Resistance Training Reduces Skeletal Muscle Work Efficiency in Weight-Reduced and Non–Weight-Reduced Subjects

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Objective: The objective of this study is to determine whether resistance training is similarly effective in reducing skeletal muscle efficiency and increasing strength in weight-reduced and maximal weight subjects.

Methods: This study examined the effects of supervised resistance exercise on skeletal muscle in 14 individuals with overweight and obesity sustaining a 10% or greater weight loss for over 6 months and a phenotypically similar group of 15 subjects who had not reduced weight and were weight stable at their maximal lifetime body weight. We assessed skeletal muscle work efficiency and fuel utilization (bicycle ergometry), strength (dynamometry), body composition (dual energy x-ray absorptiometry), and resting energy expenditure (indirect calorimetry) before and after 12 weeks of thrice-weekly resistance training.

Results: Non–weight-reduced subjects were significantly (10%-20%) stronger before and after the intervention than weight-reduced subjects and gained significantly more fat-free mass with a greater decline in percentage of body fat than weight-reduced subjects. Resistance training resulted in similar significant decreases (~10%) in skeletal muscle work efficiency at low-level exercise and ~10% to 20% increases in leg strength in both weight-reduced and non–weight-reduced subjects.

Conclusions: Resistance training similarly increases muscle strength and decreases efficiency regardless of weight loss history. Increased resistance training could be an effective adjunct to reduced-weight maintenance therapy.

Introduction

Most individuals find that it is harder to sustain weight loss than to lose weight. Maintenance of a 10% or greater diet-induced weight loss is accompanied by decreases in energy expenditure to levels significantly (~300-400 kcal/d) below those predicted solely on the basis of changes in weight and body composition as well as increased hunger and delayed satiety (1). This decline in energy expenditure does not abate over time, and individuals who are successful at keeping weight off for prolonged periods of time report that to do so, they must decrease their energy intake and substantially increase their energy expenditure via exercise (usually aerobic for 200-300 more minutes per week) compared to individuals at the same weight who have never lost weight (2,3). Increased physical activity is clearly associated with less weight regain after otherwise successful weight loss (4,5). However, an important question is whether the benefits of increased exercise in sustaining weight loss are dependent on the type of exercise performed as well as the number of calories expended.

Skeletal muscle is the primary effector organ for the disproportionate decline in energy expenditure following 10% or greater weight loss (6). Molecular changes in skeletal muscle following dietary weight loss result in an ~20% increase in muscle work efficiency at low levels...
TABLE 1

| Subjects | Pretraining | Posttraining | Delta | Weight-reduced subjects | Pretraining | Posttraining | Delta | Group | Time | Group x time |
|----------|-------------|--------------|-------|--------------------------|-------------|--------------|-------|-------|------|-------------|
| Gender   | 5 M, 10 F   | 4 M, 10 F    |       | 9 M, 20 F                |             |              |       |       |      |             |
| Age      | 40.1 (8.2)  | 36.7 (6.6)   | 3.4   | 91.8 (16.3)              | 93.0 (10.3) |              | 1.2   |       |      |             |
| Height (cm)| 91.8 (16.3)| 93.3 (16.9)  | 1.5   | 32.5 (6.1)               | 33.2 (5.0)  |              | 0.7   |       |      |             |
| Weight (kg)| 26.7 (6.9) | 27.3 (3.3)   | 0.6   | 36.4 (10.9)              | 35.6 (12.2) |              | 0.8   |       |      |             |
| BMI (kg/m²)| 26.2 (3.0) | 26.7 (6.9)   | 0.5   | 35.3 (11.8)              | 36.5 (6.2)  |              | 1.2   |       |      |             |
| FFM (kg) | 56.4 (10.9)| 58.3 (8.9)   | 1.9   | 33.4 (4.8)               | 33.6 (4.9)  |              | 0.2   |       |      |             |
| FM (kg)  | 35.3 (11.8)| 35.6 (6.2)   | 0.3   | 35.6 (12.2)              | 36.5 (6.2)  |              | 0.9   |       |      |             |
| % Fat    | 35.3 (11.8)| 36.5 (6.2)   | 1.2   | 35.6 (12.2)              | 36.5 (6.2)  |              | 1.2   |       |      |             |
| REE (kcal/d)| 26.2 (3.0)| 26.7 (6.9)   | 0.5   | 35.3 (11.8)              | 36.5 (6.2)  |              | 1.2   |       |      |             |
| RER      | 0.85 (0.05)| 0.84 (0.08)  | -0.01 | -0.01 (0.07)             | 0.82 (0.06) |              | 0.0   |       |      |             |

There were no significant differences between groups at baseline. But there were significant group time effects in the intervention, such that non-weight-reduced individuals gained more FFM and had a higher reduction in

of power output, which is significantly correlated with the degree of disproportionate decline in energy expenditure that occurs following weight loss (6). Decreasing skeletal muscle work efficiency would therefore be advantageous in sustaining weight loss, especially if the decrease in efficiency, and therefore increased caloric expenditure per unit of work, occurred at levels of physical activity commensurate with those of daily living. Energy expended during exercise at the level described above is similar to that expended during activities of daily living outside of voluntary exercise, which is defined as nonexercise activity thermogenesis (7). This decline in efficiency would essentially “reverse” some of the changes in muscle metabolism that occurred as a result of dietary weight loss. Muscle resistance training is a potential means to achieve this goal (8,9).

In individuals stable at their usual weight, resistance training is associated with increased strength (10) and decreased skeletal muscle contractile efficiency (8,9). In contrast, aerobic training results in increased skeletal muscle efficiency without the increase in strength noted during resistance training (11).

The aim of the present study was to compare the effects of muscle resistance training on skeletal muscle work efficiency in weight-reduced individuals versus a control group of non–weight-reduced individuals at their maximal lifetime weights. We hypothesized that resistance training would similarly decrease skeletal muscle work efficiency and increase muscle strength in both groups. The alternative hypothesis was that restoration of body energy stores (fat) following weight loss was so vital to reproductive integrity and biological survival that the weight-reduced individual would be less responsive to the effects of resistance training on muscle.

Methods

Subjects

Twenty-nine subjects (7 male [M], 22 female [F], age range: 29-47 years) with overweight (30 kg/m² > BMI > 25 kg/m²) or obesity (BMI > 30 kg/m²) were recruited by online and newspaper advertisement and via physicians specializing in bariatric surgery and/or the treatment of obesity in New York City. Fourteen subjects (11 F, 3 M; BMI range: 25.8-41.2 kg/m²) were weight-reduced through dietary restriction (i.e., they did not report increased physical activity to lose weight) and had sustained a 10% or greater weight loss for at least 6 months following laparoscopic banding (n=6) or dietary weight loss (n=8). Fifteen subjects (11 F, 4 M; BMI range: 26.2-40.6 kg/m²) were at their maximal lifetime weights. Inclusion criteria included documentation of weight stability (within 3%) for at least 6 months, good health (without diabetes or hypertension), and capacity to engage in vigorous exercise but not currently participating in any type of regular physical training. Exclusion criteria included smoking, hypertension, diabetes, asthma, medication affecting the autonomic nervous system (e.g., beta-blockers), thyroid disease or medication, asthma requiring regular bronchodilator or steroid therapy, psychotropic medication, and any immunocompromising condition that would increase the risk of infection at biopsy sites. Subjects met with staff (MKH, SMW, or APS) on at least four occasions before enrollment to ascertain their ability to comply with the program and to attend regular exercise sessions. All subjects were prescreened by a medical doctor (LJA or MR) with a physical examination, electrocardiogram, thyroid profile, complete blood count, liver function studies, and HIV testing. Studies were approved by the institutional review board of The New York Presbyterian Medical Center and are consistent with
guiding principles for research involving humans (12). Written informed consent was obtained from all subjects. Subject characteristics are presented in Table 1.

Study design
Prior to beginning the exercise intervention, subjects underwent the following testing.

Energy expenditure. Resting energy expenditure (REE) by indirect calorimetry using a Viasys 2 hood calorimeter was measured at 9 AM in the postabsorptive state and following a 30-minute accommodation period (13).

Body composition. Fat mass (FM) and fat-free mass (FFM) were determined by dual energy x-ray absorptiometry (DXA) (13). DXA measurements were standardized. All subjects were studied following an overnight fast, and height and weight were measured just prior to scanning for entry into the DXA software. All subjects had to fit entirely within the DXA scan field of view, with arms placed at the sides of the body (no overlapping). Subjects wore a hospital gown, ensuring no metal in clothing or on body.

Skeletal muscle ergometry. Skeletal muscle work efficiency and fuel utilization were assessed by graded bicycle ergometry (13) as described previously. Briefly, after a 10-minute period of accommodation, the subjects pedaled at 60 rpm against graded resistance to generate 10 W, 25 W, and 50 W of power in successive 4-minute intervals using a Lode Corival electromagnetically braked bicycle and ergometer with electrical braking. Oxygen uptake, carbon dioxide production, and the respiratory exchange ratio (RER) were measured continuously using a Sensormedics VMAX 29 metabolic cart (14). Steady-state values were recorded at 0 W (rest), 10 W, 25 W, 50 W, and 75 W with expectation that 50 W of power is below the anaerobic threshold for even the most sedentary subjects. Steady-state oxygen uptake and carbon dioxide production are easily attained within 2 to 3 minutes of cycling (15).

31P–nuclear magnetic resonance (NMR) spectroscopy of the medial and lateral gastrocnemius muscles at rest was performed in a 1.5T Philips Intera MRI scanner. Basal concentrations of inorganic phosphate (Pi) and phosphocreatine (PCr) were measured in the medial and lateral gastrocnemius muscles as previously described (6). Pi at rest reflects the potential for muscle to oxidize free fatty acids (FFA) versus carbohydrate, and the ratio of Pi to PCr reflects the rate of energy flux (adenosine triphosphate [ATP] consumption) through muscle and is a measure of resting muscle efficiency. Subjects exercised in the magnet by depressing a pedal against varying levels of resistance to allow calculation of the recovery constant for PCr (kPCr) which is a commonly utilized index of mitochondrial capacity (16).

Muscle strength. Strength assessment was made using a Cybex Norm Dynamometer. Subjects were positioned in an adjustable chair and strapped in across the trunk, hip, and thigh and were then instructed to push as hard as they could against a shin pad at the distal tibia to obtain maximal power, torque, and muscle fatigability (decline over 25 repetitions) (17,18).

Exercise intervention. Following completion of the initial assessments described above, subjects began a 12-week resistance training circuit consisting of 45- to 60-minute sessions on Mondays, Wednesdays, and Fridays. This circuit was based on studies of the effects of different types of exercise in subjects with type 2 diabetes, the majority of whom had overweight or obesity (19). Baseline resistance loads for each subject were determined at the first session using a 10 resistance maximum protocol. Subjects acclimated to the circuit during the first 2 to 3 sessions. The intensity of the resistance training was subsequently increased as tolerated based upon subjects’ ratings of perceived exertion and under the supervision of a trainer (MKH).

Subjects began each session with a 5- to 10-minute warm-up that consisted of basic mobility movements such as knee lifts and shoulder circles and back flexion and extension exercises. This was followed by the exercise intervention, which consisted of two sets of upper-body exercises and three sets of lower-body exercises. The exercises consisted of 10 repetitions at a maximum tolerated intensity (weight) with a 1-minute rest between each set. Each subject was asked to give a rating of perceived exertion (20) for the last repetition of each set, which was used to evaluate whether an increase in the resistance load was warranted for the next session. Specifically, the resistance load was increased in increments of 5 lb if subjects expressed a rating of perceived exertion below 7 on a 10-point scale. Exercises are listed below:

i. Shoulder press (pushing handles directly upward while seated)
ii. Latissimus pull (pulling a bar directly down while seated)
iii. Seated row (pulling handles toward chest while seated)
iv. Chest press (pushing a bar away from the chest while seated)
v. Leg press (using legs to push a plate while seated)
vi. Leg extension (extending at the knees while seated)
vii. Leg curl (flexing at the knees while seated)
viii. Calf extension (extending the ankles against resistance while seated)

Selectorized resistance machines were chosen instead of free weights so that biomechanically correct movement patterns could be more easily maintained, allowing subjects to focus on muscle force production rather than balance, control, and additional aspects of proper technique that arise when using free weights. Exercises were selected to directly involve the muscles relevant to the ergometric and dynamometer studies. The NMR involves muscles used in the calf extension and the dynamometer involves muscles used in the leg press. All lower-extremity exercises were directly relevant to bicycle ergometric studies. Upper-body exercises were selected to provide participants with a “total body” workout and aid in recruitment and adherence to completion of the intervention. Exercises were consistent with recommendations from the American College of Sports Medicine (21).

Calculations and statistics. Skeletal muscle work efficiency during ergometry was calculated as delta mechanical efficiency, which is the slope of the line relating energy expended advancing from 10 W to 25 W, 25 W to 50 W, and 50 W to 75 W of power generation. The three steps were analyzed individually. Delta mechanical efficiency was chosen to avoid any skewing of the data due to training-induced changes in REE or the degree of inefficiency due to fidgeting, etc., on the bicycle (15,22) (against the possibility that subjects were better accommodated to the bicycle at the posttraining session and could pedal more efficiently). The steady-state RER was used to calculate relative fuel utilization of carbohydrates versus fatty acids at each work level (23).
Data are presented as mean (SD). Statistical significance was prospectively defined as $P < 0.05$. Between-group comparisons at baseline were made by ANOVA. Within-group comparisons were made by ANOVA with repeated measures. Comparisons of changes between groups (group x time interactions) were made by ANOVA comparing the deltas in each measure (posttraining minus pretraining) between groups. Analyses were performed using the Statistica version 10 statistical package (24).

### Results

#### Subjects

Protocol adherence was excellent; 28 out of 29 subjects attended all 36 exercise sessions and 1 subject missed only the last session. There were no significant differences between groups in subject demographics or body composition at baseline (see Table 1). Subjects in the non-weight-reduced group had significantly greater lower leg

#### Figure 1

Strength training. Data are mean (SD) lower leg extension and flexion strength. Lower leg flexion strength was significantly greater in the non-weight-reduced group compared to the weight-reduced group. Resistance training for 3 months resulted in significant increases in both extension and flexion strength in both groups. There were no significant differences in the absolute or proportional magnitudes of the treatment effects.

#### Figure 2

Muscle efficiency. Data are mean (SD) delta efficiency (defined as the slope of the line relating energy expenditure to power generated at different workloads) by graded bicycle ergometry. In all groups, resistance training resulted in a significant decline in skeletal muscle work efficiency over the power generation ranges: 10-25 W and 25-50 W. There were no significant between-group differences in the absolute or proportional magnitudes of the treatment effects.

*Training Effect $P < 0.05$ in both groups

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*P* < 0.05 vs. Pre-Training

†P < 0.01 vs. Pre-training

‡P < 0.01 vs. Non-Weight-Reduced

# P < 0.05 vs. Non-Weight-Reduced

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**Table 1**

| Group               | Lower Leg Flexion Strength (kg) | Lower Leg Extension Strength (kg) |
|---------------------|---------------------------------|-----------------------------------|
| Non-Weight-Reduced  | 1.5 (0.2)                       | 1.8 (0.3)                         |
| Weight-Reduced      | 1.3 (0.1)                       | 1.6 (0.2)                         |

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strength based on peak torque during flexion both before (63.4 [18.2] N·M in non–weight-reduced vs. 45.6 [15.3] N·M in weight-reduced individuals, \( P = 0.009 \)) and after training (88.2 [16.9] N·M in non–weight-reduced vs. 75.0 [15.9] N·M in weight-reduced individuals, \( P = 0.045 \)) (see Figure 1). Although baseline muscle work efficiency in weight-reduced subjects at 10 W to 25 W of power tended to be more efficient (the ratio of energy expended to work performed from 10 W to 25 W was 3.44 [0.98] in weight-reduced subjects versus 3.73 [0.88] in non–weight-reduced subjects), these between-group differences were not significant (see Figure 2). No significant differences in any variables were noted between subjects who had lost weight by diet versus gastric banding.

Resistance training

There were no significant changes in weight or body composition in either group during the period of resistance training, but group \( \times \) time interactions in measures of body composition were significant (see Table 1). Specifically, non–weight-reduced subjects tended to gain FFM and lose FM, whereas weight-reduced subjects tended to lose FFM and gain FM, and the percentage of fat was significant. There

![Figure 3 Fuel utilization. Data are Mean (SD) RER at rest and during bicycle ergometry to perform 10 W to 75 W of power generated. These data are also expressed as the percentage of calories utilized that come from the oxidation of FFA, which could not be assessed at 50 W or 75 W of power generated because some of the RER values were > 1.0 (43). There were no significant group \( \times \) time differences in the absolute or proportional magnitudes of the treatment effects, although there was a significant treatment-associated decrease in RER and increase in the percentage of kilocalories derived from the oxidation of FFA at 25 W of power generated in the non–weight-reduced subjects only.](image)

| NMR data             | Non–weight-reduced subjects | Weight-reduced subjects | All subjects |
|----------------------|----------------------------|-------------------------|--------------|
|                      | Pretraining | Post training | \( P \) Value | Pretraining | Post training | \( P \) value | Pretraining | Post training | \( P \) value |
| \( \text{P}_\text{i} \) at rest (mmol/kg) | 4.27 (0.91) | 4.09 (0.92) | 0.61 | 4.27 (0.74) | 4.11 (0.62) | 0.60 | 4.27 (0.88) | 4.09 (0.92) | 0.46 |
| \( \text{P}_\text{Cr} \) at rest (mmol/kg) | 38.2 (0.90) | 38.4 (0.92) | 0.61 | 38.2 (0.74) | 38.4 (0.61) | 0.60 | 38.2 (0.88) | 38.4 (0.93) | 0.46 |
| \( \text{P}_\text{i}/\text{P}_\text{Cr} \) at rest | 0.11 (0.03) | 0.11 (0.03) | 0.65 | 0.11 (0.02) | 0.11 (0.02) | 0.60 | 0.11 (0.03) | 0.11 (0.03) | 0.45 |
| \( \text{k}_\text{PCr} \) | 0.025 (0.012) | 0.026 (0.021) | 0.84 | 0.023 (0.11) | 0.018 (0.18) | 0.39 | 0.024 (0.012) | 0.022 (0.019) | 0.67 |

No significant effects of the exercise intervention were noted.

**Table 2** \( ^{31} \text{P}-\text{NMR} \) data showed no differences between groups in propensity to oxidize FFA versus glucose (\( \text{P}_\text{i} \)), resting muscle ATP consumption (\( \text{P}_\text{i}/\text{P}_\text{Cr} \)), or glycolytic potential (\( \text{k}_\text{PCr} \)) at rest or in response to the exercise intervention.
was no significant effect of resistance training on REE or resting RER in either group.

Strength in both flexion and extension of the lower extremity were significantly increased by resistance training in both groups; the magnitude of the increase was not significantly different between groups (group * time interaction *P* = 0.70 for peak torque during extension and *P* = 0.36 for peak torque during flexion; see Figure 1).

Resistance training caused significant declines in muscle work efficiency during bicycle ergometry as reflected in delta contractile efficiency (changes in energy expended/changes in work performed) in both groups at low levels of exercise (i.e., levels of exercise similar to those of activities of daily living). Specifically, the significant decline in work efficiency was evident when bicycling to generate increments between 10 W to 25 W of power (mean [95% CI] change in the ratio of energy expended/work performed as a result of resistance training in weight-reduced subjects = 0.49 [−0.01 to 0.82] and 0.46 [−0.36 to 1.27] in non–weight-reduced subjects) and 25 W to 50 W of power (mean [95% CI] change in the ratio of energy expended/work performed as a result of resistance training in weight-reduced subjects = 0.17 [−0.10 to 0.44] and 0.22 [−0.03 to 0.48] in non–weight-reduced subjects) but was not detected between 50 W to 75 W of power of mean [95% CI] change in the ratio of energy expended/work performed as a result of resistance training in weight-reduced subjects = −0.07 [−0.60 to 0.45] and 0.03 [−0.25 to 0.30] in non–weight-reduced subjects). The range in which significant decreases in muscle after resistance is similar to that within which muscle efficiency increases after weight loss (6,13). There were no significant between-group differences in the magnitude of the decline in efficiency (group * time interaction *P* values = 0.90 from 10-25 W of power generated, 0.79 from 25-50 W of power generated, and 0.90 from 50-75 W of power generated; see Figure 2).

Resistance training resulted in a significant decline in RER and an increase in the percentage of kilocalories derived from fatty acid oxidation during exercise to generate 25 W of power only. No other significant training effects on fuel utilization were noted, and there were no significant between-group differences at any degree of exercise. Group *time interaction *P* values were also not significant (see Figure 3). NMR data (Table 2) did not show the significant decrease in the resting Pi/PCr ratio, which would reflect resting muscle ATP consumption following resistance training, that has been reported elsewhere (25), and the responses of Pi, PCr, Pi/PCr, and kPCR to training were not significant in either group.

**Discussion**

The major finding of this study is that 12 weeks of resistance training causes similar increases in strength and decreases in muscle work efficiency in both weight-reduced and non–weight-reduced subjects of similar levels of adiposity that are of sufficient magnitude to significantly “reverse” some of the increased muscle efficiency that occurs as a result of weight loss. The lack of between-group differences in response to resistance training is significant in that it does not support the alternative hypothesis that the ability to affect skeletal muscle by resistance training is altered as a result of weight reduction. These findings suggest that resistance training following weight loss reverses some of the increased skeletal muscle work efficiency induced by weight loss and therefore might be a useful adjunctive therapy to help sustain weight reduction.

Attempts to sustain a 10% or greater dietary weight loss are opposed by changes in energy expenditure (about 300-400 kcal/d below predicted based on body composition), autonomic function (decreased sympathetic and increased parasympathetic nervous system tone), neuroendocrine function (decreased circulating concentrations of leptin and bioactive thyroid hormones), and energy intake (increased food reward and hunger, decreased food restraint and satiation) (1). These changes do not appear to abate over time (2,26–28), and the likelihood of losing and sustaining a 10% or greater weight reduction is only about 15% (29). The primary effector organ of adaptive thermogenesis is skeletal muscle, the efficiency of which increases by ~20% following dietary weight loss work (6).

The American College of Sports Medicine recommends 150 min/wk of moderately vigorous physical activity to sustain good health, and 200 min/wk has been shown to lessen the likelihood of weight regain following weight loss (3,30,31). In previous studies (6), we have found that the rate of energy expenditure above resting while exercising to generate 25 W of power was 3.38 (0.50) kcal/min. In the present study, the efficiency of muscle in this same exercise range decreased by 14.9 (0.3)% in the non–weight-reduced group and 8.4 (0.3)% in the non–weight-reduced group following resistance training (group * time interaction *P* = 0.58). Extrapolating from these data, resistance training would increase energy expenditure by 30 kcal/h during exercise at this level. The average residual (difference between measured energy expenditure and predicted changes in energy expenditure based on changes in weight and body composition) for nonresting energy expenditure is 201 kcal/d in subjects with obesity studied before and after a 10% and 20% weight loss (32,33). Therefore, one would need to be engaging in physical activity comparable to pedaling a bicycle to generate 10 W to 25 W of power (~200 kcal/h or 2-3 metabolic equivalents for an 80- to 100-kg adult, which is consistent with activities of daily living [34,35]) for ~7 h/d to “reverse” the adaptive thermogenesis associated with weight loss. Large population surveys (36) report that the average adult spends ~8 h/d in physical activity (predominantly in occupation-related and household-related activities), with large variation between individuals depending upon occupation and exercise habits and with the caveat that exercise efficiency studies reported here only reflect one type of activity.

Non–weight-reduced subjects were significantly stronger (see Figure 1) and tended to have lower muscle efficiency during low levels of work (10-25 W, not statistically significant) at baseline (see Figure 1). These findings are consistent with our previous observations that weight loss results in a significant increase in skeletal muscle work efficiency during low-level exercise (1,6). Subjects for the weight-reduced group were recruited based on a documented history of weight loss and sustained maintenance of reduced body weight. Given the high level of variability between individuals in energy expenditure, muscle strength, muscle efficiency, etc., it was not expected that a between-group analysis at baseline would reveal significant intergroup differences (i.e., that weight-reduced subjects would have significantly greater skeletal muscle work efficiency than non–weight-reduced subjects prior to any intervention). The hypothesis related to whether or not there were significant intergroup differences in the within-subjects analyses of response to resistance training.

We have previously shown that the RER during low-level exercise decreases following weight loss, reflecting a greater propensity to oxidize FFA (6). The reasons for the lack of a resistance training effect to increase the RER despite the decline in muscle efficiency are not clear but may reflect an overall fitness improvement in subjects, which has
been associated with a decline in the RER (37) as a result of both resistance and aerobic training.

Weight-reduced subjects gained fat and lost FFM (both not statistically significant) over the course of the intervention, with significant group x time interactions in these variables. The significant group differences in body composition changes may reflect more intense exercising in the non-weight-reduced group (by virtue of the fact that they were initially stronger); differences in tissue hydration, or dietary intake; or interactions between levels of compliance with the request to not alter usual exercise activities outside of the training intervention between groups and primary differences in energy partitioning between groups.

The strengths of this study are in the close phenotypic matching of the study groups and the uniformity of the training. Important weaknesses include inability to control exercise activity and diet outside of the training regime and the lack of between-group differences in skeletal muscle efficiency at baseline. The issue of energy intake is of particular importance in evaluating the potential efficacy of increased resistance training on long-term maintenance of reduced body weight and on the molecular physiology of muscle under these circumstances.

Based on the present study, we would predict that resistance-trained subjects, compared to nonexercising or aerobic exercising subjects, would display sustained relative increases in energy expenditure for comparable levels of physical activity and perhaps find it easier to sustain weight loss. Hunter et al. (38) reported that resistance or aerobic training blunted the declines in total energy expenditure and nonexercise activity thermogenesis during weight loss. Drenowatz et al. (39) found that men enrolled in a 16-week aerobic or resistance training regimen who were in the resistance training group were more likely to maintain moderate vigorous physical activity levels beyond the exercise regimen while in the program.

A key question in the potential efficacy of resistance training in sustaining weight loss is the extent to which this increased expenditure would be compensated by increased food intake. In 1956, Mayer et al. (40) noted that energy intake in Bengalese jute workers increased in rough proportion to any increase in expenditure but also noted that it increased in the context of an extreme sedentary lifestyle. A recent review by Blundell et al. (41) noted that appetite is affected acutely and chronically by diet composition, body composition, energy expenditure, energy balance, and numerous neuroendocrine and enteroinendocrine signals, all of which are influenced by the type and amount of exercise in a highly individualized manner. Some studies comparing the effects of the type of exercise on energy intake have reported that aerobic exercise, especially at high intensities, results in greater satiation and less hunger after exercise (42) than resistance training in non-weight-reduced subjects.

It should be emphasized that the level of resistance training was relatively low compared to maximal resistance training and high-intensity interval training, both of which have been reported to increase muscle efficiency (43,44), and that the main outcome variable of this study was muscle efficiency at low levels of exercise. Other studies describe different types of training (e.g., high-intensity interval cycling) and measure efficiency over a wider range of exercise and in ranges not examined in this study (45).

In summary, these data suggest that resistance training may “reverse” the increase in skeletal muscle contractile efficiency following dietary weight loss, thereby resulting in increased energy expenditure per unit of muscle power generation both during low-level exercise and during activities of daily living (1). The implications for future studies are clear. Longer-term studies are needed to determine whether isocaloric resistance training versus aerobic training will result in less regain of FM by virtue of differential effects on muscle contractile efficiency and energy intake after weight reduction. Our data suggest that exercise prescriptions to assist in sustaining weight loss should be modified to include a greater emphasis on resistance training.

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