Why Does Walking Economy Improve after Weight Loss in Obese Adolescents?

NICOLAS PEYROT[1], DAVID THIVEL[2], LAURIE ISACCO[2], JEAN-BENOÎT MORIN[3], ALAIN BELLI[3], and PASCALE DUCHE[2]

[1]CURAPS-DIMPS Laboratory (EA4075), University of La Réunion, UFR SHE, Le Tampon, FRANCE; [2]Laboratory of Exercise Biology (BAPS, EA 3533), University of Clermont-Ferrand, Clermont-Ferrand FRANCE; and [3]Laboratory of Exercise Physiology (EA 4338), University of Lyon, Saint-Etienne, FRANCE

ABSTRACT

PEYROT, N., D. THIVEL, L. ISACCO, J.-B. MORIN, A. BELLI, and P. DUCHE. Why Does Walking Economy Improve after Weight Loss in Obese Adolescents? *Med. Sci. Sports Exerc.*, Vol. 44, No. 4, pp. 659–665, 2012. **Purpose**: This study tested the hypothesis that the increase in walking economy (i.e., decrease in net metabolic rate per kilogram) after weight loss in obese adolescents is induced by a lower metabolic rate required to support the lower body weight and maintain balance during walking. **Methods**: Sixteen obese adolescent boys and girls were tested before and after a weight reduction program. Body composition and oxygen uptake while standing and walking at four preset speeds (0.75, 1, 1.25, and 1.5 $m{\cdot}s^{-1}$) and at the preferred speed were quantified. Net metabolic rate and gross metabolic cost of walking–versus-speed relationships were determined. A three-compartment model was used to distinguish the respective parts of the metabolic rate associated with standing (compartment 1), maintaining balance and supporting body weight during walking (compartment 2), and muscle contractions required to move the center of mass and limbs (compartment 3). **Results**: Standing metabolic rate per kilogram (compartment 1) significantly increased after weight loss, whereas net metabolic rate per kilogram during walking decreased by 9% on average across speeds. Consequently, the gross metabolic cost of walking per unit of distance–versus-speed relationship and hence preferred walking speeds did not change with weight loss. Compartment 2 of the model was significantly lower after weight loss, whereas compartment 3 did not change. **Conclusions**: The model showed that the improvement in walking economy after weight loss in obese adolescents was likely related to the lower metabolic rate of the isometric muscular contractions required to support the lower body weight and maintain balance during walking. Contrastingly, the part of the total metabolic rate associated with muscle contractions required to move the center of mass and limbs did not seem to be related to the improvement in walking economy in weight-reduced individuals. **Key Words:** OBESITY, ENERGY EXPENDITURE, METABOLIC RATE, GAIT BALANCE, THREE-COMPARTMENT MODEL

Walking is a convenient form of daily physical activity recommended for weight management. However, for obese individuals, walking may be an exhausting task requiring a considerable fraction of an individual's maximal aerobic capacity ($\dot{V}O_{2max}$), reaching ~56% at self-selected walking speeds (20). This high fraction of ($\dot{V}O_{2max}$ in obese individuals during walking is due to reductions of both relative aerobic capacity per kilogram of total body mass ($\dot{V}O_{2max/kg}$) (20,28) and walking economy (4,16,25). Walking economy is generally represented by the net metabolic rate per kilogram during walking (metabolic rate above resting ($W{\cdot}kg^{-1}$)) at a given speed, good economy being associated with a low net metabolic rate during walking and vice versa. After weight loss, both ($\dot{V}O_{2max/kg}$ and walking economy improve, but the underlying mechanisms of the increase in walking economy (i.e., decrease in net metabolic rate per kilogram) remain unclear (9,10,14).

The main hypotheses advanced to explain the decrease in net metabolic rate per kilogram during walking after weight loss were due to an increase in relative strength (14), an increase in efficiency of muscle mechanical work (26), and decreased isometric muscular contractions required to support body weight and maintain balance during walking (24). In the latter study, the authors have shown that after weight loss, some changes in the walking pattern were related to the decrease in net metabolic rate during walking. These changes included a decrease in the kinetic energy associated with mediolateral motion (e.g., lateral stability) as well as a decrease in biomechanical parameters associated with body weight support. Furthermore, these changes did not induce an increase in the external mechanical work required to lift and accelerate the center of mass. Therefore, the results of

Address for correspondence: Nicolas Peyrot, Ph.D., Université de la Réunion, Faculté des Sciences de l'Homme et de l'Environnement, Laboratoire CURAPS-DIMPS, Campus universitaire du Tampon, 117 rue du Général Ailleret, 97430 Le Tampon, île de La Réunion, France; E-mail: nicolas.peyrot@univ-reunion.fr.
Submitted for publication March 2011.
Accepted for publication September 2011.

0195-9131/12/4404-0659/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e318236edd8

APPLIED SCIENCES

Peyrot et al. (24) support the hypothesis that the decrease in net metabolic rate per kilogram during walking after weight loss may be due to a decrease in the metabolic rate of the isometric muscular contractions required to support body weight and maintain balance at each step rather than to a decrease in the metabolic rate associated with muscle contractions required to move the center of mass and limbs.

To further investigate the causes of this decrease in net metabolic rate during walking after weight loss in obese adolescents, there are theoretical models that can quantify and distinguish the possible sources of metabolic rate (17,30). Malatesta et al. (17) used a three-compartment model derived from a study by Workman and Armstrong (30) to investigate the causes of the greater metabolic rate during walking in healthy elderly versus young adults. This model differentiates the metabolic rate while walking into three compartments: standing metabolic rate (compartment 1), metabolic rate associated with maintaining balance during walking (compartment 2), and metabolic rate associated with muscle contractions required to move the center of mass and limbs (compartment 3). The model of Workman and Armstrong (30) has been derived to better assess the differences in metabolic rate between static balance with double support during standing and dynamic balance in single support, which is metabolically more costly (17). The new compartmentalization of the three-compartment model proposed by Malatesta et al. (17) tended to be correlated with gait instability ($P = 0.07$) and hence with muscle contractions required to maintain balance during walking. However, we proposed that compartment 2 of the model of Malatesta et al. represents not only the metabolic rate to maintain balance but also the metabolic rate to support body weight during walking. Indeed, during the single-limb support phase of walking, energy-consuming isometric contractions are necessary to both maintain balance and support body weight because the knee joint is not locked in extension such as during standing (13,22,27). Therefore, this could explain why compartment 2 of the model of Malatesta et al. (17) was not significantly and highly correlated with gait instability ($P = 0.07$). This model offers an interesting tool for investigating the causes of the decrease in net metabolic rate (per kilogram) during walking after weight loss in obese individuals. We hypothesized that in obese adolescents, the decrease in net metabolic rate during walking after weight loss could be induced by the lower metabolic rate required to support the lower body weight and maintain balance.

The aim of this study was to determine whether the decrease in net metabolic rate during walking after weight loss in obese adolescents was due to the lower metabolic rate of the isometric muscle contractions required to support the lower body weight and maintain balance during walking. To this aim, we measured the metabolic rate of overground walking at different speeds before and after a weight loss program in obese adolescents.

APPLIED SCIENCES

METHODS

Participants. The present study included 16 obese adolescents (7 boys and 9 girls) who were involved in an obesity management program in the Children's Medical Center of Romagnat (Centre Médical Infantile), France. None of them was regularly practicing any sport activity or receiving any medication that could interfere with their walking pattern or influence their energetic metabolism. The main inclusion criteria were age between 12 and 16 yr and body mass index (BMI ($kg \cdot m^{-2}$)) above age- and gender-specific cutoff points for obesity as defined by Cole et al. (7).

Subjects were housed at the medical center (except during weekends, which were spent at home) where they underwent a 12-wk voluntary weight reduction program including nutritional education, caloric restriction, and physical activities. The latter consisted of 40-min sessions of aerobic fitness, strength training, and supervised free practice per week. Diet composition was formulated according to the French-recommended dietary allowances (19), and on average, subjects lost 1 kg of total body mass per week before a stabilization phase that lasted about 2 wk before leaving the center. The physical characteristics of the subjects before and after weight loss are presented in Table 1.

Information on the objective of the trial was provided to the adolescents and their parents, and signed written informed consent was obtained from both. This study was approved by the regional ethics committee and performed in accordance with the Declaration of Helsinki II.

Experimental procedures. Subjects were tested twice in the same conditions: the first test was done before weight loss on the first or second day of the obesity management program, and the second was done during the last week of the stabilization phase. Body composition was assessed on the day of each test or on the day before.

For each subject, the standing rates of oxygen uptake ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) were first measured for 10 min. Then, all subjects performed five 4-min tests, walking along an athletic track lane (with two straight lines of 25 m), at different walking speeds (0.75, 1, 1.25, and 1.5 $m \cdot s^{-1}$ and preferred walking speed) in a randomized order, separated by 5 min of rest. The slope of

TABLE 1. Subjects' characteristics before and after the weight loss program.

Parameters	Before WLP ($n = 16$)	After WLP ($n = 16$)
Gender	7 M, 9 F	7 M, 9 F
Age (yr)	14.4 ± 1.6	14.7 ± 1.6
Height (m)	1.60 ± 0.10	1.61 ± 0.10
Body mass (kg)	88.8 ± 17.0*	83.4 ± 15.6
BMI ($kg \cdot m^{-2}$)	34.6 ± 5.1*	32.3 ± 4.7
LBM (kg)	48.0 ± 9.2	48.1 ± 9.0
Fat mass (%)	42.8 ± 8.6*	38.9 ± 9.4
Standing metabolic rate (W)	105.2 ± 24.9	115.7 ± 26.1
Standing metabolic rate ($W \cdot kg^{-1}$)	1.20 ± 0.26*	1.42 ± 0.35
Standing metabolic rate ($W \cdot kg^{-1}$ LBM)	2.20 ± 0.39	2.45 ± 0.57

Values are presented as mean ± SD.
* Significant difference between before and after weight loss program ($P < 0.05$).
M, male; F, female; LBM, lean body mass (the mass of nonbone lean tissue); WLP, weight loss program.

the track was tested every 1 m and ranged from −0.5% to +0.5%. The walking speed was controlled with markers set out every 5 m along the track, and subjects were instructed to walk past the markers at a pace imposed by a metronome tone. An experimenter walked alongside each subject to help him/her match the required speed. Preferred walking speed was determined by measuring the time required to walk 15 m over the central 25-m part of the straight lines during the 4-min test. The preferred walking speed was calculated as the mean of the last five measures of preferred speed. Metabolic parameters of walking were measured with a portable device carried by subjects around their chest.

Assessment of body composition. Total body fat and lean body mass (the mass of nonbone lean tissue) were measured by dual-energy x-ray absorptiometry (QDR 4005; Hologic, Inc., Bedford, MA). Percentage of total body fat was calculated by dividing total body fat mass by total body mass. For all subjects, stature was measured to the nearest 0.5 cm using a standardized wall-mounted height board, and BMI was calculated as body mass divided by height squared.

Assessment of metabolic parameters. $\dot{V}O_2$ ($mL\cdot min^{-1}$) and $\dot{V}CO_2$ ($mL\cdot min^{-1}$) were measured using a breath-by-breath portable gas analyzer (K4b^2; COSMED srl, Rome, Italy) that weighed less than a kilogram and recorded and stored the data for the entire session for each subject. The K4b^2 unit, previously validated by Duffield et al. (11), was calibrated with standard gases before each session. Average $\dot{V}O_2$ and $\dot{V}CO_2$ were calculated during 30 s taken during the last minute of each trial where $\dot{V}O_2$ and $\dot{V}CO_2$ were stable within ±10%. Gross metabolic rate (W) during walking for each 4-min test and standing metabolic rate (W) were assessed from the steady-state $\dot{V}O_2$ and $\dot{V}CO_2$ using Brockway's (3) standard equation. The RER values were <1.0 for all subjects at each trial, indicating that energy was supplied primarily by oxidative metabolism in all test conditions. Standing metabolic rate (W) was calculated during the last 4 min of the 10 min measured in the standing position, then divided by body mass to obtain the normalized standing metabolic rate ($W\cdot kg^{-1}$). Gross metabolic rate during walking was divided by body mass to obtain the normalized gross metabolic rate ($W\cdot kg^{-1}$) during walking and, finally, by walking speed ($m\cdot s^{-1}$) to obtain the normalized gross metabolic cost of walking (C_W ($J\cdot kg^{-1}\cdot m^{-1}$)). Normalized gross C_W was calculated because Browning and Kram (5) have shown that preferred walking speed corresponds to the minimum gross C_W value in obese adults. Finally, normalized net metabolic rate ($W\cdot kg^{-1}$) during walking was calculated by subtracting the normalized standing metabolic rate from the normalized gross metabolic rate during walking.

Normalized gross metabolic rates ($W\cdot kg^{-1}$) for walking at different speeds were used to calculate the characteristics of individual three-compartment models. From the data of each subject, the linear regression equations ($y = ax + b$) of the normalized gross metabolic rate during walking (y) versus squared walking speed (x) were calculated, with a as the slope and b as the y intercept (17,30). Malatesta et al. (17) define the three-compartment model derived from that of Workman and Armstrong (30) as follows: compartment 1 is the normalized standing metabolic rate; compartment 2, calculated by subtracting the normalized standing metabolic rate from b, theoretically represents the metabolic rate associated with maintaining balance and supporting body weight at zero walking speed; and compartment 3 is described by the constant a and represents the metabolic rate associated with muscle contractions required to move the center of mass and limbs.

Statistical analysis. Normal distribution of the data was checked by the Shapiro–Wilk normality test. Variance homogeneity between samples was tested by the Snedecor F-test. All variables were normally distributed, and variances were homogeneous. A two-way (period and speed) ANOVA with repeated measures was used to determine the effects of the period (before and after the weight reduction program), speed, and their interaction (period × speed) on mean normalized gross C_W and normalized net metabolic rate during walking. When an effect was identified, a Newman–Keuls *post hoc* test was performed to locate differences between conditions.

Linear regression analyses of normalized gross metabolic rate during walking versus squared walking speed were performed on the data of each subject. The equations of the linear regressions were calculated. The three compartments of the model were then compared before versus after weight loss with paired t-tests. The criterion for statistical significance was set at $P < 0.05$.

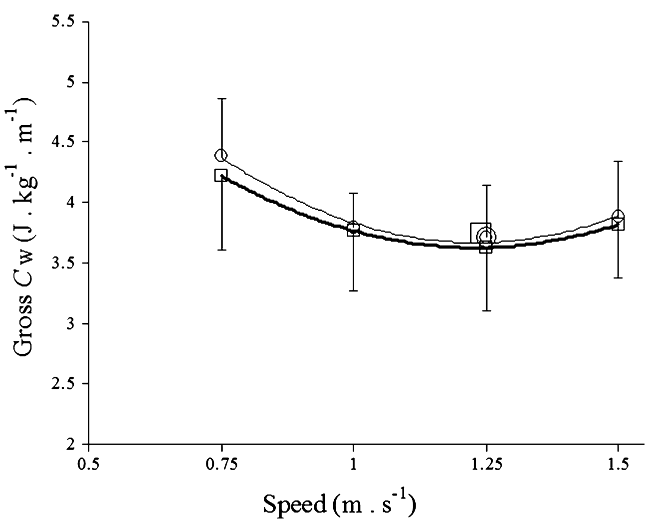

FIGURE 1—Mean ± SD values of gross metabolic cost of walking (C_W) as a function of walking speed in obese adolescents before (*open circles*, *thin line*) and after (*open squares*, *thick line*) weight loss. Both before and after weight loss, gross C_W shows a U-shaped relationship with walking speed. *Lines* represent second-order least squares regressions. Before weight loss, gross $C_W = 0.146v^2 - 0.362v + 0.407$ ($r^2 = 0.99$, $P < 0.01$). After weight loss, gross $C_W = 0.130v^2 - 0.323v + 0.382$ ($r^2 = 0.99$, $P < 0.01$). The largest *circle* and *square* represent the mean values of preferred walking speed before and after weight loss, respectively. ANOVA result is reported in the text.

APPLIED SCIENCES

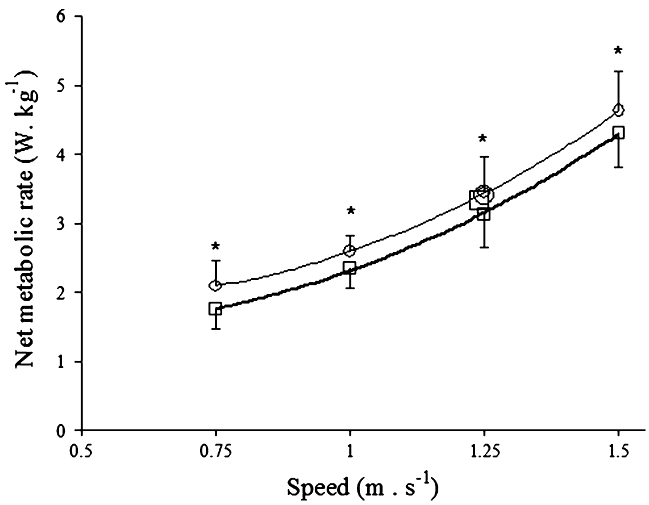

FIGURE 2—Mean ± SD values of net metabolic rate during walking as a function of walking speed in obese adolescents before (*open circles*, *thin line*) and after (*open squares*, *thick line*) weight loss. The largest *circle* and *square* represent the mean values of preferred walking speed before and after weight loss, respectively. Net metabolic rate during walking increased with walking speed and was significantly lower after weight loss at all preset speeds. *P < 0.05. ANOVA result is reported in the text.

RESULTS

The 12-wk voluntary weight reduction program was effective, as shown in Table 1. For instance, the mean weight loss was 5.5 kg (6% of body weight). Lean body mass did not change significantly with weight loss (P = 0.81; Table 1), whereas fat mass was reduced (P < 0.05) by 15%.

There was no significant difference in metabolic parameters between obese boys and girls, and no significant effect of sex was found for changes in metabolic parameters between before and after weight loss. Consequently, data of girls and boys have been pooled.

Gross metabolic cost of walking and preferred walking speed. Preferred walking speed did not change with weight loss (1.25 ± 0.14 vs 1.24 ± 0.15 m·s^{-1} before and after weight loss, respectively; P = 0.77). Obese adolescents preferred to walk at the speed at which their gross metabolic cost of walking (C_W (J·kg^{-1}·m^{-1})) was nearly minimized (Fig. 1). Gross C_W at preferred and preset walking speeds did not change significantly after weight loss despite an increase in standing metabolic rate (per kilogram) after weight loss (P < 0.05; Table 1).

TABLE 2. Three-compartment model before and after weight loss program.

Parameters	Before WLP (n = 16)	After WLP (n = 16)
a coefficient	1.48 ± 0.29	1.51 ± 0.27
b coefficient	2.36 ± 0.28	2.27 ± 0.50
Compartment 2 (W·kg^{-1})	1.17 ± 0.39*	0.85 ± 0.36

Values are presented as mean ± SD. The constant a defines compartment 3, and the constant b is the sum of compartments 1 and 2. These constants a and b are the coefficients of the model equation $y = ax + b$, where y is the gross metabolic rate in watts per kilogram and x is the squared speed in meters squared per second squared for obese adolescents before [y = 1.48 (±0.29)x + 2.36 (±0.28)] and after [y = 1.51 (±0.27)x + 2.27 (±0.50)] WLP.
* Significant difference between before and after weight loss program (P < 0.05).

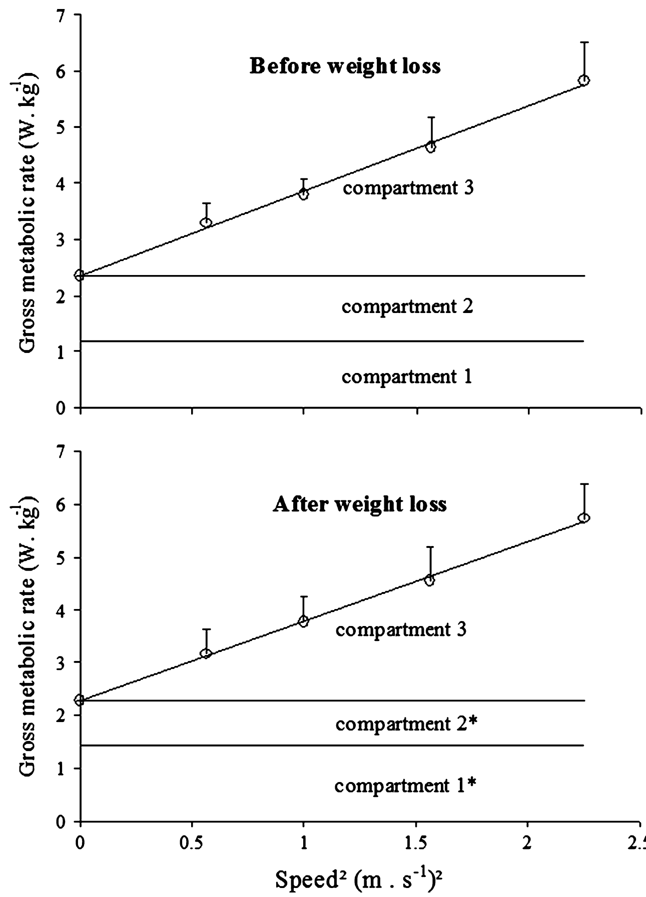

FIGURE 3—Three-compartment model analysis for obese adolescents before and after weight loss. *Open circles* are mean ± SD values of gross metabolic rate during walking as a function of squared walking speed before and after weight loss. Compartment 1 is standing metabolic rate. Compartment 2 is metabolic rate associated with supporting body weight and maintaining balance during walking. Compartment 3 is metabolic rate associated with muscle contractions required to move the center of mass and limbs. *Significant differences (P < 0.05) between before and after weight loss at a given speed.

Net metabolic rate during walking. After weight loss, the mean net metabolic rate per kilogram of body mass during walking decreased by 9% on average across speeds (P < 0.05; Fig. 2). There was no significant effect of speed on the decrease in net metabolic rate during walking (P = 0.45). *Post hoc* analyses showed a significant decrease in net metabolic rate per kilogram while walking at all preset speeds (P < 0.05) but not at the preferred walking speed (3.41 ± 0.6 vs 3.34 ± 0.9 W·kg^{-1} before and after weight loss, respectively; P = 0.48).

Three-compartment model. Coefficients of determination (r^2) of the individual linear regressions for gross metabolic rate (W·kg^{-1}) during walking–versus–squared speed relationships ranged from 0.88 to 0.99 for all subjects. All correlations were significant (P < 0.05). Variables of the three-compartment model are presented in Table 2, and a graphical display of the model is presented in Figure 3. The constants a and b are the coefficients of the model equation $y = ax + b$, where y is the gross metabolic rate (W·kg^{-1}) during walking and x is the squared speed

$((\mathrm{m{\cdot}s}^{-1})^2)$ for obese adolescents before and after weight loss. Constant a, the actual metabolic rate associated with muscle contractions required to move the center of mass and limbs (compartment 3), did not change with weight loss ($P = 0.63$). Constant b, the sum of the metabolic rates associated with standing (compartment 1) and maintaining balance and supporting body weight during walking (compartment 2), did not change with weight loss either ($P = 0.51$). However, compartment 2 significantly decreased after weight loss ($P < 0.05$; Table 2).

DISCUSSION

The main result of this study was that after weight loss, the decrease in net metabolic rate per kilogram of body mass during walking in obese adolescents was due to a lower metabolic rate related to maintaining balance and supporting body weight during walking.

Net metabolic rate during walking. The decrease in net metabolic rate per kilogram of body mass during walking in obese adolescents after weight loss (i.e., greater decrease in net metabolic rate in watts per kilogram than in body mass) was consistent with the results of previous studies undertaken in obese adults (10,14). In the present study, net metabolic rate (W) during walking decreased by 14.6% ± 14.8%, whereas body mass decreased by 6.0% ± 2.2%, which induced a 9.2% ± 15.2% decrease in normalized net metabolic rate ($\mathrm{W{\cdot}kg}^{-1}$) during walking on average across speeds (Fig. 2). Furthermore, Hunter et al. (14) have shown a 7.3% decrease in net metabolic rate per kilogram during walking after a weight loss induced by a hypocaloric diet and resistance training, which is similar to our results. However, *post hoc* analyses showed in the present study only a decrease at preset walking speeds and not at the preferred walking speed. This unexpected result could be due to methodological limits. Indeed, despite a similar mean value for the group, individual preferred walking speeds changed between before and after weight loss. This phenomenon has induced a high SD in the changes in net metabolic rate during walking with weight loss at this preferred walking speed. For instance, net metabolic rate during walking at 1.5 $\mathrm{m{\cdot}s}^{-1}$ decreased by 6.0% with an SD of 11.0%, whereas net metabolic rate during walking at preferred walking speed did not significantly change (−1.2%) but had an SD of 24.8%. To avoid this issue, we should have measured net metabolic rate during walking after weight loss at the same speed that corresponded to the preferred walking speed before weight loss. We assume that this result represents a measurement artifact induced by a methodological limit more than a true result.

Gross metabolic cost of walking. The U-shaped gross metabolic cost of walking (C_W ($\mathrm{J{\cdot}kg}^{-1}{\cdot}\mathrm{m}^{-1}$))–versus-speed relationships obtained before and after weight loss were not significantly different. This similarity could not be further discussed because, to our knowledge, no such relationships (both before and after weight loss) have been reported in previous studies. However, contrary to our results, a slight decrease in gross C_W (per kilogram) at a given speed (∼4% at 1.34 $\mathrm{m{\cdot}s}^{-1}$) has been reported after a weight loss induced by a hypocaloric diet and resistance training (14), yet there was no change in gross C_W when weight loss was induced by a hypocaloric diet alone (12,14). In the present study, the similarity of the U-shaped gross C_W–versus-speed relationships before and after weight loss was primarily due to the greater standing metabolic rate (per kilogram) after weight loss that offset their lower net metabolic rate during walking. The increase in standing metabolic rate per kilogram after weight loss was likely resulting from the decrease in fat mass (i.e., nonmetabolically active tissue), whereas lean body mass did not change. Indeed, when expressed in watts or in watts per kilogram of lean mass, standing metabolic rate did not change with weight loss (Table 1). This result is consistent with those of Browning et al. (4) and Browning and Kram (5), who showed that when standing metabolic rate is expressed per kilogram of lean mass, the difference between obese and normal-weight individuals disappears, which suggests that lean body mass is the primary determinant of the standing metabolic rate.

However, the finding that gross C_W per kilogram was unchanged although net metabolic rate per kilogram during walking did change suggests that weight-reduced obese individuals do not have to alter exercise (increase intensity and/or duration) to expend an equivalent amount of energy relative to body weight.

Mean preferred walking speed. For each individual, mean preferred walking speed did not change with weight loss and was close to the speed minimizing gross C_W. Before weight loss, the mean value of preferred walking speed in the obese adolescent population tested was similar to what is usually reported for obese adults (∼1.2 $\mathrm{m{\cdot}s}^{-1}$) (18,20,21). However, contrary to our results, Ohrström et al. (23) have shown a lower preferred walking speed before weight loss in obese women and an increase of this preferred speed after a 12-month weight loss induced by vertical banded gastroplasty (from 0.75 to 1.06 $\mathrm{m{\cdot}s}^{-1}$, $P < 0.05$). The discrepancy between these results could be due to methodological differences. Indeed, we measured preferred walking speed outdoors, whereas Ohrström et al. (23) used a treadmill. It has recently been shown that the preferred walking speed determined on a treadmill is lower than the one determined over ground (8). The authors postulated that walking on a treadmill requires greater balance and coordination, which may result in the slower preferred walking speed observed. Moreover, the subjects of the study of Ohrström et al. (23) were severely obese, which could also explain their much lower preferred walking speeds. Consequently, the increase in preferred walking speed after weight loss reported by Ohrström et al. (23) may be induced by a familiarization with treadmill walking and/or the much higher weight loss experienced by their participants (22% of body weight vs 6% in the present study).

Three-compartment model. The mean value of compartment 3 of the model in the present study is consistent with that obtained by Malatesta et al. (17) in normal-weight subjects. However, it is difficult to compare values of compartments 1 and 2 because Malatesta et al. (17) only presented results of the alternative three-compartment model (where compartment 1 is the standing metabolic rate) for healthy octogenarians. The results for the three-compartment model in the present study showed that compartments 1 and 2 changed significantly after weight loss, whereas compartment 3 did not. As previously discussed, the increase in compartment 1 (standing metabolic rate per kilogram of body mass) was likely resulting from the decrease in fat mass and did not represent an increase in the cost to maintain static balance with double support during standing. This result is supported by the fact that standing metabolic rate did not change with weight loss when expressed in watts. Our objective was to assess the metabolic rate of the isometric muscle contractions required to support body weight and maintain balance during walking before and after weight loss in obese adolescents, using compartment 2 of the three-compartment model. The results of the present study support the hypothesis that the decrease in net metabolic rate during walking after weight loss can be related to fewer muscular isometric contractions required to support the lower body weight and maintain balance during walking. These results support those of our recent study (24) in which we showed that the decrease in net metabolic rate during walking after weight loss was correlated with lower fluctuations in kinetic energy required to stabilize the center of mass in the mediolateral direction. This could have induced a lower level of muscle activation and cocontraction of antagonist muscles for stabilizing the center of mass during mediolateral motions, especially during the single-limb support phase (24). In addition, because lean body mass did not change, weight loss could have induced a decrease in the cost of supporting body weight during the single-limb support phase due to an increased relative strength of our weight-reduced subjects. This increase in relative strength could require a lower relative intensity for walking at a given speed and, in turn, reduced muscle activation and fast glycolytic fibers recruitment to support body weight (14,26). These fibers have been shown to be less economical than slow oxidative ones, especially when they are forced to shorten at less than optimal velocity, i.e., the velocity at which maximum power is developed and efficiency is optimized (1,15). Thus, changes in muscle activation and in mediolateral movements of the center of mass after weight loss could explain the decrease in the metabolic rate (per kilogram) of the isometric muscle contractions required to support body weight and maintain balance during walking.

The results also showed that compartment 3, which represents the metabolic rate associated with muscle contractions required to move the center of mass and limbs, did not change with weight loss. This result is consistent with those of previous studies showing a similar external mechanical work (per kilogram) between obese and normal-weight subjects (6,18,25) and between before and after weight loss (24). Moreover, we have also shown in a recent study that although weight-reduced individuals walk with narrower lateral leg swing, these reduced walking movements did not lead to a decrease in net metabolic rate during walking (24). Thus, the present results support the fact that the metabolic rate (per kilogram) associated with muscle contractions required to move the center of mass and limbs did not change with weight loss (24).

These results could have important practical applications for clinicians. The type of exercise prescription could be recommended from these results for obese individuals to improve walking economy. High-intensity intermittent exercise in addition to continuous exercise, which typically involves repeated brief sprinting at an all-out intensity followed by low-intensity exercise, could induce a greater increase in lower limb muscle strength (2). In turn, increased lower limb muscle strength could allow obese individuals to better stabilize and support their body weight during walking. This could result in a decrease in the metabolic rate (per kilogram) of the isometric muscle contractions required to support body weight and maintain balance during walking. This hypothesis is supported by the results of Hunter et al. (14), who showed that increasing knee extension strength was positively and independently related to walking economy after weight loss. Moreover, emerging research examining high-intensity intermittent exercise indicates that it may be more effective at reducing subcutaneous and abdominal body fat than other types of exercise (2). Consequently, weight loss programs including high-intensity intermittent exercise such as cycling in addition to continuous exercise could be effective to improve walking economy and reduce body fat. However, because there are likely considerable risks associated with weight bearing exercises for obese individuals in high-intensity intermittent exercise (risk of acute/chronic musculoskeletal injury due to greater loads placed on the musculoskeletal system), non–weight bearing exercises such as cycling must be used for such a protocol in obese individuals.

Some methodological limitations should be addressed in this study, such as the normal adolescent development that may have influenced the outcomes of this study. Indeed, adolescents (and especially boys) grew taller during the 12-wk period, which could have interfered with the weight loss program itself. We can reasonably assume that without this growth effect (obviously inevitable), the weight loss program could have induced an even greater decrease in body mass. Moreover, in addition to weight loss, the 1-cm (0.5%) increase in adolescents' average height may have induced changes in their walking mechanics and hence in the metabolic cost of walking. Weyand et al. (29) have recently shown an inverse relationship between mass-specific transport costs and stature. Thus, the increase in height of our subjects could explain part of the improvement in walking economy during the weight loss period. However, we can note that although adolescents grew taller during the 12-wk period, this has not induced any change in subjects' preferred walking speed, which was close to the speed that minimized gross C_W.

In conclusion, this study shows that after weight loss, the increase in obese adolescents' walking economy (i.e., decrease in net metabolic rate per kilogram during walking) may be induced by the lower metabolic rate of the isometric muscular contractions required to support the lower body weight and maintain balance during walking. The metabolic rate associated with muscle contractions required to move the center of mass and limbs did not change with weight loss and thus could not be responsible for the increase in walking economy in weight-reduced individuals. Future studies are needed to confirm the relative importance of the metabolic rate required to support body weight and maintain balance during walking in obese and weight-reduced individuals.

This research program was supported by the French Auvergne and Rhône-Alpes regions thanks to the European Regional Development Fund.

The authors thank the subjects for their commitment during this study and Michel Taillardat and the staff of the Centre Médical Infantile of Romagnat for their collaboration in this study.

The authors declare that they have no conflict of interest.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. Bottinelli R, Reggiani C. Human skeletal muscle fibres: molecular and functional diversity. *Prog Biophys Mol Biol*. 2000;73(2–4): 195–262.
2. Boutcher SH. High-intensity intermittent exercise and fat loss. *J Obes*. 2011;2011:868305.
3. Brockway JM. Derivation of formulae used to calculate energy expenditure in man. *Hum Nutr Clin Nutr*. 1987;41(6):463–71.
4. Browning RC, Baker EA, Herron JA, Kram R. Effects of obesity and sex on the energetic cost and preferred speed of walking. *J Appl Physiol*. 2006;100(2):390–8.
5. Browning RC, Kram R. Energetic cost and preferred speed of walking in obese vs. normal weight women. *Obes Res*. 2005;13(5): 891–9.
6. Browning RC, McGowan CP, Kram R. Obesity does not increase external mechanical work per kilogram body mass during walking. *J Biomech*. 2009;42(14):2273–8.
7. Cole TJ, Bellizzi MC, Flegal KM, Dietz WH. Establishing a standard definition for child overweight and obesity worldwide: international survey. *BMJ*. 2000;320(7244):1240–3.
8. Dal U, Erdogan T, Resitoglu B, Beydagi H. Determination of preferred walking speed on treadmill may lead to high oxygen cost on treadmill walking. *Gait Posture*. 2010;31(3):366–9.
9. de Souza SA, Faintuch J, Sant'anna AF. Effect of weight loss on aerobic capacity in patients with severe obesity before and after bariatric surgery. *Obes Surg*. 2010;20(7):871–5.
10. Doucet E, Imbeault P, St-Pierre S, et al. Greater than predicted decrease in energy expenditure during exercise after body weight loss in obese men. *Clin Sci (Lond)*. 2003;105(1):89–95.
11. Duffield R, Dawson B, Pinnington HC, Wong P. Accuracy and reliability of a Cosmed K4b^2 portable gas analysis system. *J Sci Med Sport*. 2004;7(1):11–22.
12. Froidevaux F, Schutz Y, Christin L, Jequier E. Energy expenditure in obese women before and during weight loss, after refeeding, and in the weight-relapse period. *Am J Clin Nutr*. 1993;57(1): 35–42.
13. Grabowski A, Farley CT, Kram R. Independent metabolic costs of supporting body weight and accelerating body mass during walking. *J Appl Physiol*. 2005;98(2):579–83.
14. Hunter GR, McCarthy JP, Bryan DR, Zuckerman PA, Bamman MM, Byrne NM. Increased strength and decreased flexibility are related to reduced oxygen cost of walking. *Eur J Appl Physiol*. 2008;104(5):895–901.
15. Hunter GR, Newcomer BR, Larson-Meyer DE, Bamman MM, Weinsier RL. Muscle metabolic economy is inversely related to exercise intensity and Type II myofiber distribution. *Muscle Nerve*. 2001;24(5):654–61.
16. Lafortuna CL, Agosti F, Galli R, Busti C, Lazzer S, Sartorio A. The energetic and cardiovascular response to treadmill walking and cycle ergometer exercise in obese women. *Eur J Appl Physiol*. 2008;103(6):707–17.
17. Malatesta D, Simar D, Dauvilliers Y, et al. Energy cost of walking and gait instability in healthy 65- and 80-yr-olds. *J Appl Physiol*. 2003;95(6):2248–56.
18. Malatesta D, Vismara L, Menegoni F, Galli M, Romei M, Capodaglio P. Mechanical external work and recovery at preferred walking speed in obese subjects. *Med Sci Sports Exerc*. 2009;41(2): 426–34.
19. Martin A. The "apports nutritionnels conseillés (ANC)" for the French population. *Reprod Nutr Dev*. 2001;41(2):119–28.
20. Mattsson E, Larsson UE, Rossner S. Is walking for exercise too exhausting for obese women? *Int J Obes Relat Metab Disord*. 1997; 21(5):380–6.
21. Melanson EL, Bell ML, Knoll JR, et al. Body mass index and sex influence the energy cost of walking at self-selected speeds. *Med Sci Sports Exerc*. 2003;35(5 suppl):S183.
22. Neptune RR, Zajac FE, Kautz SA. Muscle mechanical work requirements during normal walking: the energetic cost of raising the body's center-of-mass is significant. *J Biomech*. 2004;37(6): 817–25.
23. Ohrström M, Hedenbro J, Ekelund M. Energy expenditure during treadmill walking before and after vertical banded gastroplasty: a one-year follow-up study in 11 obese women. *Eur J Surg*. 2001; 167(11):845–50.
24. Peyrot N, Morin JB, Thivel D, et al. Mechanical work and metabolic cost of walking after weight loss in obese adolescents. *Med Sci Sports Exerc*. 2010;42(10):1914–22.
25. Peyrot N, Thivel D, Isacco L, Morin JB, Duche P, Belli A. Do mechanical gait parameters explain the higher metabolic cost of walking in obese adolescents? *J Appl Physiol*. 2009;106(6): 1763–70.
26. Rosenbaum M, Vandenborne K, Goldsmith R, et al. Effects of experimental weight perturbation on skeletal muscle work efficiency in human subjects. *Am J Physiol Regul Integr Comp Physiol*. 2003; 285(1):R183–92.
27. Russ DW, Elliott MA, Vandenborne K, Walter GA, Binder-Macleod SA. Metabolic costs of isometric force generation and maintenance of human skeletal muscle. *Am J Physiol Endocrinol Metab*. 2002;282(2):E448–57.
28. Vanhecke TE, Franklin BA, Miller WM, deJong AT, Coleman CJ, McCullough PA. Cardiorespiratory fitness and sedentary lifestyle in the morbidly obese. *Clin Cardiol*. 2009;32(3):121–4.
29. Weyand PG, Smith BR, Puyau MR, Butte NF. The mass-specific energy cost of human walking is set by stature. *J Exp Biol*. 2010; 213(Pt 23):3972–9.
30. Workman JM, Armstrong BW. Metabolic cost of walking: equation and model. *J Appl Physiol*. 1986;61(4):1369–74.