve the recovery of mechanical energy, a phenomenon that has been observed in penguins (21).

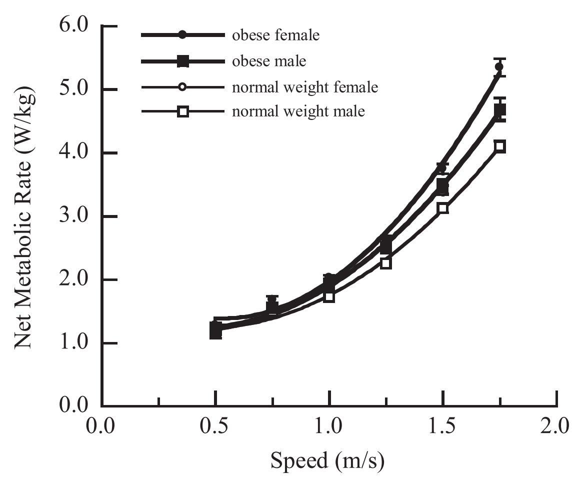

Fig. 3. Net metabolic rate vs. walking speed for obese and normal-weight women and men. Metabolic rate for obese men and normal-weight women was similar and thus the line for normal-weight women is obscured. Net metabolic rate vs. speed relationship for each group was curvilinear (second-order least squares regression, $r^2 = 0.94$). Values are means ± SE. Some error bars are obscured by the size of the symbols.

Table 3. *Thigh and shank mass, composition, and moment of inertia for the right leg of obese and normal-weight adults*

Segment Characteristic	Women		Men	
	Obese (n = 9)	Normal (n = 10)	Obese (n = 10)	Normal (n = 10)
Thigh mass, kg	13.5 (2.7)*	7.9 (1.7)	13.7 (1.5)*	9.7 (0.7)
M_T/M_B ratio	0.142 (0.009)	0.134 (0.01)	0.132 (0.006)†	0.130 (0.006)
Thigh fat, %	55.4 (2.8)*	43.3 (5.4)	41.4 (4.7)*†	24.5 (5.3)†
I_{com} thigh, kg-m^2	0.242 (0.081)*	0.145 (0.040)	0.266 (0.057)*	0.198 (0.019)
Shank mass, kg	3.9 (0.82)*	2.6 (0.37)	4.1 (0.47)*	3.2 (0.42)
Shank fat, %	44.5 (3.4)*	32.6 (6.3)	30.1 (5.3)*†	18.5 (6.3)†
I_{com} shank, kg-m^2	0.040 (0.014)	0.028 (0.007)	0.046 (0.011)	0.041 (0.007)

Values are means (±SD); n, no. of subjects. M_T/M_B ratio, ratio of thigh mass to body mass; I_{com}, frontal plane moment of inertia. *$P < .05$, obese vs. normal weight of that sex. †$P < 0.05$, women vs. men of that group (obese or normal weight).

Body Mass Distribution and Energetics

Contrary to our hypothesis, the greater net metabolic cost of walking for obese women was not due to body mass distribution. The use of DEXA allowed the determination of a thigh mass-to-body mass ratio and the I_{com} of the thigh. The obese women had a 62% greater body mass and their thigh mass was 70% greater than the normal-weight women. The obese men had a 40% greater body mass, and their thigh mass was 41% greater than the normal-weight men. As a result, the thigh mass-to-body mass ratio was slightly greater for the obese women (~14%) vs. the other groups (~13%), indicating that they have relatively heavier legs. In addition, the I_{com} of the thigh was greater in the obese women. The greater mechanical work required to swing the relatively heavier legs of obese women may increase the metabolic cost of walking (38), especially at faster walking speeds. However, recent evidence suggests that in normal-weight adults leg swing only accounts for ~10% of the total metabolic cost of walking (19). On the basis of this finding, to account for the 10% increase in net metabolic rate in obese vs. normal-weight women, the cost of leg swing would have to increase by 100%. Therefore, the relatively small difference in the thigh mass-to-body mass ratio between obese women and obese men does not seem to be sufficient to elicit a measurable influence on net metabolic rate.

Our segment mass and I_{com} data highlights the importance of individual subject anthropometric data. We compared our shank segment masses obtained via the DEXA software with values obtained using the regression equations developed by Durkin and Dowling (12). Differences between measured and calculated shank mass were relatively large (root-mean-square error of 19.9, 9.5, 11.7, and 8.4% for the obese women, obese men, normal-weight women, and normal-weight men, respectively), despite similar segmentation. One possible explanation for this difference is that although Durkin and Dowling's study included obese individuals, their regressions were based on groups with a wide range of individual adiposity. The development of regression equations to calculate anthropometric parameters for obese individuals is clearly needed, especially for biomechanical studies.

We found that the percent of body fat explains ~45% of the variance in the net metabolic rate of walking. Obese men and normal-weight women had similar body composition and also had similar net metabolic rates. The thigh and shank fat percents were even more similar between the obese men and normal-weight women, but these measures were strongly correlated to body fat percent, and including them in the multiple regressions did not improve the correlation between body fat

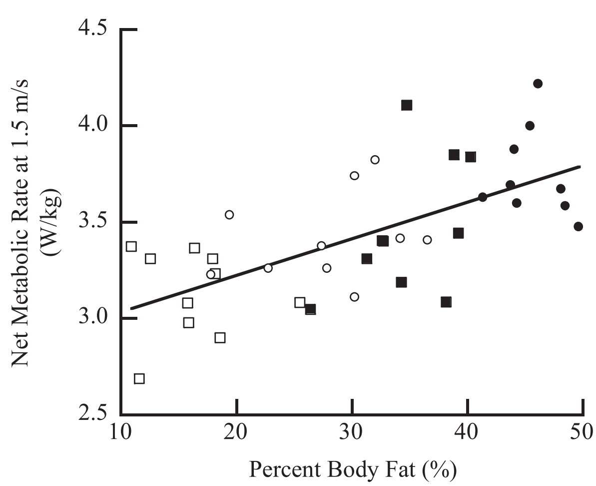

Fig. 4. Net metabolic rate of walking at 1.5 m/s vs. percent body fat for all subjects (n = 39). ●, Obese women; ■, obese men; ○, normal-weight women; □, normal-weight men. Line is least squares linear regression, $y = 0.019x + 2.844$, $r^2 = 0.43$, $P < 0.001$.

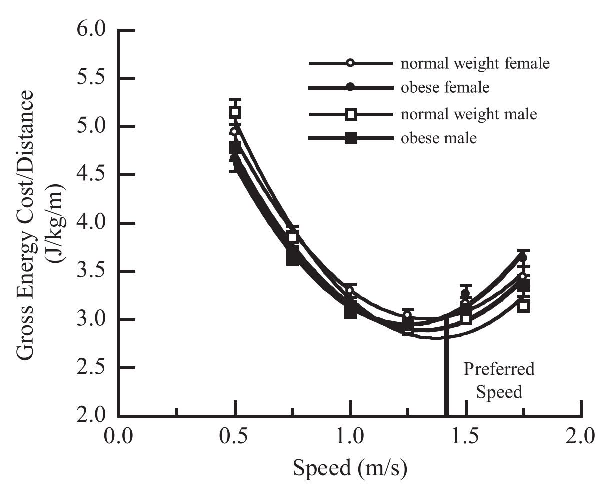

Fig. 5. Gross energy cost per distance for obese and normal-weight women and men. The speed that minimized energy cost per distance speed was slower for obese women (1.25 m/s) compared with obese men (1.32 m/s; $P = 0.055$) and normal-weight women (1.33 m/s; $P = 0.006$). Solid vertical line indicates preferred walking speed, which was similar for all groups (1.42 m/s). Lines are second-order least squares regressions. Values are means ± SE.

Table 4. *Preferred walking speed and speed of minimum energy cost per distance for obese and normal-weight women and men*

	Women		Men	
	Obese (n = 9)	Normal (n = 10)	Obese (n = 10)	Normal (n = 10)
V_{Pref} m/s	1.41±0.02	1.47±0.04	1.42±0.06	1.41±0.03
V_{MECD} m/s	1.25±0.02*	1.33±0.03	1.32±0.02	1.38±0.01

Values are means (±SE); *n,* no. of subjects. V_{Pref}, preferred walking speed; V_{MECD}, speed of minimum energy cost per distance. *P < 0.05 obese vs. normal-weight women.

and mean net metabolic rate. The fact that body fat is related to the net metabolic cost of walking is not surprising given how increasing body fat reduces standing metabolic rate (36) but does not change the gross metabolic cost of walking.

Preferred Walking Speed and Gross Energy Cost per Distance

As we hypothesized, preferred walking speeds were not different between the groups and were near the speed that minimized gross energy cost per distance. Our measured preferred speeds were faster than previous reports for obese adults. Mattsson et al. (31) and Melanson et al. (32) measured preferred speeds of 1.18 and 1.19 m/s, respectively, for class II obese adults. Although the differences in preferred speed appear large (1.4 vs. 1.2 m/s), they are in the region where the energy cost per distance vs. walking speed relationship is relatively flat (i.e., the bottom of the U-shaped curve) and may not reflect different strategies for selecting preferred walking speed. Preferred speed has been shown to be slower in older adults (>65 yr old) (29), but the subjects in the studies of Mattsson et al. (31) and Melanson et al. (32) were younger (mean age ~45 yr old). Thus differences in age are not likely to account for the differences observed in preferred speed.

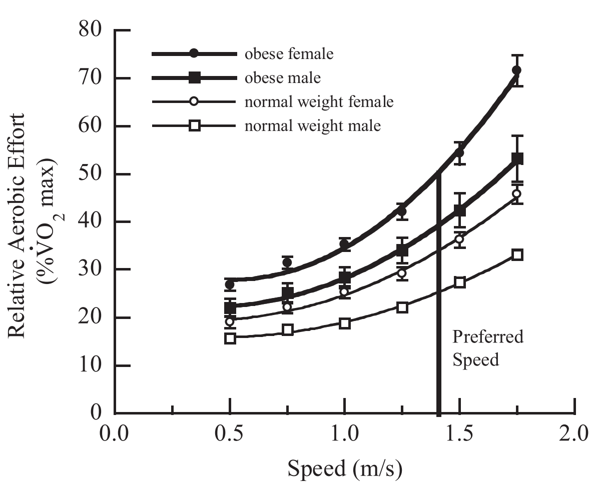

Fig. 6. Relative aerobic effort [% maximal $\dot{V}O_2$ ($\%\dot{V}O_{2\,max}$)] for obese and normal-weight women and men. The relative aerobic effort was significantly greater for the obese vs. normal weight at all speeds (P < 0.001) and was greater for women compared with men (P < 0.001). Solid vertical line indicates preferred walking speed (1.42 m/s). Values are means ± SE.

Relevance for Exercise Prescription

Our results also show that equations that predict mass-specific $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) during walking based on treadmill speed provide reasonable estimates for obese adults. For example, the mean mass-specific gross $\dot{V}O_2$ of obese groups in our study during level walking at 1.5 m/s was ~13.5 ml·kg^{-1}·min^{-1}, similar to predicted values of 12.5 and 14.5 ml·kg^{-1}·min^{-1} using the equations provided by Franklin et al. (17) and Pandolf et al. (33), respectively. However, these relatively small differences between the measured and predicted values of energy expenditure may be important given that a small positive energy balance (<100 kcal/day) has been associated with the development of obesity (25).

Although our emphasis has been on the similarity of the metabolic energy expended per kilogram of body mass, the total metabolic cost may be more important for exercise prescription. For example, if an obese person (150 kg) and a normal-weight person (75 kg) seek to counteract an excess intake of 400 kJ (100 kcal) of energy, the obese person only needs to walk half as far. Or, perhaps more optimistically, the

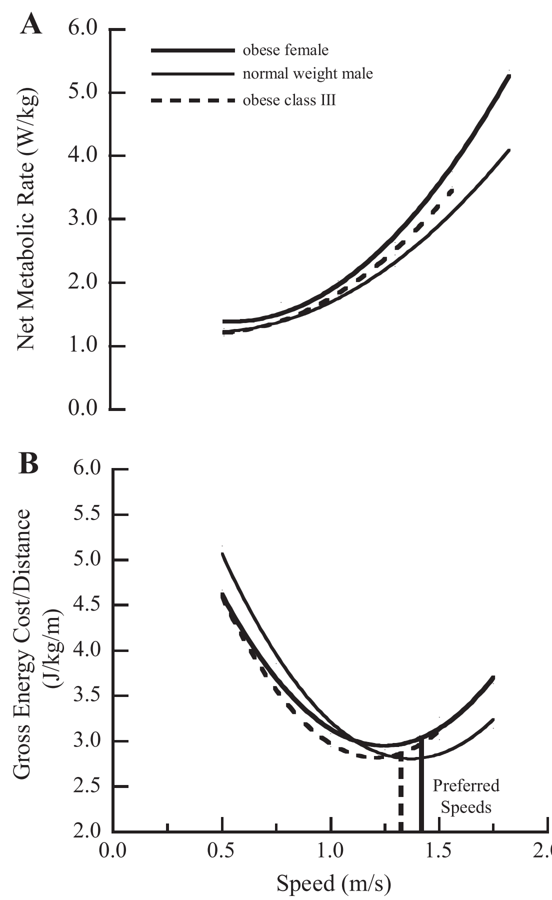

Fig. 7. Net metabolic rate vs. walking speed (*A*) and energy cost/distance vs. walking speed (*B*) for class III obese compared with obese women and normal-weight men. For clarity, metabolic rate and energy cost/distance for obese men and normal-weight women are not shown. Net metabolic rate for class III obese subjects was similar to obese men and normal-weight women. Speed that corresponded to the minimum energy cost/distance was slower in the class III obese (1.21 m/s), as was preferred speed (1.32 m/s). Minimum energy cost/distance was 2.82 J·kg^{-1}·m^{-1} for the class III obese subjects, which was similar to normal-weight men (2.81 J·kg^{-1}·m^{-1}).

obese person would expend slightly more than twice as many total kilocalories by walking the same distance.

The relative aerobic effort required to walk at the preferred speed was greater in the obese than normal-weight groups (Fig. 6). Walking at the preferred speed required 50, 40, 36, and 25% of mass-specific $\dot{V}O_{2\,max}$ for the obese women, obese men, normal-weight women, and normal-weight men, respectively. At preferred walking speed, the obese adults were at a moderate-intensity effort (40–55% $\dot{V}O_{2\,max}$/kg). Although walking faster than their preferred speed will provide an increase in energy expenditure, it may also increase the risk of musculoskeletal injury. Obese adults have a much greater risk of developing knee osteoarthritis (14) than normal-weight adults. In normal-weight subjects, faster walking speeds result in increased biomechanical loads on the lower extremities (28), which may increase the risk of chronic injuries and osteoarthritis. A strategy of walking slower for a defined distance may effectively maintain or even increase energy expenditure ($J \cdot kg^{-1} \cdot m^{-1}$), while reducing the risk of lower extremity injury.

Class III Obesity Data

The degree of obesity may affect the net metabolic rate of walking. The data of Freyschuss and Melchner (18) suggest that net metabolic rate was ~60% greater in class III (BMI = ~49 kg/m^2) obese men and women compared with normal-weight controls walking at 1.0 m/s across a range of inclines. To begin to address the question of the effects of increasing adiposity on net metabolic rate, we have collected metabolic data on five class III obese subjects (3 men, 2 women, mass = 153 kg, BMI = 47.1 kg/m^2) while they walked on the level at 0.50–1.5 m/s. Surprisingly, the net metabolic rate (W/kg) vs. speed relationship was similar compared with the class II obese subjects (Fig. 7*A*). The similarity in net metabolic rate of class II and class III obese subjects is likely due to the fact that as BMI increases above the class II obesity standard, the slope of the percent body fat vs. BMI relationship decreases (15). As a result, our class III obese subjects may have had body fat percents that were similar to our class II subjects, although we could not determine body composition due to weight limitations of the DEXA device. This idea is supported by our finding that standing metabolic rates (1.14 W/kg) of the class III obese subjects were also similar to the class II obese subjects, despite having a 50% greater body mass. Class III obese have been shown to walk with a shorter stride length (9). The shorter stride length may reduce the metabolic cost of walking by reducing the mechanical work associated with redirecting the center of mass during the double-support phase (11).

The preferred speed of our class III obese subjects was 1.32 m/s and was near the speed that minimized the gross energy cost per distance (1.24 m/s) (Fig. 7*B*). The energy cost per distance curve for the class III obese was shifted slightly, toward slower speeds. This shift is a result of the steeper slope of the metabolic rate vs. speed relationship. These data suggest that increasing levels of adiposity do not alter the strategy of selecting preferred speed based on minimizing energy cost per distance. Other factors may cause preferred speed to slow (e.g., joint pain), but our subjects were young and asymptomatic for pain during walking.

In conclusion, we found that the mass-specific net metabolic rate of walking was greater in obese adults and that sex also affects the metabolic cost of walking. Obese women had a 10% greater net metabolic rate than obese men and normal-weight women and a 20% greater net metabolic rate compared with normal-weight men. Body mass distribution did not explain the differences in net metabolic rate between the groups. Preferred walking speeds were similar for all the groups and were near the speed that minimized the energy cost per distance. Future studies on the effects of obesity on the biomechanics of walking are needed to investigate whether obese individuals adopt novel energy-saving mechanisms during walking.

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REFERENCES

1. **Ayub BV and Bar-Or O.** Energy cost of walking in boys who differ in adiposity but are matched for body mass. *Med Sci Sports Exerc* 35: 669–674, 2003.
2. **Biewener AA, Farley CT, Roberts TJ, and Temaner M.** Muscle mechanical advantage of human walking and running: implications for energy cost. *J Appl Physiol* 97: 2266–2274, 2004.
3. **Bloom WL and Marshall FE.** The comparison of energy expenditure in the obese and lean. *Metabolism* 16: 685–692, 1967.
4. **Heymsfield SB, Allison DB, Wang ZM, Baumgartner RN, and Ross R.** Evaluating total and regional body composition. In: *Handbook of Obesity*, edited by Bray GA, Bouchard C, and James WPT. New York: Dekker, 1998, p. 41–77.
5. **Brockway JM.** Derivation of formulae used to calculate energy expenditure in man. *Hum Nutr Clin Nutr* 41: 463–471, 1987.
6. **Browning RC and Kram R.** Energetic cost and preferred speed of walking in obese vs. normal weight women. *Obes Res* 13: 891–899, 2005.
7. **Cunningham JJ.** Body composition as a determinant of energy expenditure: a synthetic review and a proposed general prediction equation. *Am J Clin Nutr* 54: 963–969, 1991.
8. **De Leva P.** Adjustments to Zatsiorsky-Seluyanov's segment inertial parameters. *J Biomech* 29: 1223–1230, 1996.
9. **DeVita P and Hortobagyi T.** Obesity is not associated with increased knee joint torque and power during level walking. *J Biomech* 36: 1355–1362, 2003.
10. **Donelan JM, Kram R, and Kuo AD.** Mechanical and metabolic determinants of the preferred step width in human walking. *Proc R Soc Lond B Biol Sci* 268: 1985–1992, 2001.
11. **Donelan JM, Kram R, and Kuo AD.** Mechanical work for step-to-step transitions is a major determinant of the metabolic cost of human walking. *J Exp Biol* 205: 3717–3727, 2002.
12. **Durkin JL and Dowling JJ.** Analysis of body segment parameter differences between four human populations and the estimation errors of four popular mathematical models. *J Biomed Eng* 125: 515–522, 2003.
13. **Durkin JL, Dowling JJ, and Andrews DM.** The measurement of body segment inertial parameters using dual energy X-ray absorptiometry. *J Biomech* 35: 1575–1580, 2002.
14. **Felson DT, Anderson JJ, Naimark A, Walker AM, and Meenan RF.** Obesity and knee osteoarthritis: the Framingham study. *Ann Intern Med* 109: 18–24, 1988.
15. **Fernandez JR, Heo M, Heymsfield SB, Pierson RN, Pi-Sunyer FX, Wang ZM, Wang J, Hayes M, Allison DB, and Gallagher D.** Is percentage body fat differentially related to body mass index in Hispanic Americans, African Americans, and European Americans? *Am J Clin Nutr* 77: 71–75, 2003.

16. **Foster GD, Wadden TA, Kendrick ZV, Letizia KA, Lander DP, and Conill AM.** The energy cost of walking before and after significant weight loss. *Med Sci Sports Exerc* 27: 888–894, 1995.
17. **Franklin BH, Whaley GP, and Howley ET.** *ACSM's Guidelines for Exercise Testing and Prescription*. Philadelphia, PA: Lippincott Williams & Wilkins, 2000.
18. **Freyschuss U and Melcher A.** Exercise energy expenditure in extreme obesity: influence of ergometry type and weight loss. *Scand J Clin Lab Invest* 38: 753–759, 1978.
19. **Gottschall JS and Kram R.** Energy cost and muscular activity required for forward propulsion and leg swing during walking. *J Appl Physiol* 99: 23–30, 2005.
20. **Grabowski A, Farley CT, and Kram R.** Independent metabolic costs of supporting body weight and accelerating body mass during walking. *J Appl Physiol* 98: 579–583, 2005.
21. **Griffin TM and Kram R.** Penguin waddling is not wasteful. *Nature* 408: 929, 2000.
22. **Griffin TM, Roberts TJ, and Kram R.** Metabolic cost of generating muscular force in human walking: insights from load-carrying and speed experiments. *J Appl Physiol* 95: 172–183, 2003.
23. **Heglund NC, Willems PA, Penta M, and Cavagna GA.** Energy-saving gait mechanics with head-supported loads. *Nature* 375: 52–54, 1995.
24. **Hill JO and Peters JC.** Environmental contributions to the obesity epidemic. *Science* 280: 1371–1374, 1998.
25. **Hill JO, Wyatt HR, Reed GW, and Peters JC.** Obesity and the environment: where do we go from here? *Science* 299: 853–855, 2003.
26. **Jakicic JM, Winters C, Lang W, and Wing RR.** Effects of intermittent exercise and use of home exercise equipment on adherence, weight loss, and fitness in overweight women: a randomized trial. *JAMA* 282: 1554–1560, 1999.
27. **Kriska AM.** Modifiable Activity Questionnaire. *Med Sci Sports Exerc* 29: S73–S78, 1997.
28. **Lelas JL, Merriman GJ, Riley PO, and Kerrigan DC.** Predicting peak kinematic and kinetic parameters from gait speed. *Gait Posture* 17: 106–112, 2003.
29. **Malatesta D, Simar D, Dauvilliers Y, Candau R, Borrani F, Prefaut C, and Caillaud C.** Energy cost of walking and gait instability in healthy 65 and 80 yr olds. *J Appl Physiol* 95: 2248–2256, 2003.
30. **Margaria R.** *Biomechanics and Energetics of Muscular Exercise*. Oxford, UK: Clarendon, 1976.
31. **Mattsson E, Larsson UE, and Rossner S.** Is walking for exercise too exhausting for obese women? *Int J Obes Relat Metab Disord* 21: 380–386, 1997.
32. **Melanson EL, Bell ML, Knoll JR, Coelho LB, Donahoo WT, Peters JC, and Hill JO.** Body mass index and sex influence the energy cost of walking at self-selected speeds (Abstract). *Med Sci Sports Exerc* 35: S183, 2003.
33. **Pandolf KB, Givoni B, and Goldman RF.** Predicting energy expenditure with loads while standing or walking very slowly. *J Appl Physiol* 43: 577–581, 1977.
34. **Prampero PE di.** The energy cost of human locomotion on land and water. *Int J Sports Med* 7: 55–72, 1986.
35. **Ralston HJ.** Energy-speed relation and optimal speed during level walking. *Int Z Angew Physiol* 17: 277–283, 1958.
36. **Ravussin E, Lillioja S, Anderson T, Christin L, and Bogardus C.** Determinants of 24-hour energy expenditure in man: methods and results using a respiratory chamber. *J Clin Invest* 78: 1568–1578, 1986.
37. **Rose J, Ralson HJ, and Gamble JG.** Energetics of walking. In: *Human Walking,* edited by Rose J and Gamble JG. Baltimore, MD: Williams & Wilkins, 1994, p. 45–72.
38. **Royer TD and Martin PE.** Manipulations of leg mass and moment of inertia: effects on energy cost of walking. *Med Sci Sports Exerc* 37: 649–656, 2005.
39. **Shipman DW, Donelan JM, Kram R, and Kuo AD.** Metabolic cost of lateral leg swing in human walking. In: *Proceedings of the World Congress of Biomechanics*, Calgary, Alberta, Canada, Aug. 4–9, 2002.
40. **Spyropoulos P, Pisciotta JC, Pavlou KN, Cairns MA, and Simon SR.** Biomechanical gait analysis in obese men. *Arch Phys Med Rehabil* 72: 1065–1070, 1991.
41. **Waters RL and Mulroy S.** The energy expenditure of normal and pathologic gait. *Gait Posture* 9: 207–231, 1999.
42. **World Health Organization.** *Obesity. Preventing and Managing the Global Epidemic*. Geneva: World Health Organization, 1998.
43. **Zarrugh MY, Todd FN, and Ralston HJ.** Optimization of energy expenditure during level walking. *Eur J Appl Physiol* 33: 293–306, 1974.