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Brief Review

Physical Activity and Muscle Function but Not Resting Energy Expenditure Impact on Weight Gain

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Abstract. Hunter, G.R., and N.M. Byrne. Physical activity and muscle function but not resting energy expenditure impact on weight gain. *J. Strength Cond. Res. 19(1):225–230. 2005.*—Understanding whether metabolic factors are predictive of weight gain is important for developing strategies for prevention of weight gain. Recent research has shown that sleeping and resting energy expenditure are not predictive of weight gain. However, exercise endurance, muscular strength, ^{31}P MRS muscle metabolic economy, and maximum oxygen uptake are independently related to weight gain. Activity-related energy expenditure and the time spent in physical activity are also related to weight gain, with low physical activity explaining approximately 77% of weight gain at 1 year. In addition, weight maintainers spend 80 minutes per day, whereas weight gainers spend less than 20 minutes per day in physical activity equivalent to an intensity of about 4 METS. It is proposed that strength, aerobic fitness, and physical activity are important factors for reducing the rate of weight gain. Although further research is required, these results are suggestive that weight maintenance programs will be more successful if some relatively high-intensity training is included to complement large amounts of low to moderate intense physical activity.

Key Words. obesity, strength, set-point theory

Introduction

Obesity continues to be a growing problem in the United States (7). Understanding factors that predict weight gain is important for developing strategies for preventing weight gain. Metabolic factors such as a low resting energy expenditure (REE) (28) and low fat oxidation rates (29, 35, 48) have been proposed as predictors of weight gain. However, a number of studies do not support REE and lipid oxidation rates as major contributors to weight maintenance (12, 35, 45).

To understand the potential causal role of metabolic abnormalities (i.e., REE, lipid oxidation rates, and physical activity–related energy expenditure) to weight gain or maintenance, it is important to examine individuals before they become obese. However, it is very difficult to predict who is going to become obese. This is probably best accomplished using the postobese model (38). This model compares weight-reduced and thus weight-gain–prone individuals (approximately 80% of weight-reduced individuals regain more than ½ the weight lost within 1 year (38, 45)) with obesity-resistant never-obese individuals. This model increases the likelihood that some individuals will gain weight and others will maintain weight over the study period, allowing the study of metabolic factors that predispose weight gain. Confirmation of the potential contribution of metabolic abnormalities to weight gain can be assessed by examining their predictive value for long-term weight gain. However, in each case, accurate data depend on the presence of energy-balance conditions after weight loss and tight control of dietary intake for a sustained time before any assessment. Failure to control these factors can confound any assessment of metabolic rate and fuel use (33). Such rigorous and sustained control has been followed in few studies. Fewer have conducted long-term follow-up analyses and attempted to predict weight gain from metabolic patterns. Implications of results from studies that do not follow this rigorous control are reflecting physiological responses to energy restriction rather than reduced-weight physiology.

Expenditure of energy through physical activity (AEE; kcal·day^{-1}) can potentially play a very important role in weight maintenance because it is the most variable component of energy expenditure, varying over 30-fold in a free-living environment (42). There are few data using doubly labeled water to measure AEE to support the theory that more physically active individuals gain less weight, although an inverse relationship between current physical activity and obesity has been reported (16, 17, 30). These associations suggest that physical activity may help to prevent weight gain and obesity; however, they do not exclude the possibility that inactivity is caused by weight gain and obesity.

Even more rare are data examining fitness variables that may influence the likelihood of gaining weight. Given the potential for AEE in weight maintenance and the reluctance of most Americans to participate in physical activity, identification of fitness variables that may affect energy expenditure through either REE or by making it easier for individuals to be more physically active is also of extreme interest. Our purpose is to review recent findings that highlight the importance and delineate the amount of time spent in physical activity (PA) needed to prevent weight gain. In addition, a positive feedback model for weight gain in which low PA lead to reduced fitness and weight gain and low PA and weight gain lead to further decreases in PA is proposed (Figure 1).

Resting Energy Expenditure

Obese individuals tend to regain weight after weight loss (38, 45), raising suspicions that metabolic factors such as low REE are important in body weight regulation. The resultant set-point theory is based on the premise that the body has a homeostatic feedback system for regulation of fat stores, which operates, at least in part, by up- or down-regulation of the efficiency of metabolic processes (2). In other words, weight loss would be accompanied by

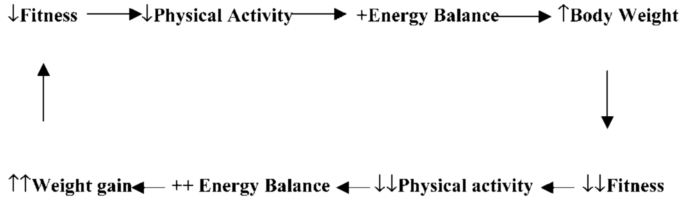

FIGURE 1. Model for progressive decrease in physical activity (PA) and increased weight gain.

a reduction in REE in excess of what would be expected at the reduced weight.

A recent review by Astrup et al. (1) suggests that weight-reduced individuals have REEs lower than lean control subjects. In addition, the metabolic ward studies of Leibel et al. (24) suggest that weight and weight gain result in adaptive changes in REE, causing individuals to return to the previous body weight. We, however, have shown that sleeping energy expenditure (SEE), REE, and lipid oxidation rates are not predictive of who gains weight under tightly controlled energy balance conditions in which the subject has been weight stable for at least 4 weeks (44). Consistent with these findings, Wyatt et al. (47) have reported that body composition-adjusted REE was not significantly different between weight-reduced subjects and of weight-matched controls.

As mentioned earlier, the primary argument for the set-point theory is the concept that weight regain after weight loss is at least partially caused by a down-regulation of REE. Data from our labs indicates that there is a transient hypothyroid-hypometabolic state that occurs during energy restriction, but this state normalizes after 10 days of energy balance, even after the loss of almost 13 kg (44) and 19 kg (4). Figure 2 combines data from these 2 cohorts, 1 (A) consisting of women 59 ± 5 years old with a body mass index (BMI) of 27.9 ± 1.8 kg·m^{-2} (44) and the other (B) consisting of men and women 42 ± 11 yrs old with a BMI of 39.9 ± 6.4 kg·m^{-2} (4). The two studies followed very similar designs, with an initial evaluation conducted after 2 weeks of weight stable conditions, 2 evaluations during caloric restriction, and a final evaluation after 2 weeks of weight-stable conditions in the weight-reduced state. In the study of Weinsier et al. (44), the second evaluation was made 2 weeks after initiation of a caloric restriction, 800 kcal per day, and the third evaluation was after a weight loss of ≅13 kg (but still adhering to the 800 kcal diet). In the more obese cohort (4), the second and third evaluations were made after adherence to a 500 kcal per day ketogenic diet for 1 month and 2 months, respectively. At the final evaluation, subjects had lost an average 18.6 ± 5.2 kg. The variation in REE and triiodothyronine follow a similar time course for both studies: a reduction during energy restriction and an increase to baseline after weight loss but re-establishment of energy balance. In addition to triiodo-

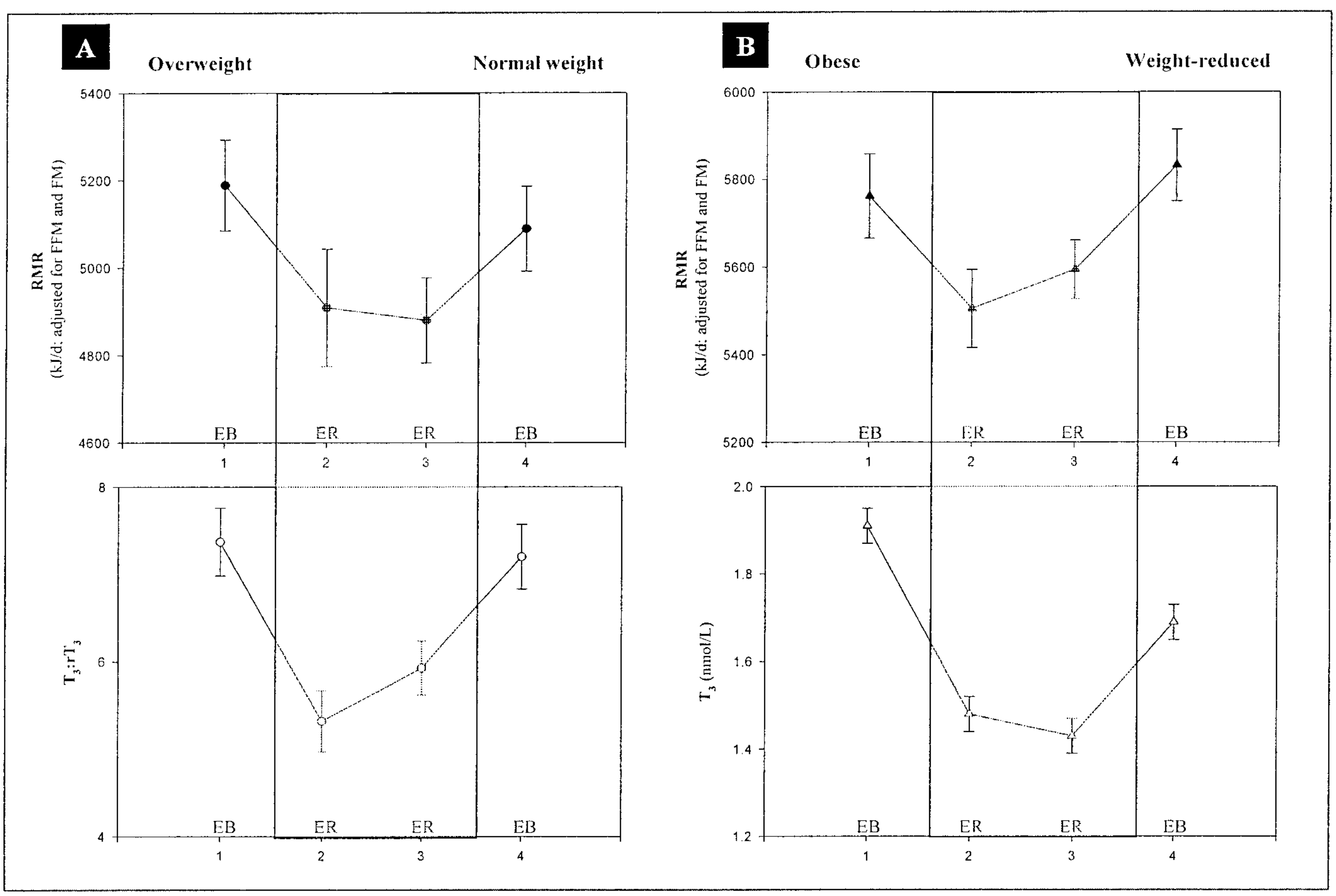

FIGURE 2. Resting energy expenditure (RMR) and thyroid hormone data from overweight (A—Weinsier et al. 2000) and obese (B—Byrne et al. 2002) cohorts before, during, and after weight loss. Both cohorts were assessed in energy balance (EB) before (1) and after (4) weight loss and during energy restriction (ER; 2–3).

thyronine, the ratio of triiodothyronine:reverse triiodothyronine has been shown to be related to low energy intake (5), whereas Danforth (6) lends further support to the idea that triiodothyronine:reverse triiodothyronine ratio is reflective of energy imbalance. The triiodothyronine:reverse triiodothyronine ratio also follows the exact same pattern as triiodothyronine (44), further supporting the premise that the hypothyroid-hypometabolic state occurs only during energy restriction and not in energy balance conditions, even after weight loss. These studies show that, at least in energy balance conditions, inherently low REE does not contribute to significant amounts of weight gain in relatively sedentary individuals. However, the idea that factors that may increase REE, such as high intensity exercise (20), may play a role in assisting individuals to increase total energy expenditure and thus maintain weight should not be rejected.

Free-Living Physical Activity and Activity-Related Energy Expenditure

Generally, it is accepted that low PA has contributed to the increased prevalence of obesity worldwide (10, 13, 26, 31, 39, 46). However, few prospective studies have been conducted that have related PA to subsequent long-term weight gain. This is particularly the case when accurate methods for assessing PA are used. Therefore, until recently, only speculation could be made concerning the overall impact PA might have on weight-gain trends and what volume of exercise might be required to prevent weight gain.

Use of doubly labeled water is considered the most direct and accurate way to measure AEE. PA and AEE are highly related but are slightly different things. AEE is the result of the exercise task, i.e., walking a mile, and how economically the individual does the task. Because the *SD* for the energy cost of performing various tasks varies 10–15% around the mean for that task, the variability in energy cost for doing a task or group of tasks can be quite large. For example, the weight-adjusted *SD* for net oxygen uptake (in ml $O_2 \cdot kg^{-1}$ body weight$\cdot min^{-1}$) for 4 submaximal tasks (walking at 3 mph flat and up one grade, climbing stairs, and riding a bicycle ergometer at 50 W) is 10.8% (18). The *SD* for individual tasks is even greater. Some individuals are just more economical at doing exercise than others. That means that two individuals who are the same size and doing exactly the same tasks may have quite different AEEs, varying by over 20% (i.e., 2 *SD*).

If how economically an individual does physical activity is known, AEE can be adjusted to take exercise economy into consideration. Based on responses from a sample of subjects, we selected the 5 tasks (walking at 3 mph flat and up a grade, climbing stairs, riding a bicycle ergometer at 50 W, and carrying a load equivalent to 30% of maximum elbow flexion strength while walking at 2 mph) to represent activities that are common to most of our subjects. An average above-sleeping energy cost of doing these 5 tasks (AEC; kcal per minute) was determined for each subject in the laboratory using indirect calorimetry. Activity-related time equivalent (ARTE) index (in minutes per day) was then calculated by dividing AEE by AEC (43). The calculation of ARTE allows comparisons of duration of physical activity between subjects who have different energy costs of movement because of differences in body mass or energy economy of exercise (34). This could be particularly important in making PA comparisons between groups that vary in exercise economy (34).

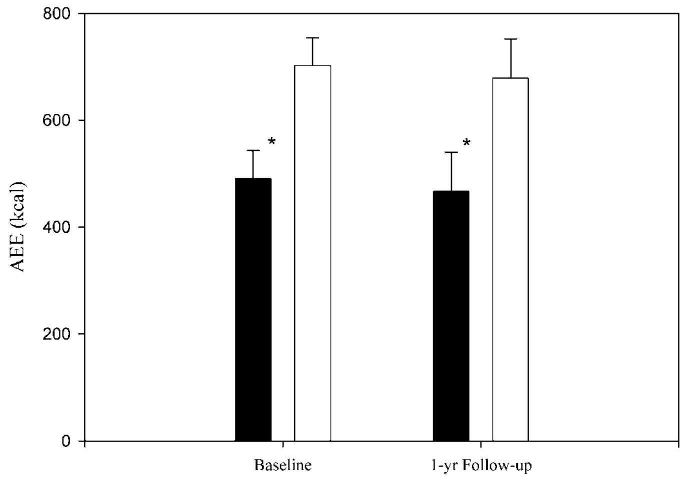

FIGURE 3. Activity-related energy expenditure of gainers and maintainers.

If increased PA is causative in helping to prevent weight gain, high levels of PA should be predictive of low levels of weight gain. Using the postobese model and under tightly controlled 4-week energy balance conditions, we have found that premenopausal women who are weight maintainers (<2 kg of weight gain in 1 year) had AEEs >42% (Figure 3) and ARTE indexes >40% more than women who were weight gainers (>6 kg of weight gain in 1 year) (41). The ARTE and AEE values were almost identical in the baseline measurement (before weight gain or maintenance) and 1 year later (after weight gain or maintenance). The increased AEE in the maintainers group resulted in an increased total energy expenditure (TEE) of 1,096 kJ per day (268 kcal per day) over the gainers.

Using dual-energy X-ray absorptiometry, we found the gainers in this study gained 8.9 kg more fat mass and 1.6 kg more lean mass than the maintainers during the average of 1.1 years of follow-up. Using the equations reported by Spady et al. (36) and Forbes et al. (8, 9) we calculated that the degree of positive energy balance required to produce this difference in body composition was 274 kcal per day (12 kcal/g of fat mass and 1.8 kcal/g of lean mass). Our group difference of 212 kcal per day for AEE accounted for 77% of the positive energy balance between the 2 groups, suggesting that physical activity had a strong influence on the resistance to weight gain demonstrated in the weight maintainers group, probably even stronger than dietary intervention (41).

ARTE index is based on energy expenditure above SEE and thermogenesis of food. However, some of the ARTE index includes the additional energy expended in sedentary activities, such as sitting and standing, fidgeting, brushing teeth, and typing. Sedentary TEE has been estimated to be approximately 1.4 times resting energy expenditure (40). To compare estimates of time spent in physical activity to other studies (i.e., time spent in moderate intensity exercise above a sedentary existence), physical activity was calculated based on energy expenditure above 1.4 times REE, assuming an intensity of 4 METs. Figure 4 contains the estimates of time spent in moderate intensity exercise for the gainers and maintain-

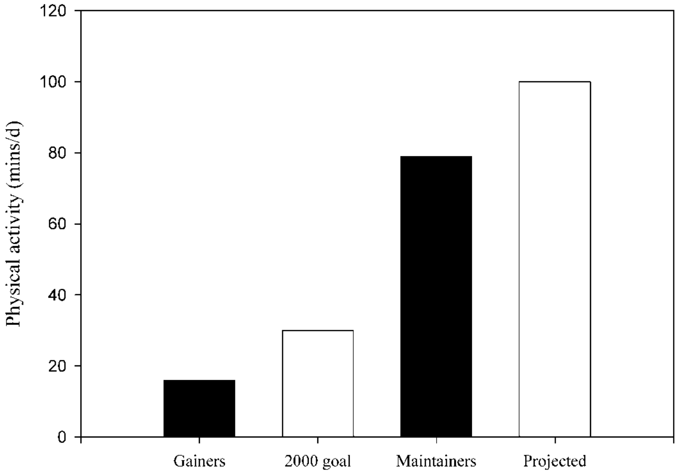

FIGURE 4. Estimated physical activity required to prevent weight gain (minutes per day).

ers. The gainers in this study spent an average of 16 minutes and the maintainers spent an average of 79 minutes in physical activity. Supporting the 79 minutes found for the maintainers, Schoeller et al. (32) have recently estimated that 80 minutes per day of moderate intensity exercise is required for prevention of weight gain. In addition, consensus of the ISSO Stock Conference in 2002 (31) was that there is compelling evidence that prevention of weight regain in formerly obese individuals requires 60–90 minutes of moderate intensity activity or smaller amounts of vigorous intensity activity.

Because our data suggests that only 77% of the difference in weight gain between the gainers and maintainers is explained by differences in AEE, it is probable that dietary modification was also part of the weight maintenance strategy for the maintainers. If no dietary restrictions were present (differences in AEE accounting for all of the difference in time spent in PA between the gainers and maintainers), 101 minutes of moderate intensity exercise would be required to maintain weight (Figure 4). It is interesting to observe that the estimated weight gain for individuals who follow the year 2000 federal minimal recommendations of 30 minutes per day of moderate intensity exercise would be just over 9 kg. Because many individuals will not have the time or motivation to participate in 100 minutes per day or even 80 minutes per day of physical activity, weight maintenance may entail dietary restraint as well as an active life style.

Whereas these data collected in studies of women are provocative, similar data are yet to be collected in men and the elderly. In addition, dietary intervention cannot occur in studies that are designed to determine who will gain weight under free-living conditions. Therefore, diet was not controlled during 1-year follow-up in which weight was gained or maintained in either the Weinsier et. al. (41) or Schoeller et. al. (32) studies. Therefore, no conclusions can be made concerning the interaction of different diet regimes on either physical activity or 1-year weight gain.

Muscle Function

It is possible that endurance and strength influence the difficulty of being physically active, thus increasing the inclination to be physically active and the probability of maintaining weight. In keeping with this hypothesis, we have recently shown that high maximum oxygen uptake ($\dot{V}O_2max$) is associated with decreased exercise difficulty, as measured by submaximum heart rate, ventilation, and perceived exertion during activities such as walking, climbing stairs, and riding a bicycle ergometer (22). Reduced measures of difficulty are, in turn, related to increased AEE and PA. Because African American women have higher submaximum heart rates, ventilation, and perceived exertion during walking, climbing stairs, and cycling, increased exercise difficulty, at least in part, explains lower AEE found in African American women when compared with white women (22).

To further explore the relationship between function, participation in physical activity, and long-term weight gain, we have used ^{31}P magnetic resonance spectroscopy (^{31}P MRS) to measure ATP generation from oxidative, glycolytic, and creatine kinase reactions during exercise. Muscle aerobic capacity and metabolic economy can be estimated from ^{31}P MRS exercise studies. It is thus possible to examine how various measures of muscle metabolism relate to muscular strength, whole body aerobic capacity, and exercise performance and, finally, how these measures of muscle function and fitness relate to physical activity and long-term weight maintenance.

We have recently shown that quadriceps isometric strength and ^{31}P MRS muscle oxidative capacity (postexercise ADP recovery rate $\times$ volume of muscle $\div$ body weight) are independently related to treadmill endurance time (23). Almost identical results were found when whole body $\dot{V}O_2max$ was substituted for muscle oxidative capacity. These results suggest that both strength and aerobic capacity independently influence walking endurance for a maximal task of approximately 6–7 minutes (a modified Bruce treadmill protocol to exhaustion). Although oxidative capacity would be expected to be related to an endurance task of this duration, it is interesting to observe that strength is independently related to endurance. Previous studies have shown that strength increases after resistance training are related to increased time-to-exhaustion in endurance activities, even though little or no increase in aerobic capacity was found (11, 14, 27, 37). One possible explanation for a relationship between physical strength and endurance performance is that less muscle activation would be required to perform a task when a muscle is stronger (20), hence delaying fatigue.

As would be expected $\dot{V}O_2max$ and treadmill endurance time are negatively related to weight gain over 1 year (23). In addition, women who maintain weight over 1 year are stronger and have better muscle metabolic economy than women who gain weight. Multiple regression analysis reveals that muscle metabolic economy, $\dot{V}O_2max$, and quadriceps strength all are independently related to reduced rate of weight gain (model $R = 0.48$; $p < 0.01$). We know of no other studies that have shown that muscle metabolic economy and leg strength are related to subsequent weight gain, although Borg et al. (3) have recently shown that weight-reduced obese men who resistance trained gained less body fat than nonexercisers and walkers during the 6 months after a 2-month dietary intervention that produced a 14.3 kg weight loss.

Previously, we have found that 9 weeks of resistance training improves whole-body exercise economy, at least for the specific task for which an individual trains (15), whereas it has been shown that running economy is im-

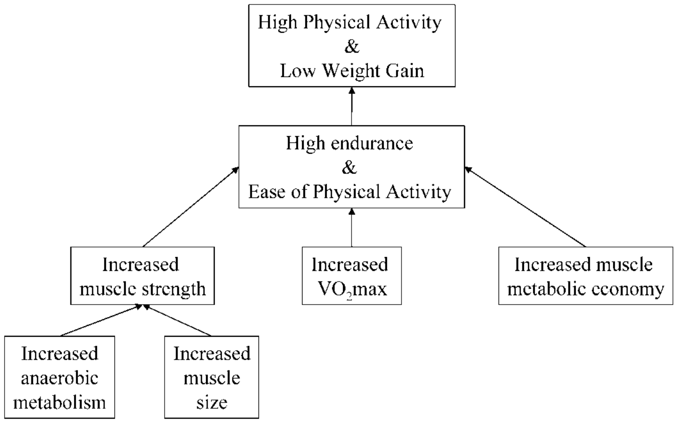

FIGURE 5. Summary of factors that predict a low rate of weight gain.

proved in trained runners after 14 weeks of resistance training (25). We have also found that ease of performing daily tasks as measured by normalized electromyography and heart rate response is reduced after 16 weeks of resistance training (19, 27). These findings suggest that improved muscle metabolic economy and strength may make it easier to be physically active. It is plausible that stronger individuals will be more economical during physical activity, making physical activity less demanding, increasing the likelihood of being physically active, and thus increasing AEE and decreasing vulnerability to weight gain. Specifically, if myofibers are larger and stronger and therefore capable of greater force development, more work can be accomplished by low-threshold, efficient fatigue-resistant (type I) motor units, decreasing the need to activate less-efficient, fatigable type II motor units (20). Not only are weight maintainers stronger than weight gainers, women who regularly participate in relatively large amounts of physical activity (>60 minutes per day) have more leg strength and muscle maximal creatine kinase activity than women who regularly participate in low levels of physical activity (<20 minutes per day) (21).

PRACTICAL APPLICATIONS

Although further research is required, these studies indicate that relatively high volumes of physical activity (~80 minutes per day of physical activity at an average MET level of 4) are present in women who maintain weight, whereas women who gain weight (an average of 9.5 kg over 1 year) average only 16 minutes per day of physical activity. Increased muscular strength, aerobic fitness, endurance, and economical movement patterns may be helpful in maintaining weight by increasing the ease of being physically active, thereby increasing the odds of selecting a more active lifestyle (Figure 5). Very large amounts of moderate intensity exercise (80–100 minutes per day) may be required for maintaining weight without dietary intervention. Inclusion of higher-intensity training may be helpful in not only increasing the rate of calorie expenditure and thereby reducing the physical activity time needed for weight maintenance, but also may increase the desire to be physically active by increasing the ease of participating in an active lifestyle. Because most individuals will not have the time or inclination to participate in such extreme exercise regimes, it should be recognized that a combination of dietary restraint and physical activity may be needed to maintain body weight in our progressively mechanized society. Long-term intervention studies that compare the effects of various exercise-training regimes on long-term weight maintenance are required before definitive recommendations can be made on the mode, intensity, and volume of physical activity that is most conducive to weight maintenance.

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