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Effects of combined whole-body vibration and resistance training on muscular strength and bone metabolism in postmenopausal women

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ABSTRACT

Whole-body vibration (WBV) has been shown to be osteogenic in animal models; however, its application in humans is not clear. The purpose of this study was to examine the effects of an 8-month program involving WBV plus resistance training on bone mineral density (BMD) and bone metabolism in older postmenopausal women. Fifty-five estrogen-deficient postmenopausal women were assigned to a resistance training group (R, $n=22$), a WBV plus resistance training group (WBVR, $n=21$), or a control group (CON, $n=12$). R and WBVR performed upper and lower body resistance exercises 3 days/week at 80% 1 Repetition Maximum (1RM). WBVR received vibration (30–40 Hz, 2–2.8*g*) in three different positions preceding the resistance exercises. Daily calcium intake, bone markers (Bone alkaline phosphatase (Bone ALP); C-terminal telopeptide of Type I collagen (CTX), and BMD of the spine, dual femur, forearm, and total body (DXA) were measured at baseline and after the intervention. At baseline, there were no significant group differences in strength, BMD, or bone marker variables. After 8 months of R or WBVR, there were no significant group or time effects in Bone ALP, CTX, or total body, spine, left hip or right trochanter BMD. However, right total hip and right femoral neck BMD significantly ($p<0.05$) decreased in all groups. A group × time interaction ($p<0.05$) was detected at radius 33% BMD site, with CON slightly increasing, and WBVR slightly decreasing. R and WBVR significantly ($p<0.05$) increased 1RM strength for all exercises, while CON generally maintained strength. WBVR had significantly ($p<0.05$) greater percent increases in muscular strength than R at 4 months for lat pull down, seated row, hip abduction and hip adduction and at 8 months for lat pull down, hip abduction and hip adduction. Bone metabolism in postmenopausal women was not affected by resistance training either with or without WBV. In contrast, the addition of WBV augmented the positive effects of resistance training on muscular strength in these older women.

Introduction

Osteoporosis is a serious bone disease, affecting approximately 10 million individuals in the United States over the age of 50 [1]. According to the American College of Sports Medicine, moderate to high intensity weight bearing endurance activities, activities that involve jumping, and resistance exercise may help to preserve bone health during adulthood [2]. Resistance exercise has potential to improve bone health both through mechanical stresses placed on bone during muscle contractions and by increasing the amount of muscle mass available to load the bone [3,4]. However, high intensity resistance exercise may be difficult for older women to maintain throughout their lifespan.

Whole-body vibration (WBV) training involves exposure to mechanical oscillations transmitted to the body at frequencies typically ranging from 20 to 50 Hz at low amplitudes, resulting in gravitational accelerations (*g*) in the magnitude of 0.1 *g* to 25.6 *g* [5,6]. In addition, vibration platforms can oscillate in a vertical direction or they can rotate side-to-side, a characteristic shown to affect the amount of neuromuscular activation of leg musculature in response to an acute vibration stimulus [7]. Previous research has shown that WBV training has profound effects on muscle performance by significantly increasing strength [8]. In addition, vibration exercise has been used as an effective countermeasure to attenuate bone [9] and muscle mass losses associated with prolonged periods of bed rest [10,11].

Studies using adult rodent models have provided convincing evidence that vibration signals can induce an osteogenic response by increasing bone formation, decreasing bone resorption, resulting in increased bone mass and strength [12–14]. The mechanism for the bone response is not clear. Tanaka et al. [12] suggested that the stochastic resonance phenomenon, i.e., enhancing the response of a

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nonlinear system to a weak signal by the addition of a noise vibration, causes the osteogenic response to mechanical loading. Judex and Rubin [15] propose three possible pathways for the bone cell response to vibration; the stimulus is received directly by the bone cells, the stimulus activates muscle motor units causing muscle contractions that load the bone, and increases in muscle strength and muscle mass place greater stresses on the bone. Bone adaptations to vibration may be modified by age and estrogen status, as it was recently shown that WBV did not have positive effects on bone in aged mice [16] or in ovariectomized female adult rats [17].

Inconsistent findings have been reported for the efficacy of WBV on bone adaptations in humans. Verschueren et al. [18] and Gusi et al. [19] both found significant increases in hip BMD in postmenopausal women after vibration training for 6 and 8 months, respectively. Other studies in older women [20–22] did not observe positive BMD results; however, the conservative approach in application of the vibration stimulus, in terms of magnitude (<1 *g*) and/or exposure duration, may have been the reason for the lack of bone response.

The addition of a vibration stimulus to resistance exercise may be an effective way to potentiate musculoskeletal responses to resistance exercise alone. The purpose of this study was to compare the effects of combined WBV plus resistance training to resistance training alone on bone metabolism and muscular strength of estrogen-deficient postmenopausal women. We hypothesized that the addition of the vibration signal (>2 *g*) before specific sequences of resistance exercises would have anabolic effects on both muscle and bone in this cohort of older women.

Methods

Subjects

Estrogen-deficient postmenopausal women between 55 and 75 years of age ($n=55$) were recruited for this study. Subjects read and signed a written informed consent form and all methods and procedures were approved by the University of Oklahoma Institutional Review Board. Inclusion criteria were: (1) healthy women volunteers, 55–75 years of age; (2) subjects who were at least 5 years postmenopausal; (3) subjects who were not taking hormone replacement therapy (HRT); (4) previous HRT users had not taken HRT for at least 1 year; (5) subjects who had not participated in a weight training program for at least 1 year prior to the study; (6) subjects who were medically stable, ambulatory, and capable of undergoing physical strength testing and training; and (7) subjects who were of a mental capacity to give written informed consent and comply with the protocols. Exclusion criteria were: (1) women with diagnosed osteoporosis or a BMD site with a *T*-score less than −2.5; (2) women with physical disabilities preventing them from being strength tested and trained, including orthopedic or arthritic problems; (3) women with heart problems such as congestive heart failure and arrhythmias, chronic high blood pressure, or those on Beta Blockers; (4) current smokers or past smokers within the previous 15 years; (5) women with current diagnosis or a history of renal disease, chronic digestive or eating disorders, rheumatoid arthritis, or uncontrolled thyroid disease; and (6) women taking medications that affected bone density, such as steroid hormones, calcitonin, or corticosteroids. In addition, none of the women were currently taking medications for osteoporosis treatment, including bisphosphonates, selective estrogen receptor modulators, or parathyroid hormone.

After screening, 62 women met the inclusion/exclusion criteria and were enrolled in the study. Seven of the 62 subjects later dropped out or were excluded due to poor attendance, thus, 55 subjects completed the entire 32 weeks of the study. The compliance for both training protocols was excellent, with WBV plus resistance training and resistance training only participants attending an average of 92% and 90% of the training sessions, respectively.

Research design

Subjects obtained medical clearance from their personal physician prior to participation in study testing procedures. Once cleared, the subjects were assigned to a resistance training group (R, $n=22$), a WBV plus resistance training group (WBVR, $n=21$), or a control group (CON, $n=12$) based on their availability to attend the scheduled training sessions. At baseline, subjects completed questionnaires about physical activity patterns (Physical Activity Scale for the Elderly (PASE)) [23], menstrual history, calcium intake [24], and health status; and they had baseline bone scans and blood draws. A two-week acclimation period was given to the subjects to ensure participant comfort and familiarity with the equipment. Subjects then began an 8 month training program held three days per week. Strength was assessed at baseline and every four weeks during training so that the principle of progressive overload could be applied. Blood draws and bone scans were obtained at baseline and after the 8 months of training.

Muscular strength assessment

Participants performed strength testing for 5 lower body (supine two leg press, hip flexion/extension (right leg), hip abduction/adduction (right leg)) and 3 upper body resistance exercises (seated military press, latissimus (lat) pull down, seated row) using Cybex® isotonic weight training equipment (Ronkonkoma, NY). A two-week acclimation period was given to ensure participant comfort and familiarity with the equipment. Proper lifting techniques were taught to the subjects during this period by trained personnel. The third week was considered the first week of the training program, during which the 1 repetition maximum (1RM) for the eight exercises was determined. A proper warm up, consisting of a 5-min walking or cycling warm up and a warm up at each exercise machine, was administered before the onset of strength testing protocol. The 1RM was obtained by finding the maximum weight lifted through an entire range of motion in a single repetition and it was determined within 5 attempts. One minute of rest was allowed between attempts. 1RM testing was monitored and recorded by project staff.

Resistance and WBVR training protocols

Both R and WBVR groups performed resistance training that consisted of exercises specifically targeting clinically important BMD sites (hip and spine). R and WBVR performed three sets of 10 repetitions at 80% 1RM for the following eight exercises: (1) supine two leg press, (2) hip flexion, (3) hip extension, (4) hip abduction, (5) hip adduction, (6) seated military press, (7) lat pull down, and (8) seated row. Note that the hip exercises were done for both right and left legs using the same loads and rate of progression, but strength testing was conducted only for the right leg due to time constraints. Subjects also performed dumbbell wrist curls and seated abdominal flexion, at a self-selected light to moderate intensity; however, these exercises were not tested for 1RM. Each session was completed in less than 1 h.

WBV training consisted of a high frequency (30–40 Hz) vibration stimulus at the low setting (2–4 mm peak to peak) on a Power-Plate® vibration platform (Power-Plate North America, Inc., Northbrook, IL). This type of vibration device uses a triplanar action, oscillating in three planes. Mean acceleration magnitudes, measured using a triaxial accelerometer, were reported to range from 2.16 *g* (30 Hz) to 2.8 *g* (40 Hz) [25]. Subjects received the vibration in three different positions, each of which preceded specific resistance exercises. Exposure to the vibration occurred in one or more 15- to 60-s intervals with at least 15 s of rest between vibration bouts. The subjects performed dynamic movements during vibration, which were then followed by a high intensity dynamic loading stress. The vibration position and specific

resistance exercises that followed were: (1) seated on platform, performing shoulder press movements with rigid straps (attached to the platform) followed by shoulder press, hip abduction/adduction, and abdominal flexion resistance exercises; (2) seated on the platform performing wrist curls using the rigid straps (attached to the platform) followed by wrist curls, lat pull down, seated row resistance exercises; and (3) standing on the platform (with their athletic shoes on) performing dynamic squat movements, followed by leg press, hip flexion/extension resistance exercises. The order of the vibration and resistance exercise sequences was not controlled.

The vibration stimulus began on week two of the study following the baseline 1RM testing to eliminate a vibration effect on initial strength measures. The principle of progressive overload was applied to the vibration stimulus and intensities were gradually increased by manipulating frequency, duration, and number of bouts. Vibration amplitude was held constant at the low (2–4 mm) setting. Vibration exposure began at 30 Hz with 1 set of 15 s (2.16 *g*) and gradually increased to the final exposure at 40 Hz with 2 sets of 60 s (2.8 *g*) (Table 1).

Bone Mineral Density Measurements

Dual Energy X-Ray Absorptiometry ((DXA) GE Lunar Prodigy enCORE software version 8.80, GE Medical Systems, Madison WI) was used to assess the BMD of total body; AP lumbar spine (L1–L4); dual proximal femur (femoral neck, trochanter, total hip); and the forearm (33% radius) sites assessed at baseline and after the eight month training period. Subjects removed all metal and plastic before being positioned on the DXA table. Because body mass and tissue type affect energy attenuation, scan mode for the total body and spine were selected based on the subject's measured trunkal thickness: Thick, >25 cm; Standard, 13–25 cm; and Thin, <13 cm. The detail scan mode was used for all hip scans. One qualified technician performed all scan analyses and quality assurance and spine phantom calibration procedures were performed daily prior to each scanning session to ensure no machine drift occurred during the intervention period. Radius BMD data were reported using the Prodigy BMD Forearm Calibration software selection. The *in vivo* precision for this DXA technician for the total body, spine, trochanter, total hip, and forearm BMD sites are 0.5%, 0.8%, 1.7%, 1.2%, and 1.5% respectively.

Bone Turnover Markers

Blood collection occurred in the morning with the subjects in an 8-h fasting state. Resting 6 ml blood samples were obtained by venipuncture at baseline and 1–3 days after the last training session. The samples were centrifuged; serum was aliquoted into 0.5 ml vials, and then frozen at −70 °C until the time of the assays. To reduce protein degradation, the vials were thawed only one time prior to each bone marker assay. The bone resorption marker was C-terminal telopeptide of Type I collagen (CTX) in human serum. CTX was measured in duplicate by enzyme-linked immunosorbent assay (ELISA) (Nordic Bioscience Diagnostics, Denmark). CTX units are reported in ng/ml. The intra-assay coefficient of variation ranged from 0.1% to 4.7% and the inter-assay coefficient of variation range was 0.4–4.7%. Bone alkaline phosphatase (Bone ALP) was measured as the bone formation marker. Bone ALP was measured in duplicate with the Metra BAP EIA kit (Quidel Corporation, Mountain View, CA). Values are expressed as Units per Liter (U/L). The intra-assay coefficient of variation ranged from 0.3% to 12% and the inter-assay coefficient of variation range was 0.1–12.5%.

Table 1
Training progression of WBV stimulus.

Week	Set number	Duration (s)	Frequency (Hz)	Mean acceleration[a] (*g*)
2- 3	1	15	30	2.16
4–8	2	15	30	2.16
9	3	15	30	2.16
10–12	2	30	30	2.16
13	2	30	30/35	2.16/2.49
14–16	2	30	35	2.49
17	3	30	30	2.16
18, 19	2	45	30	2.16
20	3	30	35	2.49
21–25	2	45	35	2.49
26–28	2	60	35	2.49
29	2	60	35/40	2.49/2.80
30–32	2	60	40	2.80

[a] Measured with a triaxial accelerometer [25].

Data analyses

All data are reported as means ± standard error (SE). Descriptive statistics were computed for the dependent variables by group. The effects of the intervention on BMD, bone markers, and muscular strength dependent variables were analyzed by two-way repeated measures ANOVAs (Group × Time). When a significant interaction was detected, paired *t*-tests were used to determine significant time differences within each group. Relative (percent) changes in muscular strength from baseline to the mid point and post-test were calculated for each resistance exercise. Percent changes from baseline to post-test were calculated for BMD and bone marker variables. The Kolmogorov–Smirnov procedure was used to test the normality of the percent change variables' distributions. When a distribution was not normal, the Kruskal–Wallis one-way ANOVA test with multiple pairwise comparisons was used to determined group differences. Otherwise, one-way ANOVA, with the Bonferroni post hoc procedure, was used to determine group differences in normally distributed percent change variables. The significance level was set at $p \leq 0.05$ and statistical analysis was performed by SPSS for Windows (version 17.0).

Results

Subject characteristics

Table 2 displays the baseline physical characteristics, calcium intake, and physical activity (PASE) data for each group. There were no significant differences between groups at baseline. Subjects with calcium intakes less than 1500 mg/day were instructed to increase their intake to at least 1500 mg/day. There was a significant ($p < 0.05$) time effect for increasing calcium intake at month 8 of the intervention from baseline.

Bone turnover marker responses

In Table 3, the data for Bone ALP and CTX are shown for each group at baseline and post-training. The Bone ALP value for one R subject was extremely high, thus, it was omitted from the analysis as an

Table 2
Physical characteristics.

Variable	Group		
	WBVR ($n=21$)	R ($n=22$)	CON ($n=12$)
Age (years)	62.8 ± 1.1	64 ± 0.9	63.1 ± 1.4
Height (cm)	164.0 ± 1.5	160.6 ± 1.7	162.9 ± 1.5
Weight (kg)	73.56 ± 2.82	76.6 ± 3.16	77.92 ± 4.53
BMI (kg/m^2)	27 ± 1	30 ± 1	29 ± 1
PASE Score	183 ± 16	158 ± 16	150 ± 18
Ca^{2+} Intake (mg/day) Pre	1597 ± 132	1373 ± 173	1376 ± 138
Post	1987 ± 98*	1844 ± 57*	1746 ± 63*

Values are means ± SE; PASE—Physical Activity Scale for the Elderly; Ca^{2+}—Calcium; WBVR—Whole-body Vibration + resistance training; R—resistance training only; CON—control group *$p < 0.05$ significant vs. pre.

Table 3
Bone marker responses.

Variable	Group					
	WBVR ($n=21$)		R ($n=22$)		C ($n=12$)	
	Pre	Post	Pre	Post	Pre	Post
Bone ALP (U/L)	39.54 ± 2.56	40.96 ± 2.66	42.38 ± 3.27	43.20 ± 3.41	37.47 ± 2.48	37.28 ± 2.77
% Δ from Pre		5.9 ± 5.1		3.7 ± 4.9		−0.1 ± 5.2
CTX (ng/ml)	0.559 ± 0.043	0.594 ± 0.055	0.703 ± 0.073	0.729 ± 0.059	0.605 ± 0.081	0.603 ± 0.062
% Δ from Pre		8.8 ± 5.9		33.2 ± 27.9		49.2 ± 52.0

Values are Mean ± SE; Bone ALP—bone alkaline phosphatase; CTX—C-telopeptide of Type I collagen; WBVR—Whole-body Vibration + resistance training; R—resistance training only; CON—control group; % Δ—percent change.
No significant group, time, or group × time effects.

outlier. There were no significant group, time, or group × time interaction effects detected for the bone marker data. There were no significant group differences in percent change bone marker variables.

Table 4
BMD responses.

Site	Group		
	WBVR ($n=21$)	R ($n=22$)	CON ($n=12$)
Total body[a]			
Baseline BMD (g/cm^2)	1.135 ± 0.017	1.150 ± 0.021	1.132 ± 0.020
Post BMD (g/cm^2)	1.135 ± 0.017	1.149 ± 0.022	1.133 ± 0.018
Absolute change (g/cm^2)	−0.0002 ± 0.0049	−0.0015 ± 0.0044	0.0010 ± 0.0045
Percent change	−0.05 ± 0.43	−0.16 ± 0.37	−0.13 ± 0.38
Spine L1-L4[b]			
Baseline BMD (g/cm^2)	1.129 ± 0.034	1.163 ± 0.028	1.131 ± 0.036
Post BMD (g/cm^2)	1.119 ± 0.032	1.156 ± 0.030	1.129 ± 0.038
Absolute change (g/cm^2)	−0.0080 ± 0.0084	−0.0072 ± 0.0056	−0.0027 ± 0.0083
Percent change	−0.73 ± 0.69	−0.67 ± 0.48	−0.24 ± 0.75
Radius 33%			
Baseline BMD (g/cm^2)	0.825 ± 0.017	0.825 ± 0.023	0.809 ± 0.028
Post BMD (g/cm^2)	0.814 ± 0.020*	0.827 ± 0.023	0.826 ± 0.029*
Absolute change (g/cm^2)	−0.0111 ± 0.0059	0.0018 ± 0.0051	0.0168 ± 0.0065**
Percent change	−1.48 ± 0.74	0.27 ± 0.64	2.07 ± 0.75**
Right total hip[b]			
Baseline BMD (g/cm^2)	0.954 ± 0.024	0.955 ± 0.025	0.940 ± 0.020
Post BMD (g/cm^2)	0.947 ± 0.023*	0.952 ± 0.024*	0.938 ± 0.021*
Absolute change (g/cm^2)	−0.0072 ± 0.0028	−0.0033 ± 0.0032	−0.0027 ± 0.0030
Percent change	−0.72 ± 0.27	−0.33 ± 0.34	−0.29 ± 0.31
Right femoral neck[b]			
Baseline BMD (g/cm^2)	0.908 ± 0.027	0.902 ± 0.021	0.907 ± 0.025
Post BMD (g/cm^2)	0.896 ± 0.026*	0.898 ± 0.021*	0.905 ± 0.026*
Absolute change (g/cm^2)	−0.0127 ± 0.0034	−0.0037 ± 0.0040	−0.0018 ± 0.0045
Percent change	−1.36 ± 0.36	−0.35 ± 0.45	−0.24 ± 0.51
Right trochanter[b]			
Baseline BMD (g/cm^2)	0.758 ± 0.023	0.768 ± 0.022	0.770 ± 0.016
Post BMD (g/cm^2)	0.750 ± 0.022	0.764 ± 0.022	0.770 ± 0.016
Absolute change (g/cm^2)	−0.0084 ± 0.0046	−0.0036 ± 0.0045	−0.0002 ± 0.0043
Percent change	−1.05 ± 0.55	−0.39 ± 0.62	−0.01 ± 0.56

Values reported as Mean ± SE; WBVR—Whole-body Vibration + resistance training; R—resistance training only; CON—control group; [a] $n=21$ for R; [b] $n=20$ for WBVR.
* $p<0.05$ significant vs. baseline; ** $p<0.01$ WBVR vs. CON. There were no significant effects for the left hip sites (data not shown).

BMD responses

Table 4 shows the group comparisons for baseline BMD, post-test BMD, absolute BMD changes, and percent changes in BMD. For all total body BMD analyses, one R subject was omitted as she refused to have her head scanned. Also, WBVR had spine BMD data omitted for one subject with severe spine curvature and hip BMD data omitted for a different subject with double hip replacements. There were no significant group differences in baseline BMD at any site. Also, no significant group or time main effects were detected by two-way repeated measures ANOVA for total body, lumbar spine, right trochanter, and left hip (total, trochanter, femoral neck) BMD sites. The data are not shown for the left hip BMD sites. There was a significant time effect for both right total hip ($p<0.05$) and right femoral neck ($p<0.05$), which significantly decreased from baseline (right total hip grand mean—0.952 ± 0.014 to 0.947 ± 0.014 g/cm^2; right femoral neck grand mean—0.905 ± 0.014 to 0.899 ± 0.014 g/cm^2). Repeated measures ANOVA detected a significant ($p<0.05$) Group × Time interaction for radius 33% BMD site, which significantly decreased for WBVR but increased for CON. Also, there was a significant group effect ($p<0.01$) in percent change and absolute change from pre to post at the radius 33% site; CON increased radius 33% BMD, while WBVR decreased radius 33% BMD. No significant group differences in percent changes or absolute changes for the total body, lumbar spine, or hip BMD sites were detected.

Muscle strength responses

At baseline, there were no significant group differences in strength variables (Table 5). WBVR and R significantly ($p<0.05$) increased 1RM strength for all exercises at months four (mid) and eight (post), compared to baseline; whereas CON strength values remained unchanged with the exception of a significant ($p<0.01$) decrease in hip extension strength at 8 months. Generally, both training groups, WBVR and R, had significantly ($p<0.05$) greater 1RM strength at mid and post-test times compared to CON. For lat pull down strength, WBVR was significantly ($p<0.05$) higher than CON at mid and post-

Table 5
Baseline muscle strength.

Strength (kg)	Group		
	WBVR ($n=21$)	R ($n=22$)	CON ($n=12$)
Seated row	34.0 ± 1.7	36.0 ± 1.5	33.8 ± 1.9
Latissimus pull down	30.0 ± 1.3	33.6 ± 1.6	33.8 ± 2.7
Shoulder press	29.5 ± 1.6	28.5 ± 1.4	28.4 ± 2.3
Leg press	83.2 ± 5.6	72.1 ± 4.4	85.0 ± 7.4
Hip abduction	29.7 ± 2.1	33.7 ± 1.7	31.5 ± 3.1
Hip adduction	37.3 ± 2.1	41.0 ± 2.2	37.5 ± 2.6
Hip extension	52.4 ± 3.9	54.5 ± 3.6	54.6 ± 3.9
Hip flexion	35.6 ± 1.7	35.5 ± 2.3	36.9 ± 4.5

Values reported as Mean ± SE; WBVR—Whole-body Vibration + resistance training; R—resistance training only; CON—control group; no significant group differences.

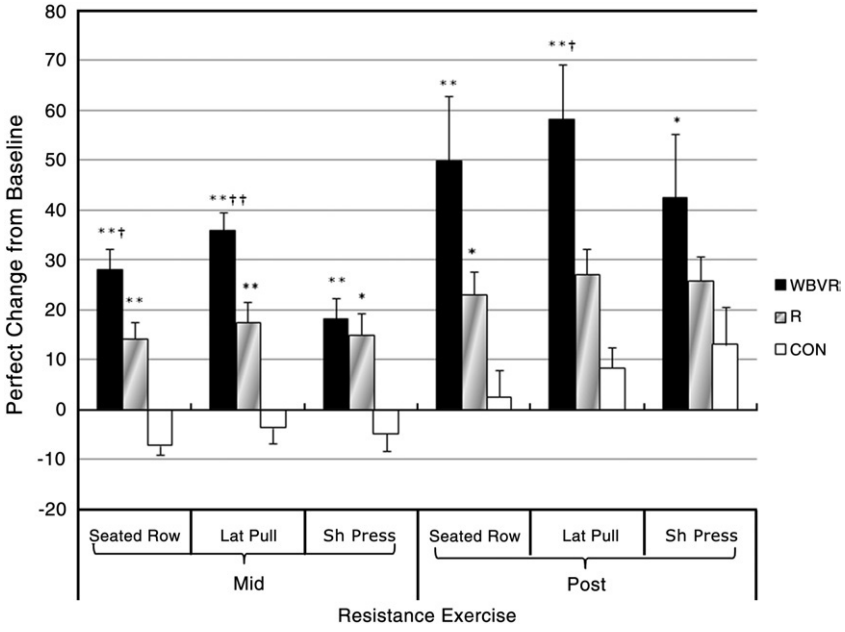

Fig. 1. Percent changes in upper body strength at 4 (mid) and 8 (post) months of training. Values reported as Mean ± SE. WBVR—Whole-body Vibration + resistance training; R—resistance training only; CON—control group; Lat Pull—Latissimus Pull down; Sh Press—Shoulder Press. $^{*}p<0.05$ vs. CON; $^{**}p<0.01$ vs. CON; $^{\dagger}p<0.05$ vs. R; $^{\dagger\dagger}p<0.01$ vs. R.

test times, but R was significantly ($p<0.05$) higher than CON only at post. Group differences in mid and post shoulder press strength occurred with only WBVR being significantly ($p<0.05$) higher than CON. WBVR leg press strength was significantly ($p<0.05$) higher than CON only at post-test time.

Both treatment groups, especially WBVR, showed dramatic relative increases, ranging from 23% to 138%, in muscle strength (Figs. 1 and 2). There were significant ($p<0.01$) group differences in percent changes from baseline to the mid time point (month 4) for all exercises. At the 8-month post-test, significant ($p<0.01$) group differences were detected in the seated row, shoulder press, lat pull down, hip abduction/adduction, and hip flexion/extension percent changes, but no significant group differences were observed for leg press.

Percent changes in strength at mid and post-test time points for upper body exercises are shown in Fig. 1. The Kruskal–Wallis test with pairwise comparisons was used to analyze group differences in percent changes from baseline to post-test time points for seated row, shoulder press and hip extension, which were not normally distributed. For the seated row mid point, WBVR increased more than R and CON; and R was significantly ($p<0.05$) greater than CON. At the 8 month post-test, the percent changes for WBVR and R were significantly ($p<0.05$) greater than CON for this exercise, but WBVR and R were no longer significantly different from each other. WBVR also had greater percent increases ($p<0.05$) in lat pull down than R both at mid and post-test time points. Significant group differences ($p<0.05$) in shoulder press percent change were detected at the mid time point, with both WBVR and R being greater than CON; however,

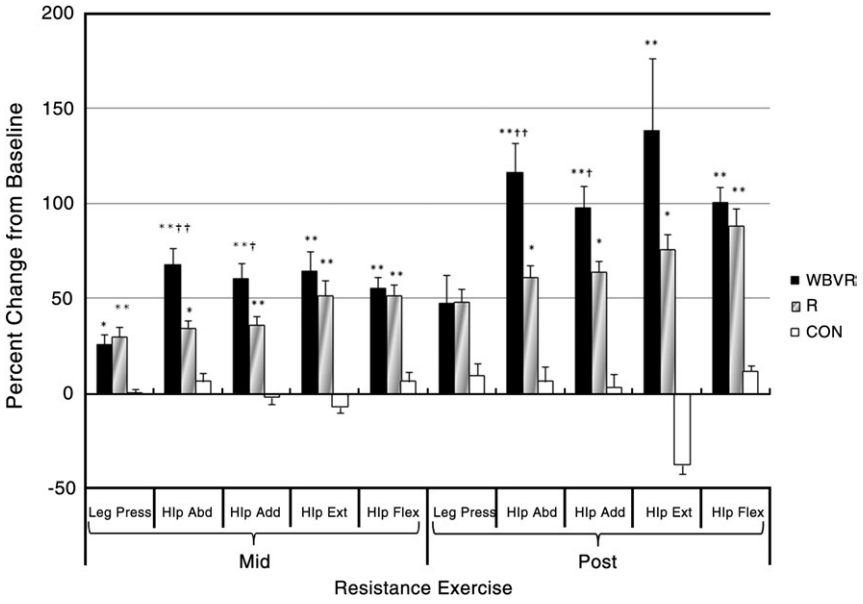

Fig. 2. Percent changes in lower body strength at 4 (mid) and 8 (post) months of training. Values reported as Mean ± SE. WBVR—Whole-body Vibration + resistance training; R—resistance training only; CON—control group; Hip Abd—hip Abduction; Hip Add—Hip Adduction; Hip Ext—Hip Extension; Hip Flex—Hip Flexion. $^{*}p<0.05$ vs. CON; $^{**}p<0.01$ vs. CON; $^{\dagger}p<0.05$ vs. R; $^{\dagger\dagger}p<0.01$ vs. R.

at the post-test, only WBVR was significantly ($p<0.05$) greater than CON.

Relative strength changes for lower body exercises are shown in Fig. 2. The added benefit of WBV was evident for hip abduction and hip adduction exercises as WBVR had significantly greater ($p<0.05$) percent increases for these exercises than R at both mid (Abduction—WBVR 68% vs. R 34%; Adduction—WBVR 60% vs. R 36%) and post-test time points (Abduction—WBVR 116% vs. R 61%; Adduction—WBVR 98% vs. R 64%). WBVR and R showed similar percent increases in leg press strength (about 48%), which were significantly ($p<0.05$) greater than CON only at mid (month 4). WBVR and R also had similar percent increases in hip extension and hip flexion strength, but WBVR and R responses were significantly ($p<0.05$) greater than CON at both mid and post-test time points.

Discussion

Although we designed this study to determine the effectiveness of WBV combined with resistance training on bone metabolism in healthy postmenopausal women, our primary finding was that WBV enhanced the muscular strength gains associated with resistance training. In contrast to previous studies that utilized WBV alone [18,26], we had our participants perform the WBV protocol immediately preceding resistance exercises, in attempt to "excite" the bone cells' response to the mechanical loading of muscular contraction. von Stengel [27] used an approach similar to ours to examine the potentiating effect of WBV combined with a multi-component exercise intervention on BMD in postmenopausal women study. They reported that lumbar spine BMD significantly improved with exercise alone and exercise + WBV; however, WBV did not enhance the benefits of the exercise intervention.

Our BMD findings do not agree those of Verschueren et al. [18] who reported a small significant increase (+0.93%) in hip BMD with their WBV intervention, which employed a much longer duration exposure (~20 min) than our protocol (<6 min). Rubin et al. [21] examined the effects of a very low magnitude high frequency vibration stimulus (0.2 *g*, 30 Hz, two 10-min bouts per day) on BMD in postmenopausal women. No significant changes in spine, hip, or distal radius BMD were detected with intention-to-treat analyses; however, women who were at least 86% compliant showed a 2.17% benefit at the femoral neck and a 1.5% benefit at the spine, relative to controls. Russo et al. [20] used higher vibration magnitudes (>1 *g*) in an eight month training study, and did not find significant BMD responses in postmenopausal women. We did not find any significant bone turnover marker responses to resistance training either with or without WBV, which agrees with previous findings in young women [28,29] and in postmenopausal women [18]. Previous research on bone marker responses to chronic resistance training in older populations is equivocal as bone formation markers (osteocalcin, Bone ALP) have been reported to increase [30,31], or not change [32,33].

It appears that there are several key issues to consider for vibration training; high (>1 *g*) vs. low (<1 *g*) acceleration magnitude, duration, and frequency of exposures. The research design of the our study approached the vibration stimulus in the same manner that one approaches resistance training with respect to bone adaptation, which is that it should be of a high magnitude [3,34]. This may not be the best approach when bone is the main outcome of vibration training, since animal studies [15] have shown that the bone response to WBV is not dose-dependent. For example, Christiansen & Silva [14] found that trabecular bone volume increased in mice exposed to vibration at 0.1 *g* and 1.0 *g* but not to 0.3 *g*. The optimal magnitude and frequency of vibration to stimulate bone formation in humans is not yet clear. Our WBV protocol was associated with a BMD decrease at the radius, suggesting the possibility that the vibration signal was too high for this sample of postmenopausal women.

Our combined WBV + high intensity resistance training protocol resulted in very large increases in muscular strength that were greater than resistance training alone for most exercises. Also, we reported previously that both training groups had significant increases in bone free lean body mass, although only the WBVR group showed a significant decrease in percent body fat [35]. Improvements in muscle performance from WBV alone are well-documented in the literature [8,18,20,26]. A unique aspect to our application of the WBV stimulus was having subjects sitting on the platform and holding straps connected to the platform so that the stimulus would be distributed to a greater proportion of the entire body. Theoretically, some of the vibration signal is lost at the spine and hip when standing on the platform; and transmission of the signal is also affected by how the person stands on the platform, with greater amounts of flexion causing a greater loss of the signal to the hip and spine [36]. Therefore, we had subjects sit on the platform holding straps connected to it in an attempt to expose the upper body to larger amounts of the vibration stimulus. Although we did not document the neuromuscular activation with electromyography, it appears that this method of applying vibration to the upper body was effective as evidenced by greater gains in seated row and lat pull down strength compared to resistance exercise alone, both at four months (WBVR 28–35% vs. R 15–18%) and at eight months (WBVR 59% for lat pull down vs. R 28%). More dramatic training protocol differences were observed for hip exercises, as WBVR had 39–52% greater increases in hip abduction and adduction strength compared to R.

There are several important limitations to our study. Subjects were not randomly assigned to treatment groups, which could lead to subject selection bias. Since we were limited to specific times to hold the workout sessions in the training facility, women were allowed to select the sessions that best fit their schedules. We did not control dietary intakes of calcium and vitamin D during the intervention nor did we provide calcium or vitamin D supplements to the subjects. Calcium intake was estimated by a food frequency questionnaire, and individuals were provided with exact recommendations needed to meet the 1500-mg daily requirement. The fact that each group significantly increased their calcium intakes at post-testing suggests the women followed our recommendations. Although our interventions incorporated the mode and intensity of exercise sufficient to facilitate an osteogenic response, it is possible that more time is required to allow the observed increases in muscle strength to impose stresses on the skeleton to elicit an osteogenic response. The estrogen deficient status of our subjects also may have necessitated a longer duration, since bone may be less responsive to mechanical loading in low estrogen conditions [37]. Several studies in young women have reported positive changes in BMD with WBV alone [29,38] and in combination with resistance exercise [29].

As indicated by other investigators [18,27], the WBV stimulus was well-tolerated by our older women participants, and no adverse side effects were reported. According to the literature, whole-body vibration (25–45 Hz) appears to be a safe and effective mode of enhancing muscular strength in a variety of populations. Although we did not observe direct benefits to bone, the increases in muscular strength and muscle mass [35] have important implications for osteoporosis prevention. Aging is associated with osteopenia and sarcopenia, often with sarcopenia preceding the loss of bone [39,40]. For this reason, low muscle strength is a risk factor for hip fracture [41].

In conclusion, whole-body vibration enhanced the positive effects of resistance training on upper and lower body muscular strength in postmenopausal women. In contrast, neither training protocol induced positive bone adaptations in this group of older women. Future research should continue to explore the optimal magnitude, duration, and frequency for vibration signals to elicit osteogenic responses; and whether it is beneficial to perform WBV in conjunction with resistance training protocols.

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