

Bone strength and density via pQCT in post-menopausal osteopenic women after 9 months resistive exercise with whole body vibration or proprioceptive exercise

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Abstract

Objectives: In order to better understand which training approaches are more effective for preventing bone loss in post-menopausal women with low bone mass, we examined the effect of a nine-month resistive exercise program with either an additional whole body vibration exercise (VIB) or balance training (BAL). **Methods:** 68 post-menopausal women with osteopenia were recruited for the study and were randomised to either the VIB or BAL group. Two training sessions per week were performed. 57 subjects completed the study (VIB n=26; BAL n=31). Peripheral quantitative computed tomography (pQCT) measurements of the tibia, fibula, radius and ulna were performed at baseline and at the end of the intervention period at the epiphysis (4% site) and diaphysis (66% site). Analysis was done on an intent-to-treat approach. **Results:** Significant increases in bone density and strength were seen at a number of measurement sites after the intervention period. No significant differences were seen in the response of the two groups at the lower-leg. **Conclusions:** This study provided evidence that a twice weekly resistive exercise program with either additional balance or vibration training could increase bone density at the distal tibia after a nine-month intervention period in post-menopausal women with low bone mass.

Keywords: Elderly, Osteopenia, Weight Training, Vibration Exercise, Bone Density

Introduction

Osteoporosis is an increasingly common disease in aging societies. As we age, muscle mass, force and power and bone density reduce¹⁻⁵. These effects are particularly noticeable in the load-bearing regions of the body⁶, although physical activity can help to hinder this decline⁷. One consequence of decline in neuromuscular function can be an increased occurrence of falls, particularly in the older physically inactive individual^{8,9}. Such

falls can result in bone fractures^{10,11}. Post-menopausal women with low bone density are a risk group of particular concern.

With research in the past decades, our knowledge of the most effective modalities for improving bone density and strength has become more refined. Resistive exercise may, at the very least, prevent the decline in bone density with age¹², especially in lumbar spine¹³ and is also very effective in improving muscle mass and force production¹⁴. Both high (80% 1-repetition maximum) and moderate (50% 1-repetition maximum) resistive exercise is known to positively influence muscle strength¹⁵. Some authors have suggested that loading of the bone via the musculature is critical in modulating bone density¹⁶ and that this relationship may be stronger in older individuals¹⁷. There is evidence from animal models¹⁸ and cross-sectional studies in athletes¹⁹ that exercise protocols which lead to greater bone deformation may be more effective in building denser and stronger bone. One mode of potentially increasing bone strain is by applying vibratory stimuli²⁰ and a clinical trial²¹ has shown that it can be effective in increasing hip bone density. In clinical practice, patients are more likely to be compliant with shorter duration training sessions, but it is not clear what effect a short-duration vibration exercise may have on bone. One of our

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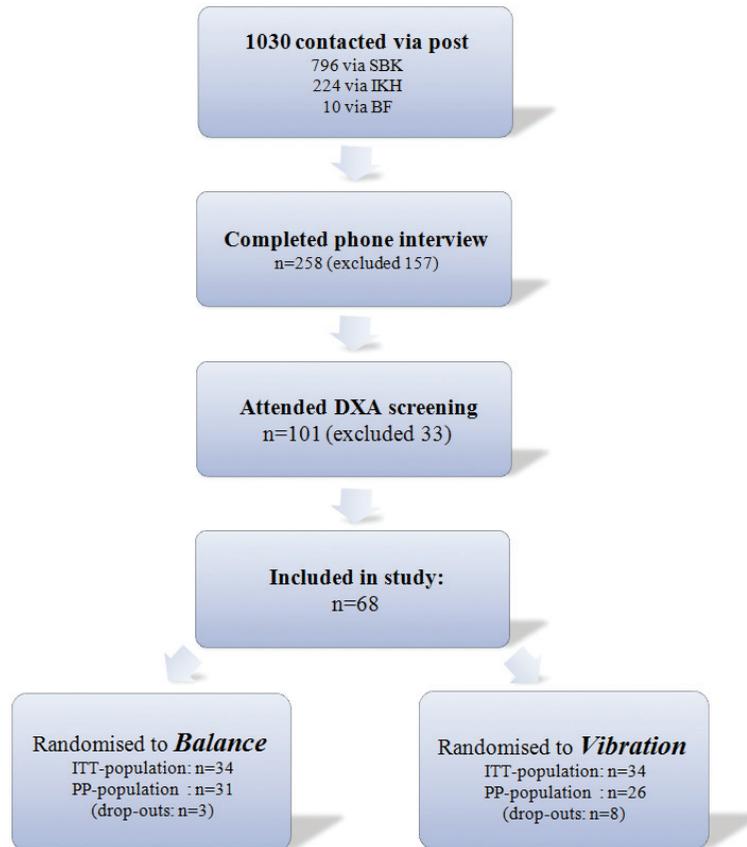


Figure 1. Subject flow. (SBK – Siemens Betriebskrankenkasse; IKH – Immanuel Krankenhaus; CBF – Charité Campus Benjamin Franklin; DXA – Dual X-ray absorptiometry. ITT: “intent-to-treat”, PP: “per-protocol”).

goals was to examine the effect of a training program that could realistically be implemented in the community.

The effect of loading on bone is specific to the region of bone where the load is applied^{22,23}. Therefore, to examine any additional effect of whole-body vibration exercise, which is typically applied at the feet, it may be appropriate to measure bone locally at the lower leg. Peripheral quantitative computed tomography (pQCT) is a methodology commonly implemented to examine bone density at the periphery. The main goal of the current work was to examine the effect of resistive exercise with either additional short-duration whole-body vibration exercise or balance training on bone, as measured by pQCT, in post-menopausal osteopenic and osteoporotic women.

Furthermore, in pQCT studies of bone at the periphery focus is generally placed tibia in the lower leg and radius in the forearm. Recent cross-sectional studies in female athletes have suggested that the impact of exercise on bone density and strength at the proximal forearm may be more strongly reflected in the ulna^{24,25} and that fibula bone strength, although not the major load bearing bone in the lower limb, may also be impacted by exercise protocols²⁶. The available data suggest that changes in bone structure in response to exercise, such as through a more dense trabecular network or changes in cortical

geometry, are more decisive in determining improvements in bone strength²⁷. Consequently a secondary goal of the current work was to examine the contribution of the fibula and ulna to pQCT measured bone strength indices including assessment of bone geometry in post-menopausal osteopenic women undergoing the nine-month exercise protocol in the current study.

In a recent study, we evaluated the effect of vibration exercise versus proprioceptive training on postural control in post-menopausal osteopenic women²⁸. This study provided the opportunity to address the goals of the current investigation. Our primary hypothesis for the current study was that the addition of whole-body vibration would be more effective than balance training in improving bone parameters at the tibia.

Materials and methods

Study design, sample size estimate and subjects

The current study was a randomised, controlled study which was approved by the ethical commission of the Charité Universitätsmedizin Berlin and the German Federal Office for Radiation Protection. All subjects gave their informed written consent prior to inclusion in the study. Sixty eight post-menopausal women with reduced bone density took part in a

Baseline Characteristics	VIB (N=34)	BAL (N=34)
Age (years)	67.2(3.7)	66.0(4.5)
Height (cm)	161.6(5.4)	161.9(5.5)
Weight (kg)	63.7(6.5)	63.2(10.3)
Body Mass Index (BMI)	24.4(2.6)	24.0(4.2)
T-Score LWS (L1-L4)	-2.5(0.3)	-2.4(0.4)
T-Score hip total	-1.4(0.8)	-1.7(0.9)
T-Score hip neck	-1.6(0.6)	-1.7(0.9)

Values for age, height, weight, body mass index (BMI), for LWS (L1-L4), hip total and hip neck are mean (SD). VIB: resistive exercise with whole-body vibration group. BAL: resistive exercise with balance training group. There were no differences between groups for any of these variables.

Table 1. Baseline subject characteristics of the intent-to-treat population.

nine month intervention randomised into either a whole-body vibration (VIB) or balance (BAL) training group (Figure 1). The primary outcome measure for this sub-project was cortical bone mineral density at the distal tibia.

The inclusion criteria were: a minimum of eight years post-menopausal, no recent (last six months) involvement in whole-body vibration exercise, balance training or resistive exercise and a total hip or lumbar spine (L1-L4) T-score from -2.0 to -3.0 SD (osteopenic) on dual energy X-ray absorptiometry (DXA; Lunar Prodigy Advance, GE Medical Systems, Wisconsin, USA; Encore Software v9.3; Table 1). Exclusion criteria were: any metal implants, known disturbance of the vestibular system, prior experience with the testing apparatus, bone fractures within the last year, neuromuscular and neurological diseases, acute thrombosis in the last 24 months, coronary heart disease, pacemaker, acute arthritis, smoking of more than 20 cigarettes per day (assessed per telephone interview) and alcohol consumption of more than one standard drink (14g of alcohol) per day (assessed per telephone interview). Thus all subjects were, aside for low bone density, healthy individuals and able to walk without any assistance. Although it was not a specific exclusion criterion, none of the subjects included in the study participated in organised sports during the study or in the six months prior to the study.

The subjects for the study were recruited via the Siemens Betriebskrankenkasse, Centre for Muscle and Bone Research (Charité Universitätsmedizin Berlin) and the Immanuel Krankenhaus Berlin. After written contact and initial telephone contact, if candidates were suitable for participation in the study, they attended the bone density screening (DXA). If this inclusion criterion was fulfilled, candidates attended another appointment to screening by a medical doctor and also a sports-medicine examination (cycling ergometry with electrocardiogram, blood pressure and heart rate measurement). From 101 women who were screened for the study, 68 subjects were included, from which 57 subjects finished the study (N=26 in the VIB group and N=31 in the BAL group). Drop-outs were due to injury or illness not associated with the study (N=8 in the VIB group, N=3 in the BAL group). The first subject began

Exercise	Balance Group		Vibration Group	
	Baseline	Month-9	Baseline	Month-9
Hip abduction	20(5)	35(13)‡	20(5)	30(13)‡
Hip adduction	28(5)	40(13)‡	25(5)	38(13)‡
Trunk flexion	28(6)	40(11)‡	34(6)	40(11)‡
Leg press	45(5)	65(20)‡	50(14)	68(20)‡
Hip extension	25(10)	45(14)‡	25(10)	45(20)‡
Lat-pull downs	25(8)	33(10)‡	25(8)	30(8)‡
Trunk rotation	20(5)	40(10)‡	23(5)	35(19)‡
Trunk extension	25(10)	46(12)‡	25(7)	39(18)‡
Seated cable pull	20(6)	40(18)‡	20(6)	36(19)‡

Values are median(inter-quartile range) in kilograms. Significance of change within each group indicated by: ‡: p<0.001. There were no significant differences between groups.

Table 2. 10 repetition-maximum in each exercise at the start and end of nine-months training.

the study in November 2007 and the final subject completed the study in October 2009.

The sample size of the study was based upon postural balance parameters, not the bone or muscle force parameters evaluated here. Our own (*unpublished*) observations indicate that pQCT measurements are more reproducible than DXA and thus the focus was placed upon pQCT outcome measurements. A larger sample size would have been necessary to reasonably expect to detect significant changes in DXA measurements. Data (*unpublished observations*) from 79 female subjects between the ages of 50 and 75 years on short-term repeatability, with complete repositioning on the same day, of tibial diaphysis cortical bone mineral density from pQCT shows a coefficient of variation of 0.35% (95% confidence interval: 0.31-0.42%; 95% minimal detectable change²⁹: 1.41mg/cm³) and a correlation of 0.99. Given these data, a pool of 57 subjects completing the study, an alpha of 0.05 and power of 0.8 a difference between the groups of 0.09% should be detectable in this parameter after the intervention period. These calculations were performed with G*Power (Version 3.1³⁰).

Interventions

The training interventions took place at a local sports club (Sport-Gesundheitspark Berlin e.V.). Each subject attended two training appointments per week. Group training was performed with a maximum of 10 subjects per session. The two different intervention groups were not strictly separated. During all training and measurement sessions subjects wore flat soled gym- or running-shoes. Subjects were required to attend at least 75% of all training sessions and to not miss more than four trainings sessions in a row.

At the start of each training session a short warm up of 15 minutes of cycle ergometry was performed. This was followed by resistance exercise. In the first two training sessions the subject was familiarised with the training devices and the load were modified such that at the third training session the subject

could perform 10 repetitions until exhaustion. The loading level at the third training session was taken as the “start weight” for use in further analysis (Table 2). One set of repetitions was performed per exercise to reduce exercise time¹⁴. If the subject progressed and could achieve 20 repetitions, the load was increased at the next exercise session such that the subject could perform at least 10 repetitions. This progression regime was based upon prior work³¹ which showed that strength training to “moderate” subjective levels of fatigue is capable of improving strength in an 8-week exercise program. The following resistive exercises were conducted using standard gym equipment: bilateral leg press in lying, bilateral hips abduction in sitting, bilateral hip adduction in sitting, hip extension in standing (left and right), trunk flexion in sitting, trunk extension in sitting, trunk rotation in sitting, lat-pull downs in sitting, and seated cable pull in standing. The resistive exercise component lasted approximately 30 minutes. Following this exercise, subjects performed either balance training (BAL) or whole-body vibration (VIB). In the last resistive exercise session at the end of the nine-month intervention period, the 10 repetition-maximum was retested (Table 2).

The BAL-group performed a progressive proprioceptive and balance program by the use of a variety of exercises, equipment (such as staves and balls) and/or different surfaces (foam mats, pillows, wobble-boards). The following exercises were progressed in difficulty over the 9-month intervention period:

- Romberg, tandem and single-leg stance were performed on surfaces of varying degrees of instability and at varying degrees of difficulty: firm mat, soft mat, wobble-board, air-pillows, with and without shoes, with eyes open or with eyes closed.
- Softballs, tennis balls, staves, elastic bands were used for coordination training involving throwing, catching, passing around the body, passing underneath a leg, flipping between hands.

The exercises were performed either alone, or in the case of throwing and advanced balance exercises, with a partner. The exercises were progressed by the trainer from one week to the next. The balance training lasted approximately 15 minutes.

At the same time, subjects of the VIB-group trained three consecutive times on the Galileo Fitness (Novotec, Pforzheim, Germany), a side-alternating vibration device. Amplitude of vibration began at 2 mm (4 mm peak-to-peak) in the first week and was progressed to 4 mm (8 mm peak-to-peak) within the next four weeks in the course of the study. A one minute break was given between each vibration exercise. Three different exercises were performed:

1. Standing for 1.5 minutes with lightly bended knees and hips with a straight back. Vibration frequency beginning at 22 Hz (3.9 g) and progressed to 24 Hz (9.3 g) after one to two weeks.
2. Continuous squatting from erect standing to 90° knee flexion (2 seconds down, 2 seconds up) for 1.5 minutes. Vibration frequency beginning at 22 Hz (3.9 g) and progressed to 24 Hz (9.3 g).
3. One minute of continuous stance in 90° knee flexion. Vibration frequency set to 26 Hz (10.9 g) for the duration of the study.

The subjects were motivated to contract the lower-limb muscles as strongly as they could during the vibration exercises. The vibration training lasted a total of 4 minutes. The duration of vibration training was kept brief in order to understand the efficiency of short-duration training.

Peripheral Quantitative Computed Tomography (pQCT)

An XCT 2000 (Stratec Medizintechnik, Pforzheim, Germany) was used to obtain pQCT scans from the left lower leg and the left forearm. Scout-views were generated in the frontal plane to identify the tibio-talar and radio-carpal clefts to position the reference line. Sectional images were then obtained at 4% (distal epiphysis) and 66% (diaphysis) of tibia and ulnar length. The integrated XCT 2000 software (version 6.20A) was used to analyse the pQCT images.

At the distal radius and tibia (4% site), total and trabecular bone mineral density (BMD) was determined using a detection threshold of 180 mg/cm³ (contour mode 1, peel mode 1). Cortical BMD at the diaphysis (66% site) was assessed with a threshold of 711 mg/cm³ (cortical mode 1). In contrast to the distal epiphysis, at the 66% site there is very little trabecular bone and a cortical bone measure is more appropriate. Periosteal circumference (ring-model), endosteal circumference (ring-model), density weighted polar moment of inertia and section modulus at the diaphysis (66% site) were assessed with a detection threshold of 480 mg/cm³ (cortical mode 1). Gross anatomical muscle area was obtained from the scans taken at the diaphysis (66% site) of the forearm and leg and was calculated as total bone area (detection threshold of 280 mg/cm³; contour mode 1, peel mode 1, filter 2: F03) subtracted from the combined muscle and bone area (detection threshold of 45 mg/cm³; contour mode 3, peel mode 1, filter 2: F03F05). The same highly experienced operator performed all pQCT measurements.

pQCT measurements were defined as “invalid” if any movement artefacts were present in the image and the measurement was then repeated. A maximum of two measurements per subject per testing session were permitted according to radiation-exposure guidelines. If an invalid measurement was still obtained after the second attempt, this data point became missing data.

Statistical analyses

Analysis was performed on an “intent-to-treat” (ITT) approach. Those subjects who dropped out of the study and had their missing data filled via “last observation carried forward”³². Where data loss occurred due to technical difficulties or movement artefacts, in the ITT-analysis it was assumed that no change occurred in these subjects over time. A “per-protocol” (PP) analysis of all subjects completing the study as planned was also performed and the main findings did not differ to the ITT-analysis.

Linear mixed-effects models³³, with subsequent analysis of variance (ANOVA), were used to model time-point and subject-group main effects and their interaction. Allowances for heterogeneity of variance, such as due to group and/or time-point, were made when necessary and random effects for each subject were modelled. Where no significant between-group differences were seen, secondary analyses also considered the effects over time with both groups pooled.

Parameter	Balance Group		Vibration Group	
	Baseline	Month-9	Baseline	Month-9
<i>Tibia</i>				
4% total BMD (mg/cm ³)	234.2(35.0)	235.3(35.1)	230.5(24.0)	231.2(24.0)*
4% trabecular BMD (mg/cm ³)	187.9(37.0)	189.2(37.1)*	182.0(24.6)	182.6(24.6)*
66% cortical BMD (mg/cm ³)	1101.6(39.6)	1103.6(39.0)	1099.8(29.8)	1101.2(29.8)
66% density weighted polar moment of inertia (Ipw; mm ⁴)	37270(8070)	37424(8070)*	35348(8993)	35439(8993)*
66% section modulus (Rp; mm ³)	2097(365)	2094(365)	1981(445)	1986(445)
66% periosteal circumference (mm)	88.4(6.2)	88.5(6.1)	86.0(11.1)	86.3(11.1)†
66% endosteal circumference (mm)	64.2(7.4)	64.3(7.2)	62.7(10.8)	63.2(10.7)†
<i>Fibula</i>				
4% total BMD (mg/cm ³)	362.1(71.1)	361.2(72.0)	381.1(67.4)	380.8(66.7)
4% trabecular BMD (mg/cm ³)	160.6(75.8)	163.0(76.9)	157.6(48.6)	158.5(49.8)
66% cortical BMD (mg/cm ³)	1078.5(47.4)	1081.4(46.2)	1090.7(30.9)	1092.0(29.5)
66% density weighted polar moment of inertia (Ipw; mm ⁴)	941(292)	940(293)	1953(4902)	1954(4902)
66% section modulus (Rp; mm ³)	128(31)	129(31)	189(247)	189(247)
66% periosteal circumference (mm)	35.2(3.2)	35.4(3.2)	37.6(8.7)	37.5(8.7)
66% endosteal circumference (mm)	23.0(3.3)	23.3(3.1)	24.5(7.7)	24.4(7.6)

Values are mean(SD). BMD= Bone Mineral Density. Significance of change within each group indicated by: *: $p < 0.05$, †: $p < 0.01$. No significant differences between groups were seen.

Table 3. Changes in lower leg bone parameters after nine month intervention period.

Loading levels during resistive exercise could only be progressed in steps of a minimum of 2.5 kg and hence these data represent ordinal variables. Here a non-parametric analog of repeated measures ANOVA³⁴ was implemented. Correlation analyses also evaluated the relationship between the percentage change in load in each of the exercises and percentage change in each of the bone parameters presented here. Pearson's correlation co-efficient was calculated and a Bonferroni adjustment performed.

An alpha-level of 0.05 was taken for statistical significance. The “nlme” package was used for linear mixed-effects modelling in the “R” statistical environment (version 2.10.1, www.r-project.org). Unless otherwise specified, results are presented as mean (SD).

Results

Aside from a larger arm muscle area in the VIB-group at baseline ($p=0.011$), no significant baseline differences were seen between the two groups for any of the parameters measured ($p \geq 0.08$) or anthropometric data (Table 1). Of the 57 subjects that completed the study, forearm pQCT data from two subjects (both VIB-group) and lower-leg pQCT data from one VIB-subject could not be used due to technical difficulties. VIB-subjects completed 91.1(6.4)% of all scheduled training sessions and the BAL-subjects completed 90.5(7.5)% sessions.

Data on loading levels during resistive exercise at the start and end of the nine-month intervention period are reported in Table 2. Whilst significant increases in loading levels occurred after nine months (p all ≤ 0.001), load progression was the same in both groups (group×time: p all ≥ 0.08).

Based upon data from all subjects, the fibula contributed 4.1(11.5)% of total polar moment of inertia at the 66% site whereas the tibia contributed 95.9(11.5)%. At the proximal forearm (66% site) the radius contributed 41.7(4.3)% and the ulna 58.3(4.3)% of total polar moment of inertia.

Changes in bone mineral density and strength

With the exception of total bone mineral density at the distal radius (group×time: $F=5.2$, $p=0.026$; per-protocol analysis: $p=0.023$), no significant differences were apparent between the two groups for any of the bone parameters measured (group×time: F all ≤ 3.1 , p all ≥ 0.08) at all sites (lower leg and forearm). Significant changes in some parameters were seen after the nine month intervention period, however (Tables 3 and 4, Figures 2 and 3).

At the tibia, trabecular BMD of the distal epiphysis (4% site) increased significantly in the BAL (+0.52(1.35)%, $p=0.021$) and VIB-groups (+0.32(0.83)%, $p=0.033$) with a corresponding increase in total BMD of the distal epiphysis (BAL: +0.48(1.44)%, ns; VIB: +0.33(0.75)%, $p=0.015$). At the tibial diaphysis (66% site) no significant changes in BMD were seen within each group, though the density weighted polar moment of inertia (+0.26(0.65)%, $p=0.027$), periosteal circumference (+0.44(0.82)%, $p=0.004$) and endosteal circumference (+0.81(1.52)%, $p=0.004$) increased in the VIB-group. When pooled across both groups, a significant increase in tibia cortical density was seen (+0.16(0.51)%, $p=0.014$) after nine months. Increases in the moment of inertia were seen in both groups (Table 3).

No significant changes were seen in the fibula.

At the radius, significant increases in trabecular BMD (+1.05(2.69)%, $p=0.032$) and total BMD (+1.06(2.95)%, $p=0.046$) were seen at the distal epiphysis (4% site) in the VIB-

Parameter	Balance Group		Vibration Group	
	Baseline	Month-9	Baseline	Month-9
<i>Radius</i>				
4% total BMD (mg/cm ³)	78.9(58.9)	276.6(57.9)	285.2(40.8)	288.2(41.7)*
4% trabecular BMD (mg/cm ³)	151.6(44.8)	151.9(44.7)	152.5(31.5)	154.1(31.8)*
66% cortical BMD (mg/cm ³)	1135.7(37.3)	1140.4(37.3)†	1131.6(31.4)	1132.8(29.2)
66% density weighted polar moment of inertia (Ipw; mm ⁴)	1555(368)	1563(370)	1612(393)	1608(394)
66% section modulus (Rp; mm ³)	214(32)	216(33)	224(38)	223(38)
66% periosteal circumference (mm)	39.3(2.4)	39.3(2.2)	39.8(2.4)	39.7(2.5)
66% endosteal circumference (mm)	25.3(2.9)	25.3(2.6)	25.8(2.7)	25.9(2.7)
<i>Ulna</i>				
4% total BMD (mg/cm ³)	266.2(59.5)	266.0(59.6)	282.0(51.6)	283.7(49.1)
4% trabecular BMD (mg/cm ³)	207.1(50.2)	205.9(50.2)	216.4(30.9)	217.9(31.4)
66% cortical BMD (mg/cm ³)	1167.8(33.2)	1167.8(31.9)	1159.2(25.6)	1162.4(24.7)†
66% density weighted polar moment of inertia (Ipw; mm ⁴)	2101(425)	2124(423)†	2276(410)	2279(408)
66% section modulus (Rp; mm ³)	264(43)	269(42)*	282(38)	282(37)
66% periosteal circumference (mm)	41.2(2.5)	41.2(2.3)	42.2(2.0)	42.2(2.1)
66% endosteal circumference (mm)	23.2(3.1)	23.1(2.6)	24.3(2.5)	24.2(2.7)

Values are mean(SD). BMD = bone mineral density. Significance of change within each group indicated by: *: p < 0.05, †: p < 0.01. With the exception of total bone mineral density at the distal radius (p=0.026), no significant differences were apparent between the two groups.

Table 4. Changes in forearm bone parameters after nine month intervention period.

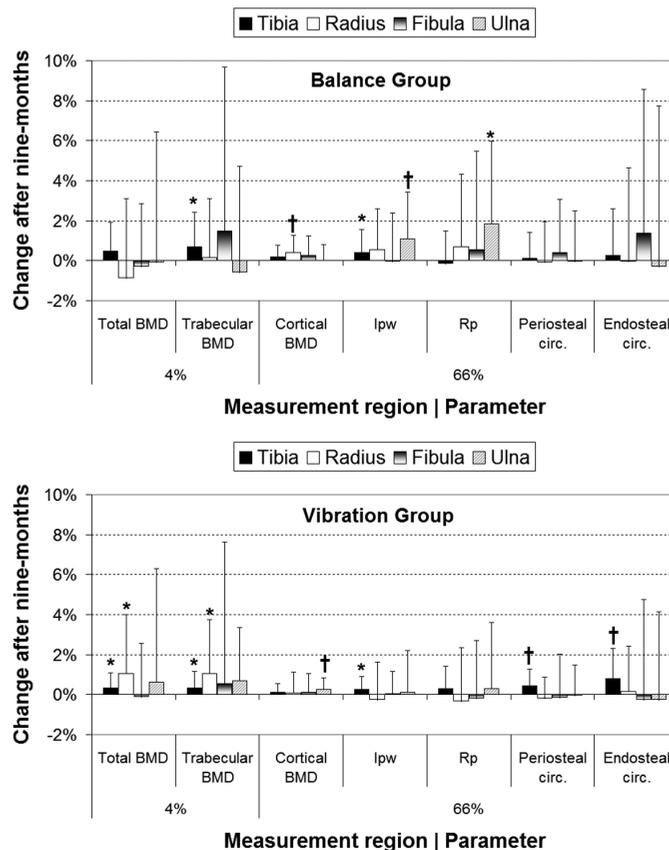


Figure 2. Bone changes in the balance (top) and vibration (bottom) groups. (Values are mean(SD) percentage change compared to baseline. *: p<.05; †: p<.01 and indicate significance of difference to baseline. Ipw: density weighted polar moment of inertia, Rp: section modulus, circ.: circumference).

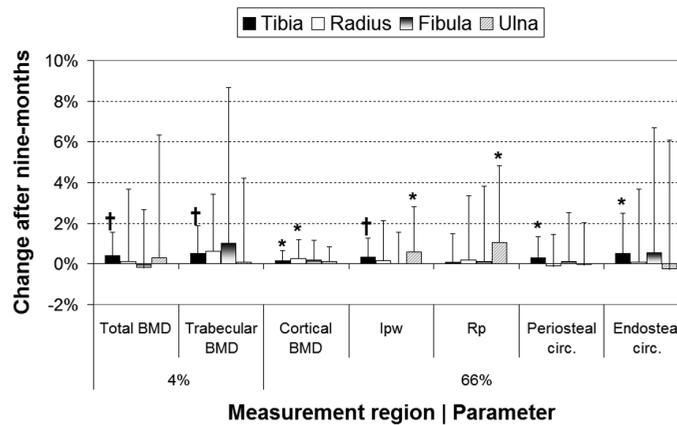


Figure 3. Bone changes for all subjects pooled together. (Values are mean(SD) percentage change compared to baseline. *: $p < 0.05$; †: $p < 0.01$ and indicate significance of difference to baseline. Ipw: density weighted polar moment of inertia, Rp: section modulus, circ.: circumference).

group and significant increases in cortical BMD at the diaphysis (66% site) in the BAL-group (0.42(0.86)%, $p=0.008$). These effects were not associated, however, with increases in bone mineral content, rather with decreases in bone area (distal radius trabecular area -0.9(2.0)%, [$p=0.013$] in VIB; radius diaphysis cortical area -0.2(2.4)% [ns] in BAL). The significant ($p=0.023$) between-group effect seen on ANOVA for total BMD at the distal radius epiphysis (BAL: -0.8(3.9)%, ns ; VIB: +1.05(2.69)%, $p=0.046$) was associated with changes in bone area in the VIB-group (BAL: +0.2(3.3)%, ns ; VIB: -(-0.9(2.0)%, $p=0.013$) with no change in bone mineral content (BAL: -0.4(1.6)%, ns ; VIB: 0.0(1.2)%, ns).

At the ulna, significant increases in the moment of inertia (+1.11(2.30)%, $p=0.009$) and section modulus (+1.86(4.11)%, $p=0.014$) were seen in the BAL-group at the diaphysis (66% site), although no changes in BMD were seen at this site. In the VIB-group cortical density increased (+0.27(0.57)%, $p=0.0086$), and this was associated with a decrease in cortical bone area (-0.7(1.8)%, $p=0.037$).

Lower leg and forearm muscle cross-sectional area

The muscle cross-sectional area increases at the radius diaphysis (66% site) in the VIB-group did not reach significance (baseline: 24.3(3.5)cm², end: 24.5(3.6)cm²; +0.8(2.5)%, $p=0.062$) and no significant changes were seen in the BAL-group (baseline: 22.3(2.4)cm², end: 22.4(2.5)cm²; +0.2(2.8)%, ns). At the tibia diaphysis (66% site) muscle size did not change significantly in either BAL (baseline: 58.4(7.3)cm², end: 58.5(7.3)cm²; +0.1(4.2)%, ns) or VIB (baseline: 59.5(9.2)cm², end: 59.7(9.4)cm²; +0.4(3.2)%, ns). There were no significant between group interactions on analysis of variance (F both ≤ 1.2 , p both ≥ 0.28).

Correlation between resistive exercise load progression and pQCT measures

Correlation analyses showed no significant relationship between the percentage changes in load during resistive exercise

and percentage changes in bone parameters or muscle cross-sectional area over the course of the study (r all ≤ 0.3).

Discussion

The hypothesis of the current study was that the addition of whole-body vibration training to resistive exercise, performed twice weekly over nine-months, would have a greater impact on bone parameters at the tibia in post-menopausal women than the addition of balance training to resistive exercise performed at the same time intervals. The findings of the current study do not conclusively support this hypothesis. Whilst we found increases in trabecular BMD at the distal epiphysis of the tibia in both groups, we found no significant differences between the two groups.

On face value, the results suggest that if there were any additional effect of the vibration exercise protocol in the current study, then its effect is smaller than measurement reproducibility. According to our sensitivity analysis, this effect size must be near to or less than 0.09% for cortical density at the tibia diaphysis. One caveat on this sensitivity analysis is that it was based upon data from short-term reproducibility. Longer-term reproducibility may indeed be lower. Hence, the minimally detectible effect size between the two groups in the current study may indeed be larger than estimated by the sensitivity analysis.

Some, but not all, clinical studies have shown that whole-body vibration exercise can have a positive effect on bone. Since planning of the current study began in 2006 a number of other studies have been published on vibration exercise. For specific details on methodologies and results we refer the reader to recent systematic reviews and meta-analyses³⁵⁻³⁷. Prior studies^{21,38-46} on whole-body vibration have employed DXA as an outcome measurement. In considering the literature there are a number of methodological differences between studies that make it difficult to compare their results. Nonetheless, based on current data, it may be possible to make some

general statements regarding what kinds of vibration exercise are more likely to be effective for bone.

The current study implemented vibration exercise twice weekly for four minutes each time with vibration acceleration of approximately 9.3-10.9 g for nine months. In some recent studies a relatively short duration of training was also performed. In one study⁴⁷, eight months of vibration training was performed twice weekly for 2x3 min or 1x15 min with 0.3-1.0 g acceleration and in another study 44 eight months training, three times weekly, and vibration at 20-40 Hz was performed. In these studies there were neither improvements in BMD within groups nor differences between the groups. Another study³⁸ also with eight months training, thrice weekly, 6x1 min at 12.6 Hz and 3 mm amplitude showed significant effects of vibration exercise on femoral neck BMD, but not lumbar spine. A further work⁴² in young female subjects over approximately four months, performing vibration training twice weekly in addition to resistive exercise, 3x1 min per session and at 50 Hz showed significant improvements of femoral neck and lumbar spine BMD. In conjunction with our data the literature suggests that short-duration vibration exercise performed 2-3 times a week without any additional resistive exercise is unlikely to provide sufficient stimulus to modulate BMD.

Other studies have attempted much more intensive vibration exercise. Slatkovska and colleagues⁴⁵ implemented 12 months of daily vibration exercise, for twenty minutes at 30 or 90 Hz (0.3 g) and Rubin et al⁴⁸ also implemented twelve months of daily vibration exercise for 2x10 minutes at 30 Hz (0.2 g). Neither of these studies showed significant improvements in BMD at the hip or lumbar spine, despite the greater training duration. In contrast, Gilsanz et al⁴⁰ implemented twelve months of daily vibration exercise for ten minutes at 30 Hz (0.3 g). Another study³⁹ implemented ten minutes of vibration training five times per week at 30 Hz and 5 mm amplitude for six months, and a further study⁴⁶ also conducted six months of daily training for twenty minutes at 0.5-0.8 g and showed significant improvements in both femoral neck and lumbar spine BMD. On face value, reconciling the contrasting findings of these studies is difficult. Likely meta-analysis of a series of studies could be of assistance in the future. Recent systematic reviews and meta-analyses^{35-37,49} have shown that vibration training can impact positively upon bone density, although there is not yet agreement on the optimal approach on frequency, duration and number of repetitions of training.

In the community, clinical experience has shown that it is difficult to motivate individuals to perform more than one or two exercise sessions per week. Time, money and motivation all play a role here. Daily training is, in our view, unrealistic for implementation in a clinical or community health setting. Thus, it will be necessary for the future to adjust training intensities to have the best possible time efficiency. It may be worth considering the vibration amplitude more in future work. Most studies^{45,47,48} implement a relatively small vibration amplitude. Typically no or little improvement of BMD was seen in these works. Other studies^{38,39,42}, which implemented a larger amplitude of vibration typically showed improvements in BMD. We suggest in future studies to more closely examine

the impact of vibration amplitude on bone adaptation.

A significant difference between the balance and vibration groups of the current study was seen at the distal radius. This effect persisted on the per-protocol analysis. In the VIB-group there was a non-significant increase in total BMD at this measurement region and a non-significant decrease in the BAL-group. Since the vibration exercise was not targeted at the arms, it is unclear whether this effect represents a spurious finding, or a real effect. This would need to be tested in future work.

The current study supports the idea, however, that resistive exercise could be of benefit for preventing bone loss in postmenopausal women. Although we had no inactive control group, the available data suggest that bone loss would occur over time in such individuals⁵⁰. The available data also suggest that muscle performance in the elderly can be improved by both high- and low-load resistance exercise^{15,51,52}. However, the low rates of loading during resistive exercise may still not be the most optimal exercise form for bone⁵³. Also, animal studies have shown that exercise need not be performed for lengthy periods in order to be effective⁵⁴. On the one hand, it may be that the bone strain afforded by the vibration exercise protocol was insufficient to generate a stimulus above that of the remaining exercises performed. Conversely, it is also worth considering that the frequency and duration of vibration training was an insufficient stimulus. Any potential synergistic role of combining vibration and restive exercise in ambulant populations could be considered more in future work.

It is worth noting that the size of the detected effect was quite small. Previous works have shown that a 5-6% change in BMD is associated with much larger (ca. 60-165%) changes in bone strength⁵⁵. This relationship between BMD and bone strength is likely non-linear. Hence, the extent to which the changes in BMD seen in the current study, which were typically less than 1%, are potentially clinically relevant would need to be evaluated in future work.

A secondary goal of the current study was to examine the value of including measurements of the fibula and ulna in this clinical study. Significant changes were seen in ulna bone strength parameters at the proximal forearm in the BAL-group. It should be stressed that the difference between the two training groups was not significant for the ulna. Nonetheless, the balance exercise program involved a number of arm exercises, whereas the vibration exercise group did not perform any such exercises. Also, based upon our data (pooled from both groups) the ulna contributes approximately 58% of total bone strength (polar moment of inertia) at the proximal forearm whereas the fibula only 4% at the proximal leg. A number of important arm muscles attach to the ulna and this bone is involved in movements of the arm. Based upon bone geometry alone, we can assume that at the distal forearm, the radius transmits most forces whereas at the proximal forearm the ulna is more important. At the lower-leg the fibula appears to have less of a load-bearing role. Also, the results from the fibula were typically more variable than from the other bones. Overall, the results of the current study suggest that future work should also consider the ulna in evaluating exercise interventions, particularly those involving the arms.

It is important to consider some of the limitations of the current study. As measurements of the hip and spine were not performed, we cannot comment whether the vibration exercise may have had an additional effect in these body regions. For logistical reasons, we were restricted to two groups. An additional group, such as an inactive control or a vibration exercise only group, would have helped to differentiate between the causes of some of the effects we saw. Prior physical activity likely had an influence on baseline bone density, but prior sports or baseline daily activity levels were not measured. Although footwear was restricted to gym-type shoes, there will nonetheless be some difference between shoe types in the transmission of vibration. To better understand the intensity of the vibration training, future work could consider examining parameters such as change in blood lactate levels, oxygen uptake and muscle blood volume. Important also would be examination of actual bone strain during vibration exercise. Furthermore, the main goal of the study in which this sub-project was performed was postural control²⁸. Consequently, the resistive exercises were designed as part of a general whole-body strengthening program, and not to load specific bones. Similar to this, the sample size was based upon postural control parameters and not bone parameters. A larger sample size may well have been necessary to find significant differences between groups in a number of the parameters of the current study.

In conclusion, the current study provided evidence that a twice weekly resistive exercise program could increase bone density at the distal tibia after a nine-month intervention period in post-menopausal women with low bone mass. However, the addition of four minutes of whole-body vibration per training session or fifteen minutes of balance training did not modulate this effect. The additional measurements of the ulna and fibula suggest that the ulna provides the majority of bone strength at the proximal forearm and that measuring this bone via pQCT is of value in clinical studies.

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