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ORIGINAL ARTICLE

Intensity of exercise is associated with bone density change in premenopausal women

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Abstract *Introduction:* High-impact exercise is known to be beneficial for bones. However, the optimal amount of exercise is not known. The aim of the present study was to evaluate the association between the intensity of exercise and bone mineral density (BMD). *Methods:* We performed a 12-month population–based trial with 120 women (aged 35–40 years) randomly assigned to an exercise group or to a control group. The intensity of the physical activity of 64 women was assessed with an accelerometer–based body movement monitor. The daily activity was analyzed at five acceleration levels (0.3–1.0 g, 1.1–2.4 g, 2.5–3.8 g, 3.9–5.3 g, and 5.4–9.2 g). BMD was measured at the hip, spine (L1–L4), and radius by dual-energy x–ray absorptiometry. The calcaneus was measured using quantitative ultrasound. *Results:* Physical activity that induced acceleration levels exceeding 3.9 g correlated positively with the BMD change in the hip area ($p<0.05$–0.001). L1 BMD change correlated positively with activity exceeding 5.4 g ($p<0.05$) and calcaneal speed of sound with the level of 1.1–2.4 g ($p< 0.05$). Baseline BMD was negatively associated with the BMD change at the hip. *Conclusion:* The intensity of exercise, measured as the acceleration level of physical activity, was significantly correlated with BMD changes. Bone stimulation is reached during normal physical exercise in healthy premenopausal women. In the hip area, the threshold level for improving BMD is less than 100 accelerations per day at levels exceeding 3.9 g.

Keywords Accelerometry · Body movement monitor · High-impact exercise · Osteoporosis · Physical activity · Prevention

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Introduction

Bone adaptation is a function of mechanical loading, and bone remodeling is influenced by the level and distribution of daily mechanical strain [1, 2]. Mechanical loading by physical exercise has been the subject of extensive experimental and clinical research. The response of bone to mechanical stimuli has been shown to be threshold driven [3, 4]. Therefore, specific studies on the effects of the quality and quantity of exercise are needed to develop optimal preventive strategies for osteoporosis.

In previous studies, physical activity was found to have beneficial health effects by increasing the peak bone mass in prepubescent youth, reducing age- and menopause–related bone loss in middle–aged populations, and decreasing the incidence of falls in the elderly by improving strength and coordination [5–8]. Exercise intervention studies in premenopausal women have frequently reported increases in bone mineral density (BMD), although contradictory evidence also exists [9, 10]. High-impact activities especially have been suggested to be effective in improving femoral neck BMD [9]. High-impact, exercise-induced benefits on BMD have also been shown to be maintained after the intervention [11].

There are several studies on high-impact exercise interventions with varying characteristics of exercise, but few have estimated loadings [12–15]. These estimations have been based on calculations of the ground reaction forces (GRF) of single jumps or parts of regimens. The variation of loads in these jumping regimens has been equivalent to 2–6 times the body weight per jump. However, GRF measurements on a force platform are limited to a fixed place and time. The accelerometer-based measurement of movement is an accepted method for monitoring physical activity with reasonable reproducibility [16–19].

Accelerations during exercise have also been shown to be related to impact load forces [16, 20]. Thus, it might be supposed that high peak accelerations are associated with high peak strains. Accelerometers have been used to evaluate the association between changes in physical activity and bone structure in young children [21]. However, continuous long-term measurements during exercise and normal life have not been published so far, and there are no quantitative data to evaluate the intensity and amount of exercise needed for strengthening bone. This is the first long-term study to evaluate the relationship between daily physical activity at different acceleration levels and BMD at various bone sites.

Subjects and methods

Study subjects

The study design was a population-based randomized controlled trial (Fig. 1) that has been described previously in more detail [22]. The subjects of the study were randomly obtained from the cohort of all women aged 35–40 years residing in the city of Oulu, Finland, in March 2002 (n=5161). According to preceding power calculations, 120 subjects were needed. The names, addresses, and Social Security numbers of the women in the cohort were obtained from the National Population Register of Finland. Thereafter, the names were randomly sequenced, and the women were contacted in this random order. Recruited subjects were randomly assigned to an exercise group (n=60) or to a control group (n=60). The exclusion criteria for the exercise intervention were any functional limitation or chronic disease that might have limited training and testing of the cardiovascular, musculoskeletal, and respiratory systems; any disease or medication known to affect bone metabolism; pregnancy or lactation; and current or previous participation in impact-type exercise. The study protocol was approved by the institutional ethical committee, and all participants gave informed written consent. The procedure of the study was in accordance with the Declaration of Helsinki.

Questionnaires and anthropometry

A self-administered health questionnaire was mailed to all contacted women [22]. Information was elicited about weight history and height; occupational history [23]; current and past physical activity [5]; medical factors; fractures beyond the age of 15; menarcheal age; menstrual status; parity; months of breastfeeding; current and previous use of hormones; current and previous dietary factors, includ-

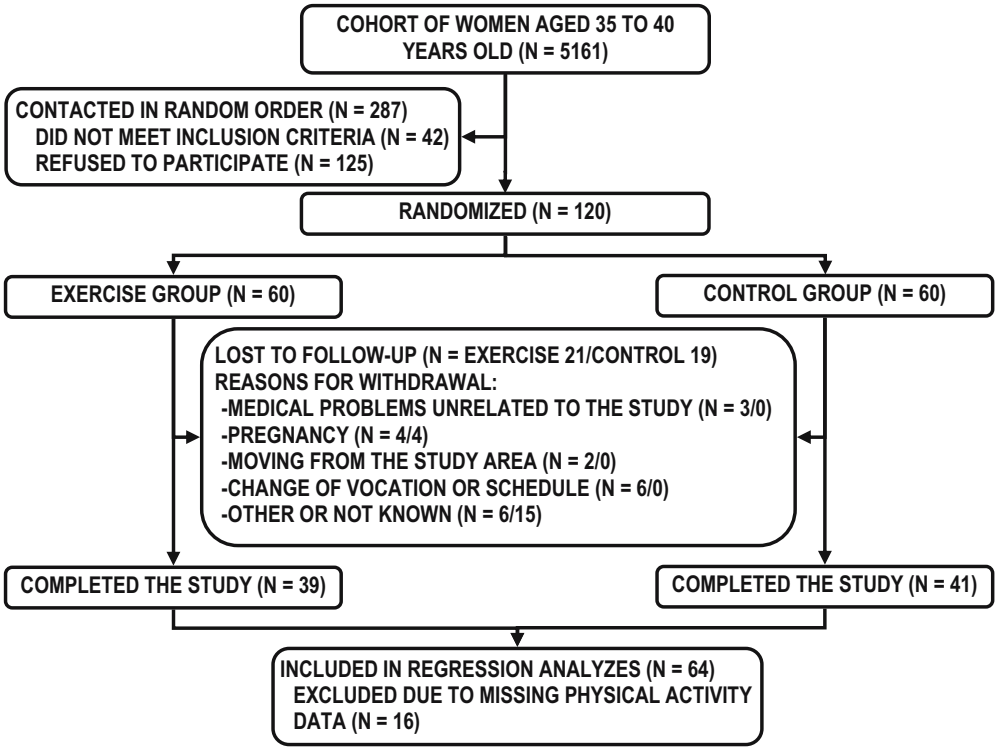

Fig. 1 Trial profile

ing calcium intake [24]; current and past smoking habits and consumption of alcohol; and possible vitamin or mineral supplementation. Body weight and height were measured, and the body mass index (BMI) was calculated at baseline and at 12 months.

Bone measurements

Areal bone mineral density (g/cm^2) was measured by dual-energy x–ray absorptiometry (DXA; Hologic Delphi QDR, Bedford, Massachusetts, USA) at the lumbar spine (L1–L4) and the left proximal femur. The femoral neck, trochanter, and Ward's triangle regions of the femur and the L1–L4 vertebras were analyzed separately. All scanning and analyses were performed by the same operator. The scanner was calibrated daily by bone phantoms (Hologic, Bedford, Massachusetts, USA) for quality assurance, and no evidence of machine drift appeared during this study. BMD was also measured by peripheral DXA (Osteometer DTX 200, Osteometer Meditech, Rødovre, Denmark) at the distal radius and the ultradistal radius. Calcaneal broadband ultrasound attenuation (BUA; dB/MHz) and speed of sound (SOS; m/s) were measured using quantitative ultrasound (QUS; Hologic Sahara, Bedford, Massachusetts, USA). The measurements were performed at the beginning and at the end of the intervention.

Exercise training protocol

The training sessions were carried out three times a week for 12 months by the same physiotherapist. Each workout lasted for 60 min and included step patterns, stamping, jumping, running, and walking. The programs were modified bimonthly and became progressively more demanding, including higher jumps and drops. Additionally, the participants were given a home program, including patterns of exercise similar to those undertaken during the supervised sessions. The women in the control group were asked to continue their normal daily lives and to maintain their current physical activity during the 12 months. The exercise regimen has been described in more detail previously [22].

Measurement of physical activity

In the present study, we recorded the vertical acceleration peaks and analyzed their number at different acceleration levels to describe the intensity of exercise. Previously, we tested the reliability of the accelerometer-based method using a three-dimensional prototype [25]. The average peak amplitude error of the device was less than 2%. We performed a preliminary study with 10 women (aged 20–58 years, BMI 19.1-29.7 kg/m^2) to estimate typical vertical acceleration levels attained in different exercise patterns, using the prototype. The acceleration of gravity (1 g) was subtracted, so that a value of zero corresponded to standing. The peak values were predominantly obtained immediately after the heel contact. The average peak accelerations in different exercise patterns are shown in Fig. 2. The reproducibility error, given as the root–mean–square coefficient of variation (CV_{RMS}), was 4%. The peak acceleration values had a high correlation (R=0.989, n=572 recordings) with the values obtained simultaneously using a standard optical motion analysis system [26], showing that the method reliably measures the local acceleration at the hip. The acceleration values also correlated significantly with the GRF (R=0.735 for the peak acceleration values and R=0.937 for the area under the acceleration peaks, n=462 recordings), measured with a force plate (Kistler 9287A with a Kistler 9865C charge amplifier, Kistler Instrumente, Switzerland), when the acceleration values were multiplied by body weight.

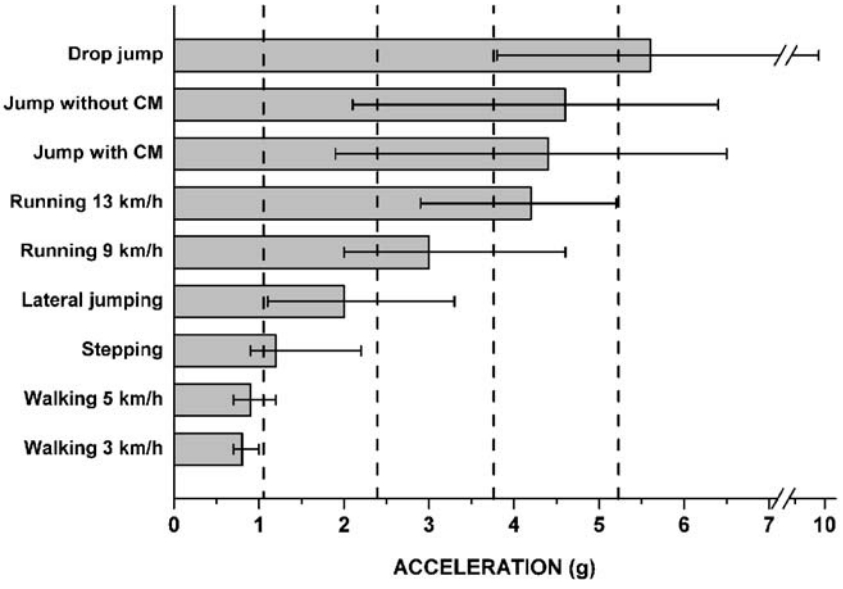

Fig. 2 The average acceleration peak values for different exercise patterns measured from 10 subjects (*CM* countermovement). *Error bars* are shown for the range of individual means. *Dotted lines* represent the acceleration levels used in the analysis

Table 1 Baseline characteristics of the subjects (*BMI* body mass index, *BMD* bone mineral density, *SOS* speed of sound, *BUA* broadband ultrasound attenuation)

Characteristics	Control group, mean (SD), *n*=30	Exercise group, mean (SD), *n*=34
Age, years	38.3 (1.6)	38.3 (1.9)
Height, cm	164.3 (5.9)	162.9 (6.0)
Weight, kg	67.3 (12.9)	67.6 (11.9)
BMI, kg/m^2	25.0 (4.7)	25.5 (4.6)
Calcium intake, mg/day	1,007.6 (547.9)	1,101.1 (532.7)
Smokers, %	23.3	21.2
Hormone users (contraceptives), %	36.7	39.4
L1 BMD, g/cm^2	0.936 (0.109)	0.910 (0.119)
L2 BMD, g/cm^2	1.033 (0.111)	1.020 (0.118)
L3 BMD, g/cm^2	1.061 (0.122)	1.044 (0.106)
L4 BMD, g/cm^2	1.061 (0.120)	1.034 (0.112)
Lumbar total BMD, g/cm^2	1.027 (0.111)	1.007 (0.102)
Femoral neck BMD, g/cm^2	0.807 (0.109)	0.789 (0.096)
Trochanter BMD, g/cm^2	0.700 (0.089)	0.696 (0.095)
Femoral total BMD, g/cm^2	0.944 (0.099)	0.936 (0.106)
Ward's triangle BMD, g/cm^2	0.700 (0.114)	0.685 (0.100)
Distal radius BMD, g/cm^2	0.451 (0.052)	0.463 (0.060)
Ultradistal radius BMD, g/cm^2	0.353 (0.050)	0.365 (0.057)
Calcaneal SOS, m/s	1567.1 (25.5)	1567.7 (28.2)
Calcaneal BUA, dB/MHz	87.35 (13.88)	83.20 (13.17)

In the present intervention study, the vertical acceleration peak values were recorded with an accelerometer-based human body movement monitor (Newtest, Oulu, Finland). In simultaneous measurements during exercise training, the correlation between the activity monitor and the prototype was high (R=0.971, n=41 subjects). The monitor was worn on a belt close to the right iliac crest. For the individual quantification of their daily physical activity, all 120 subjects were asked to carry the monitor during all waking hours for 12 months. The data were transferred to a server computer every second week. The number of daily acceleration peaks was recorded at 33 acceleration levels from 0.3 to 9.9 g. The individual daily average number of peaks at each acceleration level was calculated for the analysis.

Statistical analysis

The individual daily average number of acceleration peaks at each of the 33 levels was normalized relative to the corresponding mean value of the controls. The normalized values were then averaged over five acceleration levels, based on the data presented in Fig. 2, describing the different patterns of physical activity–0.3–1.0 g (e.g., walking), 1.1–2.4 g (e.g., stepping), 2.5–3.8 g (e.g., jogging), 3.9–5.3 g (e.g., running, jumping), and 5.4–9.2 g (e.g., jumping, drop-jumping)–to obtain the relative number of acceleration peaks at each of these levels.

The independent samples t–test (or Mann–Whitney U–test if the distribution was not normal) was used to compare the groups with respect to changes from baseline in BMD.

Table 2 Daily number of acceleration peaks (mean; 95% CI) at the different acceleration levels [g acceleration of gravity (9.81 m/s^2)]

	All (n=64)		Control group (n=30)		Exercise group (n=34)	
	Daily number[a]	Relative daily number[b]	Daily number[a]	Relative daily number[b]	Daily number[a]	Relative daily number[b]
0.3–1.0 g	8,411.9 (7,504.7–9,319.1)	1.1 (0.9–1.2)	7,928.7 (6,353.9–9,503.6)	1.0 (0.8–1.2)	8,838.3 (7,782.8–9,893.7)	1.1 (1.0–1.3)
1.1–2.4 g	529.7 (432.0–627.4)	1.4 (1.1–1.8)	393.1 (273.0–513.2)	1.0 (0.6–1.4)	650.3 (506.8–793.8)	1.8 (1.4–2.3)
2.5–3.8 g	103.3 (67.8–138.8)	1.8 (1.2–2.4)	60.0 (13.1–106.9)	1.0 (0.2–1.8)	141.5 (90.3–192.7)	2.4 (1.5–3.3)
3.9–5.3 g	34.3 (23.9–44.6)	2.7 (1.9–3.6)	13.3 (3.4–23.1)	1.0 (0.2–1.8)	52.8 (37.5–68.0)	4.2 (3.0–5.5)
5.4–9.2 g	15.5 (10.3–20.6)	3.4 (2.3–4.6)	4.5 (1.9–7.5)	1.0 (0.4–1.7)	25.2 (16.9–33.4)	5.6 (3.8–7.4)

[a]Daily average number of acceleration peaks
[b]Daily average number of acceleration peaks normalized relative to the mean values of the controls

Table 3 Correlation coefficients between the relative daily number of acceleration peaks at the different acceleration levels and the 12-month bone mineral density (BMD) change[a] [n=64; g acceleration of gravity (9.81 m/s^2), *SOS* speed of sound, *BUA* broadband ultrasound attenuation]

Variable	0.3–1.0 g	1.1–2.4 g	2.5–3.8 g	3.9–5.3 g	5.4–9.2 g
L1 BMD	−0.018	0.100	0.084	0.202	0.273[b]
L2 BMD	−0.105	−0.072	−0.087	−0.069	−0.013
L3 BMD	−0.048	−0.032	−0.030	−0.007	0.038
L4 BMD	0.153	−0.027	0.006	0.052	0.132
Lumbar total BMD	0.011	−0.005	−0.002	0.082	0.182
Femoral neck BMD	0.058	0.075	0.157	0.343[c]	0.379[c]
Trochanter BMD	0.186	0.170	0.187	0.347[c]	0.413[d]
Femoral total BMD	0.189	0.194	0.174	0.230	0.214
Ward's triangle BMD	0.196	0.102	0.200	0.305[b]	0.382[c]
Distal radius BMD	0.172	0.081	0.029	0.014	−0.049
Ultradistal radius BMD	0.177	0.183	0.203	0.114	0.050
Calcaneal SOS	0.015	0.300[b]	0.124	0.141	0.123
Calcaneal BUA	−0.025	0.246	0.157	0.217	0.247

[a]Correlation coefficients, adjusted for weight change
[b]p<0.05
[c]p<0.01
[d]p<0.001

A paired sample t–test (or Wilcoxon signed–rank test) was used to analyze the percentage change from baseline within the groups. The BMD changes adjusted for weight change were also analyzed at physical activity quartiles, given as the relative number of accelerations at each acceleration level, by using the analysis of covariance. Correlation coefficients (Pearson's) were used to study the association between the relative number of acceleration peaks at each level and the percentage BMD changes. Partial correlation was used to control for the influence of weight change on the correlation coefficients. Multiple stepwise regression analysis was used to quantify the effect of exercise at different acceleration levels on BMD at each measured bone site, the relative number of accelerations at each level being entered separately into the models. The variables used for the stepwise regression analyses were the relative number of accelerations at each level, weight change, baseline BMD, calcium intake, smoking (dichotomous variable), use of oral contraceptives (dichotomous variable), baseline weight, and height. Analyses of correlation and regression were performed within the pooled groups. In all tests, p<0.05 was considered statistically significant. The data were analyzed using the SPSS statistical package (SPSS 11.5 for Windows, SPPS, Chicago, Illinois, USA).

Results

The characteristics of the study subjects are shown in Table 1. The detailed results concerning the compliance and the effect of the trial on BMD separately in the exercise and control group and difference between the groups have been reported and discussed in detail earlier [22]. Bone density measurements and physical activity recordings from 64 subjects (30 in the control group and 34 in the exercise group) were available and included in the correlation and regression analyses. The physical activity data were not available for 16 out of 80 women who completed the original intervention study because they were not willing to use the device or to visit the research unit to download the data (Fig. 1). The average compliance, defined as the number of exercise sessions attended, was 1.0 times per week in supervised sessions and 2.4 in home sessions for the women in the exercise group used in this study (n=34). The distribution of the daily average number

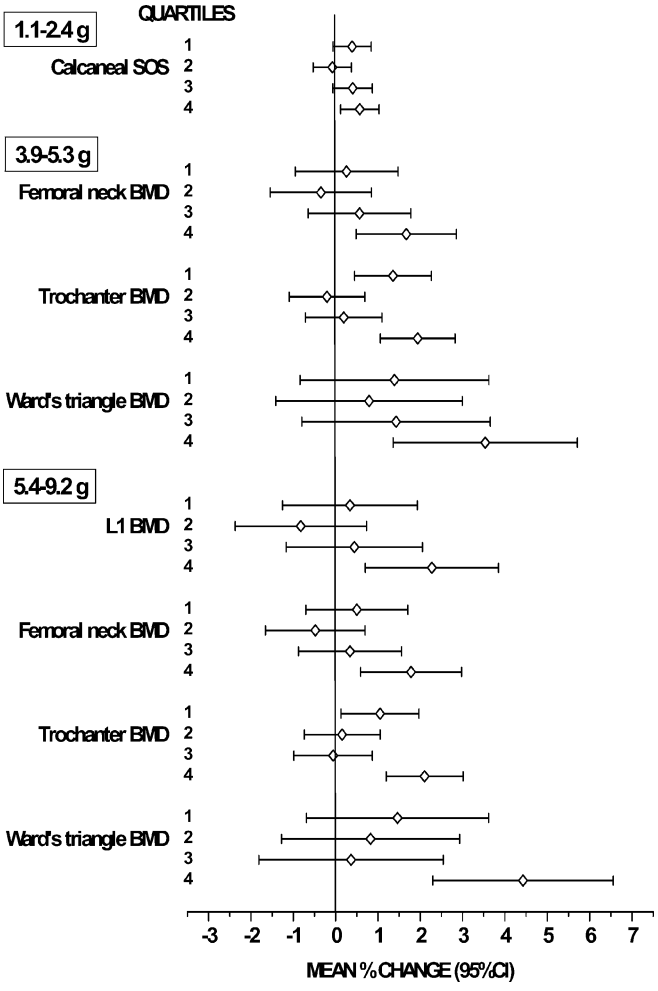

Fig. 3 BMD changes (adjusted for weight change) at physical activity quartiles. The quartiles are defined by the relative number of daily accelerations at each acceleration level. Only the parameters with statistically significant correlations between BMD change and physical activity (Table 3) are shown

of acceleration peaks at each acceleration level is shown in Table 2. The number of accelerations at the lowest level was similar in the study groups. At higher acceleration levels, however, the daily average numbers in the exercise group compared with the controls were approximately twofold within 1.1–2.4 g (650.3 vs. 393.1), twofold within 2.5–3.8 g (141.5 vs. 60.0), fourfold within 3.9–5.3 g (52.8 vs. 13.3), and nearly sixfold within 5.4–9.2 g (25.2 vs. 4.5).

Table 3 shows the association between the BMD changes and the relative number of acceleration peaks at the different levels in the pooled groups. The BMD change was related to the physical activity data, especially at the hip. The relative daily number of accelerations at the levels of 3.9 g or more correlated significantly and positively with the 12-month BMD change at the femoral neck ($p<0.01$), trochanter ($p<0.01$–0.001), and Ward's triangle ($p<0.05$–0.01). The L1 BMD change also correlated positively with the activity level of 5.4 g or more ($p<0.05$). Calcaneal SOS, in contrast, correlated positively with the activity level of 1.1–2.4 g ($p<0.05$). Acceleration level was not associated with the change in BMD at the distal radius or L2–L4. Each significant correlation was accompanied with a significant increase in BMD at the highest exercise quartile (Fig. 3).

Table 4 Significant predictors of percentage change in bone mineral density (BMD) and calcaneal quantitative ultrasound in stepwise multiple linear regression analysis[a] [*β* regression coefficient, *SE* standard error of the regression coefficient, *g* acceleration of gravity (9.81 m/s^2), *SOS* speed of sound, *BUA* broadband ultrasound attenuation]

	β	SE	p[b]	R^2		p[c]
				Regression model	Accelerations[d]	
Femoral neck BMD						
Regression model 1				0.176		0.004
3.9–5.3 g	0.043	0.016	0.009		0.107	0.008
Baseline BMD	−5.844	2.648	0.03			
Regression model 2				0.186		0.002
5.4–9.2 g	0.018	0.006	0.005		0.125	0.004
Baseline BMD	−5.512	2.571	0.04			
Trochanter BMD						
Regression model 1				0.109		0.008
3.9–5.3 g	0.045	0.017	0.008		0.109	0.008
Regression model 2				0.115		0.002
5.4–9.2 g	0.021	0.006	0.002		0.115	0.002
Ward's triangle BMD						
Regression model 1				0.176		0.004
3.9–5.3 g	0.072	0.028	0.01		0.082	0.02
Baseline BMD	−10.497	4.071	0.01			
Regression model 2				0.255		<0.001
5.4–9.2 g	0.037	0.011	0.001		0.123	0.004
Weight change	0.216	0.114	0.06			
Baseline BMD	−10.189	3.802	0.009			
L1 BMD						
Regression model 1				0.286		0.001
5.4–9.2 g	0.022	0.010	0.03		0.051	0.07
Weight change	0.324	0.104	0.003			
Baseline BMD	−7.653	3.922	0.06			
Smoking	−2.033	1.058	0.06			
Contraceptives	−1.631	0.908	0.08			
Calcaneal SOS						
Regression model 1				0.159		0.007
1.1–2.4 g	0.029	0.012	0.02		0.106	0.01
Weight change	-0.052	0.027	0.06			
Calcaneal BUA						
Regression model 1				0.123		0.02
1.1–2.4 g	0.365	0.189	0.06		0.075	0.03
Weight change	−0.764	0.426	0.08			
Regression model 2				0.111		0.03
3.9–5.3 g	0.170	0.100	0.10		0.054	0.07
Weight change	−0.821	0.426	0.06			
Regression model 3				0.126		0.02
5.4–9.2 g	0.132	0.067	0.05		0.075	0.03
Weight change	−0.776	0.424	0.07			

[a]The variables for the stepwise regression procedures were the relative daily number of acceleration peaks, weight change, baseline BMD, calcium intake, smoking, use of oral contraceptives, baseline weight, and height. The relative number of acceleration peaks was entered separately by each acceleration level into the models. The variables included are given under each model

[b]*p*-values for β

[c]*p*-values for R^2

[d]Independent contribution of the relative number of acceleration peaks

The multiple regression analyses showed that the relative number of acceleration peaks at the different acceleration levels were predictors of BMD change at every measured hip site, the L1 vertebra and the calcaneus (Table 4). The relative numbers of accelerations at the levels of 3.9–5.3 g and 5.4–9.2 g were the most significant predictors of the change in femoral neck BMD, with coefficients of determination of 11% and 13%, respectively. The same acceleration levels were also statistically significant predictors of BMD change at the trochanter and Ward's triangle. Physical activity at the acceleration level of 5.4–9.2 g with weight change, baseline BMD, smoking, and use of oral contraceptives explained nearly 30% of the change in L1 BMD. Low-acceleration loadings of 1.1–2.4 g with weight change explained 16% of the change in calcaneal SOS. The change in calcaneal BUA was positively associated with physical activity, both at the low-acceleration level 1.1–2.4 g and at all high acceleration levels above 3.9 g. Baseline BMD was negatively associated with the BMD change at the femoral neck and Ward's triangle (p<0.01–0.042; Table 4).

Discussion

The aim of the present study was to evaluate the relationship between the intensity of physical activity and change in BMD in premenopausal women. The study showed that physical activity including accelerations of 3.9 g or more was positively associated with BMD changes of the proximal femur, whereas activity at lower intensity did not correlate with BMD changes. Effective intensity was achieved during normal physical training activities, such as running and jumping. The efficient frequency of these high-intensity accelerations appeared to be less than 100 per day, based on the upper 95% confidence limit for the average of the exercise group.

We also found that only high accelerations of 5.4 g or more had positive effects on the lumbar spine. In contrast, changes in calcaneal bone were found at the much lower intensity level of 1.1–2.4 g. These findings suggest that the effect of impact exercise is site-specific and that the optimal intensity may vary between different bone sites. However, the differences in sensitivity may be influenced by the site-specificity of our physical activity measurements, since we measured the local accelerations in the hip area. Local accelerations, such as in the calcaneum, may be different because the human body is not a mechanically rigid structure. Thus, interpretations concerning the calcaneum should be taken with caution. Another limitation of our study is that the exercise might also have had some effects on the structure and redistribution of bone that were not identified by the DXA- and QUS–based measurements [27].

It has been reported that impact and nonimpact exercises have a positive effect on the lumbar spine BMD, but only impact exercise has a positive effect on the femoral neck BMD in premenopausal women [10]. High-impact exercise interventions in premenopausal women have been successful in increasing BMD [13, 14, 28, 29]. The current exercise regimen also proved efficient in improving bone mass within the exercise group at each measured proximal femur site, the calcaneus, and the first lumbar vertebra [22]. The baseline BMD appeared to be negatively associated with the BMD change at the proximal femur. This indicates that exercise is most effective for people with low BMD, i.e., persons with an increased risk of osteoporotic hip fracture.

In the present study we used continuous, long-term, accelerometer-based monitoring of physical activity. There are several methods for analyzing accelerometric data; for example, root–mean–square average, power spectrum integral, and acceleration count have been used as measures of activity [16, 19, 21, 30, 31]. In the vertical direction, the highest acceleration is mainly related to the heel strike [19, 30–34]. Here, we used the daily count of vertical acceleration peaks at different acceleration levels to assess the intensity of exercise. The reproducibility of our method was fairly good and similar to that of previous studies [19, 35]. The acceleration levels were also found to correlate with ground reaction forces during different exercise patterns. Previously, Janz et al. found a significant correlation between acceleration count and GRF during walking and running but not during jumping [20]. However, they did not report results at different acceleration levels, and their measurement device was designed to measure accelerations only below 2 g.

In previous intervention studies, the assessment of exercise intensity has been based on the ground reaction forces of model performances. A 5-month training period with 50 vertical jumps on six days per week significantly increased the trochanter BMD in the hip area of premenopausal women but not of postmenopausal women [13]. The resulting mean ground reaction forces were 3.0 times the body weight for premenopausal women and 4.0 times the body weight for postmenopausal women. Positive exercise effects on the femoral neck and lumbar spine BMDs were achieved in premenopausal women after 18 months of exercise, where the peak forces varied between 2.1 and 5.6 times the body weight [14]. In postmenopausal women, 50 daily heel drops during a 12-month period, producing GRFs between 2.5 and 3.0 times the body weight, were inefficient [12]. Witzke et al. previously defined "high intensity" as corresponding to mechanical loading forces greater than four times the body weight, "moderate intensity" as two to four times the body weight, and "low intensity" as less than two times the body weight [36]. Our findings complement these results, providing information on the acceleration thresholds for exercise. Here, low– or moderate–intensity impact training below the acceleration level of 4 g was not as effective as high-impact exercise, including accelerations of 4 g or more. However, any comparison of the results of the previous studies with our data is difficult due to the different methods employed for assessing the intensity of exercise.

Our intervention included high-impact exercise that has been shown to result in peak compression strains of approximately 1,500–2,000 microstrain (με) and shear strains

of 4,000–5000 με in female tibia, the corresponding strain rates being 5,000–10,000 and 15,000–30000 με/s, respectively [37, 38]. It is well known that strain rate is more osteogenic than strain [39, 40]. Jumping has been shown to create large peak strain rates in the presence of only moderately increased peak strain magnitudes [41]. It is possible that the high peak accelerations achieved in our study are related to high strain rates. However, further studies are needed to confirm this.

Previous studies have indicated that the osteogenic response saturates during prolonged exercise [2, 42, 43]. Thus, load-induced bone formation is improved by rest periods, and osteogenic response is improved by adding more exercise sessions rather than by lengthening the duration of individual sessions [44]. In the present study, we had up to three 60-min training sessions per week with an additional daily home program. The physical activity monitor recorded the daily number of acceleration peaks, but it was not able to differentiate the rest periods.

We employed a step aerobic exercise regimen with an additional home program. Similar effects may be achieved through normal physical training activities, such as running and jumping, if they include sufficient amounts of high accelerations. However, we point out that the current exercise regimen recommended here is intended for healthy premenopausal women. The results should be confirmed with other age groups before applying them to older people.

We conclude that the acceleration level of daily physical activity is a significant determinant of changes in the BMD. Healthy premenopausal women can reach effective intensity through normal physical training activities. In the hip area, the threshold level for improving BMD is less than 100 accelerations per day exceeding 3.9 g.

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