Free-living activity energy expenditure in women successful and unsuccessful at maintaining a normal body weight¹–³

Roland L Weinsier, Gary R Hunter, Renée A Desmond, Nuala M Byrne, Paul A Zuckerman, and Betty E Darnell

ABSTRACT

Background: Although physical inactivity is believed to contribute to the rising prevalence of obesity, the role and magnitude of its contribution to weight gain are unknown.

Objective: We compared total free-living activity energy expenditure (AEE) and physical activity level in women successful and unsuccessful at maintaining a normal body weight.

Design: Premenopausal, generally sedentary women were studied at their normal weight and 1 y later after no intervention. Two groups were identified on the basis of extreme weight changes: maintainers (n = 27) had a weight gain of ≤3% of their initial body weight (≤2 kg/y) and gainers (n = 20) had a weight gain of >10% (>6 kg/y). At baseline and follow-up, evaluations were conducted during 4 wk of diet-controlled, energy-balance conditions. Free-living AEE and physical activity were assessed with the use of doubly labeled water, exercise energy economy and muscle strength with the use of standardized exercise tests, and sleeping EE and substrate utilization with the use of chamber calorimetry.

Results: Maintainers lost a mean (±SD) of 0.5 ± 2.2 kg/y and gainers gained 9.5 ± 2.1 kg/y. Gainers had a lower AEE (P < 0.02), a lower physical activity level (P < 0.01), and less muscle strength (P < 0.001); these differences between groups remained significant from baseline to follow-up. Sleeping EE, exercise economy, and sleeping or 24-h substrate utilization were not significantly different between the 2 groups. A lower AEE in the gainers explained ≈77% of their greater weight gain after 1 y.

Conclusion: The general US population should increase their daily physical activity levels to decrease the rising prevalence of obesity.


KEY WORDS  Weight gain, obesity, physical activity, energy expenditure, muscle strength, fitness, premenopausal women

INTRODUCTION

Between 1991 and 1998, the prevalence of obesity—defined as a body mass index (BMI; in kg/m²) ≥30—increased in the United States by almost 50% (1), and 55% of adults are now classified as overweight or obese (BMI ≥25) (2). The etiology of the rising prevalence of obesity is unclear. Low physical activity levels have been shown to be associated with greater weight gain (3–5), and higher physical activity levels appear to result in greater weight loss and weight-loss maintenance (5–7). However, these studies and surveys of longitudinal trends (8) were based on individual self-reports of leisure-time physical activity. Assessments of total 24-h physical activity and activity energy expenditure (AEE) in free-living conditions include measurements of both volitional and nonvolitional activities, information that is needed to accurately and objectively quantify the contribution of physical activity to the rising prevalence of obesity (9). Such assessments are relatively difficult and expensive to obtain (10, 11).

A few studies assessed free-living AEE with the use of the doubly labeled water method and, in cross-sectional analyses, showed that lower AEE levels are associated with a higher percentage body fat (12–14). These associations suggest that physical inactivity causes weight gain and obesity; however, they do not rule out the possibility that inactivity results from weight gain and obesity. In a cohort of >9000 men and women followed for 10 y in the first National Health and Nutrition Examination Survey, no relation was found between self-reported physical activity levels at baseline and subsequent weight gain (15). On the other hand, when physical activity levels increased over time, weight gain was less. These inconsistent findings led the authors to suggest that low physical activity levels may be a cause and a consequence of weight gain. More recent data, based on annual assessments of self-reported measures of exercise in >1000 men and women, suggest a causal relation because individuals who reported more physical activity initially and who increased their activity level over time gained less weight (16). One study assessed free-living AEE in weight-reduced women and found that lower AEE levels were associated with greater weight gains at follow-up (17). To our knowledge, no

¹From the Departments of Nutrition Sciences (RLW, NMB, and PAZ) and Human Studies (GRH), and the Biostatistics Unit of the Comprehensive Cancer Center (RAD), the General Clinical Research Center (BED), and the Clinical Nutrition Research Center (RLW, GRH, and RAD), the University of Alabama at Birmingham.

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³Address reprint requests to RL Weinsier, Clinical Nutrition Research Center, Webb Nutrition Sciences Building, Room 449, University of Alabama at Birmingham, Birmingham, AL 35294. E-mail: weinsier@shrp.uab.edu.

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studies have obtained repeated assessments of physical activity levels with the use of quantitative measures of free-living AEE, across time, to identify EE and metabolic characteristics of persons who are successful at maintaining a normal body weight relative to those who gain weight.

The purpose of this prospective study was to identify factors that distinguish women who are successful or unsuccessful at maintaining a normal body weight. The study was designed to measure free-living AEE, physical activity levels, and various fitness and metabolic variables in normal-weight women, at baseline and 1 y later, to determine and quantify the effect of spontaneous patterns of physical activity on weight change.

SUBJECTS AND METHODS

Subjects

Sixty-one premenopausal white or black women aged 20–46 y were first studied in the normal-weight state, defined as a BMI < 25. Of the 61 normal-weight women, 33 were originally recruited in an overweight state and participated in a weight-reduction program until they lost ≥10 kg and reached a BMI < 25. Their average BMI before weight loss was 29 ± 2 (range: 26–33). The weight-loss program was based on an energy-restricted diet only, with no exercise intervention. The other 28 women already had a normal body weight. Thus, at baseline, all women had a normal body weight (BMI: 21–25). Also, percentage body fat, levels of AEE or physical activity, and the metabolic variables sleeping EE (SEE), resting EE (REE), 24-h respiratory quotient (RQ), and insulin sensitivity were not significantly different between the postobese and previously normal-weight women (GR Hunter, RL Weinsier, BA Gower, S Snyder, unpublished observations, 2001). Consequently, this study sample was considered as one group but was chosen to reflect a range of propensity toward weight gain, which enabled investigation of factors relating to weight gain and weight maintenance. All subjects were nonsmokers, were sedentary (defined as exercising <1 time/wk in the past year), and had normal menstrual cycles. Normal glucose tolerance was documented by fasting and 2-h postprandial blood glucose concentrations after an oral glucose load. None of the subjects took medications known to affect EE or thyroid status or had ever been diagnosed as having bulimia or anorexia nervosa. According to self-reports, none of the white or black women were of other ancestry. The protocol was approved by the Institutional Review Board for Human Subjects, and informed consent was obtained from all subjects before participation in compliance with the US Department of Health and Human Services Regulations for Protection of Human Research Subjects.

Study design

All subjects were maintained in a weight-stable state for 4 wk before evaluation at the General Clinical Research Center (GCRC), during which time body weight measurements were made 3 d/wk for the first 2 wk and 5 d/wk for the last 2 wk. During the final 2-wk period, all meals were provided through the GCRC research kitchen to ensure weight stability (<1% variation from initial weight) and to maintain daily macronutrient intakes within the following ranges: 20–22% of energy as fat, 16–23% as protein, and 55–64% as carbohydrate. Given that this report reflects one phase of a larger ongoing investigation, the diet composition was the same as that used for all study conditions (overweight state, active weight loss, weight-reduced state, and follow-up). It was during this 2 wk of controlled diet and energy-balance conditions that doubly labeled water was administered. Subjects were then admitted to the GCRC for 4 d, during the follicular phase of the menstrual cycle, for assessment of body composition, physical fitness, exercise energy economy, SEE, and fuel utilization. After discharge, no attempt was made to influence the subjects’ diet or physical activity patterns, and no contact was made until ~1 y later, when the subjects returned to the GCRC for reevaluation. At the 1-y follow-up, the above-mentioned protocol was repeated, i.e., 4 wk of energy balance during a macronutrient-controlled diet followed by 4 d of admission and evaluation at the GCRC.

Methods

Body composition was determined by dual-energy X-ray absorptiometry and the scans were analyzed for total fat mass and for nonbone lean body mass (LBM) with the use of adult software (version 1.33, DPX-L; Lunar Radiation Corp, Madison, WI). SEE was assessed during the 4-d GCRC admission with a room calorimeter, as previously described (18). The period of sleep was set when the lights were turned off (0930–1100) and ended when the subjects were awakened at 0630. Radar motion sensors indicated that the subjects were inactive during the sleep period. EE was calculated with the de Weir equation (19). Relative amounts of carbohydrate and fat utilization were calculated from carbon dioxide production (VCO₂) and oxygen (VO₂) consumption in the chamber and were expressed as sleeping and 24-h RQs. Free-living total daily EE (TEE) was measured with the use of the doubly labeled water method during the 2-wk period of weight stability immediately preceding admission to the GCRC.

The previously described protocol (20) has a theoretical error of <5%. Samples were analyzed in triplicate for deuterium and 18O by isotope ratio mass spectrometry at the University of Alabama at Birmingham, as previously described (21). When all samples for deuterium and 18O were reanalyzed in 7 subjects, TEE values were in close agreement (CV = 4.3%) (20). Because the group mean (±SD) dilution space ratio (N18/16N) of 1.0488 ± 0.0557 was not significantly different from the assumed ratio of 1.0427, VCO₂ rates were measured by using the reported value of 1.0427 in Equation R2 of a study by Speakman et al (22). EE was calculated with the use of Equation 12 of de Weir (19). The food quotient value used for this calculation was 0.88, which reflected the composition of the diet provided at the GCRC during the 2-wk period of weight maintenance and the typical 24-h RQ obtained in the chamber calorimeter at the end of the 2-wk period.

AEE was defined as the level of daily EE above the SEE and was estimated by subtracting SEE from TEE after reducing TEE by 10% to account for the thermic response to meals:

\[
\text{AEE (kJ/d)} = [0.9 \times \text{TEE} - \text{SEE}] 
\]

As we previously reported (23), SEE data are thought to be preferable to REE data because they are based on a much longer period of assessment and have a 45% lower SD yet give similar results; hence, SEE data are reported herein.

Free-living physical activity was derived from AEE (kJ/d) with the use of the activity-related time equivalent (ARTE) index, as previously described (23):

\[
\text{ARTE index (min/d)} = \frac{[\text{AEE (kJ/d)}]}{\text{AEC (kJ/min)}} 
\]
The repeated-measures data consisted of 2 measurements obtained from the same subject, ie, at baseline and follow-up. The analysis accounted for a correlation between observations from the same subjects and possible nonconstant variability. The models were tested hierarchically to include an interaction term between weight-gain group and time; if this term was not significant, a reduced model was fit. The data for each study variable are reported as mean group differences; ie, differences in mean values between the maintainers and gainers across time. Probability values for the variables race, AEE, physical activity, muscle strength, and aerobic fitness were based on one-tailed t tests because of available evidence supporting a hypothesized association with weight gain. Other variables were evaluated with the use of two-tailed tests. Significance was set at $P < 0.05$ for all analyses.

RESULTS

At baseline, in the normal-weight state, the 61 women had a mean ($\pm$SD) age of 34 $\pm$ 6 y, BMI of 23.6 $\pm$ 1.1, weight of 64.2 $\pm$ 6.2 kg, and percentage body fat of 34.0 $\pm$ 4.6%. At the time of the reassessment, the average length of follow-up was $1.1 \pm 0.2$ y and the mean rate of weight gain was $3.8 \pm 4.7$ kg/y [range: $-5.6$ kg/y ($-0.10$ kg/wk) to $12.8$ kg/y ($0.25$ kg/wk)]. To identify factors that distinguish subjects who are successful from those who are unsuccessful at weight control, the women were categorized into 2 distinct groups according to either high or low rates of weight change over the period of follow-up. There was a distinct break below and above a 10% weight gain. This value, which corresponded to $>6$ kg/y (or, $>0.12$ kg/wk), was used to define gainers. With no distinct break in the rates of weight change in the lower range, a value of 3% weight gain ($\leq 2$ kg/y, or $\leq 0.04$ kg/wk) was selected to ensure a wide margin of difference from the 10% increase in weight in the gainers. These cutoffs, which provided reasonable sample sizes, were selected a priori for the analysis of the results. Of the 61 women, 27 were classified as maintainers and 20 as gainers; 14 women gained weight at an intermediate rate. Of the 33 initially overweight women who achieved a normal body weight, 6 (18%) were classified as maintainers and 19 (58%) as gainers; the remaining 8 (24%) gained weight at an intermediate rate. Of the 28 initially normal-weight women, 21 (75%) were maintainers and 1 (4%) was a gainer; the remaining 6 (21%) gained weight at an intermediate rate. Thus, whereas 95% of the gainers were previously overweight women, only 58% of the previously overweight women were gainers.

At baseline, in the normal-weight state, the maintainers group was significantly younger than the gainers group (31.7 compared with 37.6 y) and consisted of a significantly larger number of whites than blacks (Table 1). The maintainers group had a significantly lower mean BMI (23.1 compared with 24.4), whereas percentage body fat was not significantly different between the groups. The average length of follow-up was 1.1 y for both groups, ranging from 0.9 to 1.4 y in the maintainers group and from 0.9 to 1.7 y in the gainers group. On average, the maintainers group gained 0.7 kg fat mass and the gainers group gained 9.6 kg fat mass. The maintainers group lost 0.4 kg LBM and the gainers group gained 1.2 kg LBM (data not shown).

The characteristics of the 2 groups at baseline and at follow-up, determined on the basis of multivariate analysis models, are
shown in Table 2. All models were initially tested for the effects of age and race on the outcome variable, and an interaction term between weight-gain group and time was included. Except for a significant race effect on VO₂max and TEE, there were no significant effects of age, race, or group-by-time interaction in any of the models. Hence, these variables were not included in the reduced-model analyses.

Differences in mean values between maintainers and gainers across time. P values were based on one-tailed tests for AEE, physical activity, strength, and VO₂max because of evidence supporting an association with weight gain. Other variables were evaluated by using two-tailed tests. No group-by-time interaction effects were significant. Percentage in brackets.

The activity-related time equivalent index represents the portion of the day spent on free-living physical activities, with energy expenditure equivalent to the energy cost of performing 5 exercise tasks in the laboratory (see Methods).

When race was included, the value became nonsignificant.

### DISCUSSION

The findings of this study indicated that the women who successfully maintained a normal body weight over 1 y of follow-up had significantly different physical activity and muscle strength characteristics than did the women who gained weight. The results indicated that 1) the patterns of physical activity and the metabolic characteristics of the subjects were relatively consistent because these variables did not change significantly across time; 2) AEE, physical activity, and muscle strength were persistently lower in the gainers than in the maintainers group across the period of follow-up; and 3) the factors that characterized the gainers (ie, lower AEE, physical activity, and muscle strength) may influence the likelihood of weight gain and are potentially modifiable.

In the present study we observed that the gainers group gained an average of 8.9 kg more fat mass and 1.6 kg more LBM than did the maintainers group after an average of 1.1 y of follow-up. The degree of positive energy balance required to produce this difference in body composition was estimated by using data reported by Spady et al (28) and Forbes et al (29, 30); ie, 50.2 kJ/g (12.0 kcal/g) fat mass and 7.4 kJ/g (1.8 kcal/g) LBM. These values include the energy cost of forming new tissue plus its stored energy value. On the basis of these reported values, a positive energy balance of 1146 kJ/d would have been required to explain the observed difference in body composition between the gainers and maintainers groups. Our measured group difference in TEE of 1096 kJ/d (Table 2) represented 96% of the group difference in the energetics of weight gain (1096/1146 kJ/d). AEE differed between the groups by 887 kJ/d, which explained 77% (887/1146 kJ/d) of the positive energy balance. Thus, in our sample, physical inactivity accounted for most of the difference in
weight gain between the 2 groups over the 1-y follow-up. These findings are congruent with those of several studies, suggesting that physical activity has a strong influence on variations in adiposity, even stronger than dietary intake patterns (3–5).

For the gainers group to increase their TEE to match the change in body composition of the maintainers group, an additional expenditure of 17 kJ·kg\(^{-1}\)·d\(^{-1}\) (1146 kJ/d divided by the baseline body weight of 66.7 kg) would be required. Schoeller et al (17) previously studied 32 women in a weight-reduced state and their weight-gain patterns after 1 y of follow-up; their findings were similar to ours. They estimated that gainers would have to expend an additional 14 kJ·kg\(^{-1}\)·d\(^{-1}\) to achieve a threshold of EE that would confer optimal weight-loss maintenance. Schoeller et al suggested that the additional expenditure of 14 kJ·kg\(^{-1}\)·d\(^{-1}\) could be achieved with \(\approx 80 \) min/d of moderate-intensity physical activity (ie, brisk walking at 4 METs; ie, the ratio of the metabolic rate associated with a given activity to the resting metabolic rate). On the basis of this reference point, which in our subjects corresponded to \(\approx 40\% \) of \(\dot{V}O_{\text{max}}\), the gainers group would need to add \(\approx 77 \) min of moderate-intensity physical activity to their daily routine to achieve the same weight-maintenance status associated with the maintainers group.

Several groups have estimated the amount of physical activity needed to prevent weight gain, although the data are not based on objective measures of free-living EE (31–35). On the basis of the results of those studies and national consensus reports, the US Department of Agriculture’s Dietary Guidelines for Americans (36) recommends that adults engage in a minimum of 30 min moderate physical activity/d for general health, recognizing that more activity may be needed for weight control. The findings of our study and those of Schoeller et al (17) suggest that, absent dietary modification, the amount of moderate-intensity physical activity (4 METs) needed to optimize energy balance and to maintain a normal body weight in sedentary, obesity-prone persons is closer to 80 min/d, or 2.5 times the current recommendations. Alternatively, if the subjects in our study were to exercise at an intensity of 60% \(\dot{V}O_{\text{max}}\), they would probably need to add only 45 min of physical activity to their current daily routine; this amount of exercise would likely decrease to \(\approx 35 \) min/d after the subjects physiologically adapted to the exercise training. In persons for whom this amount of activity is impractical, dietary modification may be required.

The results of the present study also indicated that the maintainers group had greater physical strength than did the gainers group. In observational studies, greater muscle strength was associated with lesser degrees of obesity (37). The observed benefits of greater physical strength are that the conduct of routine activities of daily living (eg, standing from a sitting position and carrying small loads) are easier and walking velocity and endurance improve (27, 38, 39). Logically, then, greater strength would be expected to increase physical activity by making movement easier. The effect of strength on body weight in our study did not differ significantly between the maintainers and gainers groups. Although these findings differ from those of some studies (42, 43), the results of the present study are consistent with those of our previous studies in which we observed no significant differences in these variables among obesity-prone and obesity-resistant women (23, 44, 45).

In conclusion, the results of the present study indicate that women who maintain a normal body weight are characterized by sustained higher levels of non-SEE, free-living physical activity, and muscle strength than are women who are unsuccessful at weight control. Importantly, these factors are potentially modifiable through changes in patterns of daily living. On the basis of the measured difference in \(\dot{V}E\) of physical activity between the maintainers and gainers groups, it is estimated that physical inactivity alone accounted for \(> 75\% \) of the weight gain observed in the gainers group. The magnitude of the group difference in physical activity also suggests that current national guidelines recommending a minimum of 30 min moderate physical activity daily may need to be increased to as high as 80 min/d (depending on whether diet is included as a weight-control strategy) to prevent weight gain. Finally, SEE, substrate utilization, and exercise energy economy—which are less easily modifiable factors—were not significantly different between the maintainers and gainers groups. Collectively, these findings lend support to national efforts to decrease the rising prevalence of obesity by identifying and emphasizing strategies to facilitate incorporation of more physical activity into the daily lives of the general US population.

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