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Effect of 8-Month Vertical Whole Body Vibration on Bone, Muscle Performance, and Body Balance: A Randomized Controlled Study

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ABSTRACT

Recent animal studies have given evidence that vibration loading may be an efficient and safe way to improve mass and mechanical competence of bone, thus providing great potential for preventing and treating osteoporosis. Randomized controlled trials on the safety and efficacy of the vibration on human skeleton are, however, lacking. This randomized controlled intervention trial was designed to assess the effects of an 8-month whole body vibration intervention on bone, muscular performance, and body balance in young and healthy adults. Fifty-six volunteers (21 men and 35 women; age, 19–38 years) were randomly assigned to the vibration group or control group. The vibration intervention consisted of an 8-month whole body vibration (4 min/day, 3–5 times per week). During the 4-minute vibration program, the platform oscillated in an ascending order from 25 to 45 Hz, corresponding to estimated maximum vertical accelerations from 2*g* to 8*g*. Mass, structure, and estimated strength of bone at the distal tibia and tibial shaft were assessed by peripheral quantitative computed tomography (pQCT) at baseline and at 8 months. Bone mineral content was measured at the lumbar spine, femoral neck, trochanter, calcaneus, and distal radius using DXA at baseline and after the 8-month intervention. Serum markers of bone turnover were determined at baseline and 3, 6, and 8 months. Five performance tests (vertical jump, isometric extension strength of the lower extremities, grip strength, shuttle run, and postural sway) were performed at baseline and after the 8-month intervention. The 8-month vibration intervention succeeded well and was safe to perform but had no effect on mass, structure, or estimated strength of bone at any skeletal site. Serum markers of bone turnover did not change during the vibration intervention. However, at 8 months, a 7.8% net benefit in the vertical jump height was observed in the vibration group (95% CI, 2.8–13.1%; $p = 0.003$). On the other performance and balance tests, the vibration intervention had no effect. In conclusion, the studied whole body vibration program had no effect on bones of young, healthy adults, but instead, increased vertical jump height. Future human studies are needed before clinical recommendations for vibration exercise. (J Bone Miner Res 2003;18:876–884)

Key words: whole body vibration, bone, performance, osteoporosis

INTRODUCTION

OSTEOPOROSIS, FALLS, AND related fractures of elderly people have become a worldwide epidemic,[1–7] and because of the severe consequences of these incidents, many prevention and treatment strategies and regimens have been developed to lessen this increasing public health problem. Because osteoporotic fractures are a result of a combination of bone fragility (osteoporosis) and the force applied to the bone (usually as a result of a fall),[4,8] attention has been paid to improve both the quality and quantity of the bone tissue and the functional capability of the elderly people.

It is known that adaptation of bone to physical activity and mechanical loading is crucial in improving and main-

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taining bone mass and strength,[9–14] but the specific mechanisms behind this adaptation are unknown. Deformations in bone tissue (*strains*), which result from the mechanical stress within the bone tissue, or their immediate consequences (e.g., changes in the intralacunar pressure or fluid flow inside the bone), are believed to be important in increasing bone mass.[15] According to the conventional wisdom, mechanical stress should be different from that experienced habitually to have influence on bone tissue.[16] However, it has also been presented that mechanical loading, which does not contain abnormally high-magnitude strains but instead involves strains that are imposed with a high strain rate and/or distributed to bone in an uncustomary way, can also be osteogenic.[11,15,17,18] Furthermore, very recent experimental studies have suggested that even extremely low-magnitude strains, several orders of magnitude below those that damage bone tissue, can efficiently increase bone mass and improve bone morphology if they are applied at high frequency[19–24]: Rubin et al. showed that after a 1-year period of high-frequency (30 Hz), small-amplitude (0.3*g*) mechanical vibration (applied for 20 min/day for 5 days/week), the trabecular bone density of the proximal femur was 34% greater in the vibrated sheep than control sheep.[21] In addition, vibration loading has been suggested to efficiently prevent ovariectomy-induced bone loss.[25]

Thus, it is not surprising that mechanical vibration has recently aroused great interest in osteoporosis research and exercise physiology. To make the vibration stimuli even more compelling in the prevention of osteoporosis-related fractures, some clinical studies have suggested further that vibration may, besides being osteogenic, improve muscular performance and body balance.[26–32] These features make vibration very appealing approach, because good functional performance of the elderly subjects is known to be one of the major factors in prevention of falls.[4,33–38]

Despite the preliminary positive results and high anticipations for vibration loading, randomized controlled human studies on the effects of vibration on mass, structure, and mechanical competence of bone, as well as on the fall-related risk factors of osteoporotic fractures, are lacking. The objective of this study was, therefore, to investigate with a randomized controlled study design the effects of an 8-month whole body vibration intervention on bone, muscular performance, and body balance in healthy, young volunteers. The study also addressed the safety issues of the long-term vibration loading.

MATERIALS AND METHODS

Subjects and study design

Fifty-six young healthy nonathletic volunteers (21 men and 35 women; age, 19–38 years) from the local university participated in the study. The subjects were randomly assigned to the vibration group or control group using computer-generated random numbers. All baseline measurements (see below) were done before the randomization, which was done very close to the start of the intervention. The men and women were randomized separately into these two groups so that the number of men and women would be similar in both groups. The exclusion criteria from the study were any cardiovascular, respiratory, abdominal, urinary, gynecological, neurological, musculoskeletal, or other chronic diseases; pregnancy; prostheses; medications that could affect the musculoskeletal system; menstrual irregularities; and participation in impact-type exercises more than three times a week.

The vibration protocol consisted of an 8-month whole body vibration training (see below). The effects of vibration intervention on bone mass, structure, and strength were evaluated by DXA and peripheral quantitative computed tomography (pQCT) at baseline and at the end of the study. Serum markers of bone turnover were analyzed at baseline and at 3, 6, and 8 months. The physical performance tests were done at baseline and at 8 months (see below).

The subjects completed a questionnaire detailing their physical activity and calcium intake (from a 7-day calcium intake diary)[39] at the beginning of the study and at 2-month intervals thereafter. All participants gave their informed written consent before enrollment, and the study protocol was approved by the Institutional Review Board as well as the Ethics Committee of the Tampere University Hospital, Tampere, Finland.

Vibration loading intervention

The vibration loading was carried out in a standing position on a whole body vibration platform (Kuntotäry; Erka Oy, Kerava, Finland), and the vibration-group subjects were asked to train with it three to five times a week. The control subjects were asked not to change their current physical activity. The peak-to-peak amplitude of the vertical vibration was 2 mm. The duration of daily stimulus was 4 minutes. While standing on the platform, the subjects repeated a 60-s light exercise program four times according to instructions. The purpose of the exercise program was to provide a multidirectional vibration exposure on the body and to make standing on the platform less monotonous. The program consisted of light squatting (0–10 s), standing in the erect position (10–20 s), standing in a relaxed position with slightly flexed knees (20–30 s), light jumping (30–40 s), alternating the body weight from one leg to another (40–50 s), and standing on the heels (50–60 s). During the 8-month vibration intervention, the vibration frequency increased in 1-minute intervals. In the first 2 weeks, the duration of the loading was 2 minutes, and frequency of vibration was 25 Hz for the first minute and 30 Hz for the second minute (a run-in period). During the next 1.5 months, the duration of the vibration loading was 3 minutes and frequency 25 Hz for 1 minute, 30 Hz for 2 minutes, and 35 Hz for 3 minutes. During the following 2 months, the duration was 4 minutes and the frequency was 25 Hz for 1 minute, 30 Hz for 2 minutes, 35 Hz for 3 minutes, and 40 Hz for 4 minutes. During the final 4 months, the frequency of vibration was increased further: 30 Hz for 1 minute, 35 Hz for 2 minutes, 40 Hz for 3 minutes, and 45 Hz for 4 minutes.

Bone measurements

DXA: Bone mineral content (BMC, g) was measured according to our standard procedures from the lumbar spine (L2–L4), right proximal femur (femoral neck and trochanter

area of the femur), calcaneus, and nondominant distal radius using DXA (Norland XR-26; Norland Inc., Fort Atkinson, WI, USA).[40]

The heights of the region-of-interest (ROI) used in the DXA analyses were adjusted to be anatomically comparable between the subjects, as well as between the two measurements of the same subject.[40] The femoral neck BMC and trochanter BMC were normalized by the length of the respective ROI. This normalization not only provides a comparable in vivo precision to bone mineral density (BMD) measurement but also provides a physical interpretation to normalized BMC, that is, the average cross-sectional area of the femoral neck and trochanter occupied by bone mineral.[41] In our laboratory, the in vivo day-to-day precision (CV%) is about 1%.[40] According to our quality control procedure,[42] there was no scanner drift during the study period.

pQCT: The pQCT measurements (peripheral quantitative computed tomography XCT 3000; Stratec GmbH, Pforzheim, Germany) were evaluated at the midshaft (cortical bone) and distal site (trabecular bone) of the right tibia. The analyzed variable for the distal tibia was the trabecular density (TrD, g/cm^3), and those for the tibial shaft were the cortical density (CoD, g/cm^3), cortical area (CoA, mm^2), and bone strength index (BSI, mm^3). BSI denotes density-weighted polar section modulus and reflects torsional and bending rigidity of the long bone shaft. In our laboratory, the in vivo CV% in different pQCT variables for the tibia ranges from 0.9% to 2.5%.[43]

The DXA and pQCT operators were not aware of the group assignment of the study.

Serum markers of bone turnover: Osteocalcin (OC) and aminoterminal propeptide of type I procollagen (PINP) were selected as markers of bone formation.[44] Bone resorption was estimated by carboxy-terminal collagen cross-links (β-CTx) and osteoclast-derived TRACP isoform 5b (TRACP-5b).[45]

Venous blood samples were obtained at 8:00–10:00 a.m. after a 12-h fast. Serum was separated by centrifugation (+4°C for OC and TRACP, and +15°C for PINP and CTx), aliquotted, and stored at −20°C (PINP) or −70°C (CTx, OC, and TRACP) until the analyses. OC was assessed by the electrochemiluminescence immunoassay for N-MID osteocalcin (Elecsys Systems 1010; Roche Ltd., Basel, Switzerland). PINP was analyzed by radioimmunoassay (Orion Diagnostica, Espoo, Finland). β-CTx was also determined by electrochemiluminescence immunoassay (β-CrossLaps/serum, Elecsys System 1010; Roche Ltd.), and TRACP-5b determinations were performed by solid phase immunofixed-enzyme activity assay (BoneTRAP; SBA, Turku, Finland).

The total analytical variations ranged from 2.5% to 3.0% for OC at concentration levels of 19.5–171.7 μg/liter; from 2.4% to 2.7% for PINP at concentrations of 41.4–115.9 μg/liter; from 4.0% to 6.2% for CTx at concentrations of 0.30–0.80 ng/ml, and 4.0% for TRACP-5b at a concentration of 3.0 U/liter. The variations were calculated from the commercial control materials of the assay kits (except CTx). PINP and TRACP analyses were done as duplicates.

Performance tests

At the beginning of each test session, a 4-minute warm-up was performed on a bicycle ergometer (workload, 40 W for women and 50 W for men). The subjects wore the same shoes during both performance test sessions (baseline, 8 months), and the order of the performance tests was the same in both test sessions. Use of alcohol or strenuous physical activity was not allowed during the test day or the day before.

A *vertical countermovement jump test* was used to assess the lower-limb explosive performance capacity.[46] The tests were performed on a contact platform (Newtest, Oulu, Finland), which measures the flying time. The obtained flight time (t) was used to estimate the height of the rise of body center of gravity (h) during the vertical jump (i.e., $h = gt^2/8$, where $g = 9.81\ m/s^2$). The median value of three measurements was used as a test score.

Maximal isometric strength of the leg extensors was measured with a standard leg press dynamometer.[47] The subjects sat on the dynamometer chair with their knees and ankles at 90° flexion while pressing maximally against strain gauges (Tamtron, Tampere, Finland) under their feet. The isometric strength was recorded for three maximal efforts, and the median value of three readings was used as the test score.

G*rip strength* was measured using a standard grip strength meter (Digitest, Muurame, Finland). The median value of three readings was used as a test score.

A s*huttle run test* over a 30-m course was used to assess the dynamic balance or agility.[48] The subjects were asked to run as fast as possible six times between markers placed 4 m apart, touch the floor after each 4-m run, and run a 6-m course over the finish line. A single performance was done, and the running time was recorded with photoelectric cells.

A *postural sway platform* (Biodex Stability System, Biodex, New York, NY, USA) was used to assess the body balance.[49] The subjects stood on a labile platform on both legs, with eyes opened and arms beside the trunk. The platform provides eight different stability levels: level 8 is virtually stable and level 1 is the most labile. As a test, we used a 40-s protocol in successive 10-s intervals: level 5 (0–10 s), level 4 (10–20 s), level 3 (20–30 s), and level 2 (30–40 s). The system provides a numerical stability index, which reflects the body sway variation around the center of gravity of the body so that the lower the index the better the stability.[49] Each subject's foot position coordinates on the platform were recorded after the first stability measurement, and the same coordinates were used at 8 months to obtain consistency between the tests. The mean value of two stability indices was used as the test score. Before each test, the subjects did one to two familiarization trials.

Safety issues

Possible side effects or adverse reactions were collected in a written format from the subjects of the vibration group monthly and from the control group in 2-month intervals. The subjects also could consult the responsible physician (PK) whenever needed. In addition, magnetic resonance imaging (MRI; Artoscan, Esaote s.p.a., Genova, Italy) was

used to study the effect (safety) of the long-term vibration loading on the articular cartilage[50]; the images were taken from the right ankle joint in eight subjects of the vibration group and four subjects of the control group at baseline and after the 8-month intervention.[50]

Statistical analysis

Mean and SD are given as descriptive statistics. The DXA- and pQCT-based BMC and bone strength parameters with the muscular performance and balance tests were the primary outcome measures of the study; all the remaining measures were secondary outcomes. The primary analysis was done by intention-to-treat basis (all randomized subjects were included in the analysis), and the secondary analysis was done by active-treatment approach (efficacy analysis), which was based on the data from 7 and 14 of the most compliant subjects (the number of vibration exercises during the intervention was greatest in these subjects).

The 8-month effects of the whole body vibration on individual physical performance were defined as relative differences (with 95% CI) between the vibration and control groups. The relative differences were achieved through log-transformation of the variables. The one-way analysis of covariance (ANCOVA) with the baseline measurements as the covariate was used to analyze the effect of vibration at 8 months.

In all tests, p values less than 5% (<0.05) were considered statistically significant. Using this α level ($\alpha = 0.05$) and regarding some 5% between-group difference in the primary outcome measures as a clinically important result, the sample size (25 participants per group) was calculated to give 80% statistical power for the study.

RESULTS

The vibration intervention succeeded well and was safe to perform. In the vibration group, the reported mean vibration training attendance was 2.8 ± 0.8 times per week (a recommended minimum was three times per week), and no vibration-related side effects or adverse reactions were observed. Twenty-seven of 28 subjects in the vibration group and 26 of 28 control subjects completed the study. Two participants in the control group withdrew from the study because of loss of interest, and one participant in the vibration group withdrew because of a musculoskeletal problem (independent of the vibration loading). In neither group did the MRI examination show changes in the articular cartilage or bone tissue of the ankle joint.

The basic characteristics of the subjects who completed the study (27 subjects in the vibration group and 26 in the control group) are given in Table 1. These characteristics did not differ between the groups, and the weight of the subjects did not change significantly during the study. There were no changes in the subjects' physical activity or calcium intake during the intervention.

Because there were no gender differences in the time effect at the 8-month tests, the data for women and men were pooled and analyzed together. Results of the efficacy analyses did not differ from those of the intention-to-treat analysis reported below, and therefore the former is not reported further.

Table 1. Basic Characteristics of the Vibration Group and Control Group (Mean ± SD)

	Vibration group (n = 27)	*Control group (n = 26)*
Women/Men (number)	18/9	16/10
Age (years)	23.1 ± 4.3	25.5 ± 5.8
Height (cm)	174.4 ± 7.8	174.0 ± 7.7
Weight (kg)		
At baseline	71.6 ± 13.1	71.1 ± 12.8
At 8 months	70.6 ± 11.9	70.8 ± 12.7

Bone measurements

The 8-month whole body vibration intervention had no effect on mass, structure, or estimated mechanical strength of bone at any of the measured skeletal sites in the pQCT and DXA measurements (Tables 2 and 3).

Biochemical markers of bone turnover

OC, PINP, CTx, and TRACP-5b values did not change during the 8-month vibration intervention (Table 4).

Muscle performance and body balance

Strength tests: The vertical jump height increased 2.1 cm after the 8-month vibration intervention compared with a mean decrease of 0.3 cm in the control group, resulting in a significant 7.8% net benefit (95% CI, 2.8–13.1; $p = 0.003$) for the vibration group (Table 5; Fig. 1A).

No effect was observed in the isometric lower limb extension strength (1.9%; 95% CI, –2.6–6.6; $p = 0.402$), and as expected, no effect was observed in the grip strength test after the 8-month intervention (1.6%; 95% CI, −0.9–4.1; $p = 0.217$; Table 5; Figs. 1B and 1C).

Stability tests: There was no difference in the shuttle run test between the vibration and control group after the 8-month intervention (−0.2%; 95% CI, –2.0–1.7; $p = 0.840$; Table 5; Fig. 1D). There was no effect observed in the score of the stability platform test (−1.7%; 95% CI, –15.0–13.6; $p = 0.811$; Table 5; Fig. 1E).

DISCUSSION

Bone is known to adapt to altered loading conditions,[14] and the loading-induced *strains* are believed to underlie the adaptation of the bone tissue.[14,15] This strain-related osteogenic stimulus is dependent on different parameters of the strain environment, for example, the number of strains, strain rate, peak strain magnitude, and strain direction and distribution.[11,15,17,18] A conventional perception of bone adaptation is that the mechanical signals must create high peak strains to influence bone morphology.[16] Accordingly, these few peak signals cause microdamage to the bone tissue, which will then become repaired by osteoblasts activity.[51] However, several studies have shown that, to be osteogenic, mechanical loading does not necessarily need to contain abnormally high-magnitude strains if it involves

TABLE 2. DXA-DERIVED BMC VALUES AT BASELINE AND AFTER THE 8-MONTH WHOLE BODY VIBRATION INTERVENTION: MEAN ± SD AND MEAN BETWEEN-GROUP DIFFERENCE FOR THE RELATIVE CHANGE BY TIME (PERCENTAGE, 95% CI, AND *p* VALUE)

	Vibration group (n = 27)	*Control group (n = 26)*	*Between-group difference for the relative change by time (%)**		
			Mean	*95% CI*	p *Value*
Lumbar spine (g)					
Baseline	51.950 ± 9.687	52.059 ± 10.599			
8 Months	52.404 ± 9.693	52.085 ± 9.939	0.6	−0.9 to 2.0	0.431
Femoral neck (g)					
Baseline	3.698 ± 0.690	3.659 ± 0.761			
8 Months	3.731 ± 0.696	3.688 ± 0.760	0.1	−1.6 to 1.8	0.917
Trochanter (g)					
Baseline	7.118 ± 1.347	7.351 ± 1.385			
8 Months	7.197 ± 1.339	7.359 ± 1.250	0.4	−2.3 to 3.2	0.780
Calcaneus (g)					
Baseline	10.123 ± 2.523	10.612 ± 2.933			
8 Months	10.296 ± 2.235	10.730 ± 2.969	0.6	−2.6 to 3.9	0.705
Distal radius (g)†					
Baseline	1.777 ± 0.415	1.702 ± 0.395			
8 Months	1.807 ± 0.433	1.732 ± 0.381	−0.3	−2.7 to 2.1	0.780

* Analysis of covariance.
† $n = 24$ in the vibration group and $n = 22$ in the control group.

TABLE 3. PQCT DATA AT BASELINE AND AFTER THE 8-MONTH WHOLE BODY VIBRATION INTERVENTION: MEAN ± SD AND MEAN BETWEEN-GROUP DIFFERENCE FOR THE RELATIVE CHANGE BY TIME (PERCENTAGE, 95% CI, AND *p* VALUE)

	Vibration group (n = 27)	*Control group (n = 26)*	*Between-group difference for the relative change by time (%)**		
			Mean	*95% CI*	p *Value*
Distal tibia					
Trabecular density (mg/cm^3)					
Baseline	249.0 ± 26.3	240.8 ± 32.4			
8 Months	253.2 ± 26.4	245.7 ± 31.5	−0.3	−1.2 to 0.7	0.614
Tibial shaft†					
Cortical density (mg/cm^3)					
Baseline	1103.2 ± 23.8	1107.2 ± 24.2			
8 Months	1136.4 ± 19.3	1135.7 ± 31.6	0.4	−0.5 to 1.3	0.406
Cortical area (mm^2)					
Baseline	316.6 ± 40.5	316.6 ± 58.6			
8 Months	329.2 ± 42.9	329.1 ± 61.8	0.0	−0.8 to 0.8	0.999
Bone strength index (mm^3)					
Baseline	1906.9 ± 334.0	1887.4 ± 437.9			
8 Months	2031.4 ± 372.0	2009.0 ± 482.8	0.0	−1.4 to 1.5	0.958

* Analysis of covariance.
† $n = 25$ in the vibration group and $n = 24$ in the control group.

high strain rates and/or an unusual strain distribution.[11,15,17,18] Furthermore, very recent experimental studies have suggested that extremely low-magnitude (several orders of magnitude below those that damage bone tissue) but high-frequency mechanical vibration can also strongly influence bone morphology.[21–24]

Besides being osteogenic, the low-amplitude, high-frequency mechanical stimulus has currently been considered a potentially efficient training method for skeletal muscle, because clinical studies have suggested that whole body vibration may also improve muscular performance[26–28,30–32]: a single vibration bout has been shown to result in a significant temporary increase in muscle strength of lower extremities,[28,31] and long-term vibration interventions in young adults suggested that neural adaptation in explosive power performance takes place in response to vibration stimuli.[26,32] Similar results have also been seen in a 2-month intervention of elderly people.[30]

Thus, it is not surprising that vibration stimulus has recently aroused great interest among osteoporosis researchers as a very promising method to prevent age-related fractures.[19,21–24] In this randomized, controlled study of young, healthy adults, the 8-month whole body vibration loading induced a significant enhancement in the jump

TABLE 4. OSTEOCALCIN, PINP, CTX, AND TRACP-5B VALUES AT BASELINE AND AFTER THE 8-MONTH WHOLE BODY VIBRATION INTERVENTION: MEAN ± SD AND MEAN BETWEEN-GROUP DIFFERENCE FOR THE RELATIVE CHANGE BY TIME (PERCENTAGE, 95% CI, AND *p* VALUE)

	Vibration group (n = 26)	*Control group (n = 26)*	*Between-group difference for the relative change by time (%)**		
			Mean	*95% CI*	p *Value*
Formation					
Osteocalcin					
Baseline	42.7 ± 14.2	43.4 ± 14.8			
8 Months	40.1 ± 12.9	41.0 ± 13.4	−1.1	−10.7 to 9.5	0.828
PINP					
Baseline	71.6 ± 31.7	65.4 ± 21.1			
8 Months	63.0 ± 24.1	60.4 ± 21.9	−1.6	−13.9 to 12.4	0.807
Resorption					
CTx					
Baseline	0.70 ± 0.28	0.63 ± 0.28			
8 Months	0.65 ± 0.28	0.64 ± 0.32	−6.3	−19.0 to 8.5	0.378
TRACP-5b[†]					
Baseline	3.88 ± 0.79	3.60 ± 0.99			
8 Months	3.83 ± 0.96	3.84 ± 1.00	−6.3	−15.5 to 3.8	0.206

* Analysis of covariance.
[†] $n = 24$ in the vibration and control groups.

TABLE 5. THE MUSCULAR PERFORMANCE AND BALANCE TEST PARAMETERS AT BASELINE AND AFTER THE 8-MONTH WHOLE BODY VIBRATION INTERVENTION: MEAN ± SD AND MEAN BETWEEN-GROUP DIFFERENCE FOR THE RELATIVE CHANGE BY TIME (PERCENTAGE, 95% CI, AND *p* VALUE)

	Vibration group (n = 27)	*Control group (n = 26)*	*Between-group difference for the relative change by time (%)**		
			Mean	*95% CI*	p *Value*
Vertical jump (cm)					
Baseline	27.1 ± 7.8	28.9 ± 8.2			
8 Months	29.2 ± 8.5	28.6 ± 7.9	7.8	2.8 to 13.1	0.003
Lower limb extension strength (kg)					
Baseline	191.9 ± 65.0	216.5 ± 103.4			
8 Months	210.8 ± 73.2	233.5 ± 116.3	1.9	−2.6 to 6.6	0.402
Grip strength (kg)					
Baseline	31.3 ± 8.2	32.4 ± 9.8			
8 Months	31.1 ± 8.2	31.8 ± 9.7	1.6	−0.9 to 4.1	0.217
Shuttle run (s)					
Baseline	11.0 ± 1.2	11.2 ± 1.4			
8 Months	10.7 ± 1.3	10.9 ± 1.5	−0.2	−2.0 to 1.7	0.840
Postural sway (stability index)					
Baseline	3.1 ± 1.7	3.5 ± 1.2			
8 Months	2.7 ± 1.2	3.1 ± 1.2	−1.7	−15.0 to 13.6	0.811

* Analysis of covariance.

height, and although no neurogenic enhancement or changes in the morphological structure of the muscles could be demonstrated (because neither electromyographic (EMG) recordings nor muscle biopsy specimens were performed), the enhanced jump height suggested neuromuscular adaptation to the vibration stimulus.[52–54]

However, our vibration intervention had no effect on the other variables of muscular performance and body balance or on the mass, structure, and estimated mechanical strength of bone. The reasons for nonresponse of these variables could be that the participants were young, their basic physical performance was relatively good, and their bones were probably in good condition and could cope well with the given vibration stimuli. In other words, as also speculated by Rubin et al.,[22] it is possible that the musculoskeletal tissues of these young adults had no particular physiological need to adapt themselves to this kind of loading, and bone and performance responses to vibration stimulus might have been seen if the participants had been older or their bone weaker. On the other hand, vibration loading as a treatment regimen is very new, and convincing evidence of its safety (e.g., on the cartilages of the joints) has been lacking. Thus,

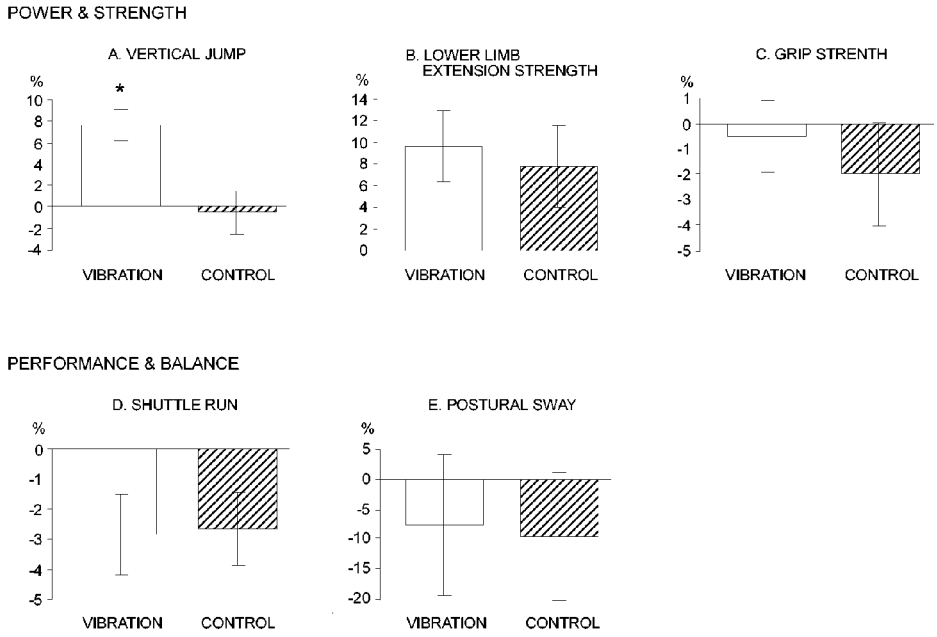

FIG. 1. The percentage changes in power, strength, performance, and balance after the 8-month whole body vibration intervention. Mean and 95% CI. $*p < 0.05$.

we felt it important to carefully evaluate the possible side effects or adverse reactions of long-term vibration in young and healthy adults before initiating studies with elderly people.

When comparing our results to positive findings of the animal experiments,[21–24] it has to be kept in mind that the anatomy and structure of lower extremities of animals are very different than those of humans, and thus, the responses of the animals to mechanical loading and vibration can be different. For example, sheep have hard and stiff hooves, which may not absorb the given loading stimulus to a considerable degree, and thus the mechanical vibration wave can easily traverse through the hoof to the lower limb skeleton without substantial attenuation. It is also possible that the loading waveform may play a central role in osteogenicity. Theoretically, an undisturbed sinusoidal loading waveform (i.e., one exact frequency) is possible only if the maximum acceleration of the vibration platform does not exceed 1*g*. If not so, the subject cannot stand steadily on the platform, and the actual loading becomes intermittent. In the studies of Rubin et al.,[21–24] the acceleration of the platform was 0.3*g*, whereas in our study, it was substantially higher than 1*g* (estimated, 2–8*g*). Consequently, in the vibration regimens of Rubin et al.,[21–24] the loading waveform remained sinusoidal, whereas in our study, it was apparently distorted. If the pure sinusoidal loading waveform at a certain frequency, not the peak load, is the key factor behind the osteogenic response (as Rubin's study indicates), it would be a fundamental observation. The optimal vibration frequency is, however, yet unknown, but because the 1*g* threshold constrains the simultaneous ranges of vibration frequency and amplitude, the search for the most optimal vibration frequency for bone formation may be alleviated.

At the beginning of this randomized study, it was not clear what kind of vibration stimulus would be most effective for the musculoskeletal system, because, besides safety, adherence, and compliance issues, information about the clinical efficacy of any type of vibration loading on human bone and physical performance was minimal. We had to rely on the most popular concept that vibration-induced mechanical stimulus must be a relatively high magnitude (high peak strains), provide a multidirectional exposure to the skeleton, and be progressive and long term by nature.[3,4,13,15,16,18,55] However, one has to recall that vibration stimulus can be varied in multiple ways (including type, magnitude, frequency, and duration), and thus, the result can also be different from that we observed in our trial.

In conclusion, except for the enhanced vertical jump height, the results of this randomized clinical trial were not positive as suggested by the previous experimental and clinical investigations, and thus, future human studies are needed before any clinical recommendation can be given for vibration exercises. Such studies should vary the type, magnitude, frequency, and duration of the vibration, and if effective and safe modes of vibration can be found for young healthy adults, these potential modes could then also be applied to other age groups (prepubertal, pubertal, and elderly persons) as the target population.

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