Effects on muscles of dieting with or without exercise in overweight postmenopausal women

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Svendsen, Ole Lander, Marcin Krotkiewski, Christian Hassager, and Claus Christiansen. Effects on muscles of dieting with or without exercise in overweight postmenopausal women. *J. Appl. Physiol.* 80(4): 1365–1370, 1996.— The main aim of this study was to investigate the effect of an energy-restrictive, high-protein diet with or without exercise on muscle morphology and biochemistry. Moderately overweight postmenopausal women (49–58 yr, body mass index: 25–42 kg/m^2) were randomly assigned to three groups for 12 wk of intervention; namely, a control group, a group on a 4.2 MJ/day diet, and a group on 4.2 MJ/day diet combined with aerobic and anaerobic exercise. Muscle morphology and biochemistry analysis were performed in 69 and 58 women, respectively. In contrast to the diet-only group, the diet-plus-exercise group significantly increased the muscle fiber areas by 20–25%, the number of capillaries per muscle fiber type I by ~20%, and the activities of citrate synthase by ~35% and hexokinase by ~20% ($P < 0.05$). There were no statistically significant changes in any other muscle variable ($P > 0.05$). The respiratory exchange ratio decreased in both intervention groups by 2–4% ($P < 0.01$). It is concluded that 12-wk period of an energy-restrictive high-protein diet was not associated with major changes in muscle morphology or biochemistry. The addition of exercise to the diet led to an adaptive increase in muscle fiber areas and in the oxidative capacity of the muscles.

diet; weight loss; obesity; muscle morphology; muscle enzymes; respiratory exchange ratio

THE DIFFERENT TYPES OF MUSCLE FIBERS have different oxidative and glycolytic enzymatic capacities, which are reflective of the kind of metabolic fuel used. A low percentage of type I muscle fibers (adapted to fat oxidation), a high percentage of type IIB muscle fibers (adapted to anaerobic glucose oxidation), and a low muscular capillary density are reported to be associated with insulin resistance and total body and abdominal fatness (9, 10, 13, 14, 27). Thus the muscle fiber composition has recently been suggested to be an etiologic factor for obesity (27). Some previous studies suggest that a diet-induced weight loss causes muscular hypotrophy (17–19). Athletes who engage in physical training have more type I fibers, less type IIB, and a higher enzymatic oxidative capacity than sedentary people (22). Longitudinal studies of exercise without dietary restrictions suggest that exercise may cause conversion of type IIB fibers into type IIA, may increase the density of capillaries, and may increase the enzymatic oxidative capacity and the metabolism of fat, whereas physical inactivity may cause the reverse (3, 6, 10, 11, 16, 20). However, as there may be considerable intraindividual variations over time of the histo- and biochemical values of muscles (2, 21), a drawback of previous studies is the lack of control groups and randomization.

We have previously shown, in a controlled randomized study, that the addition of exercise to an energy-restrictive high-protein diet in overweight postmenopausal women increased the loss of fat and preserved the lean tissue mass (25). The primary aim of the present paper was to report the effects on muscle morphology and biochemistry from that study. The secondary aim was to assess the associations between muscle morphology or biochemistry and total body or abdominal fatness.

SUBJECTS AND STUDY DESIGN

One hundred twenty-one healthy overweight postmenopausal women [age: 49–58 yr, body mass index (BMI): 25–42 kg/m^2] were randomized to three groups for 12 wk of intervention, namely a diet-only group (n = 51), a diet-plus-exercise group (n = 49), and a control group (n = 21), as described previously (25). Briefly, the diet consisted of the formula diet NUPO (Oluf Mørk Biochemie, Rødovre, Denmark) supplying 65 g of protein and 1.6 MJ daily (within which international recommendations are met) and an additional 2.6 MJ daily from food freely chosen according to a "counter-diet system." The exercise consisted of supervised combined aerobic exercise [bicycling, stair walking, or treadmill running with a heart rate above that corresponding to ≥70% of maximal oxygen uptake ($\dot{V}O_{2max}$)] and resistance weight training (2–3 periods of 8 exercises including all major muscle groups, with 7–15 repetitions of each exercise with a load of ≥65% of maximum weight-lifting capacity) for 1 h, increasing to 1.5 h, 3 times/wk. The control group maintained usual exercise and dietary pattern.

The study was carried out in accordance with the Declaration of Helsinki II and with the approval of the Ethical Committee of Copenhagen County.

One hundred eighteen women completed the 12-wk study, the results of which have been reported elsewhere (25). Table 1 gives some key data. There were no significant differences between the groups at baseline, which is why these data are pooled. Briefly, the energy intake, weight, fat and lean tissue masses (FTM and LTM, respectively), and $\dot{V}O_{2max}$ did not change in the control group. The diet-plus-exercise group significantly increased the $\dot{V}O_{2max}$ (attendance at exercise sessions: 97%), decreased FTM, and preserved LTM, compared with the diet-only group. Both intervention groups significantly increased the daily protein intake,

Table 1. *Subjects' characteristics*

	Baseline	Group			ANOVA, $P<$
		Control	Diet only	Diet + exercise	
Body weight, kg	78.0 ± 0.8	0.5 ± 0.4	−9.5 ± 0.4	−10.3 ± 0.4	0.001
Fat tissue mass, kg	31.8 ± 0.6	0.5 ± 0.3	−7.8 ± 0.4	−9.6 ± 0.4*	0.001
Lean tissue mass, kg	42.3 ± 0.3	0.6 ± 0.3	−1.2 ± 0.2	0.0 ± 0.2*	0.001
Waist-to-hip ratio	0.84 ± 0.007	0.01 ± 0.007	−0.03 ± 0.004	−0.03 ± 0.006	0.001
Energy intake, kJ/day	7,868 ± 190	−59 ± 335	−3,287 ± 297	−3,526 ± 347	0.001
Protein intake, g/day	61.2 ± 1.4	−2.0 ± 2.8	33 ± 2.1	33 ± 2.6	0.001
$\dot{V}O_{2max}$, ml·min^{-1}·kg^{-1}	20.1 ± 2.4	1.8 ± 2.4	2.3 ± 0.3	6.9 ± 1.4*	0.001

Values are means ± SE. $\dot{V}O_{2max}$, maximal O_2 uptake; ANOVA, analysis of variance. *$P < 0.05$ of difference in change between diet-only and diet-plus-exercise groups. (Data from Ref. 25).

although they decreased energy intake. Both intervention groups decreased the abdominal-to-total-body fat by ~10% and the waist-to-hip ratio by ~4%.

In the present study, we report on muscle biopsy analyses in a random subsample (muscle morphology: $n = 69$, biochemistry: $n = 58$).

METHODS

With the women wearing light indoor clothes and no shoes, weight was measured to the nearest 0.1 kg and height to the nearest 0.5 cm. Waist and hip circumferences were measured in a standing postition to the nearest 0.5 cm at the smallest circumference below the ribs and at the largest circumference at the buttocks, respectively. The circumferences were measured twice, and the means were used in the calculations.

Body Composition

Body composition was measured with a total body dual-energy X-ray absorptiometry (DXA) scanner (DPX, Lunar Radiation, Madison, WI; software version 3.2) (24, 26). The FTM, the LTM, and the total body bone mineral were measured. The FTM is not solely adipose tissue but the sum of the fatty elements of all the soft tissue. Similarly, the LTM is not an anatomical entity but represents the sum of all chemical fat-free soft tissue elements. Abdominal FTM was measured between the first and the fourth lumbar intervertebral disk by adjusting the lines of the right rib box (standard software option) (26). The precisions (coefficients of variation) are 4.7, 1.5, and 0.9% for total body FTM, LTM, and total body bone mineral, respectively (26), and 4.3% for measurement of abdominal FTM (24). We have previously validated measurements of abdominal FTM by DXA against computerized tomography ($r = 0.9$, %SE of estimate = 7%) (26).

$\dot{V}O_{2max}$ and the Submaximal Respiratory Exchange Ratio (RER)

$\dot{V}O_{2max}$ and submaximal RER were measured with a Medgraphics CPX system (Medical Graphics, Minneapolis, MN) by performing an exercise test with an interfaced computer-controlled cycle ergometer (MedGraphics CPE 2000), where the workload was increased by 1 W every 3 s until a submaximal workload at 30 W was reached and then maintained by the subjects for 5–8 min of cycling. Thereafter the workload was increased again by 1 W every 3 s until exhaustion set in or a RER ≥1.1 was reached. Measurements were performed breath by breath, and the mean was taken every 30 s for the calculations. The submaximal RER was defined as the mean value of the last 2–3 min at the submaximal workload (30 W). If the submaximal RER was higher than 1.05, it was excluded from the analysis ($n = 3$).

Seven-day food diaries were kept before the intervention and in *week 12* of the intervention. The diaries were checked by a clinical nutritionist and, if found inadequate or erroneous, were discussed with the women. The consumption of nutrients was determined from computerized food-composition tables (DanKost, software version 1.3b, Danish Food Administration, Søborg, Denmark).

Muscle Biopsies

Muscle biopsies were taken from the middle one-third of the lateral portion of the right vastus lateralis muscle under local anesthesia with a pair of alligator forceps by using a minor surgical technique. The postintervention biopsies were taken just distally to the incision cicatrix from the preintervention biopsy. All biopsies were taken by the same doctor (O. L. Svendsen).

Two muscle specimens were taken both pre- and postintervention. One was frozen immediately in liquid nitrogen for biochemical measurements. The other was trimmed, mounted, and frozen in isopentane (cooled by liquid nitrogen) for histochemical analyses. Both specimens were then stored at −80°C. The biopsies were blinded and were send to Sweden (M. Krotkiewski), where a random subsample was analyzed for histochemistry ($n = 69$) and biochemistry ($n = 58$).

Histochemistry. Serial cross sections (10 μm) were cut with a cryotome at −21°C. The specimens were stained for myofibrillar adenosinetriphosphatase. The reactions were carried out at pH 9.4 after alkaline preincubation at pH 10.3. Thereafter, the muscle fibers could be classified into type I (oxidative slow-twitch) and type II (fast-twitch) fibers. The type II fibers were further classified into IIA (predominantly oxidative) and IIB (predominantly glycolytic) by preincubation at pH 4.6 and 4.4. Amylase-periodic acid-Schiff staining to visualize capillaries was used for capillary analyses. Fiber type, area, and capillary measurements were computerized, by using SBsysCOMFAS (Scan Beam, Hadsund, Denmark). The average number of fibers and capillaries counted in each women was 292 ± 97 and 281 ± 132, respectively.

Biochemistry. The protein content of the sample, the activities of hexokinase (HK), citrate synthase (CS), triosephosphate dehydrogenase, the glycogen concentration, and the glycogen synthase activity were measured as previously described (11, 12). The glycogen synthase activity was measured at 0.3 and 6.0 mM [maximal velocity (V_{max})] glucose 6-phosphate concentrations. The fractional velocity (FV; %) of glycogen synthase was the activity at 0.3 mM divided by V_{max}. The enzyme activities were measured at 25°C. Due to the paucity of muscle tissue in some of the samples, all enzyme activities were not measured in all subjects.

Calculations and Statistical Analysis

The waist-to-hip circumference ratio and the abdominal-to-total body FTM (by DXA) were calculated as indicators of fat distribution. Differences of changes between groups were compared by one-way analysis of variance, and if $P < 0.05$, pairwise comparisons between the individual groups were performed with an unpaired t-test. Bonferroni adjustment was used for the pairwise comparisons.

Because of the number of correlation analyses performed, only correlation coefficients with $P < 0.01$ were considered significant. The Statistical Analysis System (SAS Institute, Cary, NC) was used for all analyses.

RESULTS

The abdominal-to-total-body FTM tended to be positively correlated with the diffusion index (muscle area per capillary) of muscle fiber type I, IIA, and IIB (r = 0.2–0.3) at baseline. However, there were no statistically significant correlations between body weight, BMI, FTM and LTM, the waist-to-hip ratio or the abdominal-to-total-body FTM, and muscle morphology or biochemistry at baseline. The $\dot{V}O_{2max}$ per kilogram body weight was positively correlated to the number of capillaries per fiber type I, IIA, and IIB (r = 0.3–0.4, $P < 0.01$) but not to the fiber area or composition. The $\dot{V}O_{2max}$ was, furthermore, positively correlated with the activities of CS and glycogen synthase (both V_{max} and FV) (r = 0.3–0.4).

The RER at the submaximal workload (30 W) was not correlated with muscle morphology or biochemistry, except from a negative correlation with glycogen synthase (V_{max} and FV; r about −0.3). Furthermore, there were no statistically significant correlations between RER and weight, BMI, FTM and LTM, the waist-to-hip ratio, or the abdominal-to-total-body FTM.

There were no significant associations between changes in RER, BMI, $\dot{V}O_{2max}$, body composition, or fat distribution parameters and changes in muscle morphology or biochemistry parameters.

There were no statistically significant differences between groups in baseline values, which is why the pooled baseline muscle data are given in Tables 2 and 3. At baseline, the women had a very high proportion of type IIB muscle fibers, nearly double as many as type IIA fibers (Table 2).

The muscle fibers and capillaries tended to change, although not statistically significantly, in the control group (Table 2). Figure 1 shows the relative changes in percentage of baseline. The changes in the control group have been subtracted from the changes in the intervention groups. There were no difference between the changes in the diet-only group and the control group ($P > 0.05$). On the other hand, the diet-plus-exercise group did significantly increase the area of muscle fiber type I and IIA by ~20–25%, and the number of capillaries per muscle fiber I by ~20%.

Table 3 gives baseline values and changes in muscle glycogen content and enzyme activities, whereas Fig. 2 shows the relative changes in the diet-only and diet-plus-exercise group after subtraction of the changes in the control group. There were no significant changes in the diet-only group compared with the control group. On the other hand, the diet-plus-exercise group did significantly increase the activity of CS by ~35% and of HK by ~20% compared with the diet-only group.

The RER (baseline: 0.86 ± 0.06) was significantly decreased in the diet-plus-exercise (−0.039 ± 0.06) and the diet-only groups (−0.017 ± 0.09), compared with the control group (+0.042 ± 0.07) ($P < 0.002$), but with no difference between the two intervention groups.

DISCUSSION

The subjects in the present study were a random subsample of overweight healthy postmenopausal women aged 48–58 yr. These women had a remarkably high percentage of type IIB fibers of the right vastus lateralis muscle. Similarly high percentages of muscle type IIB fibers have previously been reported in over-

Table 2. *Changes in muscle fibers and capillarization in overweight postmenopausal women*

		Group			
	Baseline, n = 69	Control, n = 11	Diet only, n = 29	Diet + exercise, n = 29	ANOVA, $P<$
Mean fiber area (μm²)					
Type I	6,327 ± 192	−1,431 ± 777	−653 ± 243	331 ± 303*	0.01
Type IIA	4,811 ± 191	−972 ± 676	−578 ± 216	362 ± 361*	0.05
Type IIB	4,687 ± 152	−603 ± 516	−479 ± 243	264 ± 268	0.1
Total no. of fibers, %					
Type I	42.4 ± 1.7	5.6 ± 5.2	−4.2 ± 2.5	−1.0 ± 2.3	0.2
Type IIA	20.9 ± 1.2	−1.1 ± 2.0	0.1 ± 1.7	0.6 ± 1.7	0.9
Type IIB	36.6 ± 1.5	−4.4 ± 3.7	4.1 ± 2.4	0.4 ± 2.3	0.2
Capillaries per fiber					
Type I	2.4 ± 0.07	−0.4 ± 0.2	−0.2 ± 0.1	0.1 ± 0.1	0.05
Type IIA	1.8 ± 0.08	−0.1 ± 0.2	−0.1 ± 0.1	0.1 ± 0.1	0.6
Type IIB	1.7 ± 0.05	−0.1 ± 0.2	−0.1 ± 0.1	0.1 ± 0.1	0.3
Diffusion index [area (μm²) per capillary]					
Type I	2.7 ± 0.08	−0.2 ± 0.4	0.01 ± 0.2	0.02 ± 0.1	0.8
Type IIA	2.8 ± 0.1	−0.35 ± 0.4	−0.2 ± 0.3	0.08 ± 0.1	0.5
Type IIB	2.9 ± 0.1	−0.4 ± 0.4	−0.01 ± 0.2	0.00 ± 0.1	0.6

Values are means ± SE; n, no. of subjects. *$P < 0.05$ of difference in change between diet-only and diet-plus-exercise groups.

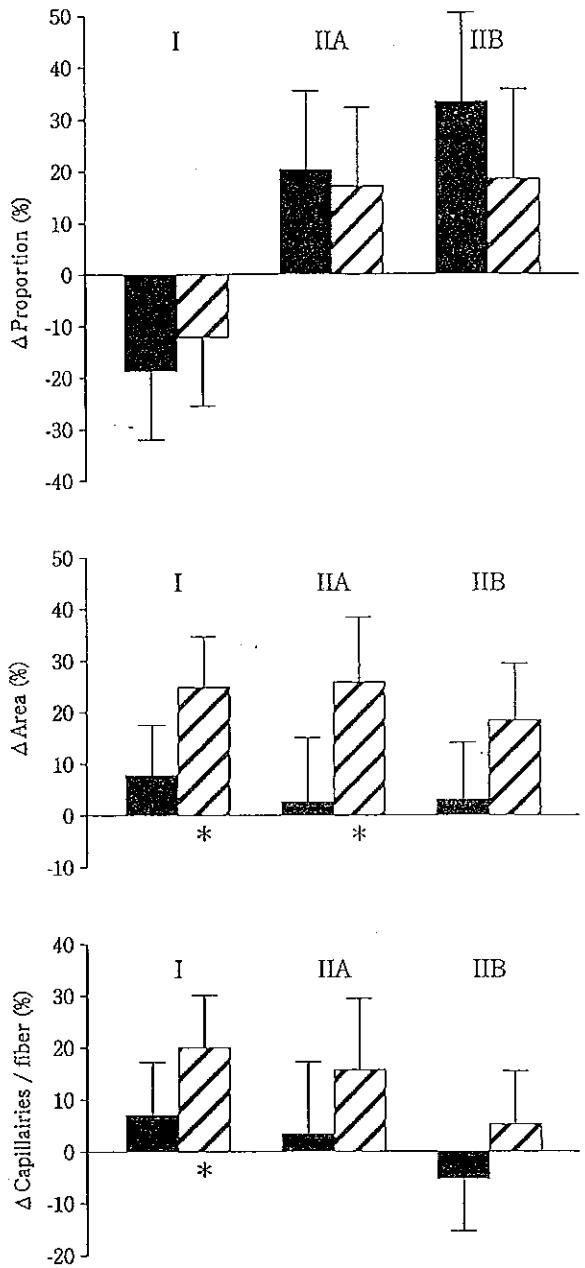

Fig. 1. Changes (%baseline) in muscle morphology after subtraction of changes in control group (n = 11). Solid bars, diet-only group (n = 29); hatched bars, diet-plus-exercise group (n = 29). Values are means ± SE. *Significantly different from control group ($P < 0.05$).

weight women (12) and sedentary subjects (22). However, in previous reports on this topic, the subjects have mostly been more obese and sedentary than those in the present study (7, 8, 13, 16).

The measurement of body composition in the present study was performed with DXA, which is a new precise and accurate method for direct noninvasive measurement of total body FTM and LTM as well as fat distribution. We have previously validated measurements of total body fat by DXA against chemical analysis and of measurements of abdominal fat by DXA against computerized tomography (24, 36). In our population of postmenopausal overweight women, we failed to find any significant association between fatness or fat distribution and muscle morphology or biochemistry. This may in part be due to the homogeneity of our subjects, who had a narrow age range, were all postmenopausal, and the majority were slightly overweight. Previous studies in women have found no significant correlations between muscle fiber composition and body fat (13), but a negative correlation was found between the proportion of type I fibers and the waist-to-hip ratio (9, 13). In men, on the other hand, both body fat and the waist-to-hip ratio were negatively correlated with percentage of muscle fiber type I and the density of capillaries and positively correlated with type IIB fibers (9, 14, 27). Furthermore, we found no correlations between the RER (indicator of carbohydrate and fat oxidation) and fatness or muscle fiber composition, which has been reported in men (27). These topics have recently been reviewed by Krotkiewski (7, 8).

We found some changes in the muscle morphology variables in the control group, which was controlled for by comparing differences of changes between groups rather than testing whether changes in the intervention groups were different from zero, which could have led to erroneous conclusions. The decrease in the muscle morphology variables in the control group might be due to the fact that the preintervention biopsies were taken in July/August and the postintervention biopsies in November/December. The level of physical activity and muscle morphology and biochemistry variables may change with the time of the year, at least in athletes (5). To our best knowledge, there have been no reports of any randomized controlled human interven-

Table 3. *Changes in muscle glycogen content and enzyme activities in overweight postmenopausal women*

		Group			
	Baseline, n = 37–58	Control, n = 6–8	Diet only, n = 14–29	Diet + exercise, n = 17–22	ANOVA, $P<$
Glycogen, μmol/g wet wt	88.6 ± 3.4	14.0 ± 13.4	−3.0 ± 6.3	13.1 ± 8.9	0.3
Glycogen synthase					
V_{max}, μmol·min^{-1}·g wet wt^{-1}	0.39 ± 0.02	0.01 ± 0.04	0.01 ± 0.03	0.02 ± 0.03	0.95
$FV_{0.3}$, %	6.7 ± 0.4	1.7 ± 2.5	4.5 ± 1.6	−1.2 ± 0.9*	0.05
Citrate synthase, μmol·min^{-1}·mg protein^{-1}	36.4 ± 1.6	−0.6 ± 3.4	−0.4 ± 1.7	13.2 ± 2.3*	0.001
Hexokinase, μmol·min^{-1}·mg protein^{-1}	5.5 ± 0.1	1.2 ± 0.5	0.6 ± 0.2	1.6 ± 0.2*	0.02
Triosephosphate dehydrogenase, μmol·min^{-1}·mg protein^{-1}	1,021 ± 25	−1.0 ± 0.05	−1.0 ± 0.05	−1.0 ± 0.04	0.6

Values are means ± SE; n, no. of subjects. For control/diet-only/diet-plus-exercise groups, n values were as follows: glycogen: 6/14/1[illegible] glycogen synthase: 8/29/21; other enzyme activities: 7/19/22. V_{max} and $FV_{0.3}$, velocity at 6.0 and 0.3 mM glucose 6-phosphate, respectively. *P < 0.05 of difference in change between diet-only and diet-plus-exercise groups.

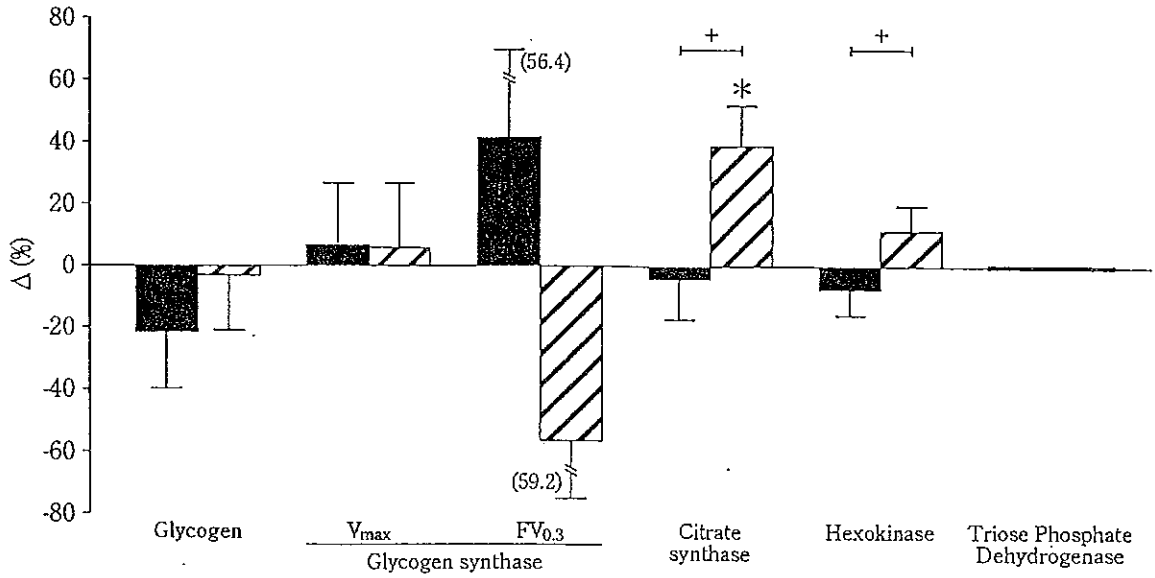

Fig. 2. Changes (Δ; %baseline) in muscle glycogen and enzyme activities after subtraction of changes in control group (n = 6–8). Solid bars, diet-only group (n = 14–29); hatched bars, diet-plus-exercise group (n = 17–22). Values are means ± SE. V_{max}, maximal velocity; $FV_{0.3}$, velocity at 0.3 mM glucose 6-phosphate. *Significantly different from control group ($P < 0.05$); + significant difference between diet-only and diet-plus-exercise groups ($P < 0.05$).

tion study of dieting or exercise on muscle morphology or biochemistry. One study of overweight women on a very-low-calorie diet for 2 wk suggested hypotrophy of muscle fiber type II (19), whereas in another study, 2 wk of a very-low-calorie diet with a high protein intake resulted in no significant changes in muscle fibers but it did induce a change in glycogen content and glycogen synthase (18). However, 2 wk of energy restriction is too short to expect any major changes in muscle morphology. A weight loss of 35% in male monkeys over 12-wk period was followed by muscular hypotrophy, which was reversed after nutritional rehabilitation (17). A 6-mo diet in men with impaired oral glucose tolerance was followed by a 20% decrease in muscle area with no changes in capillaries per fiber, whereas the diffusion index, i.e., muscle area supplied by one capillary, was decreased. There were no changes in muscle fiber composition or muscle enzyme activities (15). In the present study, we found that 12 wk of an energy-restrictive high-protein diet did not result in significant changes in muscle fiber areas, whereas the addition of combined aerobic and anaerobic exercise to the energy-restrictive high-protein diet caused hypertrophy, i.e., increased the areas of muscle fiber type I and IIA and tended to increase the area of muscle fiber type IIB. This is in accordance with the finding that resistance weight training with (4) or without dietary restrictions (23) in women may cause muscular hypertrophy. The question is, however, whether these changes found in a muscle biopsy from the right vastus lateralis muscle truly reflect changes in total body skeletal muscle. We found only a minor loss of LTM, as measured by DXA, due to the diet, which was prevented by the addition of exercise. The LTM measured by DXA consists of all chemical fat-free soft tissue elements. Thus DXA cannot differentiate between the muscular component and the other components of LTM, such as body water, connective tissue, vessels, and blood. The combination of a minor decrease in LTM and no change in the muscle area in the diet-only group could be interpreted as if it was some other component of LTM than muscles that were lost. When exercise was added, the loss of LTM was prevented, and there was an increase in the muscle area. This could be interpreted as if the muscular component of LTM had increased while the nonmuscular component of LTM had decreased. Thus the present study could suggest that with a high-protein, energy-restrictive diet no muscular tissue is lost and is even increased if exercise is added.

We found no changes in the proportions of the different muscle fiber types. Several previous studies of exercise in normal and overweight women have suggested an increase in the proportion of type IIA fibers and, in some of these, a decrease in the proportion of type IIB fibers (1, 3, 9–11, 16). We found an increase in the number of capillaries per muscle fiber type I but no changes for fiber type IIA or IIB or in the diffusion index for any of the fibers. The lack of change in diffussion index was probably caused by the weight-resistance training, increasing the muscle volume along with the number of capillaries. Others (9, 16), but not all (1), have found an increase in the numbers of capillaries per fiber type IIA. The discrepancy between our study and the other studies cited may be due to different study design, different subjects, and/or different type and duration of the intervention. The duration of the intervention in the present study may have been too short. However, the duration of most of the cited studies has been of similar length, i.e., ~3 mo. Three months should be long enough to induce changes in muscle morphology in untrained sedentary obese subjects. In moderately overweight subjects with normal physical activity, a longer duration of exercise may be needed. Another explanation for the discrepancy be-

tween our study and other studies may be the use in our study of a combination of aerobic endurance training and anaerobic weight training. However, Staron et al. (23) reported that 20 wk of weight-lifting training in women led to a significant increase in muscle fiber type IIA and a decrease in IIB, the same changes as have been reported with endurance training. It may be a combination of exercise and dietary restriction that inhibits an increase in type IIA fibers and a decrease in type IIB fibers.

Our finding of increased CS and HK activities and decreased RER during submaximal work suggest an increase in the enzymatic respiratory capacity for fat oxidation of the muscle due to exercise, which is in accordance with previous findings (6, 7–9, 20).

In summary, in overweight postmenopausal women with a relativly narrow range of body fat, there were no associations between muscle morphology or biochemistry and fatness, except that the diffusion distance, i.e., muscle area supplied by one capillary, was increased with increasing abdominal fatness. Weight loss induced by an energy-restrictive high-protein diet did not cause any changes in muscle morphology, capillarization, glycogen content, or enzyme activities, whereas the addition of exercise caused hypertrophy of muscle fiber type I and IIA, increased the number of capillaries per muscle fiber type I, and increased the oxidative capacity of muscles as judged from the increased enzyme activities.

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REFERENCES

1. Aniansson, A., P. Ljungberg, Å. Rundgren, and H. Wetterqvist. Effect of a training program for pensioners on condition and muscular strength. *Arch. Gerontol. Geriatr.* 3: 229–41, 1984.
2. Blomstrand, E., F. Celsing, J. Fridén, and B. Ekblom. How to calculate human fibre areas in biopsy samples—methodological considerations. *Acta Physiol. Scand.* 122: 545–551, 1984.
3. Côté, C., J.-A. Simoneau, P. Lagassé, M. Boulay, M. C. Thibeault, M. Marcotte, and C. Bouchard. Isokinetic strength training protocols: do they induce skeletal muscle hypertrophy. *Arch. Phys. Med. Rehab.* 69: 281–285, 1988.
4. Donnelly, J. E., T. Sharp, J. Houmard, M. G. Carlson, J. O. Hill, J. E. Whatley, and R. G. Israel. Muscle hypertrophy with large-scale weight loss and resistance training. *Am. J. Clin. Nutr.* 58: 561–565, 1993.
5. Green, H. J., J. A. Thomson, W. D. Daub, M. E. Houston, and D. A. Ranney. Fiber composition, fiber size and enzyme activities in vastus lateralis of elite athletes involved in high intensity exercise. *Eur. J. Appl. Physiol. Occup. Physiol.* 41: 109–117, 1979.
6. Holloszy, J. O., and F. C. Edward. Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. *J. Appl. Physiol.* 56: 831–838, 1984.
7. Krotkiewski, M. Role of muscle capillarization and morphology in the development of insulin resistance and metabolic syndrome. *Presse Med.* 23: 1353–1356, 1994.
8. Krotkiewski, M. Role of muscle morphology in the development of insulin resistance and metabolic syndrome. *Presse Med.* 23: 1393–1399, 1994.
9. Krotkiewski, M. Physical training in the prophylaxis and treatment of obesity, hypertension and diabetes. *Scand. J. Rehab.* 5: 55–70, 1984.
10. Krotkiewski, M., and P. Björntorp. Muscle tissue in obesity with different distribution of adipose tissue effects of physical training. *Int. J. Obes.* 10: 331–341, 1986.
11. Krotkiewski, M., A.-C. Bylund-Fallenius, J. Holm, P. Björntorp, G. Grimby, and K. Mandroukas. Relationship between muscle morphology and metabolism in obese women: the effect of long-term physical exercise. *Eur. J. Clin. Invest.* 13: 5–12, 1983.
12. Krotkiewski, M., G. Grimby, G. Holm, and J. Szczepanik. Increased muscle dynamic endurance associated with weight reduction on a very-low-calorie diet. *Am. J. Clin. Nutr.* 51: 321–330, 1990.
13. Krotkiewski, M., J. C. Seidell, and P. Björntorp. Glucose tolerance and hyperinsulinaemia in obese women: role of adipose tissue distribution, muscle fibre characteristics and androgens. *J. Int. Med.* 228: 385–392, 1990.
14. Lillioja, S., A. A. Young, C. L. Cutter, J. W. Ivy, W. G. H. Abbott, J. K. Zawadzki, H. Yki-Järvinen, W. Christin, T. W. Secomb, and C. Bogardus. Skeletal muscle capillary density and fiber type are possible determinants of in vivo insulin resistance in man. *J. Clin. Invest.* 80: 415–424, 1987.
15. Lindgärde, F., K.-F. Eriksson, H. Lithell, and B. Saltin. Coupling between dietary changes, reduced body weight, muscle fibre size and improved glucose tolerance in middle-aged men with impaired glucose tolerance. *Acta Med. Scand.* 212: 99–106, 1982.
16. Mandroukas, K., M. Krotkiewski, M. Hedberg, Z. Wroblewski, P. Björntorp, and G. Grimby. Physical training in obese women—effects of muscle morphology, biochemistry and function. *Eur. J. Appl. Physiol. Occup. Physiol.* 52: 355–361, 1984.
17. Metha, J., J. S. Chopra, S. Metha, C. K. Nain, A. G. Bhagwart, U. K. Dhand, and S. V. Rana. Ultrastructure and activity of some enzymes of energy metabolism of skeletal muscle in experimental energy deficiency. *Ann. Nutr. Metab.* 31: 35–46, 1987.
18. Russell, D. M., P. J. Prendergast, P. L. Darby, P. E. Garfinkel, J. Whitwell, and K. N. Jeejeebhoy. A comparison between muscle function and body composition in anorexia nervosa—the effect of refeeding. *Am. J. Clin. Nutr.* 38: 299–237, 1983.
19. Russell, D. M., P. M. Walker, L. A. Leiter, A. A. F. Sima, W. K. Tanner, D. A. G. Mickle, J. Whitwell, E. B. Marliss, and K. N. Jeejeebhoy. Metabolic, and structural changes in skeletal muscle during hypocaloric dieting. *Am. J. Clin. Nutr.* 39: 503–513, 1984.
20. Saltin, B., J. Henrikson, E. Nygaard, and P. Andersen. Fiber types and metabolic potentials of skeletal muscles in sedentary man and endurance runners. *Ann. NY Acad. Sci.* 301: 3–29, 1977.
21. Simoneau, J.-A., and C. Bouchard. Human variation in skeletal muscle fiber-type proportion and enzyme activities. *Am. J. Physiol.* 257 (*Endocrinol Metab.* 20): E567–E572, 1989.
22. Staron, R. S., R. S. Hikida, F. C. Hagerman, G. A. Dudley, and T. F. Murray. Human skeletal muscle fiber type adaptability to various workloads. *J. Histochem. Cytochem.* 32: 146–152, 1984.
23. Staron, R. S., E. S. Malicky, M. J. Leonardi, J. E. Falkel, F. C. Hagerman, and G. A. Dudley. Muscle hypertrophy and fast fiber type conversions in heavy resistance-trained women. *Eur. J. Appl. Physiol. Occup. Physiol.* 60: 71–79, 1989.
24. Svendsen, O. L., J. Haarbo, C. Hassager, and C. Christiansen. Accuracy of measurements of body composition by dual energy x-ray absorptiometry in vivo. *Am. J. Clin. Nutr.* 57: 605–608, 1993.
25. Svendsen, O. L., C. Hassager, and C. Christiansen. Effect of an energy-restrictive diet with or without exercise on lean tissue mass, resting metabolic rate, cardiovascular risk factors, and bone in overweight postmenopausal women. *Am. J. Med.* 95: 131–140, 1993.
26. Svendsen, O. L., C. Hassager, I. Bergmann, and C. Christiansen. Measurement of abdominal and intraabdominal fat in postmenopausal women by dual energy x-ray absorptiometry and anthropometry: comparison with computed tomography. *Int. J. Obes.* 17: 45–51, 1993.
27. Wade, A. J., M. M. Marbut, and J. M. Round. Muscle fibre type and aetiology of obesity. *Lancet* 335: 805–808, 1990.