JOURNAL OF BONE AND MINERAL RESEARCH
Volume 19, Number 3, 2004
Published online on December 22, 2003; doi: 10.1359/JBMR.0301245

Effect of 6-Month Whole Body Vibration Training on Hip Density, Muscle Strength, and Postural Control in Postmenopausal Women: A Randomized Controlled Pilot Study

Sabine MP Verschueren,[1] Machteld Roelants,[2] Christophe Delecluse,[2] Stephan Swinnen,[1] Dirk Vanderschueren,[3] and Steven Boonen[4]

ABSTRACT: High-frequency mechanical strain seems to stimulate bone strength in animals. In this randomized controlled trial, hip BMD was measured in postmenopausal women after a 24-week whole body vibration (WBV) training program. Vibration training significantly increased BMD of the hip. These findings suggest that WBV training might be useful in the prevention of osteoporosis.

Introduction: High-frequency mechanical strain has been shown to stimulate bone strength in different animal models. However, the effects of vibration exercise on the human skeleton have rarely been studied. Particularly in postmenopausal women—who are most at risk of developing osteoporosis—randomized controlled data on the safety and efficacy of vibration loading are lacking. The aim of this randomized controlled trial was to assess the musculoskeletal effects of high-frequency loading by means of whole body vibration (WBV) in postmenopausal women.

Materials and Methods: Seventy volunteers (age, 58–74 years) were randomly assigned to a whole body vibration training group (WBV, $n = 25$), a resistance training group (RES, $n = 22$), or a control group (CON, $n = 23$). The WBV group and the RES group trained three times weekly for 24 weeks. The WBV group performed static and dynamic knee-extensor exercises on a vibration platform (35–40 Hz, 2.28–5.09g), which mechanically loaded the bone and evoked reflexive muscle contractions. The RES group trained knee extensors by dynamic leg press and leg extension exercises, increasing from low (20 RM) to high (8 RM) resistance. The CON group did not participate in any training. Hip bone density was measured using DXA at baseline and after the 6-month intervention. Isometric and dynamic strength were measured by means of a motor-driven dynamometer. Data were analyzed by means of repeated measures ANOVA.

Results: No vibration-related side effects were observed. Vibration training improved isometric and dynamic muscle strength (+15% and + 16%, respectively; $p < 0.01$) and also significantly increased BMD of the hip (+0.93%, $p < 0.05$). No changes in hip BMD were observed in women participating in resistance training or age-matched controls (−0.60% and −0.62%, respectively; not significant). Serum markers of bone turnover did not change in any of the groups.

Conclusion: These findings suggest that WBV training may be a feasible and effective way to modify well-recognized risk factors for falls and fractures in older women and support the need for further human studies.
J Bone Miner Res 2004;19:352–359. Published online on December 22, 2003; doi: 10.1359/JBMR.0301245

Key words: whole body vibration, mechanical loading, resistance training, osteoporosis

INTRODUCTION

As the world population ages, osteoporosis and osteoporotic fracture occurrence are becoming an increasingly important public health problem.[1] By any measure, proximal femoral fracture is the most devastating complication of osteoporosis. The mortality rate in patients with hip fracture is 12–20% higher than in persons of similar age and gender who have not suffered a fracture.[2] Of those who survive the operative intervention for an osteoporotic hip fracture, less than one-third are restored to their prefracture functional state.[3] Most strategies to treat postmenopausal bone loss have been focusing on antiresorptive medication. More recently, the potential contribution of load-

The authors have no conflict of interest.

[1]Laboratory of Motor Control, Department of Kinesiology, Faculteit Lichamelijke Opvoeding en Kinesitherapie, Katholieke Universiteit, Leuven, Belgium; [2]Laboratory of Exercise Physiology and Biomechanics, Department of Kinesiology, Faculteit Lichamelijke Opvoeding en Kinesitherapie, Katholieke Universiteit, Leuven, Belgium; [3]Leuven University Center for Metabolic Bone Diseases and Division of Endocrinology, Katholieke Universiteit, Leuven, Belgium; [4]Leuven University Center for Metabolic Bone Diseases and Division of Geriatric Medicine, Faculty of Medicine, Katholieke Universiteit, Leuven, Belgium.

Table 1. Baseline Characteristics of the Vibration Group (WBV), the Resistance Group (RES), and the Control (CON) Group (Mean ± SD)

	WBV (n = *25*)	*RES* (n = *22*)	*CON* (n = *24*)	p *Value*
Age (years)	64.6 ± 3.3	63.90 ± 3.8	64.2 ± 3.1	0.79
Years since menopause	16.9 ± 6.3	15.5 ± 6.0	14.6 ± 6.6	0.47
Body mass (kg)	66.5 ± 8.9	70.47 ± 9.6	68.56 ± 14.5	0.75
Height (m)	1.59 ± 0.05	1.61 ± 0.06	1.60 ± 0.06	0.39
BMI (kg/m^2)	26.34 ± 3.6	27.4 ± 3.5	26.51 ± 5.8	0.70
BMD whole body (g/cm^2)	1.02 ± 0.09	1.01 ± 0.08	1.03 ± 0.06	0.84
BMD proximal femur (g/cm^2)	0.88 ± 0.14	0.84 ± 0.09	0.84 ± 0.11	0.64
BMD lumbar spine (g/cm^2)	0.90 ± 0.14	0.90 ± 0.14	0.93 ± 0.14	0.71
Osteocalcin (ng/ml)	36.4 ± 7.4	33.7 ± 8.3	32.4 ± 6.3	0.71
C-telopeptide (ng/ml)	0.416 ± 0.159	0.454 ± 0.154	0.477 ± 0.244	0.55
Isometric strength (N.m)	113.0 ± 22.0	115.6 ± 24.2	114.3 ± 21.1	0.17
Dynamic strength (N.m)	81.1 ± 15.2	89.2 ± 16.0	83.7 ± 15.4	0.24
Fat mass (g)	24131 ± 5583	25332 ± 6507	25914 ± 9144	0.68

bearing exercise to preserve bone density and prevent osteoporosis has received some attention. In this regard, a relatively vigorous aerobic and strength training regimen has been shown to be most effective.[4] However, this approach has the inherent disadvantage of a lack of long-term compliance and may even increase the risk of fracture.[5] It is therefore imperative to continue the search for more attractive, low-risk exercise programs, with the goal of improving the outcome.

Recently, Rubin et al.[6] provided evidence in an animal model that low-risk, high-frequency mechanical accelerations may have a strong osteogenic effect. In their study, they observed a dramatic increase of the quality and quantity of trabecular bone in sheep when exposed to low-level, high-frequency mechanical stimuli. A high-frequency loading regimen applied to ovariectomized rats was effective in preventing early post-ovariectomy bone loss.[7] Overall, these experiments have given evidence that vibration loading may have potential for preventing and treating osteoporosis. However, in postmenopausal women—who are most at risk of sustaining osteoporotic fractures—the impact of this type of approach on bone quality (and, by implication, potentially on fracture risk) has not been evaluated.

The aim of this randomized controlled trial was therefore to assess musculoskeletal effects of high-frequency whole body vibration (WBV) training in postmenopausal women. Vibration training is increasingly being promoted as a safe and efficient training method to improve muscle strength.[8] During a vibration session, the subject stands on a platform that generates vertical sinusoidal vibrations at a frequency between 35 and 40 Hz. The mechanical stimuli are transmitted to the body, where they load the bone and also stimulate sensory receptors (most likely muscle spindles). The activation of these sensory receptors results in reflexive activation of motor units similar to the tonic vibration reflex.[9]

We hypothesized that, in addition to an increase in muscle strength caused by vibration-induced muscle activity, high-frequency loading of the skeleton might improve the mechanical competence of the skeleton in postmenopausal women. BMD of the total hip was selected as primary endpoint of this trial because the measurement is not confounded by degenerative changes and is highly predictive of future hip fracture risk.[10]

MATERIALS AND METHODS

Subjects and study design

Seventy postmenopausal women volunteered to participate in the study. Assessment of eligibility for participation was based on a screening by questionnaire and a thorough medical examination. Women had to be between 60 and 70 years of age, non-institutionalized, and free from diseases or medications known to affect bone metabolism or muscle strength. Subjects with a total body BMD T-score of less than −2.5 (the WHO definition for osteoporosis) were also excluded from this study. All subjects were randomly assigned to one of the study groups using computer-generated random numbers. A total of 25 women were trained for 6 months on a vibrating platform (WBV group). A group of 22 woman participated in a resistance training program (RES group). Both training programs consisted of 72 training sessions within a 24-week period. Training frequency was three times a week, with at least 1 day of rest between two sessions. A group of 23 age-matched women served as a control group (CON group) and did not participate in any training. The baseline characteristics of both groups are indicated in Table 1. All participants gave their informed written consent before enrollment, and the study protocol was approved by the Leuven University Human Ethics Committee.

WBV

The subjects in the WBV group performed static and dynamic knee-extensor exercises on the vibration platform (PowerPlate, Amsterdam. The Netherlands): squat, deep squat, wide stance squat, one-legged squat, and lunge. Training load was low at the beginning but progressed slowly according to the overload principle.[11] The training volume increased systematically over the 6-month training period by increasing the duration of one vibration session, the number of series of one exercise, or the number of different exercises. The training intensity was increased by shortening the rest periods or by increasing the amplitude

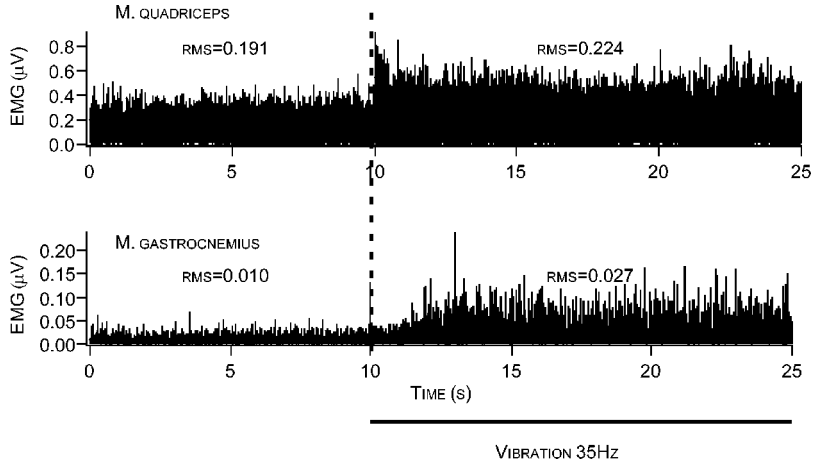

FIG. 1. Increased muscle activation in the m. rectus femoris and the m. gastrocnemius during vibrating training. RMS is the root mean square of the rectified EMG in the period without or with vibration.

(low, 1.7 mm; high, 2.5 mm) and/or the frequency (35–40 Hz) of the vibration. In addition, training load was increased by changing the execution form of the exercises from predominantly two-legged to one-legged exercises. The duration of the WBV program was a maximum of 30 minutes, which included warming up and cooling down.

The peak acceleration of the sinusoidal vibration stimulus—as recorded by an accelerometer (MTN 1800; Monitran, Bucks, UK)—varied between 2.28*g* and 5.09*g* (root mean square acceleration between 13.5 and 34.6 m/s^2). Of the 5*g* acceleration, as measured on the platform, only a fraction is transmitted through the feet to the hip and spine. However, the exact degree of transmissibility is unknown. Bipolar surface EMGs (Myosystem 2000; Noraxon, Scottsdale, AZ, USA) recorded from m. rectus femoris and from m. gastrocnemius illustrate the impact of the vibration on muscle activity (Fig. 1). During the vibration training sessions, the subjects wore similar gymnastic shoes to standardize the damping of the vibration cause by foot wear.

Resistance training

The subjects of the RES group trained in the Leuven University fitness center. They started with a standardized warm-up consisting of 20 minutes of stepping, running, or cycling. The intensity of these cardiovascular exercises was automatically controlled by heart rate (Technogym Systems, Gambettola, Italy) and systematically increased from 60% to 80% of the heart rate reserve as calculated by the formula of Karvonen.[12] After the warm-up, the participants performed a resistance training program for knee extensors on a leg extension and a leg press machine (Technogym Systems). The resistance training program was designed according to the guidelines of the American College of Sports Medicine (ASCM) for individuals older than 60 years of age: 10–15 repetitions to the point of volitional fatigue to elicit improvement in both muscular strength and endurance.[13] During the first 14 weeks of training, the intensity was systematically increased from two sets of 20 repetition maximum (RM) to two sets of 15 RM, two sets of 12 RM, two sets of 10 RM, and finally two sets of 8 RM. In the last 10 weeks, training volume and training intensity varied between three sets of 12 RM and one set of 8 RM. Each RES program lasted for about 1 h in total.

Control group

Control subjects were instructed to maintain their current level of physical activity during the 24 weeks of the study and not to engage in any new form of exercise. The subjects completed a questionnaire detailing their physical activity at the beginning of the study and at monthly intervals thereafter.

BMD assessment

At baseline and at 6 months, areal BMD of the total hip and the total body was assessed by DXA using the QDR-4500A device (Hologic, Waltham, MA, USA). Standard positioning was used, with anterior–posterior scanning of the right proximal femur.[14] Lean body mass, fat mass, and percent fat were obtained from the DXA scan of the total body. All scans were performed by the same experienced technician, who was unaware of the patient's intervention type. The CV for total hip DXA measurement in our laboratory is 0.56%.

Assessment of bone turnover

At baseline and at 6 months, serum osteocalcin and C-telopeptide levels (CTX) were determined as markers of bone formation and resorption, respectively. At these time points, fasting blood samples were collected from all individuals and stored at −70°C until they were analyzed. Circulating osteocalcin was measured using a previously developed radioimmunoassay (RIA).[15] Serum CTX was assessed by Serum CrossLaps One-Step ELISA (Osteometer BioTech, Herlev, Denmark) by a method previously described in detail.[16]

Assessment of muscle strength

The strength of the knee extensors was evaluated on a motor-driven dynamometer (REV9000; Technogym Systems) by isometric tests and dynamic tests.

Isometric strength: The subjects performed a maximal voluntary isometric contraction of the knee extensors twice. The knee joint angle was 130°. The isometric contractions lasted 3 s each and were separated by a 2-minute rest interval. The highest torque (N.m) was recorded as isomet-

ric strength performance. The CV for isometric strength measurement in our laboratory is 3.7%.

Dynamic strength: The subjects performed a series of four consecutive isokinetic flexion–extension movements against the lever arm of the dynamometer that moved at a velocity of 100°/s. The knee extension was initiated at a joint angle of 90° and ended at 160°. After each extension, the leg was returned passively to the starting position from which the next contraction was immediately initiated. Maximal dynamic strength was determined as the peak torque (N.m) recorded during these series of knee extensions. The CV for dynamic strength measurement in our laboratory is 3.3%.

Assessment of postural control

Postural sway was measured before and after the 24 week period using a Bertec force plate connected to a CED Micro 1401 data acquisition system and using spike2 software. Postural sway of each subject was tested under four conditions: quiet stance with vision, quiet stance with vision occluded by means of liquid-cristal goggles, quiet stance after a perturbation by a brief voluntary abduction of the arms to horizontal, and quiet stance after a brief anteflexion of the arms to horizontal. Postural sway was assessed in the WBV group and CON group, but not in the RES group.

Statistical analysis

A one-way ANOVA was used to test for baseline differences among the WBV group, the RES group, and the CON group. The effects of the interventions were analyzed by means of repeated measures ANOVA. After an F value was found to be significant for the interaction between group and time, preplanned contrast analyses were performed to evaluate significant pre–post changes in each group. A Bonferroni correction was used to adjust the p value in relation to the number of contrasts that were performed. All analyses were executed using the statistical package Statistica (version 6; Statsoft, Hamburg, Germany.). The level of significance was set at $p < 0.05$.

Table 2. Mean Changes and Between-Group Differences in Muscle Strength, Hip Bone Density, and Body Composition During the Intervention Period

	WBV group	*CON group*	*Between-group difference*	
			Mean	p *Value*
Isometric strength	+15.10	−2.49	17.59	<0.001
Isotonic strength	+16.47	+2.23	14.24	<0.001
Total hip BMD	+0.93	−0.62	1.55	0.005
Total body BMD	+0.44	−0.28	0.72	0.24
Muscle mass	−0.08	−1.2	−1.12	0.57
Fat mass	−2.3	+0.5	2.8	0.09

	WBV group	*RES group*	*Between-group difference*	
			Mean	p *Value*
Isometric strength	+15.10	+16.49	−1.39	0.99
Isotonic strength	+16.47	+10.59	5.88	0.54
Total hip BMD	+0.44	+0.14	0.30	0.01
Total body BMD	+0.93	−0.51	1.44	0.99
Muscle mass	−0.08	+0.06	−0.14	0.99
Fat mass	−2.3	−3.1	0.66	0.99

	RES group	*CON group*	*Between-group difference*	
			Mean	p *Value*
Isometric strength	+16.49	−2.49	18.98	<0.001
Isotonic strength	+10.59	+2.23	8.36	0.05
Total hip BMD	+0.14	−0.28	0.42	0.99
Total body BMD	−0.51	−0.62	0.11	0.99
Muscle mass	+0.06	−1.2	1.26	0.37
Fat mass	−3.1	+0.5	−3.60	0.01

RESULTS

No significant differences were observed at baseline between the experimental and the control groups in terms of age, weight, body mass, years since menopause, BMD, serum levels of osteocalcin and CTX, isometric and dynamic muscle strength, fat mass, or lean body mass (Table 1).

Isometric strength of the knee extensors increased by 15% (95% CI, 10.6–19.5; $p < 0.001$) in the WBV group and by 16% in the RES group (95% CI, 9.1–23.9; $p < 0.001$). In the control group, a nonsignificant decline of 2% was observed (95% CI, −6.9–2.01; $p = 0.57$). Compared with the CON group, the 6-month vibration intervention resulted in a significant 17.6% net benefit in isometric quadriceps strength ($p < 0.001$; Table 2). A similar benefit was observed in the RES group (+18.9% versus the CON group, $p < 0.001$).

Dynamic strength increased by 16.5% (95% CI, 9.4–23.5) and 10.6% (95% CI, 5.6–15.5) in the WBV group and RES group, respectively ($p < 0.001$). In the controls, no significant change was observed (+2.2%; 95% CI, −1.5–5.9; $p = 1.14$). Again, both the WBV and RES groups showed a significant net benefit over time compared with the CON group (+14.2% and + 8.4%, respectively; $p < 0.001$).

As shown in Fig. 2, total hip BMD increased over time in the WBV training group (+0.93%; 95% CI, 0.13–1.71; $p = 0.03$), whereas no changes in hip BMD were observed in women participating in resistance training or age-matched controls (−0.51%; 95% CI, −1.13 to −0.11; $p = 0.41$ and −0.62%; 95% CI, −1.30–0.07; $p = 0.16$, respectively). Compared with the RES group, the 6-month vibration intervention resulted in a significant 1.51% net benefit in total hip BMD ($p < 0.05$). A similar net benefit (1.53%, $p < 0.01$) was observed in comparison with the CON group. The gain in total hip BMD in the WBV group was statistically unrelated to the increases in isometric or dynamic strength ($r = -0.23$, $p = 0.29$ and $r = 0.28$, $p = 0.20$, respectively).

Total body BMD and lumbar spine BMD did not change over time in any of the groups, and none of the between-group differences were statistically significant. Similarly, no significant between-group differences were observed in the markers of bone remodeling, osteocalcin, and CTX (Table 3).

The gain in muscle strength in the WBV and RES groups was not associated with a significant change in lean body

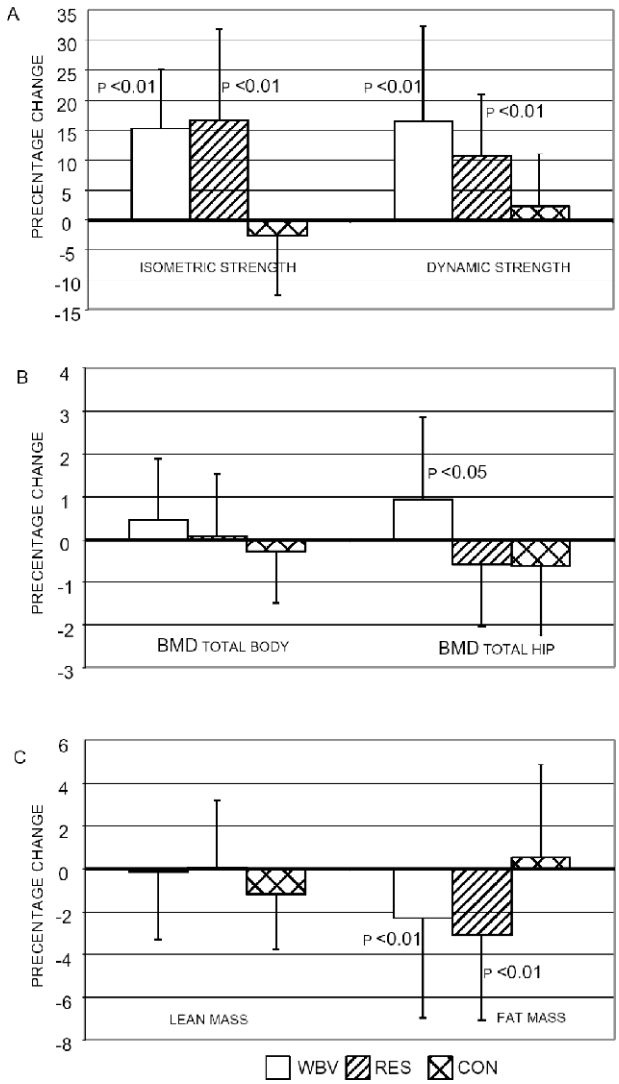

FIG. 2. Percent changes across 24 weeks in (A) isometric and dynamic muscle strength, (B) total body and total hip BMD, and (C) lean and fat mass in the three experimental groups (WBV, RES, and CON).

mass (Table 3). However, in both groups, total fat mass decreased significantly during the intervention period (−2.3%; 95% CI, −4.3 to −0.4; $p = 0.01$ in the WBV group and −3.1%; 95% CI, −4.9 to −1.3; $p < 0.001$ in the RES group). In contrast, no significant change in fat mass was observed in the CON group (+0.5%; 95% CI, −1.3–2.4, $p = 0.60$).

The effects of WBV training on postural sway are summarized in Table 4. Postural sway (rms and peak-to-peak amplitude) during unperturbed stance with or without vision did not change because of WBV training (data not shown). After a fast, brief abduction of the arms, the peak-to-peak amplitude of sway in the anterior–posterior direction was significantly decreased during the WBV training ($p < 0.05$). Similarly, the peak-to-peak amplitude of sway in medio–lateral direction after a brief anteflexion of the arms was significantly decreased because of WBV training ($p = 0.05$). None of these variables changed across the 24 weeks in the CON group.

DISCUSSION

There is increasing evidence that load-bearing represents a very important functional influence on bone mass.[5] Increased bone density after loading shows that bone tissue accommodates to changes in the mechanical environment; this process allows the skeleton to resist the rigors of functional activity.[17,18] However, particularly in elderly individuals, strenuous load-bearing exercises may increase the risk for injuries.[19] Moreover, there is evidence that the osteogenic effect of load-bearing may decline with aging.[20] The search therefore continues for alternative strategies that make loading less risky and/or may enhance the effectiveness of the adaptive bone response to loading. The training paradigm presented here might potentially offer such a strategy for postmenopausal woman, because the results show that 24 weeks of WBV training—which mechanically loads the bone and evokes reflexive muscle contractions—was not associated with vibration-related side effects and resulted in increased hip BMD. The mean change in total hip BMD in the WBV group (with a net benefit of about 1.5% at 6 months compared with controls) is similar in magnitude to the gain in (hip) BMD observed with antiresorptive agents at the 6-month time point in recent osteoporosis trials,[21,22] supporting its *potential* clinical relevance. We found no effect of the vibration intervention on bone turnover rate, indicating that its positive impact on BMD did not result from reduced bone resorption. In line with the lack of significant changes in overall rate of bone turnover, no changes were observed in total body or lumbar spine BMD, suggesting that the effects of vibration on total hip BMD reflect a local (site-specific) loading effect of vibration.

In addition to their gain in BMD, and not unexpectedly,[8] the subjects in the vibration group showed improved recovery of balance after ballistic abduction or anteflexion of the arms and experienced an increase in (isometric and isokinetic) muscle strength and a decline in fat mass. The changes in muscle strength were similar in magnitude than those in the resistance training group. The gain in BMD during the 6-month intervention, however, was statistically unrelated to the increases in isometric or dynamic strength, suggesting that the osteogenic effect was not mediated by reflexive muscle contractions. This assumption is supported by the fact that the gain in lower limb extension strength in the resistance training group was not paralleled by a concomitant increase in bone density.

Controlled loading studies have indicated that high strain magnitudes and high strain rates are the most osteogenic.[23,24] The loading regimen provided by the WBV program in this study combined both. It has been commonly assumed that the large amplitude signals inherent to intense functional activity define bone morphology.[25] Strain on the bones increases linearly with increased ground reaction forces.[26] In our study, the ground reaction forces ranged between 2.5 times body weight at the start of the program to 5 times body weight from week 3 onward. The loading of the skeleton during the vibration intervention can therefore be considered as a high-strain event of similar impact than activities like basketball, volleyball, and sprinting.[27] In this regard, the results of this trial are in agreement with previ-

Table 3. Muscle Strength, Hip Bone Density, Bone Turnover, and Body Composition at Baseline and After the 6-Month Intervention Period

	WBV group	*RES group*	*CON group*	*Between-group difference for the change over time (p Value)**
BMD whole body (g/cm^2)				
Baseline	1.027 ± 0.099	1.016 ± 0.078	1.030 ± 0.068	
6 months	1.031 ± 0.096	1.016 ± 0.077	1.027 ± 0.069	0.21
BMD femur (g/cm^2)				
Baseline	0.878 ± 0.136	0.841 ± 0.094	0.846 ± 0.109	
6 months	0.886 ± 0.134†	0.836 ± 0.098	0.840 ± 0.105	0.003
BMD L_1–L_4 (g/cm^2)				
Baseline	0.904 ± 0.143	0.900 ± 0.136	0.926 ± 0.146	
6 months	0.901 ± 0.145	0.901 ± 0.135	0.930 ± 0.146	0.33
Osteocalcin				
Baseline	36.4 ± 7.3	33.7 ± 8.2	32.4 ± 6.3	
6 months	30.9 ± 5.4	34.7 ± 4.5	33.5 ± 5.4	0.19
C-telopeptide				
Baseline	0.416 ± 0.160	0.454 ± 0.154	0.477 ± 0.244	
6 months	0.332 ± 0.128	0.411 ± 0.166	0.379 ± 0.198	0.33
Isometric strength (Nm)				
Baseline	113.0 ± 22.0	115.7 ± 24.2	114.3 ± 21.0	
6 months	131.3 ± 23.8†	132.5 ± 22.1†	110.6 ± 19.0	<0.001
Isotonic strength (Nm)				
Baseline	81.1 ± 15.2	89.2 ± 16.0	83.7 ± 15.4	
6 months	94.8 ± 16.2‡	97.9 ± 16.7‡	85.4 ± 16.1	<0.001
Muscle mass (g)				
Baseline	40030 ± 3853	41305 ± 4323	39877 ± 5125	
6 months	39967 ± 3802	41339 ± 4510	39357 ± 4828	0.25
Fat mass (g)				
Baseline	24131 ± 5583	25332 ± 6507	25914 ± 9144	
6 months	23550 ± 5499*	24504 ± 6466‡	26044 ± 9307	0.01

*Group-by-time interaction in repeated measures ANOVA on pre–post data.
†,‡Significant pre–post difference within group ($^\dagger p < 0.05$ and $^\ddagger p < 0.01$).

ous studies showing positive effects of high-impact exercise regimens on bone density.[28] It has been hypothesized that loading reduces the rate of bone resorption and increases bone formation in proportion to the peak strain magnitude.[23] However, while we observed an increase in hip bone density in the vibration group within 6 months, positive effects of high-impact exercises on BMD have not even been observed within the first year of training.[28]

It is therefore tempting to speculate that the high frequency of vibration (35–40 Hz; i.e., the high strain rate) may have played a key role in the early osteogenic effect observed in this study. Whereas loads applied at 1 Hz must exceed 1000 microstrain to stimulate bone formation,[29] 30-Hz loads only need strains of 50 microstrain to achieve similar results.[30] Animal research by Rubin et al.[6,17] has provided evidence that these low-level, high-frequency mechanical stimuli may be anabolic to (trabecular) bone. In their experiments in adult female sheep, histomorphometric examination of the femur after 1 year of stimulation revealed an increase in bone volume per total volume by 32%, resulting in a 27% improvement in trabecular bone strength. However, although bone morphology and structure were dramatically being reinforced, no changes were identified with DXA measurements. This made Rubin et al.[17] conclude that when DXA does identify change, as in our trial, the change is likely to be relevant.

In a very recent well-designed study in young healthy adults, Torvinen et al.[31] found no effect of WBV training on mass, structure, and estimated strength of bone. The authors argued that one reason for this nonresponse could be the good basic physical condition of the young subjects, with the musculoskeletal tissues of these young adults having no particular physiological need to adapt to the vibration loading. They suggested that a skeletal response to vibration might have been observed in older individuals, as is the case in our study. However, as Torvinen et al.[31] indicated as well, the vibration stimulus can be varied in multiple ways (including type, magnitude, frequency, and duration), and different types of vibration loading are likely to result in different effects on bone mass and structure. In their trial, the duration of daily stimulus was only 4 minutes, three to five times per week, considerably less than the 20-minute stimulus in this study. Their stimulus might have been insufficient to require adaptation.

To date, the mechanism underlying the osteogenic effect of high-frequency stimuli is not completely understood. Rubin et al.[17] hypothesized that the adaptive response of the bone to high-frequency stimuli may not be a direct consequence of bone tissue deformation (as during high-impact loading), but may rather be mediated by byproducts of the high-frequency strain signal, such as shear stress arising from fluid flow. Alternatively, the mechanism be-

Table 4. Postural Sway (Peak-to-Peak) Recovery After Abduction or Anteflexion of the Arms at Baseline and After the 6-Month Intervention Period

	WBV group	*COM group*	*Between-group difference for the change over time**
Abduction A-P (mm)			
Baseline	9.6 ± 3.3	7.7 ± 2.1	
6 months	8.1 ± 2.2†	8.6 ± 3.4	0.003
Abduction M-L (mm)			
Baseline	4.4 ± 1.2	3.9 ± 1.1	
6 months	4.0 ± 1.2	4.1 ± 1.1	0.10
Anteflexion A-P (mm)			
Baseline	9.1 ± 2.7	8.3 ± 1.9	
6 months	8.7 ± 1.9	8.4 ± 1.4	0.59
Anteflexion M-L (mm)			
Baseline	4.7 ± 1.7	4.2 ± 1.1	
6 months	4.1 ± 1.0†	4.4 ± 1.2	0.03

*Group-by-time interaction in repeated ANOVA on pre–post data.
†Significant pre–post difference within group ($p < 0.05$).

hind the frequency-dependent adaptive response of bone to loading might be the so-called stochastic resonance. Stochastic resonance is a phenomenon in which mechanical noise (broad-band frequency of vibration) enhances the response of a nonlinear system to a weak signal by boosting it over a threshold. Previous studies have shown that stochastic resonance can enhance the mechanosensitivity of different mechanoreceptors in our body, like the muscle spindles.[32] Recent in vitro and in vivo evidence suggests that (cortical) bone formation in response to mechanical loading can be enhanced by adding noise to a (high-impact) exercise regimen.[33,34] Tanaka et al.[33] showed that a vibratory stimulus added to a low-frequency, high-amplitude strain enhances the osteogenic response of the strain by almost 4-fold. In the present trial, we applied both a large-amplitude strain and a high-frequency vibratory stimulus. Stochastic resonance may therefore have contributed to the observed increase in BMD.

In certain professions (e.g., tractor drivers, pilots, etc.) a (potential) association has been observed between long-term exposure to WBV and chronic lower back pain.[35] However, evidence in favor of a dose–response association is weak, and it remains to be clarified whether there is a causal link between work-related WBV and low back pain. As indicated, we observed no vibration-related side effects. In particular, low back pain or other symptoms or injuries did not occur. Our short-term findings are in line with those previously reported by Rittweger et al.,[36] who recently even performed a randomized controlled trial to compare lumbar extension exercise and WBV exercise for the treatment of chronic lower back pain.[37] Nevertheless, we acknowledge that the lack of safety concerns in the context of a 6-month trial in healthy volunteers does not exclude the potential for long-term side effects in unselected elderly individuals. Research is needed to further address the long-term safety of WBV training in older women.

Our study has limitations, and the results should be interpreted in the context of its design. Although we observed a significant increase in (total hip) BMD from baseline in the vibration group and significant between-group differences, we acknowledge that the number of observations was small. As indicated, we can only speculate about the mechanisms underlying the increase in BMD and the extent to which this increase reflects differential effects on cortical and trabecular bone. Many questions remain as to whether these short-term effects would persist over time and as to how the training protocol can be further optimized in terms of osteogenic effects. We selected a training program on the vibration platform that was likely to have positive effects on muscle and bone tissue. It is possible that high-frequency or even broad-frequency vibration at a lower strain amplitude, superimposed with some larger strains at intermittent intervals, might be more osteogenic (but at the expense of gain in strength). Also, our results may not be generalizable because the participants were healthy volunteers and not a random sample of the general older population. Finally, the usefulness and safety of this type of training in the long-term prevention of postmenopausal osteoporosis and osteoporotic fracture occurrence remain unknown.

In conclusion, in healthy postmenopausal women, a 24-week whole body vibration program is feasible and able to modify muscle strength, balance, and hip bone density, which are well-recognized risk factors for hip fracture.[10] Future human studies are needed to confirm these short-term findings and further explore the potential of vibration loading for preventing and treating osteoporosis.

ACKNOWLEDGMENTS

SB is a core member of the ASBMR Working Group on Musculoskeletal Rehabilitation. The authors thank all the participants for taking part in this study. They also thank G Van der Meer, J Tempelaars, and N De Poot for help in designing the training program; Drs E Van den Eede and K Pardaens for the medical screening of the subjects; and H Borghs and H Peeters for conducting the DXA measurements. This study was supported by Grant G.0171.03 from the Fund for Scientific Research-Flanders, Belgium (F.W.O.-Vlaanderen) to SB. SMPV is a postdoctoral fellow of the Fund for Scientific Research-Flanders, Belgium. SB and DV are senior clinical investigators of the Fund for Scientific Research-Flanders, Belgium. SB is holder of the Leuven University Chair in Metabolic Bone Diseases, supported by Marck Sharp & Dohme.

REFERENCES

1. Kannus P, Parkkari J, Niemi S 1995 Age-adjusted incidence of hip fractures. Lancet **346:**50–51.
2. Autier P, Haentjens P, Bentin J, Baillon JM, Grivegnee AR, Closon MC, Boonen S 2000 Costs induced by hip fractures: A prospective controlled study in Belgium. Belgian Hip Fracture Study Group. Osteoporos Int **11:**373–380.
3. Magaziner J, Simonsick EM, Kashner TM, Hebel JR, Kenzora JE 1990 Predictors of functional recovery one year following hospital discharge for hip fracture: A prospective study. J Gerontol **45:** M101–M107.
4. Gutin B, Kasper MJ 1992 Can vigorous exercise play a role in osteoporosis prevention? A review. Osteoporos Int **2:**55–69.
5. Lanyon LE 1996 Using functional loading to influence bone mass and architecture: Objectives, mechanisms, and relationship with estrogen of the mechanically adaptive process in bone. Bone **18**(Suppl 1)**:**37S–43S.

6. Rubin C, Turner AS, Muller R, Mittra E, McLeod K, Lin W, Qin YX 2002 Quantity and quality of trabecular bone in the femur are enhanced by a strongly anabolic, noninvasive mechanical intervention. J Bone Miner Res **17:**349–357.
7. Flieger J, Karachalios T, Khaldi L, Raptou P, Lyritis G 1998 Mechanical stimulation in the form of vibration prevents postmenopausal bone loss in ovariectomized rats. Calcif Tissue Int **63:**510–514.
8. Delecluse C, Roelants M, Verschueren S 2003 Strength increase after whole-body vibration compared with resistance training. Med Sci Sports Exerc **35:**1033–1041.
9. Burke D, Schiller HH 1976 Discharge pattern of single motor units in the tonic vibration reflex of human triceps surae. J Neurol Neurosurg Psychiatry **39:**729–741.
10. Cummings SR, Nevitt MC, Browner WS, Stone K, Fox KM, Ensrud KE, Cauley J, Black D, Vogt TM 1995 Risk factors for hip fracture in white women. Study of Osteoporotic Fractures Research Group. N Engl J Med **332:**767–773.
11. American College of Sports Medicine 2000. Exercise prescription. In: Franklin BA, Whaley MH, Howley ET (eds.) ACSM's Guidelines for Exercise Testing and Prescription. Lippincott Williams and Wilkins, Philadelphia, PA, USA, pp. 138–139.
12. Karvonen M, Kentala K, Mustala O 1957 The effects of training on heart rate: A longitudinal study. Ann Med Experimentalis et Biologiae Fenniae **35:**307–315.
13. American College of Sports Medicine 1998 American College of Sports Medicine Position Stand. Exercise and physical activity for older adults. Med Sci Sports Exerc **30:**992–1008.
14. Boonen S, Rosen C, Bouillon R, Sommer A, McKay M, Rosen D, Adams S, Broos P, Lenaerts J, Raus J, Vanderschueren D, Geusens P 2002 Musculoskeletal effects of the recombinant human IGF-I/IGF binding protein-3 complex in osteoporotic patients with proximal femoral fracture: A double-blind, placebo-controlled pilot study. J Clin Endocrinol Metab **87:**1593–1599.
15. Bouillon R, Vanderschueren D, Van Herck E, Nielsen HK, Bex M, Heyns W, Van Baelen H 1992 Homologous radioimmunoassay of human osteocalcin. Clin Chem **38:**2055–2060.
16. Rosenquist C, Fledelius C, Christgau S, Pedersen BJ, Bonde M, Qvist P, Christiansen C 1998 Serum CrossLaps One Step ELISA. First application of monoclonal antibodies for measurement in serum of bone-related degradation products from C-terminal telopeptides of type I collagen. Clin Chem **44:**2281–2289.
17. Rubin C, Turner AS, Mallinckrodt C, Jerome C, McLeod K, Bain S 2002 Mechanical strain, induced noninvasively in the high-frequency domain, is anabolic to cancellous bone, but not cortical bone. Bone **30:**445–452.
18. Wolff J 1986 The law of bone remodeling. In: Maquet P, Furlong R (eds.) Bone Remodeling. Springer Verlag, Berlin, Germany.
19. Kallinen M, Markku A 1995 Aging, physical activity and sports injuries. An overview of common sports injuries in the elderly. Sports Med **20:**41–52.
20. Turner CH, Takano Y, Owan I 1995 Aging changes mechanical loading thresholds for bone formation in rats. J Bone Miner Res **10:**1544–1549.
21. Ettinger B, Black DM, Mitlak BH, Knickerbocker RK, Nickelsen T, Genant HK, Christiansen C, Delmas PD, Zanchetta JR, Stakkestad J, Gluer CC, Krueger K, Cohen FJ, Eckert S, Ensrud KE, Avioli LV, Lips P, Cummings SR 1999 Reduction of vertebral fracture risk in postmenopausal women with osteoporosis treated with raloxifene: Results from a 3-year randomized clinical trial. Multiple Outcomes of Raloxifene Evaluation (MORE) Investigators. JAMA **282:**637–645.
22. Harris ST, Watts NB, Genant HK, McKeever CD, Hangartner T, Keller M, Chesnut CH III, Brown J, Eriksen EF, Hoseyni MS, Axelrod DW, Miller PD 1999 Effects of risedronate treatment on vertebral and nonvertebral fractures in women with postmenopausal osteoporosis: A randomized controlled trial. Vertebral Efficacy With Risedronate Therapy (VERT) Study Group. JAMA **282:**1344–1352.
23. Rubin CT, Lanyon LE 1985 Regulation of bone mass by mechanical strain magnitude. Calcif Tissue Int **37:**411–417.
24. Turner CH, Owan I, Takano Y 1995 Mechanotransduction in bone: Role of strain rate. Am J Physiol **269:**E438–E442.
25. Frost HM 1990 Skeletal structural adaptations to mechanical usage (SATMU): 1. Redefining Wolff's law: The bone modeling problem. Anat Rec **226:**403–413.
26. Bassey EJ, Littlewood JJ, Taylor SJ 1997 Relations between compressive axial forces in an instrumented massive femoral implant, ground reaction forces, and integrated electromyographs from vastus lateralis during various 'osteogenic' exercises. J Biomech **30:**213–223.
27. Groothausen J, Siemer H, Kemper HCG, Twisk J, Welten DC 1997 Influence of peak strain on lumbar bone mineral density: An analysis of 15-year physical activity in young males and females. Pediatr Exerc Sci **9:**159–173.
28. Heinonen A, Kannus P, Sievanen H, Oja P, Pasanen M, Rinne M, Uusi-Rasi K, Vuori I 1996 Randomised controlled trial of effect of high-impact exercise on selected risk factors for osteoporotic fractures. Lancet **348:**1343–1347.
29. Rubin CT, Lanyon LE 1987 Kappa Delta Award paper. Osteoregulatory nature of mechanical stimuli: Function as a determinant for adaptive remodeling in bone. J Orthop Res **5:**300–310.
30. Qin YX, Rubin CT, McLeod KJ 1998 Nonlinear dependence of loading intensity and cycle number in the maintenance of bone mass and morphology. J Orthop Res **16:**482–489.
31. Torvinen S, Kannus P, Sievanen H, Jarvinen TA, Pasanen M, Kontulainen S, Nenonen A, Jarvinen TL, Paakkala T, Jarvinen M, Vuori I 2003 Effect of 8-month vertical whole body vibration on bone, muscle performance, and body balance: A randomized controlled study. J Bone Miner Res **18:**876–884.
32. Cordo P, Inglis JT, Verschueren S, Collins JJ, Merfeld D, Rosenblum S, Buckley S, Moss F 1996 Noise in human muscle spindles. Nature **383:**769–770.
33. Tanaka SM, Alam IM, Turner CH 2003 Stochastic resonance in osteogenic response to mechanical loading. FASEB J **17:**313–314.
34. Tanaka SM, Li J, Duncan RL, Yokota H, Burr DB, Turner CH 2003 Effects of broad frequency vibration on cultured osteoblasts. J Biomech **36:**73–80.
35. Lings S, Leboeuf-Yde C 2000 Whole-body vibration and low back pain: A systematic, critical review of the epidemiological literature 1992–1999. Int Arch Occup Environ Health **73:**290–297.
36. Rittweger J, Beller G, Felsenberg D 2000 Acute physiological effects of exhaustive whole-body vibration exercise in man. Clin Physiol **20:**134–142.
37. Rittweger J, Just K, Kautzsch K, Reeg P, Felsenberg D 2002 Treatment of chronic lower back pain with lumbar extension and whole-body vibration exercise: A randomized controlled trial. Spine **27:**1829–1834.

Address reprint requests to:
Steven Boonen, MD, PhD
Division of Geriatric Medicine
Leuven University Center for Metabolic Bone Diseases
Universitaire Ziekenhuizen K.U. Leuven
Herestraat 49
Leuven B-3000, Belgium
E-mail: steven.boonen@uz.kuleuven.ac.be

Received in original form July 9, 2003; in revised form October 8, 2003; accepted November 4, 2003.