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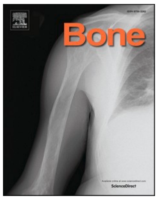

Full Length Article

Changes in femoral neck bone mineral density and structural strength during a 12-month multicomponent exercise intervention among older adults – Does accelerometer-measured physical activity matter?

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ABSTRACT

Age-related bone loss is to some extent unavoidable, but it may be decelerated with regular exercise continued into older age. Daily physical activity alongside structured exercise may be an important stimulus for maintaining bone strength, but the relationships of habitual physical activity with bone strength are sparsely investigated in older adults. Therefore, the main aim was to investigate if accelerometer-derived impact-based and intensity-minute-based measures of physical activity were associated with changes in femoral neck bone traits during a 12-month exercise intervention among community-dwelling older men and women.

Data comes from the PASSWORD study (ISRCTN52388040), a year-long multicomponent exercise intervention. Participants were 299 older adults (mean age 74 ± 4 years, 58 % women), who self-reported not to meet the physical activity guidelines for older adults but did not have any contraindications for exercising. The multicomponent training program included both supervised and self-administered exercises aimed at improving muscle strength, postural balance, and aerobic endurance. Physical activity was assessed at baseline and at six months into the intervention, and femoral neck bone properties at baseline and at twelve months. Physical activity measures were accelerometer-measured mean daily osteogenic index score, low, medium, and high intensity impact counts, and sedentary, light, and moderate-to-vigorous intensity activity minutes. Femoral neck bone mineral density (BMD) was measured with DXA and structural strength indicators (cross-sectional area [CSA] and section modulus) were subsequently derived from hip structural analysis. Longitudinal associations of physical activity and bone outcomes were analyzed with generalized estimating equation linear models. Sex was included as a moderating factor, and models were further adjusted by potentially confounding factors (age, height, weight, smoking status, medications, chronic disease conditions, and strength training adherence).

Participants increased their physical activity by all measures and decreased their sedentary time from baseline to six months. BMD decreased from baseline to post-intervention, while CSA maintained stable and section modulus slightly increased. Osteogenic index, high impacts, and moderate-to-vigorous intensity physical activity, measured across the first half of the study, were positively associated with changes in BMD over 12 months (time x physical activity interaction effect: ß = 0.065, 95 % CI [0.004, 0.126]; ß = 0.169, 95 % CI [0.048, 0.289]; and ß = 0.151, 95 % CI [0.016, 0.286], respectively). That is, the higher the physical activity was, the smaller was the decline in BMD. Any physical activity measure was not associated with changes in CSA or section modulus in the full study sample. Sex did not significantly moderate the longitudinal associations, except the association between sedentary time and CSA (sex x time x PA interaction effect: ß = −0.017, 95 % CI [−0.033, −0.002]). An inverse association was found between sedentary time and changes in CSA in women, but not in men.

In conclusion, BMD decline was less pronounced in individuals who accumulated more accelerometer-measured daily physical activity at the intensity of very brisk walking or light lateral jumping or higher intensities in a sample of relatively healthy, previously physically inactive older adults. Our findings support that

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accumulating the recommended amount of 150 or more weekly minutes of moderate-to-vigorous physical activity is also beneficial for older adults' bone health when incorporated into a multicomponent exercise program.

1. Introduction

Age-related bone loss, especially when combined with physical inactivity, is a risk factor for fragility fractures, thus creating a major public health challenge [1,2]. After the age of 70, bone mineral density (BMD) at the hip declines approximately 0.5 % per year, and the decline somewhat accelerates with increasing age [3]. Although the age-related bone deterioration is unavoidable to some extent, it may be decelerated with regular exercise continued into older age [4,5]. A multicomponent exercise routine combining resistance training and a high dose of weight-bearing impact activity is recommended and may even improve bone strength in older adults [6–8]. Impact activities are recommended to be performed throughout the week [9], and habitual daily physical activity may, alongside structured exercise, thus be an important stimulus for maintaining bone strength. However, the relationships of overall physical activity with bone strength are sparsely investigated among older adults and deserve more research.

Accelerometers are widely used to measure habitual physical activity as they can detect even brief activity periods that may be missed through self-reports. Thus far, the few studies investigating the relationships between accelerometer-measured physical activity and bone strength among older adults have shown inconsistent results. Some studies have found a positive association between moderate-to-vigorous, but not light intensity physical activity and bone traits [10,11], whereas our previous study only showed a consistent positive association between light-intensity physical activity and femoral neck bone traits [12]. Furthermore, other studies have not found any associations between accelerometer-measured physical activity and bone strength among older adults [13,14].

The traditional accelerometer-based measures such as daily minutes in specific intensity categories are, however, not optimal in assessing bone-loading during physical activity. They may conceal potentially osteogenic short bursts of high-intensity impacts, since the activity intensity is averaged over a given epoch, typically one minute [15,16]. Additional impact-based measures, underpinned by mechanobiology [17], such as impact counts or osteogenic indices, may therefore be useful when investigating the relationships between habitual physical activity and bone health. Thus far, these kinds of measures have not been widely utilized in research, and only a few studies have been conducted among older adults. Some studies have shown positive relationships between high-intensity impacts and bone, although not consistently across all measured bone sites [18,19]. In our previous study, in contrast, neither impact count of any intensity nor an osteogenic index was related to proximal femur bone traits [12]. These studies are, however, limited due to their cross-sectional nature. Longitudinal research is required to assess the relationships between impact-based activity and changes in bone strength in older age.

The existing literature is further limited by that studies mainly have focused on the effects of physical activity interventions on BMD [20–22]. However, other outcomes such as measures of bone geometry should be incorporated since physical activity may influence bone geometry positively even though no changes are seen in bone mass [23]. Physical activity may also relate to bone strength differently in older men and women owing to sex differences, which manifest in bone characteristics as well as in age-related changes in bone and may affect the bone response to exercise during aging [24–26]. Moreover, women typically accumulate lower numbers of potentially osteogenic impacts in older age than men do [27], but sex-specific differences in the longitudinal associations between accelerometer-based daily physical activity and bone strength in older age have not been investigated.

Therefore, the aim of this exploratory study was to investigate accelerometer-based physical activity and femoral neck bone mineral density and structural strength during a 12-month multicomponent exercise intervention among previously physically inactive community-dwelling older men and women. The main aim was to investigate if 1) an osteogenic index, 2) impact counts in intensity categories, and 3) minutes in physical activity intensity categories measured across baseline and six months were associated with changes in femoral neck bone traits over 12 months. A further aim was to investigate if sex moderated the longitudinal associations between PA and bone traits. Based on previous literature, we hypothesized that high-intensity impact activity, assessed as an osteogenic index and high-intensity impact counts, would show the strongest positive associations with changes in bone traits.

2. Material and methods

2.1. *Study design*

This study is an exploratory post-hoc analysis of the PASSWORD study, a randomized controlled trial conducted at the Gerontology Research Center at the Faculty of Sport and Health Sciences, University of Jyväskylä, Finland (trial registration number ISRCTN52388040). The main aim of the PASSWORD was to investigate if exercise and cognitive training had a greater effect on gait speed, executive functions, and falls compared to exercise alone among community-dwelling older adults who did not meet the physical activity recommendations of the time. Participants visited the laboratory three times for assessments: at baseline before the intervention start, at six months into the intervention, and at twelve months after the end of the intervention. Study protocol and main results have been published previously [28,29]. The PASSWORD study was approved by the Ethics committee of the Central Finland Health Care District (14/12/2016, ref.: 11/2016) and conducted in accordance with the Declaration of Helsinki. All participants signed a written informed consent before any measurements.

2.2. *Participants*

Three hundred and fourteen community-dwelling older adults from Jyväskylä, Finland, were recruited from a population-based random sample and underwent the baseline measurements between February 2017 and March 2018. Inclusion criteria were the age of 70 to 85 years, not meeting the physical activity recommendations of the time (<150 min/week of moderate-intensity activity in bouts of ≥ 10 min per week and no regular resistance training), ability to walk 500 m without assistance, and scoring ≥ 24 points in the Mini-Mental State Examination (MMSE) test. Exclusion criteria were severe chronic disease or medication affecting cognitive and/or physical function; other medical, psychological, and/or behavioral factors that could have interfered exercise safety or commitment to the study; severe vision or hearing problem; excessive alcohol use; and other family member participating the study. Participants were randomized to receive either exercise and cognitive training ($n = 155$) or exercise alone ($n = 159$). For the present analyses, data from the study groups were pooled, since no between-group differences were observed in the level of or change in any physical activity or bone outcome. Two participants who used bisphosphonates and eight participants with hip replacement on both sides were excluded from the present analyses. Additional five participants who did not have valid bone and physical activity measurements at baseline and/or follow up, were excluded. Final sample size of the present study was thus 299. Data collection for six-months assessments occurred between August 2017 and September 2018, and for the post-intervention assessments between January 2018 and February 2019. Thirteen participants dropped out before the six months measurements, seven due to health-related issues and six were no longer interested. An additional six participants dropped out before the twelve months measurements, one due to health-related issues and five were no longer interested.

2.3. Intervention

The 12-month multicomponent exercise intervention for all participants was conducted in accordance with the then current physical activity recommendations for older adults [30] and has been described in detail previously [28,29,31]. Briefly, two supervised, group-based sessions were organized weekly, one for strength and balance and the other for walking and dynamic balance training. The progressive resistance training was aimed at increasing muscle strength and power and targeted especially the lower body. Leg press, leg curl, and leg extension exercises were the core exercises for lower body, complemented with hip adduction and abduction, hip extension and heel rise. Training sessions were organized at three senior gyms that were equipped with identical resistance training machines utilizing air-pressure technology. Walking and dynamic balance training took place on a circular outdoor walking path, except during winter months in a sports hall, and consisted of warm-up with walking at a self-selected pace and walking balance exercises with increasing difficulty, and a continuous walk of 10–20 min with a somewhat hard to hard intensity. Supervised training sessions lasted for approximately 45–60 min each and were supervised by master's students of sport and health sciences and physiotherapy students. In addition, participants received a home-based strength, balance, and flexibility training program with target training frequency of two to three times per week, in which intensity of the strength exercises was increased by utilizing elastic resistance bands and the difficulty of the balance tasks was increased by reducing vision, hand, and foot support. Participants were also instructed to accumulate at least 150 min per week of moderate-intensity outdoor activity in bouts lasting at least 10 min. The intervention was constructed of training periods with varying specificity, volume, and intensity were adopted to maintain physiological responses and to avoid fatigue and overtraining. The training periods have been documented in detail by Sipilä and colleagues [28].

Half of the participants also attended computerized cognitive training targeting executive functions, which started after approximately two months of physical training. After a few initial supervised training sessions at the University, participants could continue training at the University computer class, at various locations provided by the City of Jyväskylä, or at home. Target training frequency was three to four times per week [28,29]. Participants in this combined training group did not increase their self-reported physical activity level or improve their physical capacity more during the intervention than participants in the exercise alone group [29,31].

Adverse events were tracked carefully with a questionnaire every three months and have been reported previously [29,31]. In the questionnaires, participants reported the setting in which new symptoms or injuries occurred, and an adverse event was recorded as intervention-related if it occurred during intervention-related exercise or if the participant contacted the study nurse or physician and she determined it to be caused by intervention-related exercise. Approximately 40 % of the participants reported some adversities during the intervention period and 10 % of the participants reported intervention-related adverse outcomes, which were mostly minor, e.g., transient joint or muscle pain. One participant had a non-traumatic hip fracture, which may have been related to training overload.

2.4. Measurements

2.4.1. Femoral neck bone properties

Dual energy x-ray absorptiometry (DXA, LUNAR Prodigy, GE Healthcare, Madison, WI, USA) was used to assess femoral neck bone properties. The measurements were performed at baseline and after twelve months at post-intervention. Standard procedures of the device manufacturer were followed, and the device was calibrated with a phantom every morning prior to the measurements for quality assurance. Participants were scanned in supine position in the center of the table using the default-scanning mode automatically selected by the Prodigy software (Lunar Prodigy Advance Encore v. 14.10.022). Scans were analyzed for femoral neck bone mineral density (BMD, g/cm^2). Subsequently, structural parameters at the narrowest femoral neck section, i.e., cross-sectional area (CSA [mm^2], an index of the bone's ability to resist axial compression), and section modulus (mm^3, an index of bending strength), were calculated with hip structural analysis (HSA) [32].

Images were controlled prior to the analyses to ensure right definition of the femoral neck section. If necessary, measurement areas were corrected manually in the analysis software so that the measurement areas did not cover other parts of the femur than the femoral neck, e.g., greater trochanter, and the measured areas at baseline and at twelve months became identical. Mean values of the bone traits in both femurs were calculated. For participants with hip replacement on either side, the scans of the non-operated side were used. For participants, who received hip replacement during the intervention period, only the scans of the non-operated side were used for baseline, too.

Coefficients of variation (CV%) for different DXA-based measures of femoral neck have been reported to vary from 2 % to 10 %, BMD having the lowest and section modulus the highest CV% [33]. In our laboratory, the CV% for section modulus has been reported to be notably lower, i.e., 5.1% [34], and the root mean square coefficient of variation for femoral neck bone mineral content 0.6% [35].

2.4.2. Physical activity

Daily physical activity was measured with a tri-axial accelerometer (UKK RM42, UKK Terveyspalvelut, Tampere, Finland). Measurements were performed at baseline before the intervention start and at six months into the intervention. A six-month lag between the measurements of bone-loading physical activity and bone characteristics has previously been shown to be a reasonable one [36]. Participants received the accelerometer in the end of each laboratory visit. They were instructed both orally and in writing to wear the accelerometer in an elastic waistband over their right hip during waking hours, except during water-related activities, for seven consecutive days beginning from the following morning. Participants returned the accelerometers by mail in a prepaid envelope or to the study personnel when they visited the laboratory for an initial information session before the intervention start or for supervised training.

We have previously described the raw acceleration data processing approaches utilized in the present study in detail [12,37]. Briefly, the raw data were analyzed with in-house developed MATLAB (version R2016b, The MathWorks Inc., Natick MA, USA) scripts. First, the resultant magnitude of the three axes ($\sqrt{x^2 + y^2 + z^2}$) was calculated.

Potential osteogenic impacts were investigated utilizing two different raw data processing approaches to identify peak accelerations. First, an osteogenic index, a summary score of the magnitude and volume of the impact peaks, was calculated [38,39]. All continuous acceleration peaks exceeding 1.3 g were identified and the maximum value of each peak was noted. The peaks were then assigned to 32 intensity bins from 1.3 g to 10.3 g, with all peaks exceeding 10.3 g assigned to a final bin. The daily osteogenic index score was then calculated as the logarithm of the impact count in each bin multiplied by the lower cut-off of the given bin. Second, each sample of the resultant magnitude that was higher than that of both the preceding sample and subsequent sample were identified as an acceleration peak. The magnitude of each peak was noted and categorized as low (>1.5 g to 2.0 g), medium (> 2.0 g to 2.5 g), or high (>2.5 g) impact as per Deere and colleagues [15]. Impact counts in each category were then summarized for each 24 h and daily means were calculated.

To investigate physical activity intensity, the resultant magnitude was summarized in non-overlapping five-second epochs using mean amplitude deviation (MAD), which were used to calculate mean MAD of each one-minute epoch. The mean daily minutes of physical activity were then categorized into sedentary time (<0.0167 g), light-intensity activity (0.0167 to <0.091 g), and moderate-to-vigorous intensity activity (≥ 0.091 g), utilizing previously validated cut-offs [16,40]. For all analysis approaches, any epoch of at least 60-min with the one-minute MAD values continuously below 0.02 g was considered as non-wear time. To be included in the analysis, at least three days with at least 10 h of wear-time were required [37].

2.4.3. *Covariates and descriptive characteristics*

Sex and date of birth were drawn from national population registry. Age was calculated as years at the baseline laboratory visit day. Body mass (kg) was measured with a digital scale and height (cm) with a stadiometer by the study nurse, and body mass index (BMI, kg/m^2) was calculated. Body fat percent (fat%) and appendicular lean mass (ALM, kg) were measured with DXA. Information on current medications and chronic diseases potentially affecting bone health was collected by self-report and verified from the integrated patient information system (Effica database) by the study physician. The following medications were considered: bisphosphonates, hormone replacement therapy (i.e., non-vaginal preparations including oestrogen), and oral glucocorticoids. Chronic diseases recorded were osteoporosis, rheumatic diseases, bowel disorders affecting nutrient absorption, and prostate cancer during the past five years. Smoking history and self-rated current health were reported in a questionnaire at baseline. Smoking status was categorized as current, former (smoked at least 100 times during lifetime, but no current smoking), or never smokers (smoked <100 times during lifetime). Self-rated health was categorized as very good/good or average/poor. Lower extremity physical functioning was assessed with the Short Physical Performance Battery (SPPB) test, which includes habitual walking speed over four meters, and five-time chair-stand time. Total test score ranges from 0 to 12, higher scores indicating better performance [41]. To account for muscle strengthening activities that are not well captured with accelerometry [42,43], adherence to the supervised strength training was calculated as the proportion of sessions attended from the total number of sessions provided to the participant. The number of sessions attended was derived from the resistance training machine logs.

2.5. *Statistical analyses*

Descriptive characteristics were summarized as means and standard deviations (SD) for continuous variables and as frequencies (n) and percentages (%) for categorical variables. Longitudinal data were analyzed with generalized estimating equation (GEE) linear models, using the maximum likelihood method and unstructured working correlation matrix. First, changes in each physical activity outcome from baseline to six months and in each femoral neck bone trait from baseline to twelve months were investigated separately, with the main effect of time as a single predictor. Second, the main effect of sex and the sex x time interaction effect were included in the models to investigate the moderation effect of sex.

Next, the longitudinal associations between physical activity and femoral neck bone traits were analyzed. GEE linear models were built for each bone outcome separately with one physical activity variable (PA) as a predictor at the time. PA was estimated over two time points, i.e., at baseline and at six months. All models included a three-way interaction effect of sex, time, and the PA variable in question, all two-way interaction effects (sex x time, sex x PA, and time x PA), and the main effects of sex, time, and PA. The three-way interaction effect of sex, time, and PA was included to investigate, if sex moderated the longitudinal associations between PA and bone traits. If the three-way interaction effect was not statistically significant (i.e., $p > 0.05$), the models were conducted for the interaction effect of time and PA. The two-way interaction effect was included to investigate, if PA estimated over two time points, i.e., at baseline and at six months, was associated with changes in the bone outcome during the 12-month follow-up period. The main effect of PA describes the association between the overall levels of PA and bone outcome in question.

All models were adjusted for covariates that, based on the existing literature, may influence physical activity and/or bone strength, including age, height, weight, smoking status, strength training adherence, medication (oral glucocorticoids and hormone replacement therapy), and chronic conditions (osteoporosis, rheumatic diseases, bowel disorders, and prostate cancer). In addition, an interaction effect of time and strength training adherence was included in the models to account for the effect of participating in strength training on the changes in bone. All covariates except strength training adherence were assessed at the baseline only. Next, the models investigating the associations of low, medium, and high impacts with bone traits were further adjusted with the two other impact intensity categories. Similarly, the associations of sedentary, light, and moderate-to-vigorous physical activity with bone traits were further adjusted with the two other physical activity intensity categories. Finally, all models conducted for the two-way interaction effect of time and PA were stratified by sex, which are presented as supplementary data.

All statistical analyses were performed in SPSS Statistics 28.0 (IBM Corp, Armonk, NY). A priori sample size calculations were performed for the main outcome of the PASSWORD study, i.e., 10 m maximal walking speed, and have been described in detail previously [28,29].

2.6. *Missing data*

Of the 299 participants included in the present analysis, one participant did not undergo DXA scans at the baseline, and twenty-two participants had missing data on bone measurements at follow-up. The most common reason for missing data was drop-out from the study. Regarding accelerometry, 16 participants had missing data at baseline and 30 participants at follow up. The most common reasons for missing accelerometry data were technical failure at baseline and drop-out at follow-up. There were no missing data in any covariate.

3. Results

3.1. *Participant characteristics*

Participant characteristics are summarized in Table 1 in full study sample and according to sex. Participants were on average 74 years old, and 58 % of them were women. Mean BMI was approximately 28 kg/m^2 in both sexes, whereas fat % was on average 30 % in men and 40 % in women. Approximately half of the participants rated their current health as very good or good. Adherence to the supervised strength training sessions during the intervention year was good, men attended 79 % and women 71 % of the provided training sessions, respectively. In the full study sample, the mean osteogenic index score was 173. Participants recorded on average 3924 low, 493 medium, and 156 high intensity impacts per day, whereas the average daily time spent in sedentary, light, and moderate-to-vigorous-intensity activities was 10, 2.5, and 0.5 h, respectively. In men, BMD was on average 0.935 g/cm^2, CSA 164 mm^2, and section modulus 811 mm^3, whereas the corresponding values in women were 0.886 g/cm^2, 135 mm^2, and 561 mm^3, respectively.

3.2. *Changes in physical activity and femoral neck bone traits*

Participants used the accelerometers on average for 6.6 days and 14 h per day both at baseline and at six months follow-up. Changes in physical activity outcomes from baseline to follow-up are summarized in Table 2 in the full study sample and according to sex. In the full study sample, physical activity increased by all measures. The greatest

Table 1
Descriptive characteristics at the baseline in the whole sample and according to sex, mean (SD) or n (%).

	All	Men	Women
	N = 299	*N* = 125	*N* = 174
Age, years	74.4 (3.8)	74.4 (3.9)	74.4 (3.7)
Height, cm	166 (9)	174 (6)	161 (6)
Mass, kg	77.2 (14.3)	84.2 (12.5)	72.2 (13.3)
BMI, kg/m^2	28.0 (4.8)	27.9 (3.6)	28.1 (5.4)
ALM, kg	19.5 (4.4)	23.7 (2.9)	16.4 (2.1)
Body fat, %	36.0 (8.2)	30.1 (6.0)	40.2 (6.8)
SPPB, total score	10.2 (1.5)	10.6 (1.4)	10.0 (1.5)
Self-rated health, n (%)			
Very good/good	137 (46)	57 (46)	80 (46)
Average/poor	162 (54)	68 (54)	94 (54)
Smoking status, n (%)			
Never	180 (60)	68 (54)	112 (64)
Former	107 (36)	53 (42)	54 (31)
Current	12 (4)	4 (3)	8 (5)
Medication, n (%)			
Hormone replacement therapy	23 (8)	–	23 (13)
Glucocorticoids	12 (4)	5 (4)	7 (4)
Chronic diseases, n (%)			
Osteoporosis	7 (2)	3 (2)	4 (2)
Rheumatic disease	21 (7)	8 (6)	13 (8)
Bowel disorder	6 (2)	2 (2)	4 (2)
Prostate cancer	6 (2)	6 (5)	–
Physical activity	*N* = 283	*N* = 122	*N* = 161
Osteogenic index, score	173 (46)	170 (47)	175 (46)
Low impacts, no./d	3924 (2394)	4031 (2463)	3842 (2344)
Medium impacts, no./d	493 (460)	486 (437)	498 (478)
High impacts, no./d	156 (153)	165 (188)	149 (120)
Sedentary time, min/d	603 (82)	627 (81)	585 (79)
Light intensity activity, min/d	209 (65)	197 (61)	217 (67)
Moderate-to-vigorous intensity activity, min/d	33 (20)	33 (21)	32 (20)
Femoral neck bone traits	*N* = 298	*N* = 124	N = 174
BMD, mg/cm^2	906 (133)	935 (137)	886 (127)
CSA, mm^2	147 (28)	164 (27)	135 (21)
Section modulus, mm^3	665 (183)	811 (163)	561 (112)

Note. Abbreviations: BMI = body mass index; ALM = appendicular lean mass; SPPB = Short Physical Performance Battery (total score range 0–12); BMD = bone mineral density; CSA = cross-sectional area.

increase, 44 %, was seen in the average daily number of medium impacts, whereas the number of low and high impacts increased by 23 % and 29 %, respectively. Osteogenic index score increased by 3 %, light physical activity by 15 %, and moderate-to-vigorous physical activity by 18 %, respectively. In contrast, a decline of 6 % was seen in mean daily sedentary time. Sex moderated the change in all physical activity outcomes except in light activity. Osteogenic index score increased by 7 % in men, whereas no change was observed in women. Men also increased their daily number of low, medium, and high impacts, and total volume of moderate-to-vigorous activity and decreased their sedentary time more than women did (Table 2).

Changes in femoral neck bone traits from baseline to post-intervention follow-up at twelve months are shown in Table 2. In the full study sample, a decline of 0.4 % was seen in BMD. When the main effect of sex, and the interaction effect of sex x time were included in the analyses, a 0.7 % decline in BMD was found in women, whereas no change was observed in men. Section modulus improved with an average of 0.7 % from baseline to post-intervention and CSA remained stable during the intervention in the full study sample, and sex did not moderate the changes in these outcomes (Table 2).

3.3. *Longitudinal associations of physical activity and bone properties*

The longitudinal associations between physical activity and femoral neck bone traits are shown in Table 3 in the full study sample and in Supplementary Tables 1–2 for men and women, respectively. Osteogenic index estimated over baseline and six months was positively associated with the change in BMD over 12 months (time x PA interaction effect: β = 0.065, 95 % CI [0.004, 0.126]). That is, a one-point higher osteogenic index score was associated with 0.07 mg/cm^2 less decline in BMD over the course of the intervention. In contrast, osteogenic index was not associated with changes in CSA or section modulus. However, the level of osteogenic index during the first half of the study was positively associated with the level of section modulus across the 12-month intervention (main effect of PA: ß = 0.143, 95 % CI [0.021, 0.264]). Sex did not moderate the longitudinal associations between osteogenic index and bone traits, i.e., no statistically significant three-way interaction effects of sex, time, and osteogenic index were observed in any model.

When investigating the associations between impact counts in

Table 2
Changes in accelerometer-based physical activity from baseline to six months and in femoral neck bone properties from baseline to twelve months. Unstandardized beta coefficients and 95 % confidence intervals from the generalized estimating equations.

	Model 1[a]		Model 2[b]					
	All		Men		Women		Sex x time	
	β	95 % CI	β	95 % CI	β	95 % CI	β	95 % CI
Physical activity								
Osteogenic index	6.6**	[2.3, 10.9]	12.5***	[5.2, 19.8]	2.1	[−2.9, 7.1]	−10.4*	[−19.2, −1.6]
Impacts, no./d								
Low impacts	886.7***	[619.1, 1154.4]	1232.9***	[775.1, 1710.7]	626.9***	[332.9, 921.0]	−606.0*	[−1167.0, −45.0]
Medium impacts	216.5***	[159.4, 273.6]	301.7***	[208.4, 395.0]	152.5***	[82.9, 222.1]	−149.2**	[−265.6, −32.8]
High impacts	45.3***	[25.7, 64.8]	72.4***	[36.6, 108.1]	25.1*	[4.5, 45.7]	−47.3*	[−88.5, −6.0]
Min/d in intensity categories								
Sedentary time	−34.8***	[−43.0, −26.6]	−44.2***	[−56.2, −32.3]	−27.5***	[−38.6, −16.4]	16.7*	[0.4, 33.0]
Light activity	32.3***	[25.5, 39.2]	31.3***	[20.7, 41.9]	32.9***	[24.0, 41.9]	1.6	[−12.3, 15.5]
Moderate-to-vigorous activity	6.4***	[4.3, 8.4]	9.8***	[6.4, 13.2]	3.8**	[1.3, 6,1]	−6.0**	[−10.2, −1.9]
Femoral neck bone traits								
BMD, mg/cm^2	−3.7**	[−6.2, −1.3]	−0.6	[−4.4, 0.1]	−5.9***	[−9.2, −2.7]	−5.3*	[−10.2, −0.4]
CSA, mm^2	0.0	[−0.6, 0.6]	0.4	[−0.6, 1.4]	−0.3	[−1.0, 0.4]	−0.7	[−1.9, 0.6]
Section modulus, mm^3	5.1*	[1.0, 9.2]	6.1	[−1.2, 13.3]	4.4	[−0.4, 9.2]	−1.7	[−10.4, 7.0]

Note. Abbreviations: BMD = bone mineral density, CSA = cross-sectional area.

[a] Model 1 includes only the main effect of time.

[b] Model 2 includes the main effects of time and sex, and the interaction effect of time and sex.

[*] $p \leq 0.05$.

[**] $p \leq 0.01$.

[***] $p < 0.001$.

Table 3

The association between physical activity and femoral neck bone properties. Unstandardized beta coefficients and 95 % confidence intervals from the generalized estimating equations.

Physical activity	Model[a]	Coefficient[b]	BMD		CSA		Section modulus	
			β	95 % CI	β	95 % CI	β	95 % CI
Osteogenic index	Model 1	PA	−0.001	[−0.074, 0.072]	0.012	[−0.005, 0.028]	0.143*	[0.021, 0.264]
		Time x PA	0.065*	[0.004, 0.126]	−0.002	[−0.017, 0.012]	0.010	[−0.082, 0.101]
Low impacts[c]	Model 1	PA	0.006	[−0.007, 0.018]	0.004*	[0.001, 0.007]	0.016	[−0.008, 0.040]
		Time x PA	0.009	[−0.002, 0.020]	−0.001	[−0.004, 0.001]	−0.013	[−0.031, 0.005]
	Model 2	PA	−0.002	[−0.017, 0.012]	0.002	[−0.002, 0.006]	0.012	[−0.016, 0.040]
		Time x PA	0.006	[−0.005, 0.017]	−0.002	[−0.005, 0.001]	−0.014	[−0.032, 0.004]
Medium impacts[c]	Model 1	PA	0.057*	[0.004, 0.109]	0.028***	[0.013, 0.042]	0.077	[−0.024, 0.117]
		Time x PA	0.042	[−0.005, 0.088]	−0.012	[−0.024, 0.001]	−0.053	[−0.143, 0.036]
	Model 2	PA	0.041	[−0.030, 0.112]	0.025*	[0.005, 0.045]	0.032	[−0.101, 0.165
		Time x PA	0.043	[−0.005, 0.090]	−0.012	[−0.024, 0.001]	−0.052	[−0.142, 0.038]
High impacts[c]	Model 1	PA	0.039	[−0.091, 0.169]	0.033	[−0.017, 0.083]	0.080	[−0.284, 0.444]
		Time x PA	0.169**	[0.048, 0.289]	−0.006	[−0.050, 0.037]	0.131	[−0.222, 0.484]
	Model 2	PA	−0.055	[−0.198, 0.087]	0.011	[−0.034, 0.056]	0.091	[−0.297, 0.478]
		Time x PA	0.144*	[0.017, 0.270]	−0.012	[−0.051, 0.028]	0.151	[−0.197, 0.498]
Sedentary time[d]	Model 1	PA	0.004	[−0.036, 0.043]	0.004	[−0.005, 0.014]	0.055	[−0.006, 0.117]
		Time x PA	−0.013	[−0.046, 0.019]	−0.001	[−0.009, 0.006]	−0.024	[−0.074, 0.026]
	Model 2[e]	PA	0.000	[−0.050, 0.050]	0.011	[−0.008, 0.030]	0.062	[−0.011, 0.135]
		Time x PA	−0.018	[−0.052, 0.016]	0.007	[−0.006, 0.020]	−0.023	[−0.075, 0.029]
		Sex x Time x PA			−0.017*	[−0.033, −0.002]		
Light activity	Model 1	PA	−0.028	[−0.084, 0.028]	−0.008	[−0.019, 0.003]	−0.008	[−0.084, 0.068]
		Time x PA	0.016	[−0.031, 0.063]	−0.002	[−0.012, 0.009]	−0.014	[−0.078, 0.050]
	Model 2	PA	−0.033	[−0.102, 0.037	−0.006	[−0.020, 0.008]	0.031	[−0.057, 0.119]
		Time x PA	0.018	[−0.028, 0.064]	−0.001	[−0.011, 0.009]	−0.015	[−0.078, 0.048]
Moderate-to-vigorous activity	Model 1	PA	0.090	[−0.064, 0.244]	0.050*	[0.010, 0.090]	0.074	[−0.193, 0.341]
		Time x PA	0.151*	[0.016, 0.286]	−0.003	[−0.040, 0.034]	−0.072	[−0.301, 0.156]
	Model 2	PA	0.089	[−0.066, 0.243]	0.051*	[0.011–0.091]	0.098	[−0.174, 0.370]
		Time x PA	0.149*	[0.014, 0.283]	−0.004	[−0.041, 0.039]	−0.064	[−0.292, 0.164]

Note. Abbreviations: BMD = bone mineral density; CSA = cross-sectional area.

[a] Model 1 adjusted for baseline age, sex, body mass, body height, smoking status, adherence to supervised strength training sessions, medications (oral glucocorticoids and hormone replacement therapy) and chronic conditions (osteoporosis, rheumatic diseases, bowel diseases, and prostate cancer). In Model 2, the associations of low, medium, and high impacts with bone properties further adjusted for the other impact intensity bands, and the associations of sedentary time, light and moderate-to-vigorous intensity physical activity further adjusted for the other physical activity intensity bands.

[b] Time from baseline to 12 months. Accelerometer-based physical activity variables (PA) measured at baseline and at 6 months.

[c] Regression coefficients presented for each ten impacts.

[d] Model 2 investigating the associations between sedentary time with changes in CSA includes the three-way interaction of sex, time, and sedentary time, and their two-way interactions, adjusted for baseline age, body mass, body height, smoking status, adherence to supervised strength training sessions, medications (oral glucocorticoids and hormone replacement therapy) and chronic conditions (osteoporosis, rheumatic diseases, bowel diseases, and prostate cancer), and light and moderate-to-vigorous physical activity.

* $p \le 0.05$.

** $p \le 0.01$.

*** $p < 0.001$.

intensity categories and bone traits, only high impacts measured across baseline and six months were positively associated with changes in BMD from baseline to twelve months (time x PA interaction effect: ß = 0.169, 95 % CI [0.048, 0.289]), i.e., each ten more impacts of 2.5 g or higher intensity per day were associated with 0.2 mg/cm^2 less decline in BMD. Further adjustment for other impact intensities only slightly attenuated this association. Higher level of medium intensity impacts was associated with higher level of BMD and CSA (main effect of PA: ß = 0.057, 95 % CI [0.004, 0.109] and ß = 0.028, 95 % CI [−0.013, 0.042], respectively). Additionally, there was a trend towards medium impacts to be associated with less decline in BMD and with more decline in CSA over the course of the intervention (time x PA interaction effect: ß = 0.042, 95 % CI [−0.005, 0.088] and ß = −0.012, 95 % CI [−0.024, 0.001], respectively). The level of low impacts was positively associated with the level of CSA across the intervention, but this association attenuated when further adjusted for other impact intensities. Sex did not moderate the associations between the changes in any impact intensity category and bone traits.

Regarding the relationships between daily minutes in physical activity intensity categories and bone traits, moderate-to-vigorous intensity activity estimated over two time points was positively associated with the change in BMD (time x PA interaction effect: ß = 0.151, 95 % CI [0.016, 0.286]). That is, 10 min more moderate-to-vigorous intensity activity per day was associated with 1.5 mg/cm^2 less decline in BMD over the course of the intervention. Further adjustment for other physical activity intensities did not change this association. In addition, a higher level of moderate-to-vigorous intensity activity was associated with a higher level of CSA across the measurements. No statistically significant associations were found between sedentary time or light intensity activity and bone traits in the full study sample. However, the three-way interaction effect of sex, time, and sedentary time predicting changes in CSA (β = −0.015, 95 % CI [−0.030, 0.000] indicated differences between men and women in the longitudinal association between sedentary time and CSA. Investigating the sex-stratified models revealed sedentary time was negatively associated with changes in CSA in women but not in men (time x PA interaction effect: ß = −0.011, 95 % CI [−0.019, −0.003] and ß = 0.008, 95 % CI [−0.006, 0.022], respectively; Supplementary Tables 1 and 2).

Higher strength training adherence was positively associated with favorable changes in all bone outcomes in all models conducted in the full study sample (time x strength training adherence interaction effect: BMD: β = 0.126–0.170, 95 % CI [lower bound range: −0.004-0.043, upper bound range: 0.256–0.297]; CSA: β = 0.033–0.041, 95 % CI [−0.005–0.003, 0.072–0.078]; section modulus: β = 0.229–0.273, 95 % CI [0.030–0.078, 0.428–0.469]).

4. Discussion

This study investigated accelerometer-based physical activity and femoral neck bone traits and their longitudinal associations among previously physically inactive older adults during a yearlong multicomponent exercise intervention. An increase was observed in the volume of physical activity and impact counts from baseline to mid-intervention. A modest decline in BMD and a modest increase in section modulus were observed from baseline to twelve months while CSA remained unchanged. More daily moderate and high intensity activity, measured both as an osteogenic index summary score, impact counts, and intensity minutes, was positively associated with changes in femoral neck BMD.

This study provides novel information on the changes in accelerometer-based physical activity during exercise intervention and the relationships of daily activity with changes in femoral neck bone properties among older adults. Despite the relatively high baseline level of impact counts as compared to other cohorts of older adults [27], the numbers of daily medium and high impacts increased by 30–45 % from pre- to mid-intervention. In contrast, osteogenic index score increased only slightly, indicating that there was no notable increase in very high intensity impacts. This is the first study to investigate changes in impact-based accelerometry outcomes in older adults and we can thus not compare these results to previous research. The weekly increase of approximately 40 min of moderate-to-vigorous intensity activity was, however, comparable to previous exercise intervention studies [44–47].

Despite the increases in physical activity and good adherence to the strength training protocol, we did not observe notable improvements in femoral neck BMD or bone structural strength indicators from baseline to post-intervention. Instead, we observed a decline of 0.4 % in BMD, which is comparable to the average annual bone loss in people of the same age [3]. To our knowledge, there is no previous research on longitudinal associations between accelerometer-based physical activity and BMD in older adults, and it was a novel finding that approximately 25 min more daily moderate-to-vigorous intensity activity, 880 medium or 220 high intensity impacts more per day were associated with a similar amount less annual decline in BMD during the intervention. Thus, the benefits of multicomponent exercise interventions may, in part, rely on the volume and intensity of daily physical activity. It must, however, be noted that the volume of daily moderate to high intensity activity, which was linked to the maintenance of BMD at a stable level from baseline to twelve months, was relatively high compared to the level of physical activity before and during the intervention. Although the observed effect sizes were relatively small, as can be expected with a one-year intervention, daily impact activity at the intensity of very brisk walking or more intensive activity may support the maintenance of BMD in older age, when incorporated into a weekly exercise routine following the current physical activity recommendations for older adults [48,49].

While bone-targeted physical activity trials have found positive effects on femoral neck structure and strength in older men [50,51] and women [52–54], we only observed a modest increase of 0.7 % in section modulus and no change in CSA. Furthermore, we did not find any associations between physical activity and changes in bone structural strength indicators in the full study sample, but some modest positive associations were found between the levels of moderate-to-high intensity physical activity indicators and bone structural strength. Previous research on the longitudinal associations between accelerometer-based physical activity and femoral neck structural strength in older adults is sparse. In their study, Multanen et al. [55] observed that a higher osteogenic index score was associated with an increase in section modulus, but not with changes in CSA, in 50- to 65-year-old women participating in a 12-month high-impact exercise trial, both in the intervention and control groups.

There are a few plausible explanations to why we did not observe any associations between accelerometer-based physical activity and changes in bone structural strength indicators. First, although the exercises included in our intervention were mostly weight-bearing, they were not bone-targeted, and the participants were not instructed to accumulate high-intensity impact activity. Therefore, moderate-to-high intensity physical activity captured by accelerometry may have lacked intensity or specificity for notable geometric adaptation in the present study. While femoral neck BMD may be responsive to continuous impact activity such as brisk walking [56], which was a recommended activity type in our training programs and well captured by accelerometry, adaptations to bone structural strength in older age may require bending and torsion derived from high-intensity impact training or strength training, that are inadequately captured by accelerometry. This is supported by the fact that in older adults, adaptations in bone geometry have been observed mainly after very intense or novel, bone-targeting exercises. An encouraging finding was that higher strength training adherence was positively associated with changes in all bone outcomes.

Another potential explanation for the lack of associations between physical activity and the changes in bone structural strength may relate to greater variability associated with the structural properties derived from the two-dimensional DXA-images. The observed changes in section modulus were modest and did not exceed the measurement precision error. Therefore, more research involving larger study samples, bone-targeted physical activity programs and more accurate imaging tools are required to assess the effects of increasing habitual higher intensity activity on bone structural strength in older age.

Although sex moderated the changes in most physical activity and in all bone outcomes, sex did not moderate the associations between physical activity and the changes in bone traits except for sedentary time and CSA. The sex-stratified models revealed a weak association between less sedentary time and an increase in CSA in women but not in men. It is difficult to explain this finding, but it may relate to overall sex differences in the levels of sedentary time during the intervention. In general, our findings indicate that both older men and women may benefit from increasing impact activity. It must, however, be noted that the sample size, especially the number of male participants, may not have been sufficient to detect the moderating effect of sex on the associations between the changes in physical activity and bone traits. Therefore, future research with larger samples is required.

4.1. Strengths and limitations

This study benefits of a longitudinal design and multifaceted assessment of physical activity and femoral neck bone properties in a relatively large population-based cohort of older adults, who could benefit from increasing physical activity. Two assessment periods of habitual physical activity were conducted, the first before the intervention started and the second when the intensive exercise intervention was ongoing. Furthermore, accelerometry was complemented with the assessment of strength training adherence to account for muscle strengthening activities that are typically not well captured by accelerometry. The intervention was of a sufficient length, i.e., twelve months, to induce positive changes in bone strength. This design allowed to inspect the longitudinal associations between habitual physical activity and bone properties. Furthermore, the strengths of the study include the use of several accelerometer-based physical activity data processing approaches, including two different impact-based approaches, which may be more suitable to assess bone-loading physical activity than physical activity minutes in intensity categories. In addition, hip structural strength parameters were included to widen the understanding of the associations of physical activity with the fracture-prone femoral neck. Additionally, we were able to adjust analyses for several potentially confounding factors, including medication use and chronic disease conditions verified from registry data.

The main limitation of the present study is its exploratory nature. The sample size was not powered for the present analyses, and the exercise intervention and bone measurements were not optimized for the present research questions. Additionally, the target group of the

PASSWORD study were physically inactive yet relatively healthy and well-functioning older adults, which limits the generalizability of the results. Although participants varied in their daily physical activity volume and intensity before and during the intervention, a major limitation of the present study is the lack of a non-exercising control group on the one hand, and a training group with higher volume and intensity of impact activity on the other hand. This limits our ability to draw conclusions on the actual effects of the intervention on physical activity and on the extent to which the observed changes in bone properties were exercise-induced or aging-driven, and if prescribing higher intensity impact activity would be more beneficial.

It would also have been valuable to track changes in physical activity across the intervention period and analyze the longitudinal associations between physical activity and bone over the whole twelve months period. Unfortunately, we could not capitalize on the twelve-months physical activity measurements since the assessment periods were carried out first after the post-intervention bone measurements and the results were thus not relevant for the present research questions. On the other hand, bone adaptation is relatively slow with mineralization taking several months to complete [57] and previous research has shown a six-month lag between osteogenic load assessment and bone characteristics capture to be a reasonable one [36]. We also lacked information on nutrition, which is a key determinant of bone health. Finally, we highlight the exploratory nature of this analysis and did not adjust the confidence intervals for multiple testing to reduce the risk of false negative. Due to the large number of statistical tests performed and covariates included in the models, it is important to exercise great caution when interpreting the individual analysis results.

5. Conclusion

In this exploratory post-hoc analysis, we found that daily accelerometer-measured moderate- and high-intensity physical activity, assessed both as intensity minutes and impact counts, was positively associated with changes in femoral neck BMD in older adults participating a year-long exercise program. Approximately 25 min more moderate-to-vigorous physical activity or 220 more high intensity impacts per day, corresponding to very brisk stepping or light lateral jumping or higher intensity, were linked to 4 mg/cm^2 less decline in BMD, which was the average decline during the intervention. Our findings support that accumulating the recommended amount of 150 or more weekly minutes of moderate-to-vigorous physical activity, complemented with regular strength training, is also beneficial for previously physically inactive older adults' bone health. The individual role of daily physical activity in preservation of BMD in older age deserves further research.

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CRediT authorship contribution statement

T. Savikangas: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **T.H. Suominen:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **M. Alén:** Writing – review & editing, Investigation, Conceptualization. **T. Rantalainen:** Writing – review & editing, Software. **S. Sipilä:** Writing – review & editing, Project administration, Investigation, Funding acquisition.

Declaration of competing interest

Authors declare no conflict of interest.

Data availability

The data that has been used is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bone.2023.116951.

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