Weight Lifted in Strength Training Predicts Bone Change in Postmenopausal Women

ELLEN C. CUSSLER[1], TIMOTHY G. LOHMAN[1], SCOTT B. GOING[1,2], LINDA B. HOUTKOOPER[2], LAUVE L. METCALFE[1], HILARY G. FLINT-WAGNER[1], ROBIN B. HARRIS[3], and PEDRO J. TEIXEIRA[2,4]

[1]Department of Physiology, [2]Department of Nutritional Sciences, and [3]College of Public Health, University of Arizona, Tucson, AZ; and [4]Exercise and Health Laboratory, Faculty of Human Movement, Technical University of Lisbon, PORTUGAL

ABSTRACT

CUSSLER, E. C., T. G. LOHMAN, S. B. GOING, L. B. HOUTKOOPER, L. L. METCALFE, H. G. FLINT-WAGNER, R. B. HARRIS, and P. J. TEIXEIRA. Weight Lifted in Strength Training Predicts Bone Change in Postmenopausal Women. *Med. Sci. Sports Exerc.*, Vol. 35, No. 1, pp. 10–17, 2003. **Purpose:** The aim of this study was to examine the relationship between weight lifted in 1 yr of progressive strength training and change in bone mineral density (BMD) in a group of calcium-replete, postmenopausal women. **Methods:** As part of a large clinical trial, 140 calcium-supplemented women, 44–66 yr old, were randomized to a 1-yr progressive strength-training program. Half of the women were using hormone replacement therapy. Three times weekly, subjects completed two sets of six to eight repetitions in eight core exercises at 70–80% of one repetition maximum. BMD was measured at baseline and 1 yr. **Results:** In multiple linear regression, the increase in femur trochanter (FT) BMD was positively related to total weight lifted (0.001 $g \cdot cm^{-2}$ for a SD of weight lifted, $P < 0.01$) after adjusting for age, baseline factors, HRT status, weight change, cohort, and fitness center. The weighted squats showed the strongest (0.002 $g \cdot cm^{-2}$ for a SD of weight lifted, $P < 0.001$), whereas the back extension exhibited the weakest (0.0005 $g \cdot cm^{-2}$ for a SD of weight lifted, $P < 0.26$) association with change in FT BMD. The amount of weight lifted in the weighted march exercise was significantly related to total body BMD (0.0006 $g \cdot cm^{-2}$ for a SD of weight lifted, $P < 0.01$). The associations between weight lifted and BMD for the femur neck or lumbar spine were not significant. **Conclusion:** Evidence of a linear relationship between BMD change and total and exercise-specific weight lifted in a 1-yr strength-training program reinforces the positive association between this type of exercise and BMD in postmenopausal women. **Key Words:** OSTEOPOROSIS, WEIGHT LIFTING, BONE MINERAL DENSITY, WOMEN

Osteoporosis prevention strategies have focused on increasing or maintaining bone mineral density (BMD). For women at risk, bone-building drugs, including hormone replacement therapy (HRT), calcitonin, and newer products, such as the bisphosphonates and selective estrogen receptor modulators (SERM), have been used to prevent or treat osteoporosis. These medications are costly (28) and potentially have undesirable side effects (20). Lifestyle changes, such as adequate intake of calcium from diet and supplementation, cessation of smoking, moderation in alcohol consumption, and increased resistance and weight-bearing exercise, have been proposed as less expensive alternatives to drug therapy.

Recent meta-analyses have reported retention or gains in BMD at the femoral neck (29) and at the lumbar spine (7,8,14,29) associated with weight-training exercise in postmenopausal women. However, evidence has not been consistent because studies were small or poorly designed and utilized a variety of intervention types (2,11), leading the authors of several meta-analyses, as well as the expert panel of the American College of Sports Medicine, to call for well-designed research to define more precisely the type and amount of exercise needed to stimulate bone formation (1,11).

Results of recent cell culture and animal studies have suggested that this association may be linear (22,25,27). In a review of the dose-response relationship between physical loading and bone characteristics, Smith and Gilligan (22) concluded that increased cellular activity found in cell and organ culture research presented the likelihood of proportional reactions of bone to loading (22). In rat tibia, direct evidence of a positive linear relationship was found between loading and bone formation after a strain

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Address for correspondence: Timothy G. Lohman, Department of Physiology, Ina Gittings Building, University of Arizona, Tucson, AZ; E-mail: Lohman@u.arizona.edu.
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threshold was reached (25). Umemura et al. (27) reported significant bone hypertrophy in rats executing five progressively higher jumps per day over an 8-wk period compared with controls and a trend toward increased bone mass in rat groups performing 10, 20, 40, and 100 jumps per day (27).

Human studies exploring the possibility of an association between the amount of weight lifted and BMD change are lacking and needed to define better the amount, intensity, and location of loading exercise in the prevention of bone loss (21,22,24). In the present study, the possibility of an exercise relationship was examined at two hip sites (femur trochanter (FT) and femur neck (FN)), the lumbar spine (LS), and the total body (TB) in a large sample of postmenopausal women over a 1-yr period. We hypothesized that total weight lifted and weight lifted in individual exercises would be a positively and linearly related to change in BMD at these selected sites.

METHODS

Study design. The Bone Estrogen Strength Training (BEST) study was a block-randomized clinical trial designed to examine the effects of weight bearing and resistance exercise on BMD in early postmenopausal women as they related to osteoporosis. Women took calcium citrate supplements (800 mg daily) and were randomized to either exercise or no-exercise conditions within groups blocked by HRT status. The BEST study was reviewed and approved by the University of Arizona Human Subjects Review Committee, and written informed consent was obtained from all subjects before study entry. For the present analysis, women assigned to exercise who completed baseline and year-end testing were followed over a 1-yr intervention period.

Recruitment and entry criteria. Subjects were recruited using selected zip codes for direct mailing, medical clinics, community organizations, and media advertisement. Initial telephone screening was followed by small group meetings during which study requirements were explained, informed consent procured, and initial demographic data collected. Six cohorts of women entered the study at approximately 6-month intervals over a 3-yr period.

Inclusion criteria were as follows: 40–65 yr of age; surgical or natural menopause (3.0–10.9 yr); body mass index (BMI) greater than 19.0 $kg \cdot m^{-2}$ and less than 32.9 $kg \cdot m^{-2}$; nonsmoking; no history of osteoporotic fracture and an initial BMD greater than Z-score of -3.0; undergoing HRT (1.0–5.9 yr) or not undergoing HRT ($>$1 yr); no weight gain or loss greater than 13.6 kg (30 pounds) in the previous year; cancer and cancer treatment free for last 5 yr (excluding skin cancer); not using BMD-altering medications (examined on a case-by-case basis), beta-blockers, or steroids; dietary calcium intake $>$300 $mg \cdot d^{-1}$; performing less than 120 min of low-intensity, low-impact exercise per week; and no weightlifting or similar physical activity. Participants agreed to continue their usual dietary practices, maintain their HRT status, and take daily calcium supplements provided by the study for the duration of the intervention period.

Hormone replacement therapy. Women using HRT continued to follow regimens prescribed by their physicians. Participants were asked to maintain the same regimen and to report any changes every 6 months. A variety of hormone combinations were used. However, most women took oral estrogen (32%), estrogen and progesterone (55%), or estrogen and/or progesterone by patch (10%).

Two women who were not taking HRT at baseline began after 6 months of intervention but were retained as non-HRT users in analysis. None of the women already taking HRT discontinued their use of the hormones.

Calcium supplements. Participants received 800 $mg \cdot d^{-1}$ of elemental calcium (calcium citrate; Citracal, Mission Pharmacal, San Antonio, TX) in blister packs in 2-month allotments. Subjects were instructed to take two tablets (200-mg elemental calcium/tablet) twice daily, without food and with at least 4 h between doses. Unused tablets were returned at the end of each 2-month period. Compliance was monitored through pill counts. Participants were classified as compliant if they consumed at least 80% of the prescribed pills during each 2-month period.

Anthropometry. At baseline, standing height and weight were measured with participants wearing lightweight clothing and no shoes. Height (cm) was measured to the nearest 0.1 cm with maximal inhalation with a Schorr measuring board. Weight (kg) was measured using a calibrated scale (SECA, model 770, Hamburg, Germany) accurate to 0.1 kg. The average height and weight from three trials was used to calculate BMI in kilograms: weight (kg)/height (m^2).

Dual energy x-ray absorptiometry. Regional and total body BMD ($g \cdot cm^{-2}$) were measured by dual energy x-ray absorptiometry using a total-body densitometer (model DPX-L; Lunar Radiation Corporation, Madison, WI). Subject positions for total body, anteroposterior lumbar spine (L_2–L_4), and femur (neck and trochanter) scans were standardized according to manufacturer's recommendations as previously described (12). Each subject was scanned twice at baseline and at follow-up and the mean of the two measurements was used in analyses. Initial scan analysis, including the placement of baselines distinguishing bone and soft tissue, edge detection, and regional demarcations, was done by computer algorithms (Version 1.3y, Lunar Corporation). One certified technician inspected all scans at all intervals and adjustments were made when necessary. Calibration of the densitometer was checked daily against a standard calibration block supplied by the manufacturer. A spine phantom was scanned daily to account for potential BMD variations due to machine error. The coefficient of variation (CV) of the phantom (BMD, L_2–L_4) was 0.6%. Technical errors, expressed as a percent of mean BMD, were ± 1.8%, ±2.4%, ±2.4% and ± 0.8% for LS, FN, FT, and TB

BMD, respectively, estimated from 261 study subjects with repeat scans at baseline.

Exercise program. Participants randomized to the exercise intervention were asked to train 3 $d \cdot wk^{-1}$, on nonconsecutive days, in one of four community facilities under the supervision of on-site trainers. The participant-to-trainer ratio was 5 to 1. Sessions lasted 60–75 min and included stretching, balance, and weight-bearing activities for warm-up, weightlifting, an additional weight-bearing circuit of moderate impact activities (e.g., walk/jog, skipping, and hopping), and stair-climbing/step boxes with weighted vests. Exercise attendance, weightlifting loads, sets and repetitions, steps with weighted vests, and minutes of aerobic activity were recorded in exercise logs that were monitored regularly by on-site trainers. Exercise compliance was assessed as the sessions actually attended as a percent of the maximum number of sessions prescribed for the exercise year.

Weightlifting was done using free weights and machines. Eight core exercises focused on major muscle groups with attachments on or near BMD measurement sites. These exercises included the seated leg press, latissimus dorsi pull downs, weighted march, seated row, back extension, one-arm dumbbell press or military press (right and left), Smith, hack, or wall squats, and the rotary torso machine. Women performed the seated leg press using a backrest and lowering weights to a 90° angle at the knee. In the weighted march, exercisers raised ankle-weighted legs to form an angle of 90° with the hip and knee joints while balancing with ski poles. The toe was lightly touched to the floor for one leg's repetitions. The alternate leg was then exercised. Women performed the one-arm military press sitting, pushing weights upward to an unlocked straight elbow. The weighted squats were executed from a standing position, lowering the weighted upper body to a 90° angle at the knees and hips. For all exercises except the weighted march, which was performed more quickly, trainers coached women to perform 4-s extensions and equally long releases.

Women completed two sets of six to eight repetitions (four to six repetitions for the dumbbell press to decrease injury to the shoulder) at 70% (2 $d \cdot wk^{-1}$) or 80% (1 $d \cdot wk^{-1}$) of the one-repetition maximum (1-RM). Muscle strength was measured every 2 months and weights were increased to maintain loads at 70–80% of 1-RM. Further details of the exercise program are described by Metcalfe et al. (13).

Statistical analysis. Statistical analyses were conducted using SPSS (23). Data were examined for all exercisers who completed 1-yr DXA measurements. Of the 177 women randomized to exercise who underwent baseline measurements, 142 completed the 1-yr study period (80% retention).

For the final analysis, two women were excluded. Both lifted 30% more total weight than the next highest weight lifters (1.2 million vs 0.9 million kg in 1 yr). One woman attended 50% more sessions than were prescribed by the study protocol. The second woman performed 75% more repetitions in the seated leg press and almost twice the recommended repetitions in the weighted squats. In addition to nonadherence to protocol, these outliers exhibited a sizable influence on regression results. The final analysis thus included 140 women.

At both baseline and year's end, two measurements of BMD were taken approximately 1 wk apart. If there was a difference of 5% or more between the two values, scans were reinspected and reanalyzed if necessary. The mean of the two values was then used in the analysis. Change in BMD was calculated as the difference between the average BMD ($g \cdot cm^{-2}$) at 1 yr and baseline.

The weight lifted (kg) in 1 yr was calculated for each exercise and then summed across exercises for total weight lifted.

Baseline physical characteristics of women on HRT and not on HRT were compared using Student *t*-tests. Potential differences between cohorts and fitness facilities in weight lifted and change in BMD were compared using ANOVA with Bonferroni *post hoc* tests. Pearson's correlation coefficients were computed to estimate the correlation between change at the four bone sites and exercise-specific and total weight lifted. Type 1 error was set at $\alpha = 0.05$ (two-sided) for all analyses.

Multiple linear regression models were constructed for each BMD site, with change in BMD as the dependent variable and the square of total or exercise-specific weight lifted as the independent variable. The relationship between weight lifted and change in BMD was tested for curvilinearity. Because Pearson correlation coefficients were higher using the square of weight lifted, kilograms squared were always entered in regression equations. Models were adjusted for baseline age, BMD, BMI, and HRT status, as well as 1-yr weight change, time of study entry (cohort), and fitness facility. Significant cohort differences in BMD change and substantial variation in weight lifted among cohorts suggested possible confounding by study entry time. Similar variations among fitness facilities may have resulted from equipment differences but not from the exercise program, which was uniform across training centers.

Predicted BMD changes for one standard deviation (SD) of weight lifted were computed using regression coefficients. Adjusted mean FT BMD changes were computed with the general linear model (random effects) procedure and plotted for quartiles of total weight lifted and weight lifted in the weighted squats.

RESULTS

Baseline characteristics. Although those completing the 1-yr study exhibited no significant differences in baseline characteristics compared with those who dropped out of the study, the dropouts ($N = 35$) tended to be somewhat younger, postmenopausal for slightly longer, less likely to be using HRT, and had greater body weights than those retained. For those who dropped, baseline BMD was

TABLE 1. Selected baseline characteristics of 140 women randomized to exercise intervention.

	HRT ($N = 70$)		No HRT ($N = 70$)	
	Mean	SD	Mean	SD
Age (yr)	54.8	4.0	55.7	4.7
Years Post-menopausal*	4.9	2.3	6.1	2.9
Estrone ($pg \cdot mL^{-1}$)*†	129.0	136.5	21.2	15.0
Estradiol ($pg \cdot mL^{-1}$)*†	54.6	40.7	18.5	33.6
Body Mass Index ($kg \cdot m^{-2}$)	25.6	3.7	25.6	3.7
% body fat	38.6	6.1	38.6	6.1
Lean soft tissue (kg)	38.6	4.5	38.6	4.6
BMD ($g \cdot cm^{-2}$)				
Femur trochanter	0.752	0.122	0.737	0.112
Femur neck	0.888	0.131	0.866	0.135
Lumbar spine	1.139	0.146	1.125	0.181
Total body	1.120	0.084	1.107	0.085

* $P < 0.001$; † $N = 127$.

lower in all regions; however, these differences were not statistically significant (data not shown).

Baseline age, years past menopause, blood estrogen levels, BMI, percent body fat, lean soft tissue (LST), and regional bone mass for exercisers are reported by HRT status in Table 1. Significant differences in years past menopause and estrone and estradiol levels were found between HRT users and nonusers ($P < 0.001$).

Exercise weights lifted. All exercisers who did not exceed the prescribed program recommendations and had baseline and 1-yr DXA measurements were retained in the analysis regardless of their compliance with the training program. Exercise attendance ranged from 8.0% to 98.3% with a mean of 71.5 ± 19.8%. On average, women attended approximately two sessions per week (103.5 ± 29.0 per yr) and lifted more than 5000 kg in each session (5105 ± 1185 kg). Annual weight lifted in individual exercises ranged from 8606 ± 3552 kg in the military press (right) to 173,642 ± 79,471 kg in the seated leg press (Table 2). The second largest amount of weight (97,586 ± 59,535 kg) was lifted in the weighted squats exercise. On average, women lifted a total of 528,425 ± 204,930 kg over the 1-yr intervention. Subjects were distributed nearly normally across the range of total weight lifted, from 25,125 to 913,701 kg (Fig. 1).

Pearson correlation coefficients between 1-yr BMD change and the square of kilograms of weight lifted are reported in Table 2.

Calcium and HRT compliance. More than 90% of the women ingested at least 80% of the prescribed calcium supplements. At 1 yr there was a 1.4% increase in HRT use to 51.4%. However, the change in mean estrone and estradiol levels between baseline and 1 yr was insignificant for both HRT users and nonusers (data not shown).

BMD change and weight lifted: regression analyses. Table 3 provides the results of regression models of change in regional BMD from squared kilograms of total weight lifted and weight lifted in individual exercises. For each combination of exercise and bone site, predicted change in BMD for one SD of weight lifted was calculated. Regression adjusted R^2 and *P*-values are also presented.

The greatest changes in BMD associated with a SD unit of change in the square of total weight lifted in 1 yr were found for the FT. An increase of 0.0012 $g \cdot cm^{-2}$ was predicted for one SD of total weight lifted (204,930 kg).

The FN change for one SD of total weight lifted was 0.0007 $g \cdot cm^{-2}$ ($P < 0.24$) for one SD. The smallest effects were achieved in the LS and TB BMD: 0.0001 $g \cdot cm^{-2}$ for one SD ($P < 0.82$).

TABLE 2. Weight lifted† during 1 yr of exercise and correlations between change in BMD and weight lifted†† for specific exercises and the sum of all exercises ($N = 140$ exercisers).

			Correlation Coefficients			
	Mean	SD	Femur Trochanter	Femur Neck	Spine	Total Body
Seated leg press	173,642	79,471	0.17*	−0.11	0.06	0.07
Latissimus dorsi pull	55,637	20,750	0.14	−0.04	0.22**	0.03
Weighted march (r.)	9,513	4,770	0.06	0.04	0.05	0.21**
Seated row	46,538	18,391	0.14	−0.05	0.20*	0.04
Back extension	88,557	38,681	0.07	−0.01	0.04	−0.03
Military press (r.)	8,606	3,552	0.27**	0.01	0.20*	0.03
Squats	97,586	59,535	0.28**	0.11	0.01	0.05
Rotary torso	40,031	19,554	0.12	0.23**	0.12	0.12
Total weight	528,425	204,930	0.22**	0.01	0.10	0.07

† in kilograms.
†† kg^2.
* $P < 0.05$ (two-sided).
** $P < 0.01$ (two-sided).

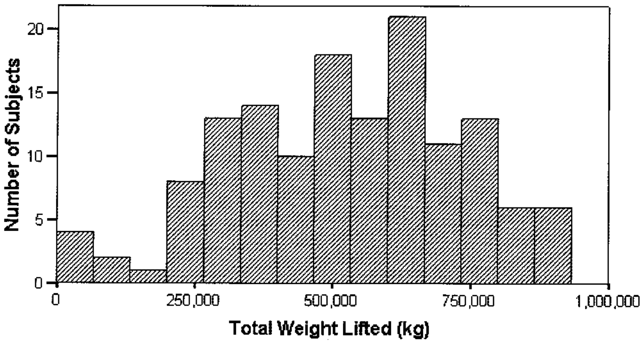

FIGURE 1—Distribution of total weight lifted by 140 exercisers.

The relation of BMD changes varied with the type of exercise. Statistically significant positive linear relationships were found between the FT and one SD of weight lifted in the weighted squats (0.0023 $g \cdot cm^{-2}$, $P < 0.001$), the military press (0.0012 $g \cdot cm^{-2}$, $P < 0.01$), the lat pull (0.0012 $g \cdot cm^{-2}$, $P < 0.01$), the seated row (0.0011 $g \cdot cm^{-2}$, $P < 0.03$), the rotary torso (0.0011 $g \cdot cm^{-2}$, $P < 0.05$), and the seated leg press (0.0011 $g \cdot cm^{-2}$, $P < 0.05$). The weighted march showed a marginally significant effect on FT BMD whereas the back extension had little effect.

FN and LS BMD changes were not related significantly to total or exercise-specific weight lifted. For the TB, there was a statistically significant effect of weight lifted in the weighted march exercise (0.0006 $g \cdot cm^{-2}$, $P < 0.01$). The weights lifted in other exercises showed no association with change in TB BMD.

Adjusted mean FT BMD changes increase with higher quartiles of weight lifted in Figure 2 (total weight lifted) and Figure 3 (weighted squats). In both analyses, significantly greater FT BMD change was found between the first and fourth quartiles ($P < 0.01$ and $P < 0.03$, respectively).

DISCUSSION

Recent longitudinal studies examining the effects of strength training on BMD change in postmenopausal women have been limited by small sample size (14–19), a short intervention period (6,19), high dropout rates (17,18), no randomization to exercise (6,19), and low exercise stimulus (19). The BEST study was designed to overcome these shortcomings, with 142 women assigned to exercise who completed 1 yr of an intensive strength-training program. The dropout rate of 20% in the BEST study was comparable to a smaller study (7) but lower than another (14). The final number of subjects completing 1 yr of intervention was larger than any previous study.

Response at different bone sites. Dividing subjects by exercise intensity in a nonrandomized intervention study, Pruitt et al. (18) found a small, but nonsignificant, greater increase in LS BMD in a high compared with a low-intensity group over a 1-yr period (18). In a randomized, controlled trial utilizing one body side as the control, Kerr et al. (7) reported proportional effects were site specific with larger osteogenic outcomes at the FT but not at the FN when high levels were compared with low levels of loading in strength training among postmenopausal women (7). Our results support and extend these latter findings.

There are several possible explanations for these bone site differences: muscle attachment, hormonal factors, differential loading or type of strain, and the nature and duration of this exercise intervention. First, previous research reporting increases in BMD at the FT, but not the FN, propose that strengthening of muscles attached to the FT may have served to promote osteogenesis at that site (7). Our results suggest as well that the muscle contractile forces may impact the FT more than the FN. Although loading occurred at both the FT and FN hip sites, muscles attachments are found on the FT and not on the FN, and transmission of impact forces through the FN may not be as effective in stimulating bone growth. If the military press exercise had been performed standing, FN BMD might have shown a response with this more direct loading.

Second, HRT use has been associated with increased maintenance of BMD in postmenopausal women irrespective of exercise status (17). In support of *in vitro* studies reporting interactions between estrogen and bone (re)modeling (4), a bone density enhancing effect of HRT has been

TABLE 3. Regression statistics for BMD change at three bone sites and for total body by weight lifted in specific exercises and in all exercises.*

	Femur Trochanter			Femur Neck			Lumbar Spine			Total Body		
	Change ($g \cdot cm^{-2}$)**	Adj. R^2	*P* Value	Change ($g \cdot cm^{-2}$)**	Adj. R^2	*P* Value	Change ($g \cdot cm^{-2}$)**	Adj. R^2	*P* Value	Change ($g \cdot cm^{-2}$)**	Adj. R^2	*P* Value
Total weight lifted	0.0012	0.13	0.007	0.0007	0.17	0.24	0.0001	0.12	0.82	0.0001	0.03	0.82
Weighted squats	0.0023	0.16	0.001	0.0011	0.18	0.17	0.0000	0.12	0.97	0.0001	0.03	0.78
Military press (r)	0.0012	0.13	0.006	0.0005	0.17	0.38	0.0006	0.13	0.24	0.0000	0.03	0.92
Lat pull	0.0012	0.12	0.01	0.0009	0.18	0.12	0.0006	0.13	0.22	−0.0001	0.03	0.76
Seated row	0.0011	0.11	0.03	0.0008	0.18	0.19	0.0004	0.12	0.44	−0.0001	0.03	0.63
Rotary torso	0.0011	0.11	0.05	0.0008	0.17	0.24	0.0004	0.12	0.46	0.0003	0.04	0.25
Seated leg press	0.0011	0.11	0.05	0.0004	0.17	0.60	−0.0003	0.12	0.65	0.0000	0.03	0.96
Weighted march	0.0008	0.10	0.08	0.0005	0.17	0.42	0.0002	0.12	0.66	0.0006	0.09	0.006
Back extension	0.0005	0.09	0.26	0.0007	0.17	0.25	0.0002	0.12	0.68	0.0000	0.03	0.87

* Adjusted for age, baseline BMD, baseline BMI, HRT status, weight change, time of study entry (cohort), and fitness facility.
** For 1 SD of weight lifted (kg^2).

reported for exercisers at three hip sites, in the lumbar spine, and for the total body in postmenopausal women (9). Although an examination of effect modification is not the focus of the present study, an independent effect of HRT use, not weight lifted, was noted in regression models of FN, LS, and TB BMD change. In addition, a significant difference in TB BMD change between HRT and non-HRT groups was found after 1 yr of exercise (data not shown). The presence of an association between HRT use and BMD change suggests that bone modeling may be mediated more by hormones than by exercise at these three sites over the 1-yr intervention period. Weight lifted in 1 yr, on the other hand, and not hormone use, was related to FT BMD change in these women.

A clear limitation of this research centers on the measurement of estrogen use. Adjusting for baseline HRT status in regression models may have inadequately controlled for the effects of estrogen since compliance to HRT was not closely monitored. However, HRT use was verified at 6 months and 1 yr and only two women had changed their status. Furthermore, baseline blood estrogen levels confirmed significant differences in hormonal status between HRT users and nonusers (Table 1). Similar blood estrogen levels were found at 1 yr, and inclusion of these levels as continuous variables in regression analyses did not alter the relationship of weight lifted to bone change (data not shown).

Third, considering only the weight lifted does not give a complete picture of the impact of the strength training process. Muscle strengthening and bone building have been elicited in both animal (22,25) and human trials (7) with increasing loads. However, quantity of weight constitutes only one way to assess the total impact of strength training (5). Weight added reflects strain size but not strain distribution or rate (3,26). Location and change in strain as well as strain magnitude may affect bone mass (8,21). Examining differences in BMD change resulting from exercise programs focused on ground (GRF) versus joint (JRF) reaction forces, Kohrt et al. (8) reported gains in FN BMD with GRF but not JRF after 11 months of exercise. These results suggest that the type of exercise impacts bone sites differently, and, therefore, magnitudes of weight lifted probably fail to capture a complete picture of exercise effect.

Finally, the FT may have responded more quickly to the BEST exercise program than the three other bone sites. Exercise-related BMD changes may appear in the FN, LS, and TB when this intervention is carried out over multiple years.

Response across exercise types. The response of BMD to different exercises was examined with the hope of detecting site-specificity (1) and providing guidance in the design of weight lifting programs for osteoporosis prevention. Specific exercises produced varying responses in BMD at the FT (Table 3).

In the BEST program, the largest concentrations of weight were placed on the large muscles adjacent to the trochanter (Table 2). The strongest effect found with the weighted squats suggested a site-targeted response. Significant correlations of BMD gains with percent increase in weight lifted in the seated leg press (measured with the 1-RM) have been reported (7). In the present study, the weight lifted in the seated leg press was related significantly to FT BMD.

An unexpected association of FT change was found with the military press. Even with the absence of direct muscle targeting at the hip site, substantial loading occurred directly above the hip region in this exercise. These results were consistent with the osteogenic effects of increases in loading reported in animal (10,23) and human studies (7). Alternatively, correlations of muscle strength in one body region with BMD in another have been reported (3), and perhaps the ability to excel in the military press corresponds to a bone-building tendency at the FT. The military press involved the least complicated and variable equipment and a relatively simple protocol and means of weight lifted in the military press were similar across fitness centers, whereas other exercises showed greater variation among fitness centers. There-

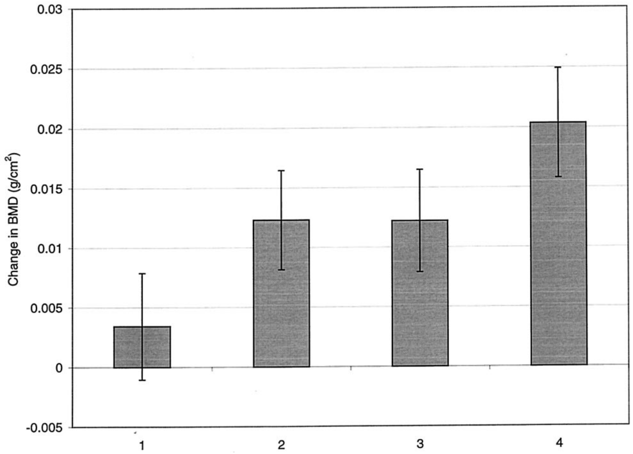

FIGURE 2—Change in FT BMD by quartiles of total weight lifted (kg); adjusted means and SE; $P < 0.01$ between quartiles 1 and 4.

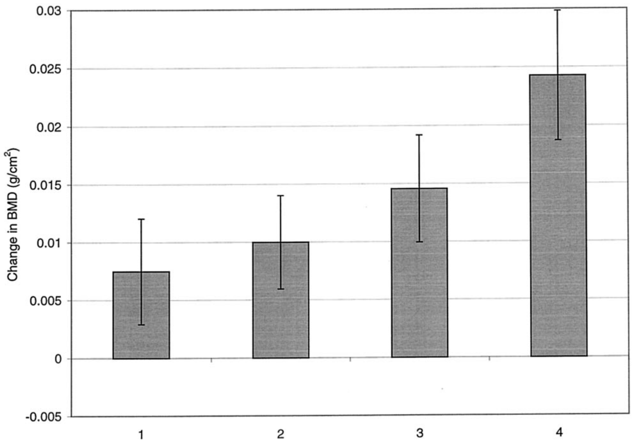

FIGURE 3—Change in FT BMD by quartiles of total weight lifted (kg) in the weighted squats; adjusted means and SE; $P < 0.03$ between quartiles 1 and 4.

fore, the higher measurement precision may have contributed to the strength of the association between the military press and FT BMD change.

The complexity of the BEST exercise program raises two concerns in the interpretation of these results. First, although warm-up exercise data were recorded, the protocol for this portion of the program was complicated and women did not consistently or accurately record their activity. In regression analyses, no association with BMD change was found with scores developed for these exercises; however, the score for the stepping portion of the warm-up period was modestly correlated with total weight lifted ($r = 0.30$; $P < 0.01$). The impact of the stepping may, therefore, have strengthened the association between weight lifted and BMD change. Although this enhancement may have affected the relationship of BMD with different types of exercises, it would probably not have changed the pattern of BMD changes across bone sites.

Second, in light of this limitation, the level of performance in the individual exercises cannot be regarded as unrelated to the entire exercise regimen despite distinct associations and varying effects between specific exercises and BMD change. Weight lifted in one exercise was not independent of the other exercises in the training program. On a practical level, we cannot, therefore, make definitive recommendations regarding site-specific training programs. However, for women with lower FT BMD, physicians could propose a comprehensive strength training routine and for those with lower levels of FN, LS, or TB BMD, hormone therapy as well.

Within the limits of weight lifted prescribed by the BEST program, the more weight these postmenopausal women lifted in 1 yr, the more their FT BMD increased. Furthermore, gains in FT BMD may accelerate as the quantity of weight lifted increases. This is the first study to report such a relationship and the results reinforce the usefulness of strength training exercise in maintaining or improving regional bone density in postmenopausal women.

BMD responded more to certain exercises and the results suggest focusing training on particular exercises. However, because the performance in one exercise may depend on success in others, a well-balanced strength-training program still provides the most sensible approach to an osteoporosis prevention program. For postmenopausal women, such a program further reduces fracture risk by benefiting overall strength and balance as well as bone density.

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