Increased energy requirements and changes in body composition with resistance training in older adults[1–4]

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ABSTRACT Body composition and the components of energy metabolism were examined in 12 men and women, aged 56–80 y, before and after 12 wk of resistance training. Subjects were randomly assigned to groups that consumed diets that providing either 0.8 or 1.6 g protein $\cdot kg^{-1} \cdot d^{-1}$ and adequate total energy to maintain baseline body weight. Fat mass decreased 1.8 ± 0.4 kg ($P < 0.001$) and fat-free mass (FFM) increased 1.4 ± 0.4 kg ($P < 0.01$) in these weight-stable subjects. The increase in FFM was associated with a 1.6 ± 0.4 kg increase in total body water ($P < 0.01$) but no significant change in either protein plus mineral mass or body cell mass. With resistance training, the mean energy intake required for body weight maintenance increased by ≈15%. Increased energy expenditure included increased resting metabolic rate ($P < 0.02$) and the energy cost of resistance exercise. Dietary protein intake did not influence these results. Resistance training is an effective way to increase energy requirements, decrease body-fat mass, and maintain metabolically active tissue mass in healthy older people and may be useful as an adjunct to weight-control programs for older adults. *Am J Clin Nutr* 1994;60:167–75.

KEY WORDS Age, elderly people, protein, strength training, resting metabolic rate, hormones, strength

Introduction

Energy balance in adults is determined by the dynamic equilibrium between the intake of energy from food and the energy expended for the maintenance of metabolic rate (60–75% of total energy expenditure), the thermic effect of feeding (≈10% of total energy expenditure), and the thermic effect of physical activity (1, 2). Energy requirements generally decrease as adults age (3, 4), in part because of a decline in physical activity (5) and a decline in metabolic rate associated with losses of fat-free mass (FFM) (primarily muscle mass) (6). For many elderly individuals, decreased energy expenditure may not be matched by decreased energy intake, thereby contributing to an increase in body fat and the onset of obesity. In elderly adults who maintain energy balance, the reduced energy and nutrient intakes may contribute to the development of nutritional deficiency states. This risk may be especially high in the oldest, most frail elderly people (7).

High-intensity resistance training has been promoted as an effective stimulus to increase muscle strength in previously untrained elderly adults (8–11). The effects of resistance training on energy intake and expenditure in elderly adults are largely unstudied and the available data are not conclusive. Voluntary energy intakes have been shown to decrease slightly in some elderly men after 12 wk of lower-body resistance training but to increase in others (12).

This controlled metabolic study assessed the effects of a 12-wk progressive program of resistance training on muscular strength, body composition, and the components of energy balance in sedentary, healthy, older adults.

Subjects and methods

Subjects

Twelve previously untrained subjects (8 men and 4 postmenopausal women) aged 56–80 y were recruited for this study. Before being accepted into the study, each subject successfully completed a physical examination that included a medical history, an electrocardiogram, routine blood and urine tests, and a psychosocial evaluation. Each subject received a complete explanation of the purpose and procedures of the investigation and signed an informed consent agreement. The study protocol and informed consent were approved by the Tufts University New England Medical Center Human Investigation Review Committee.

Experimental design

The 14-wk metabolic study consisted of an initial 2-wk baseline period during which all subjects consumed the specified diets but remained sedentary and a 12-wk period of progressive resistance training. Muscular strength, body composition, and energy metabolism testing were carried out during the baseline period

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and at the end of the resistance-training period. Each volunteer lived in the Metabolic Research Unit at the US Department of Agriculture Human Nutrition Research Center on Aging (HNRCA) at Tufts University, Boston, during all testing periods. Nine subjects lived in the HNRCA throughout the study and three subjects commuted from home each weekday during nontesting periods to pickup meals and to exercise on three of those days.

Subjects were randomly assigned to one of two dietary groups that provided either the Recommended Dietary Allowance (RDA) for protein ($0.8\ g \cdot kg^{-1} \cdot d^{-1}$, lower-protein group) or twice the RDA for protein ($1.6\ g \cdot kg^{-1} \cdot d^{-1}$, higher-protein group) for the entire study (2). The lower-protein group included three men and three women and the higher-protein group had five men and one woman. The subjects and primary investigators were blinded to the dietary treatment.

Diet

All meals were prepared by and provided to the subjects in measured amounts by the Metabolic Nutrition Laboratory at the HNRCA. Subjects in both groups consumed a basal diet that consisted of three different menus of lactoovovegetarian foods that provided $0.6\ g\ protein \cdot kg^{-1} \cdot d^{-1}$. The three menus were used on a 3-d rotating schedule that cycled repeatedly throughout the study period. The remaining protein (0.2 or $1.0\ g \cdot kg^{-1} \cdot d^{-1}$) fed to the lower- and higher-protein groups, respectively, was provided as one of two milk-based liquid formulas. Water was allowed ad libitum. Each subject scraped and rinsed all of their dishes, glasses, and utensils with water and then consumed the rinsings. The amount of energy intake was initially chosen to provide for the subject's basal energy needs, which were predicted from the sex-specific Harris-Benedict equations, plus an energy cost of activity allowance of 0.5 times this basal energy expenditure (ie, total energy intake equalled 1.5 times basal energy needs). The protein, carbohydrate, and fat contents of each of the three daily menus were calculated from the US Department of Agriculture Agricultural Research Station database *GRAND* (release 867; US Department of Agriculture HNRC, Grand Forks, ND). Total energy intake was calculated by using the values of 16.7, 16.7, and 37.7 kJ/g protein, carbohydrate, and fat, respectively. The nonprotein portion of each of the three menus (food and formula) was composed of 55% carbohydrate and 45% fat. Total energy intake was increased beginning on the first day of resistance training by adding low-protein foods and beverages to each subject's daily menu in amounts that were estimated to equal the energy expenditure of the resistance training. Thereafter, low-protein foods and beverages were either added or subtracted from each subject's daily menu as needed to maintain body weight within ± 0.5 kg of their average body weight during days 4–11 of the baseline period. No adjustments to energy intake were made during the subsequent testing periods.

Each subject consumed one multivitamin-multimineral supplement tablet daily throughout the study (Advanced Formula Centrum; Lederle Laboratories, Pearl River, NY). Two subjects who complained of symptoms that suggested lactose intolerance consumed lactase enzyme tablets (Dairy Ease; Winthrop Consumer Products, Glenbrook Laboratories, New York) before each meal to aid digestion of milk products.

Energy cost of resistance exercise

To estimate the energy cost associated with resistance exercise, a pilot study was carried out in which energy expenditure was measured by indirect calorimetry in five healthy male subjects (aged 37 ± 16 y, mean body weight 78.1 ± 3.0 kg) while they each performed a typical resistance-exercise session. The resistance-exercise sessions consisted of a 10-min warm-up of stationary cycling (heart rate < 100 beats/min) and 10 min stretching, followed by three sets of eight repetitions at 80% of their predetermined one repetition maximum (1RM) for bench press, double-knee flexion, back pull-down, and double-knee extension. The bench press and back pull-down exercises were performed on a Universal Power-Pak model 400 exercise machine (Universal; Cedar Rapids, IA) and the knee flexion and knee extension exercises were performed on a Universal gym knee-thigh machine. The energy cost of the resistance-exercise session was calculated by multiplying oxygen consumption ($\dot{V}O_2$) by the kJ/L oxygen associated with the respiratory exchange ratio (RER) of the expired air (13).

Resistance-training protocol

In the resistance-training protocol, each subject performed two upper-body (chest press and front pull-down) and two lower-body (knee flexion and knee extension) exercises at 80% of their predetermined 1RM. The initial 1RM was set as the greater 1RM value for each exercise obtained from two pretraining 1RM measurements, one during the first 3 d of baseline and one at the start of the first training session. Knee extensions were performed separately for each leg to equalize the relative training stimulus for each limb. The first subject in each dietary treatment group performed the resistance exercises on the Universal equipment described earlier. All other subjects exercised on Keiser seated chest press, back pull-down, leg curl, and leg extension machines (Keiser Sports Health Equipment, Fresno, CA). With the Keiser pneumatic resistance equipment, the force provided at the point of contact by the subject on the exercise arm (expressed in lb/in^2, psi) varies throughout the range of motion to accommodate the subject's ability to provide maximum forces at different points in the range of motion. The 1RM for each exercise was recorded as the psi the subject was working against at the beginning of the range of motion and converted to kg of force based on conversion charts provided by the manufacturer. The order of training was chest press, knee flexion, front pull-down, and knee extension.

With supervision, each subject lifted and lowered the training loads for three sets on three nonsequential days per week, for 12 wk. Eight repetitions were completed during the first two sets and repetitions were continued during the third set until voluntary muscular fatigue or until 12 repetitions were completed, whichever came first. Each repetition was performed in a slow, 4–6 s, uniform fashion, giving equal time to the concentric (lifting) and eccentric (lowering) components. About 5 s rest separated each repetition and 90–120 s rest separated each set. All exercise sessions were preceded by a warm-up period that consisted of 10 min stationary cycling at low resistance and slow speed (heart rate < 100 beats/min) and 10 min stretching of the muscle groups involved in the resistance training. A cool-down period of 5 min cycling and 10 min stretching followed each exercise session. All subjects completed a total of 35 resistance-exercise sessions. The 1RM was measured biweekly and used to progressively increase the exercise load to maintain a constant training intensity of 80% of maximum force.

Resting metabolic rate measurements

Resting metabolic rate (RMR) was measured for 10 of the 12 subjects at the end of the second week of baseline and ≈45 h after the final resistance-exercise session (measurements were not completed for one man in each dietary group because of equipment malfunctions). While in a fasted state, each subject was escorted from their residence room to the metabolic laboratory and rested in a semirecumbent position for ≈45 min before measurements were taken. Twenty minutes before the measurement of their metabolic rate, each subject consumed a milk-based beverage providing one-twelfth of their daily baseline energy and protein requirements. As a result RMR measurements for this study were made in the immediate postprandial state and can be assumed to be slightly greater than would have been measured in a fasted state (basal metabolic rate, BMR) (1, 2). The thermic effect of feeding the beverage was minimized because the RMR measurements were made shortly after the beverage was consumed [before the peak response of the thermic effect of feeding would be expected (2, 14)] and each beverage had only a small energy content. The quantity and nutrient content of the beverages consumed by each subject were the same during baseline and posttraining RMR measurements. $\dot{V}O_2$ and carbon dioxide production rates were measured from expired air samples that were collected via a ventilated-hood system. After a 10-min stabilization period under the hood, 20 consecutive 1-min measurements were taken and averaged. The hood system consisted of a turbine flow meter (Sensoredics Ventilation Measurement Module, model VMM-1; Anaheim, CA), infrared dual-channel carbon dioxide analyzer (model Uras 3G; Hartmann-Braun, Frankfurt, Germany), and a dual-channel oxygen analyzer (Model S-3AII; Ametek, Pittsburgh). An Edwards two-stage pump (model E2M5; Edwards High Vacuum Pump International, Crawley, England) pulled a constant flow at ≈40 L/min and was adjusted to maintain expired air carbon dioxide at < 1%. All digital outputs were reduced by standard algorithms by using a Zenith computer (model Z160; Heath Company, Ann Arbor, MI). Ambient barometric pressure, temperature, and dew point were entered before starting each test.

Body-composition measurements

The morning body weight of each subject was measured daily to the nearest 0.1 kg on a Toledo Weight-Plate (model 8138; Bay State Scale Co, Cambridge, MA) in a fasted state soon after the subject had voided. Nude body weight was calculated as total body weight minus robe and hospital gown weight. Body height was measured in subjects without shoes to the nearest 0.1 cm with a wall-mounted stadiometer. The height measurement was made in the morning once during study week 1 and was assumed to remain constant throughout the entire study period. Body mass index (BMI) was calculated as wt/ht^2 (kg/m^2).

Skinfold thicknesses and body circumferences were measured at baseline and after 12 wk of resistance training. Skinfold thickness was measured on the right side of the body with Lange calipers (Cambridge Scientific Industries, Cambridge, MD) to the nearest 0.5 mm at seven sites (biceps, triceps, chest, subscapula, abdomen, suprailiac, and thigh) by one investigator using standard techniques (15). The sum of skinfold thicknesses at these seven sites is reported. Body-circumference measurements were taken at the chest (at the level of the fourth costosternal joints, in the horizontal plane, at the end of a normal expiration) and midthigh (midway between the inguinal crease and the distal boarder of the patella).

Whole-body fat mass, FFM, and protein plus mineral mass were estimated during baseline and after 11 wk of resistance training from body density and total body water (TBW) by using the three-compartment model of Siri (16). Body density was determined by hydrostatic weighing with a Sauter scale (model Kizo; Denshore Scale, Holbrook, MA). Lung residual volume was determined at baseline by nitrogen dilution (17), just before hydrostatic weighing, with the subjects in a similar seated, bent-forward position for both measurements, and was assumed to remain the same throughout the study.

TBW was determined by using the deuterium oxide dilution technique (18, 19). After a 10-h overnight fast, each subject was orally dosed with 20.0 g deuterium oxide (deuterium, 99.9%; Cambridge Isotope Laboratories, Woburn, MA) mixed with 300 mL water. Urine samples were collected before dosing and at 2, 3, and 4 h after dosing. The total void volume of each sample was measured and a 10–15 mL sample was stored at −20°C for analysis. Thawed urine samples were centrifuged at 1500 × g for 10 min, aliquoted in duplicate into Conway diffusion dishes (Bel-Art Products, Pequannock, NJ) as described by Davis et al. (20), the airtight sealed dishes incubated at 45°C for 48 h, and the resulting clean deuterium oxide–water mixture stored at −20°C. Deuterium oxide concentration was measured as described previously (19, 20) by using a fixed-filter single-beam infrared spectrophotometer (Miran 1FF; Foxboro Analytical, South Norwalk, CT) interfaced with a Fluke 87 RMS multimeter (John Fluke Mfg Co, Fremont, CA). The temperature of the calcium fluoride cell was kept constant at 15°C by circulating water from an Isotemp Refrigerated Circulator (model 9500; Fisher Scientific, Pittsburgh) through a modified cell holder. Voltage output was recorded as the average of a minimum of 30 continuous 1-s recordings obtained after the sample temperature stabilized at 15°C. The multimeter was zeroed with the cell filled with distilled, deionized water. Total isotope dilution space was calculated based on a simple dilution principle (18), with corrections made for deuterium oxide loss in urine before isotopic equilibrium. TBW was calculated assuming that a 4% exchange of isotope with nonaqueous hydrogen took place during equilibration in vivo (21).

Percent body fat was calculated from body density (kg/L) and TBW (expressed as a decimal fraction of body mass) from the following equation (16):

$$\%\mathrm{Fat} = [(2.118/\mathrm{density}) - (0.78 \times \mathrm{fraction\ body\ water}) - 1.354] \times 100$$

FFM was calculated as body mass minus fat mass and protein plus mineral mass was calculated as FFM minus body water mass.

Total body potassium was measured with the HNRCA whole-body counter (22) at baseline and after 11 wk of resistance training by counting the γ rays that resulted from the decay of the natural isotope of potassium (^{40}K). Body cell mass (BCM), an index of metabolically active tissue mass, was estimated from total body potassium assuming there are 0.213 kg BCM/g potassium (23).

Blood analysis

At baseline and 45 h after completion of the last resistance-training session, fasting arterialized venous blood samples were drawn through a 5-cm tetrahydrofluoranamide catheter that had been inserted retrogradely into a hand vein by using an aseptic technique. The hand was kept warm in a 70°C hot box. The blood samples were processed and stored at −20°C before analysis. Plasma glucose was determined on a Cobas MIRA centrifugal

TABLE 1
Physical characteristics and initial body composition of subjects[1]

Measurement	Group (n = 12)	Males (n = 8)	Females (n = 4)
Age (y)	65 ± 2	62 ± 2	71 ± 3[2]
Height (cm)	173.2 ± 2.7	178.4 ± 1.4	162.9 ± 3.9[3]
Body weight (kg)	78.0 ± 2.7	82.2 ± 2.3	69.6 ± 4.2[3]
Body mass index[4]	26.0 ± 0.6	25.8 ± 0.4	26.3 ± 1.8
Body fat (%)[4]	32.1 ± 2.1	27.6 ± 1.3	41.0 ± 1.3[6]
Fat mass (kg)[5]	24.7 ± 1.4	22.6 ± 1.1	28.7 ± 2.6
Fat-free mass (kg)[5]	53.3 ± 3.0	59.5 ± 2.2	40.9 ± 1.6[6]
Protein + mineral mass (kg)[5]	14.8 ± 1.0	16.8 ± 0.8	10.8 ± 0.4[6]
Body cell mass (kg)[7]	28.2 ± 1.5	31.6 ± 0.8	21.4 ± 0.2[6]
Total body water (L)[8]	38.5 ± 2.1	42.7 ± 1.5	30.1 ± 1.3[3]
Sum of 7 skinfold thicknesses (mm)	146.2 ± 14.9[9]	124.7 ± 7.1[10]	184.0 ± 31.2[2]
Chest circumference (cm)	101.3 ± 2.4[9]	106.2 ± 1.4[10]	92.8 ± 2.6[6]
Midthigh circumference (cm)	51.8 ± 1.0	51.5 ± 1.1	52.5 ± 2.0

[1] $\bar{x}$ ± SEM.
[2,3,6] Significantly different from males: [2] $P < 0.05$, [3] $P < 0.001$, [6] $P < 0.01$.
[4] In kg/m^2.
[5] Estimated from the combined equation of body density and total body water.
[7] Estimated from ^{40}K-potassium scans.
[8] Measured by the deuterium oxide dilution technique.
[9] n = 11.
[10] n = 7.

analyzer by using the ROCHE diagnostic reagent system (Roche Diagnostic Systems, Nutley, NJ). Radioimmunoassay (^{125}I) analyses were used to determine plasma insulin concentrations (ICN Biomedicals, Inc, Costa Mesa, CA), serum cortisol concentrations (Diagnostic Products Corporation, Los Angeles), serum total thyroxine (T_4) concentrations, and unsaturated 3,5,3′-triiodo-L-thyronine binding proteins (T_3) uptake (Ciba Corning Diagnostics Corp, East Walpole, MA). Plasma glucagon concentrations were determined by double-antibody ^{125}I radioimmunoassay (Diagnostic Products Corporation) from blood samples that had been mixed with Trasylol (FBA Pharmaceuticals, West Haven, CT) in tubes containing EDTA before separation of the plasma by centrifugation.

Statistical methods

Values are reported as $\bar{x}$ ± SEM. The main effects of dietary protein, sex, and resistance training and the interactions among these dependent variables on body composition, muscular strength, fasting glucose and hormones, energy intake, and RMR were determined by using three-way repeated-measures analysis of variance. The degree of linear association between variables and between the amount of resistance training–induced change of variables with each other was established by using the Pearson product-moment correlation. All calculations were performed by using *PROC GLM* of SAS version 6.07 (SAS Institute Inc, Cary, NC) and *RS/1* (BBN Software Products Corporation, Cambridge, MA). Results were considered statistically significant at $P < 0.05$ (two-tailed).

Results

Baseline values for all of the independent variables (body composition, muscular strength, fasting glucose and hormone concentrations, energy intake, and RMR) were similar for the groups of subjects who consumed the lower- and higher-protein diets. Statistical analysis of the effect of resistance training on these variables established that no protein, sex, or protein-by-sex interactions with training existed. That is, when resistance training–induced changes in these variables occurred, these changes were not influenced by whether the subjects consumed a lower- or higher-protein diet or whether the subjects were male or female. The data on the effect of resistance training on changes in body composition, muscular strength, glucose and hormones, energy intake, and RMR are combined for all 12 subjects.

Baseline physical characteristics and body-composition data are presented for all 12 subjects together and for the men and women separately (**Table 1**). As a group, the women were older; had a lower mean height, weight, FFM, TBW, protein plus mineral mass, BCM, and chest circumference; and had a higher percent body fat and sum of seven skinfold thicknesses than the men. BMI, total fat mass, and midthigh circumference were similar for women and men.

Muscular strength

Maximum dynamic muscular strength (as measured by 1RM) increased for all trained lower- and upper-body muscle groups after resistance training (**Table 2**). The mean percentage strength increase ranged from 24% for the front pull-down to 92% for the knee flexion. Expressing maximum strength relative to FFM normalized the data for men and women, so no sex effects were found.

Body-composition changes

Body weight was stable in both males and females throughout the 2-wk baseline period and remained stable throughout the entire study period (**Table 3**). Fat mass and percent body fat decreased, and FFM increased with resistance training (Table 3). The observed increase in FFM was associated with a significant increase in TBW, whereas the protein plus mineral mass did not change. The resistance training–induced changes in FFM and TBW were highly correlated with each other (r=0.841, P

< 0.0006). TBW increased with training by an average of 4.2%. There were no significant changes in BCM (estimated from measurements of whole-body ^{40}K), sum of seven skinfold thicknesses, chest circumference, or midthigh circumference as a result of resistance training (Table 3).

As noted above, neither BCM nor protein plus mineral mass were changed with resistance training. BCM and protein plus mineral mass, which are both considered independent measures of metabolically active tissue mass, were highly correlated with each other (r=0.929, $P < 0.001$) in the group of 12 subjects.

Energy metabolism

A mean energy intake of 128 ± 3 $kJ \cdot kg^{-1} \cdot d^{-1}$ was consumed by the subjects during the baseline period, which was an amount adequate to maintain body weight throughout the 2-wk period. We purposefully increased the daily energy intake of the first two subjects who participated in the study protocol by ≈420 kJ/d (5.4 $kJ \cdot kg^{-1} \cdot d^{-1}$) on the first day of training to offset the increased energy expenditure that we estimated to be associated with the resistance exercise. However, body weights of these two subjects tended to gradually decrease during the first 2 wk of resistance training. For subsequent subjects, energy intakes were increased by ≈840 kJ/d (10.8 $kJ \cdot kg^{-1} \cdot d^{-1}$) at the start of resistance training, which resulted in an increase in mean energy intake to 139 ± 3 $kJ \cdot kg^{-1} \cdot d^{-1}$. The mean energy intake needed for maintenance of body weight increased to 149 ± 6 $kJ \cdot kg^{-1} \cdot d^{-1}$ by training week 6 and was similar (147 ± 6 $kJ \cdot kg^{-1} \cdot d^{-1}$) during the 12th week of training. Thus, these elderly subjects required increased energy intakes of ≈15% over baseline during the resistance-training period to maintain body weight.

RMRs during baseline and after 12 wk of resistance training are presented in **Table 4.** The mean RMR increased 6.8% after resistance training ($P < 0.02$) in these weight-stable subjects (kJ/h), 6.4% when the data were expressed relative to body weight ($P < 0.02$), and 8.3% ($P < 0.01$) when the data were adjusted relative to protein plus mineral mass. When expressed relative to BCM or FFM, the RMR was increased 5.0% and 3.7%, respectively, after resistance training, but this increase was not statistically significant.

A strong relationship between RMR and protein plus mineral mass was present both before (RMR = 129.8 + 11.13 × protein plus mineral mass; r = 0.86, $P < 0.001$) and after (RMR = 162.1 + 10.30 × protein plus mineral mass; r = 0.85, $P < 0.001$) resistance training (**Fig 1**). The increase in RMR (kJ/h) with resistance training is shown by the upward shift of the regression line. The change in RMR (kJ/h) with resistance training was not significantly correlated with changes in body composition (FFM, protein plus mineral mass, TBW, or BCM).

Data from the pilot study were used to estimate the energy expenditure of a typical resistance-exercise session. The total energy expenditure during the entire exercise session averaged 0.230 ± 0.021 $kJ \cdot kg\ BW^{-1} \cdot min^{-1}$ and the net energy expenditure for the exercise itself (total energy expenditure minus resting energy expenditure) averaged 0.141 ± 0.008 $kJ \cdot kg\ BW^{-1} \cdot min^{-1}$. On this basis, a 77-kg person exercising for 90 min/d (including the warm-up and cool-down periods), 3 d/wk, was predicted to expend an additional 2931 kJ/wk over their sedentary baseline expenditure of energy. Average en-

TABLE 3
Body-composition changes with resistance training[1]

Index	Change[2]
Body weight (kg)	−0.4 ± 0.3 (−1.9–1.3)
Body fat (%)[3]	−2.2 ± 0.5[4] (−5.0–0.1)
Fat mass (kg)[3]	−1.8 ± 0.4[4] (−3.9–0.2)
Fat-free mass (kg)[3]	1.4 ± 0.4[5] (−0.2–3.7)
Protein + mineral mass (kg)[3]	−0.1 ± 0.2 (−1.2–1.6)
Body cell mass (kg)[6]	0.5 ± 0.4 (−1.2–2.2)
Total body water (L)[7]	1.6 ± 0.4[5] (−0.7–4.1)
Sum of 7 skinfold thicknesses (mm)	−2.3 ± 3.1[8] (−18.0–15.4)
Chest circumference (cm)	0.7 ± 0.5[8] (−3.0–3.4)
Mid-thigh circumference (cm)	−0.2 ± 0.3 (−2.8–0.7)

[1] $\bar{x}$ ± SEM; range in parentheses. n = 12.
[2] Difference between posttraining and pretraining values.
[3] Estimated from the combined equation of body density and total body water.
[4,5] Posttraining significantly different from pretraining: [4] $P < 0.001$, [5] $P < 0.01$.
[6] Estimated from ^{40}K-potassium scans.
[7] Measured by the deuterium oxide dilution technique.
[8] n = 11.

TABLE 2
Maximum dynamic muscular strength changes with resistance training[1]

Exercise	Training status: Pretraining	Training status: Posttraining	Increase[2]
	kg/kg FFM[3]		%
Lower body			
Knee flexion	0.22 ± 0.02	0.40 ± 0.04[4]	91.7 ± 10.3 (16.2–173.3)
Right knee extension	0.27 ± 0.03	0.42 ± 0.03[4]	64.3 ± 10.0 (13.3–116.2)
Left knee extension	0.26 ± 0.03	0.41 ± 0.03[4]	65.4 ± 8.7 (14.1–115.7)
Upper body			
Chest press	0.61 ± 0.04	0.78 ± 0.05[4]	30.4 ± 4.8 (1.8–56.7)
Front pull-down	0.57 ± 0.06	0.70 ± 0.07[4]	24.2 ± 2.3 (10.8–34.8)

[1] $\bar{x}$ ± SEM. n = 12.
[2] Range in parentheses.
[3] FFM, fat-free mass, estimated from the combined equation of body density and total body water.
[4] Significantly different from pretraining, $P < 0.001$.

TABLE 4
Resistance training effects on resting metabolic rate[1]

	Training status		
	Pretraining	Posttraining	Change
			%
Resting metabolic rate[2]			
(kJ/h)	288 ± 14	307 ± 13[3]	6.8 ± 1.8
(kJ · kg body wt^{-1} · h^{-1})	3.79 ± 0.13	4.02 ± 0.12[3]	6.4 ± 2.0
(kJ · kg FFM^{-1} · h^{-1})[4]	5.68 ± 0.20	5.87 ± 0.19	3.7 ± 2.1
(kJ · kg PMM^{-1} · h^{-1})[5]	20.8 ± 0.9	22.4 ± 1.0[6]	8.3 ± 2.3
(kJ · kg BCM^{-1} · h^{-1})[7]	10.7 ± 0.4	11.2 ± 0.4	5.0 ± 2.6
Respiratory exchange ratio	0.850 ± 0.018	0.873 ± 0.018	

[1] $\bar{x}$ ± SEM; n = 10.
[2] Resting metabolic rate measurements were started 20 min after each subject consumed a formula beverage.
[3,6] Significantly different from pretraining: [3] $P < 0.02$, [6] $P < 0.01$.
[4] FFM, fat-free mass, estimated from the combined equation of body density and total body water.
[5] PMM, protein plus mineral mass, estimated from the combined equation of body density and total body water.
[7] BCM, body cell mass, estimated from ^{40}K-potassium scans.

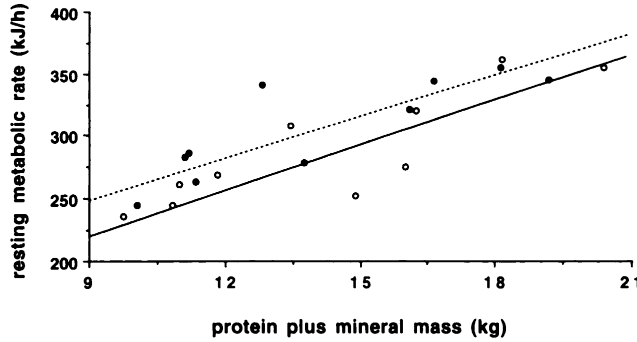

FIG 1. Correlation between resting metabolic rate (RMR) and protein plus mineral mass in older persons (n=10) before (○, —) and after (●, ---) 12 wk of resistance training. The relationship between RMR and protein plus mineral mass was (RMR = 129.8 + 11.13 × protein plus mineral mass) before (r = 0.86, $P < 0.001$) and (RMR = 162.1 + 10.30 × protein plus mineral mass) after (r = 0.85, $P < 0.001$) resistance training. RMRs were measured for each subject by indirect calorimetry. The protein plus mineral mass was estimated from the combined equation of body density and total body water by Siri (16).

ergy expenditure was therefore predicted to be 419 kJ/d (5.44 kJ · kg^{-1} · d^{-1}).

Fasting glucose and hormones

With resistance training, the concentration of fasting serum cortisol increased ($P < 0.01$) by ≈19%, whereas plasma glucose, plasma insulin, the insulin-to-glucose ratio, serum total T_4, and T_3 uptake were unchanged (**Table 5**).

Discussion

Because each subject's baseline body weight was maintained during the resistance-training period through adjustments in energy intake, we were able to accurately estimate the resistance training–induced changes in energy requirements and to measure the impact of resistance training on body composition. This controlled metabolic study shows that resistance training results in a significant and substantial increase in energy requirements in older men and women. Our subjects required ≈15% more energy intake to maintain body weight during the resistance-training period than during baseline. The mean 1.8-kg fat loss during the resistance-training period is estimated to represent an additional 2.1 kJ · kg^{-1} · d^{-1} in energy expenditure and suggests that despite the increased energy intake, our subjects were in a small energy deficit during the resistance-training period.

Previous data of Meredith et al (12) on changes in self-selected energy intake during resistance training in older subjects, assessed by the less reliable 3-d dietary-record method, provided mixed conclusions. Voluntary energy intakes tended to decline throughout a 12-wk knee flexion and extension resistance-training program in five elderly men. In contrast, six elderly men who consumed a nonmeal nutritional supplement providing 2343 kJ energy/d in addition to their self-selected diets during the same training program increased their voluntary energy intakes from meals in addition to the added energy intake from the supplements. Body weights decreased in the unsupplemented group and increased in the supplemented group. The body-composition changes reported by Meredith et al were clearly the result of both the resistance-training program and imbalances in energy intake.

The largest component of total energy expenditure is the energy expended to maintain the body's RMR. Our results (Table 4, Fig 1) agree with the 7.7% increase in RMR after resistance training in older men that was reported by Pratley et al (24) and the increased RMR reported in cross-sectional studies in resistance-trained young men (25) and women (26) compared with age-matched sedentary control subjects. In contrast with these results, Broeder et al (27) observed no change in BMR after 12 wk of resistance training in 13 previously untrained 18–35-y-old males, despite a significant increase in FFM.

The decline in RMR that normally occurs during adult aging is primarily associated with the loss of muscle mass (6, 28), whereas smaller but significant reductions in RMR may be related to decreased physical activity (29, 5) and differences in the rate of protein metabolism (28). The mechanism by which RMR is increased with resistance training is unknown at present. We observed that RMR was significantly increased after the 12-wk resistance-training period, even when it was expressed relative to metabolically active tissue mass (protein plus mineral mass) (Table 4, Fig 1). When RMR was adjusted to FFM by analysis

TABLE 5
Resistance training effects on fasting glucose and hormones[1]

	Training status	
Index	Pretraining	Posttraining
Glucose (mmol/L)	5.1 ± 0.1	5.4 ± 0.2
Insulin (pmol/L)	116 ± 9	115 ± 9
Insulin:glucose	22.9 ± 1.8	21.3 ± 1.4
Cortisol (nmol/L)	355 ± 22	422 ± 26[2]
Glucagon (ng/L)	140 ± 8	149 ± 6
T_3 uptake	0.31 ± 0.01	0.31 ± 0.01
Total T_4 (nmol/L)	88 ± 7	86 ± 6

[1] $\bar{x}$ ± SEM; n = 12. T_3, serum 3,5,3′-triiodothyronine; T_4, thyroxine.
[2] Signficantly different from pretraining, $P < 0.01$.

of covariance, it was also reported to be higher for young resistance-trained men than for young sedentary sex-matched control subjects (25), but not young resistance-trained women (26). These data support the theory that there are increased energy requirements during resistance training that are due, in part, to an increased rate of metabolic activity of lean tissue.

One factor that contributes to the resistance training–induced increase in metabolic activity observed in lean tissue may be an increase in protein turnover associated with increased muscle-protein synthesis (30) and muscle-tissue damage and repair (31). We measured a 5% increase in mean whole-body protein turnover in resistance-trained subjects (Campbell et al, unpublished observations, 1993). Because protein turnover is estimated to account for ≈20% of RMR (28), the 5% increase after resistance training would effectively increase RMR by only ≈1%. Ballor and Poehlman (26) have outlined many additional mechanisms that may contribute to the increased RMR, including increased food flux, increased activity of various enzymatic reactions, the replenishment of glycogen stores, the repair of exercise-induced trauma, and the increased concentration of metabolic hormones. Because the RMR measurements of our subjects were obtained 20 min postprandial, differences in substrate (food) utilization cannot be ruled out completely. However, the quantity and nutrient content of the beverages that were provided to each subject were the same for both RMR measurements and the RER was similar during both the baseline and postresistance training RMR measurements (Table 4), which suggests similar fuel utilization. The metabolic response to continued ingestion of meals with a higher protein content is greater than for meals with a lower protein content, but takes several hours to be manifest (14). In this study, the amount of protein intake (the suggested RDA vs two times the suggested RDA) did not influence long-term energy requirements, but this negative finding must be accepted given the possibility of a statistical Type II error. The 19% increase in mean fasting cortisol concentration may have been partially responsible for the observed increase in whole-body protein turnover and suggests an increased tissue catabolism (32). The other metabolic hormones measured (insulin, glucagon, total T_4, and T_3 uptake) were unchanged with resistance training (Table 5).

The balance between energy intake and energy expenditure during baseline and week 12 of resistance training is shown in **Figure 2** for the 10 subjects for whom complete data sets were available. The other energy expenditure was calculated by subtracting the daily energy expenditure that was due to RMR and the estimated cost of the resistance exercise from the total energy intake and includes the energy costs of the additional thermic effect of feeding (above the small thermic response accounted for in the RMR by taking the measurements in the immediate postprandial state) and daily nonresistance exercise. Mean energy intake in these 10 subjects was increased by 16 $kJ \cdot kg^{-1} \cdot d^{-1}$ from baseline to training week 12. Sixty-eight percent of this increase was due to the measured increase in RMR (5.5 $kJ \cdot kg^{-1} \cdot d^{-1}$) and the estimated energy cost of the resistance exercise (5.4 $kJ \cdot kg^{-1} \cdot d^{-1}$). The remaining 32% of the increased RMR (5.5 $kJ \cdot kg^{-1} \cdot d^{-1}$) occurred in the other energy expenditure compartment, although the baseline and postresistance-training values for other energy expenditure were not statistically different. Factors that contributed to this portion of the increased energy intake may include *1*) the increased energy cost of consuming additional food, *2*) a continued postexercise increase in metabolic rate, *3*) an increase in the energy cost of resistance exercise as the training load is increased, and *4*) a change in nonresistance training daily activity. An additional 2.1 $kJ \cdot kg^{-1} \cdot d^{-1}$ in other energy expenditure is estimated to have occurred in association with the decrease in body fat. Therefore, the net impact of the 12-wk, 3 d/wk, resistance-training program on these 10 older men and women was to induce an average 18 $kJ \cdot kg^{-1} \cdot d^{-1}$ increase in energy expenditure. These data support the use of resistance training as an adjunct to exercise-based weight-control programs.

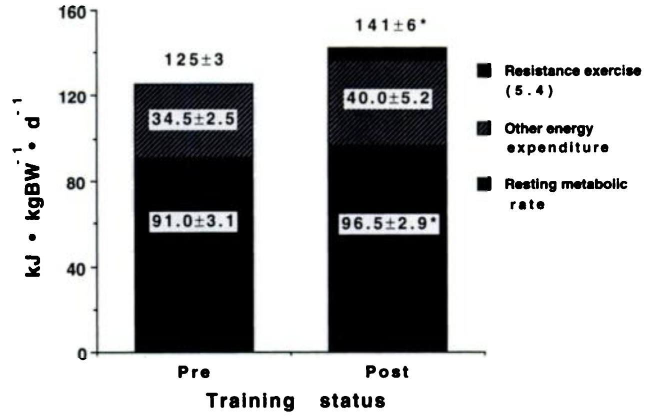

FIG 2. Increased total energy intake and expenditure in older persons during resistance training (n = 10). Values on top of the stacked bars represent the total energy intake necessary to maintain body weight (BW) before and after 12 wk of resistance training. Resting metabolic rates (RMRs) were measured in each subject by indirect calorimetry. The energy expenditure during resistance exercise was measured by indirect calorimetry in 5 men during a pilot study, and assumed to be similar in all 10 study subjects. The other energy expenditure represents the portion of the energy expenditure that was not due to RMR or resistance exercise and includes the additional thermic effect of feeding and the energy cost of nonresistance exercise daily activity. It was calculated by subtracting the daily energy expenditure due to RMR and resistance exercise from the total energy intake. *Significant increase with resistance training, $P < 0.05$.

Some of the increased energy intake required for weight maintenance may have been needed because the baseline energy requirements were underestimated. The mean baseline energy intake of our subjects (128 ± 3 $kJ \cdot kg^{-1} \cdot d^{-1}$) was similar to the energy intake recommended for older adults in the current RDAs (126 $kJ \cdot kg^{-1} \cdot d^{-1}$). Roberts et al (4) recently concluded by using doubly labeled water to measure daily total energy expenditure that the total energy expenditure of healthy older men is 140 ± 6 $kJ \cdot kg^{-1} \cdot d^{-1}$. They suggest that the current RDA for energy may be underestimated mainly due to an underestimation of the amount of energy expended for daily activity. Although no significant change or trend in daily body weights occurred during the baseline period, small deficits in energy intake may not be manifest by body-weight changes during this relatively short time. Because most of the increased energy intake was accounted for by the increased RMR, the estimated energy cost of the resistance exercise, and the possible other factors listed above, we feel that the baseline energy needs of our subjects were not significantly underestimated.

Our body-composition results (Table 3) are in general agreement with previously published results from resistance-training studies in elderly people that used whole-body resistance-training protocols (the subjects performed both upper- and lower-body resistance exercises). Many studies have shown that resistance training is an effective way to decrease body-fat mass (33–36) (**Table 6**). Whether resistance training increases FFM in older adults is much less clearly defined. In this study, contrary to our hypotheses, we did not consistently observe resistance training–induced changes in FFM when measured by several body-composition methods. FFM did not change with resistance training when estimated from body density alone (a change of 0.6 ± 0.5 kg), yet increased significantly when estimated from TBW alone (a change of 2.2 ± 0.5 kg, $P < 0.05$). In theory, body density and TBW should give similar values for FFM (16), assuming that fat mass does not contain any water. However, Siri (16) has cautioned that the true physiologic changes in body composition will not be accurately quantified using body density alone when changes occur in other tissues in addition to fat (ie, changes within the FFM compartment), such as when muscle mass is gained during resistance training (37). The combined body density and body water method increases the likelihood of detecting physiologic body-composition changes that are due to resistance training and allows for these changes to be partitioned into fat mass, water mass, and protein plus mineral mass (an improved measure of metabolically active tissue, compared with FFM) (16, 38). Our results show that although FFM increased after resistance training in these weight-stable elderly subjects, the increased FFM was mainly due to an increase in body water with no change in metabolically active tissue mass (protein plus mineral mass). The lack of change in metabolically active tissue mass was confirmed by the absence of a detectable change in BCM (estimated from measurements of ^{40}K).

The resistance training–induced increase in FFM (as assessed by either dual energy radiography or measurements of skinfold thicknesses) in older adults reported by Nichols et al (33) and Craig et al (36) (Table 6) may also have been the result of increases in TBW. In agreement with our results, TBW has been shown to also increase during resistance training in previously untrained young men (39). Although the reports of Koffler et al (34) and Hagberg et al (35) (Table 6) showed no significant change in FFM or lean body mass, respectively, there is an implication of an increase in this compartment because their subjects had a decrease in body fat while maintaining body weight. The increase in TBW without a significant change in protein plus mineral mass or BCM suggests that a significant change in FFM composition has occurred in association with resistance training. This change may reflect an increase in extracellular fluid volume or an increase in the water content of muscle tissue, possibly because of an increase in muscle glycogen stores.

In summary, our data show resistance training to be an effective way for healthy older adults to increase their energy expenditure. This increase results from the combined influences of an increase in energy expenditure associated with performing the exercise, an increase in RMR, and increases in energy expenditure from other factors as well. The increase in RMR is due to an increase in the metabolic activity of lean tissue and not an increase in the amount of lean tissue mass. With resistance training, energy and nutrient intakes may be increased, while body weight is maintained and fat mass decreased. Resistance training appears to be an effective and safe adjunct to exercise-based weight control and fat-loss programs for older adults.

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TABLE 6
Body-composition changes in older men and women during whole-body resistance training[1]

Reference (study subjects)	Training protocol	Body composition: Measurements	Body composition: Results
This study (12 RT women and men, aged 56–80 y)	12 wk, 3 d/wk, 3 set/d, 80% 1RM	Hydrodensitometry, TBW, ^{40}K-potassium scan	Unchanged BW, increased FFM, decreased fat mass, increased TBW, unchanged protein + mineral mass, unchanged BCM
33 (15 RT women, aged 68 ± 2 y)	24 wk, 3 d/wk, 3 sets/d, 80% 1RM	Dual-energy radiography	Unchanged BW, increased LTM, decreased body fat %
33 (15 NRT aerobically fit women, aged 65 ± 2 y)	NRT control	Dual-energy radiography	Unchanged body composition
36 (9 older RT men, aged 63 ± 1 y)	12 wk, 3 d/wk, 3 sets/d, 10 reps/set	Skinfold thicknesses	Increased BW, increased LBM, decreased body fat %
36 (6 young RT men, aged 23 ± 2 y)	12 wk, 3 d/wk, 3 sets/d 10 reps/set	Skinfold thicknesses	Unchanged BW, increased LBM, decreased body fat %
34 (7 RT men, aged 52–69 y)	13 wk, 3 d/wk, 1–2 sets/d, 90% 3RM	Hydrodensitometry	Unchanged BW, unchanged FFM, decreased body fat %
35 (19 RT women and men, aged 70–79 y)	26 wk, 3 d/wk, 1 set/d, 8–12 reps/set	Skinfold thicknesses	Unchanged BW, unchanged LBM, decreased sum of 7 skinfold thicknesses
35 (12 NRT women and men, aged 70–79 y)	NRT control	Skinfold thicknesses	Unchanged body composition

[1] RT, resistance-trained; 1RM, one repetition maximum; TBW, total body water; BW, body weight; FFM, fat-free mass; BCM, body cell mass; LTM, lean tissue mass; NRT, non-RT; LBM, lean body mass, 3RM, three reptition maximum.

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