Author(s): Savikangas, Tiina; Sipilä, Sarianna; Rantalainen, Timo

Title: Associations of physical activity intensities, impact intensities and osteogenic index with proximal femur bone traits among sedentary older adults

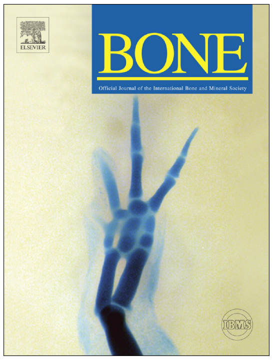
Year: 2021

Version: Accepted version (Final draft)

Please cite the original version:

Savikangas, T., Sipilä, S., & Rantalainen, T. (2021). Associations of physical activity intensities, impact intensities and osteogenic index with proximal femur bone traits among sedentary older adults. Bone, 143, Article 115704. https://doi.org/10.1016/j.bone.2020.115704

Journal Pre-proof



Associations of physical activity intensities, impact intensities and osteogenic index with proximal femur bone traits among sedentary older adults

Tiina Savikangas, Sarianna Sipilä, Timo Rantalainen

PII:	S8756-3282(20)30484-1
DOI:	https://doi.org/10.1016/j.bone.2020.115704
Reference:	BON 115704
To appear in:	*Bone*
Received date:	20 May 2020
Revised date:	9 October 2020
Accepted date:	17 October 2020

Please cite this article as: T. Savikangas, S. Sipilä and T. Rantalainen, Associations of physical activity intensities, impact intensities and osteogenic index with proximal femur bone traits among sedentary older adults, *Bone* (2020), https://doi.org/10.1016/j.bone.2020.115704

Associations of physical activity intensities, impact intensities and osteogenic index with proximal femur bone traits among sedentary older adults

Tiina Savikangas[1], tiina.m.savikangas@jyu.fi

Sarianna Sipilä[1], sarianna.sipila@jyu.fi

Timo Rantalainen[1], timo.rantalainen@jyu.fi

[1] Gerontology Research Center and Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland

Corresponding author:

Tiina Savikangas

E-mail: tiina.m.savikangas@jyu.fi

PO Box 35 (Viv 256), 40014 University of Jyväskylä, Finland

Abstract

Background

Dynamic high-intensity physical activity is thought to be beneficial for older adults' bone health. Traditional volume-based processing of accelerometer-measured physical activity data, quantified on a minute-per-minute basis, may average out sporadic high impact activity, whereas accelerometer data processing approaches based on identifying impacts can capture also these potentially beneficial short activity bursts. We investigated the associations between habitual physical activity and proximal femur bone traits among sedentary older adults utilizing three different numerical treatments of accelerometer-data to examine, if impact-based processing approaches are more suitable to assess bone loading than volume-based processing of physical activity data among older adults.

Methods

This cross-sectional study utilized the baseline data from the PASSWORD-study (n=284, mean ± SD age 74 ± 4 years, 57 % women). Total femur bone mineral content (BMC) and bone mineral density (BMD), femoral neck BMC, BMD, section modulus and minimal width (MNW) were measured with dual energy x-ray absorptiometry. Physical activity was measured for seven consecutive days with a tri-axial accelerometer. Raw acceleration data was processed in three different ways and quantified as i) mean daily minutes in sedentary, light and moderate-to-vigorous-intensity activity, ii) mean daily number of acceleration peaks divided into low (1.5 g to 2.0 g), medium (2.0 g to 2.5 g) and high (> 2.5 g) impacts, and iii) mean daily osteogenic index, which is a summary score calculated from log-transformed number of impact peaks in 32 intensity bands (≥ 1.3 g). Associations between physical activity measures and each bone trait were estimated with multiple linear regression adjusted with covariates (age, sex, weight, height, smoking, physical function, medication).

Results

Participants recorded on average 10 h sedentary, 2.5 hrs light and 32 min moderate-to-vigorous activity, and 3937 low, 494 medium and 157 high impacts per day. Mean osteogenic index score was 173. Light physical activity was positively associated with all bone traits (beta = 0.147 to 0.182, p<0.001 to p=0.005) except MNW. Sedentary or moderate-to-vigorous activity, low, medium or high impacts or osteogenic index were not associated with any bone parameter.

Conclusions

Light physical activity may decelerate the age-related bone loss in older adults who do not meet the physical activity recommendations. In this population, the amount of high impact activity may be insufficient to stimulate bone remodelling.

Keywords: accelerometer, physical activity, sedentary, older adults, bone mineral content, bone mineral density

1 Introduction

Life-long physical activity is one of the major non-pharmacological methods to prevent and treat osteoporosis [1–3] but the evidence on which exact types and intensities of exercise are sufficient to promote bone health in older age is still inconsistent [4]. Notably, specific prescription of physical activity for bone health for older people is conspicuously absent from the current American physical activity recommendations [5]. Impact activities including hopping and jogging are likely to have higher osteogenic potential than habitual walking also for older adults [6]. However, the majority of older adults do not engage in high-intensity physical activity, but prefer light activities such as walking [7].

Findings on the associations between accelerometer-based physical activity and bone parameters in older adults are scarce and inconclusive. Some [8, 9], but not all [10, 11], studies have shown a positive association between moderate-to-vigorous intensity physical activity and femoral neck bone parameters. However, accelerometer-data is usually averaged into mean intensity of each 15–60 second epoch, which may artificially prevent the ability to detect potentially osteogenic high-impact activity, which may occur in short bursts [12, 13], such as in stair climbing. Therefore, other accelerometer-data processing approaches are necessary to investigate bone loading physical activity.

A few alternative raw acceleration data processing approaches appropriate for bone loading evaluation have been developed, which capitalise on the physiological understanding that bone responds to strain magnitude and rate [14, 15]. For example, Ahola and colleagues [12] presented a method based on identifying all impact peaks present in a prolonged accelerometry recording. The osteogenic index, also known as daily impact score, is then calculated by dividing the impact peaks into 32 intensity bands (from 1.3 to 10 times body weight) based on the maximum acceleration of the peak. Subsequently the number of peaks in the bands are summed together with each band weighted with the logarithm of the peaks within it [12]. A more straightforward approach is to summarize the amount of acceleration peaks within a specified number of intensity bands, and use the count within each band as a measure [16–19].

Osteogenic indices have been shown to be associated with bone traits in premenopausal [12] and postmenopausal women [20]. Even a low volume of high impacts corresponding to jogging or running has been beneficially associated with bone traits in adolescents [21], premenopausal [19, 22], postmenopausal [22] and older women [18]. While a minimal impact threshold of around 5 times body weight has been identified for adolescents and young and middle-aged adults for positive bone adaptations [19, 21], it has been proposed that lower-intensity impacts may create similar mechanical strains and thus be associated with better bone health among older people as higher intensity activity among younger people [16, 18, 22]. However, studies among older men are lacking altogether, and a dearth of research is to be found with older women as well.

Among older adults, the amount of high intensity impacts has been very low in earlier studies [17, 18, 23]. We have previously investigated the amount of physical activity accumulated through the gradation of intensities among older men and women who were at most moderately active by self-report [24]. We observed that less than one third of participants recorded any activity at intensities corresponding to walking faster than 5 km/h during the measurement week and the amount of activity corresponding to jogging was, for all intents and purposes, non-existing [24]. However, in that study the raw acceleration data were averaged into one-minute epochs, and the amount of impacts remained unknown. Therefore, the purpose of this cross-sectional study was to investigate the amount of potentially osteogenic high-impact activity and the associations of accelerometer-based physical activity with proximal femur bone traits among older men and women who did not meet physical activity recommendations. We utilized three different accelerometer-data processing approaches. First, we divided physical activity into sedentary, light and moderate-to-vigorous intensity activity [13]. Then we calculated the amount of low, medium and high impacts [16] and finally, the osteogenic index [12]. Based on the previous literature, we hypothesized that osteogenic index and the amount of high impacts would be more strongly associated with bone properties than the volume-based (minutes of activity within a particular intensity range) physical activity measure.

2 Materials and methods

2.1 Study design and participants

This cross-sectional study utilized the baseline data of the Promoting safe walking among older people (PASSWORD, ISRCTN52388040) –study. Study design and recruitment process have been described in detail by Sipilä et al [25] and the study flow for baseline measurements by Savikangas et al [24]. Briefly, participants were eligible for the study if they were 70–85 years old, community-dwelling, lived in the city of Jyväskylä, Finland, did not meet the current physical activity recommendations by self-report (less than 150 min of walking/week and no regular resistance training), could walk 500 m without assistance, and scored ≥ 24 points in the Mini Mental State Examination (MMSE) test. Exclusion criteria were severe chronic condition and/or medication, behavioural factor that could have compromised participation in the study, severe vision or hearing problem, heavy alcohol consumption, and other family member participating in the PASSWORD-study. From the initial random sample of 3862 people drawn from the Finnish national population registry, 2684 could be contacted by phone. Of them, 401 were invited to laboratory measurements after an initial screening interview, and finally 314 were recruited to the study after additional review of the exclusion criteria at the laboratory. The final sample for the present study included 284 participants with acceptable data on accelerometer-measured physical activity and bone properties.

This study has been carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki). The study protocol was approved by the Ethics committee of the Central Finland Health Care District (14/12/2016, ref: 11/2016). Informed consent was obtained from all individual participants included in the study.

2.2 Measurements

2.2.1 Bone properties

Femoral neck and total proximal femur bone mineral content (BMC, g), bone mineral density (BMD, g/cm^2) and the T-score were measured with dual energy x-ray absorptiometry (DXA, LUNAR Prodigy, GE Healthcare, Madison, WI, USA). Subsequently, femoral neck section modulus (SM [mm^3], an index of bending strength) and minimal neck width (MNW [mm], an outer diameter of the bone) at the narrowest femoral neck section were calculated with advanced hip structural analysis (AHA). Based on the femoral neck T-score participants were categorize as normal ($\geq$ -1), osteopenic (< -1 to > -2.5) or osteoporotic ($\leq$ -2.5) [1, 26]. Mean values of the bone traits in both femurs were calculated. For participants with hip replacement on either side, the scan of the non-operated side was used. Participants with hip replacement on both sides were excluded.

Participants were scanned in supine position in the centre of the table using the default-scanning mode automatically selected by the Prodigy software (Lunar Prodigy Advance Encore v. 14.10.022). 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. Images were controlled prior to the analyses to ensure right definition of the femoral neck section. As for two participants, scans of one femur were excluded due to failed definition of femoral neck section, and the values for the other side were used. Coefficients of variation (CV%) for different femoral neck properties have been reported to vary approximately between 2–10%, SM having the highest CV of 10.1 % [27]. In our laboratory, the CV% for SM has been reported to be 5.1 % [28] and the root mean square coefficient of variation (CV_{RMS}) for femoral neck BMC 0.6% [29].

2.2.2 Physical activity

Tri-axial accelerometer (UKK RM42, UKK, Tampere, Finland) was used to measure physical activity. Participants were instructed to wear the accelerometer in an elastic waistband on their right side of the hip during waking hours, except during water activities. For all accelerometer-data processing approaches, all three axes were included by using the resultant (Euclidian norm, $\sqrt{x^2 + y^2 + z^2}$) acceleration in data processing. We have described the numerical approach used to divide the 24 h hour minute by minute recordings into sedentary (less than 0.0167 multiples of gravity [g]), light (0.0167 g to 0.091 g), moderate (0.091 g to 0.414 g) and vigorous (0.414 g or more) categories in a previous publication from the same dataset [24]. Briefly, the resultant was taken from each 3D sample, mean amplitude deviation was then calculated in non-overlapping 5 s epochs, and the mean of 12 consecutive epochs was used to produce a minute-by-minute intensity array from mid-night to mid-night. The array was then transformed into a histogram with the aforementioned bin cut-offs to produce daily minutes spent in the four categories, and the mean of all included days (at least 3 days with at least 10 h wear-time was required to be included in statistical analyses) is given as the result. Due to the very limited amount of vigorous activity, moderate and vigorous intensity activities were combined into one category for further analysis. The processing approach and cut-offs have been validated among younger adults [13, 30].

Our in-house implementation of Deere and colleagues [16] acceleration peak calculation was used to identify each sample of the resultant acceleration recording, which was higher than the preceding and the subsequent sample as an acceleration peak. The magnitude, and the time stamp of the peak were noted. The peaks were then divided into 24 hour epochs, and a three category histogram (low [1.5 g to 2.0 g]; medium [2.0 g to 2.5 g]; high [higher than 2.5g]) was calculated to represent each day. The mean of days selected for physical activity evaluation is reported as the outcome.

Our in-house implementation of Ahola and colleagues [12] osteogenic index calculation was used to calculate an osteogenic index for each 24 h period of recording and the mean of each included day is reported as the outcome. We have described our implementation in a previous publication [31]. Briefly, the norm (resultant) of each sample was calculated and the data was subsequently considered in 24 h epochs from mid-night to mid-night. All continuous peaks above 1.3 g were identified, and the maximum value of a given peak was noted. The resulting peak array was transformed into 32 bin histogram from 1.3 to 10.3 g with values higher than 10.3 g assigned to the final bin. The daily osteogenic index was then calculated as the sum of the logarithm of peaks in a bin multiplied by the lower cut-off of a given bin.

2.2.3 Covariates

Sex and date of birth were drawn from population registry, and age in years at the laboratory visit day was calculated. Body weight (kg) and height (cm) were measured with standard procedures and body mass index (BMI, kg/m^2) was calculated. Physical functioning was assessed with the Short Physical Performance Battery (SPPB), which consists of four meters habitual walking speed, five time chair rise time and standing balance tests [32]. Information on current medication use, including hormone replacement therapy, bisphosphonates and oral glucocorticoids, was collected by self-report at nurse's examination and verified from the integrated patient information system utilized by the national health services (Effica database) by the study physician. All non-vaginal preparations including oestrogen were considered as hormone replacement therapy. Smoking history was self-reported and categorized as current smoker, former smoker (smoked at least 100 times during lifetime, but reported no current smoking), or never smokers (smoked < 100 times during lifetime).

2.3 Statistical analyses

Descriptive data are presented as means and/or medians with standard deviations (SD) and/or inter-quartile range (IQR) for continuous variables and frequencies (n) and percentages (%) for categorical variables in all participants and for men and women separately. To illustrate the distribution of impacts within each intensity band utilized to calculate osteogenic index, logarithm of the mean daily amount of impacts at each level from 1.3 g onwards is presented in a histogram. Based on visual inspection, medium and high impacts were skewed to the right and thus log-transformed for further analyses. In addition, Kolmogorov-Smirnoff –tests indicated moderate-to-vigorous intensity activity, low impacts and osteogenic index to have skewed distributions. As for these physical activity variables, initial analyses were therefore performed with both original and log-transformed values. Since the results did not differ, original values were used in the analyses.

Associations of physical activity variables with each others were assessed using Pearson's correlation coefficient *r*. Associations of proximal femur bone traits with physical activity were tested utilizing multiple linear regression. Separate models were built for each bone trait and each physical activity variable. Models were adjusted with factors known to be associated with bone health and/or physical activity, including sex, age, weight, height, smoking status, SPPB score, hormone replacement therapy, oral glucocorticoids, and bisphosphonates. All variables were tested for multicollinearity. To adjust the associations of physical activity intensities and impact intensities with other intensity bands, a second set of models was built, one including sedentary, light and moderate-to-vigorous intensity activity and all covariates, and the second including low, medium and high impacts and all covariates. Additional sensitivity analyses were performed, in which all participants using hormone replacement therapy, bisphosphonates or oral glucocorticoids were excluded. Statistical analyses were performed with IBM SPSS Statistics 26 (SPSS Inc., Armonk, NY). Statistical significance level was set at 0.05 for all analyses.

To investigate the strength of the associations of impacts within each intensity band utilized to calculate osteogenic index, partial correlation coefficients were calculated for log-transformed number of impacts within each intensity band and each bone variable. Correlations were adjusted with those covariates that had $p<0.1$ in some of the regression models of the bone variable in question. Results are presented in graphs as correlation coefficient r and 95% confidence interval (CI). The graphs were created with RStudio version 1.2.1335 (RStudio Inc., Boston, MA).

A priori power analyses were calculated as for the main outcome, 10 meters maximal walking speed, of the PASSWORD-study (Sipilä et al 2018). Additional post hoc power calculations were performed for the present study. For the studied variables, a sample size of 284 yields a power over 98 % to show a contribution to the explained variance of 10 % in a linear regression model with 10–12 predictors (including interactions, but not constant) if the probability level (alpha) is set at 0.05. Sample size of 284 yields even weak correlation coefficients ($r=0.12$) statistically significant ($p <.001$, two-tailed).

3 Results

Descriptive data of participant characteristics are presented in Table 1. Mean age was 74 years, and 57 % were women. Mean BMC at the femoral neck was 4.440 g and mean BMD 0.905 g/cm^2. Nearly half of the participants had femoral neck T-score below -1, which indicates potential osteopenia.

Participants spent on average 10 h per day sedentary, 2.5 hrs in light activity and half an hour in moderate-to-vigorous activity. Participants had on average (median; IQR) 3937 (4591; 2103–5177) low, 494 (347; 164–662) medium and 157 (112; 70–181) high impacts per day. Mean osteogenic index score was 173 (Table 1). The distribution of log-transformed mean daily number of impacts throughout the intensity range utilized to calculate osteogenic index is presented in Figure 1. The average amount of impacts within each intensity band decreased from over 5000 impacts in the 1.3 to <1.5g bin to less than 10 daily impacts in the 3.1 to <3.3g bin. The mean amount of impacts within each bin exceeding the intensity of 6.1g was less than one, except in the last bin including all impacts of ≥ 10.3 g.

Bivariate correlations between physical activity variables are shown in Table 2. Strongest associations (r>0.7) were observed between moderate-to-vigorous activity and low impacts, low and medium impacts, medium and high impacts, and osteogenic index and high impacts.

The associations of proximal femur bone traits with physical activity and impact intensities and osteogenic index are presented in Tables 3–4. Light physical activity was positively associated with femoral neck BMC and BMD, total femur BMC and BMD and with SM (beta = 0.147 to 0.182, p<0.001 to p=0.005), but not with MNW (Table 3). Ten minutes increase in mean daily light activity was associated with 0.024 g higher femoral neck BMC and 0.003 g/cm^2 higher femoral neck BMD. Sedentary time or moderate-to-vigorous activity were not associated with any bone trait. When adjusted with other intensity bands, light physical activity remained positively associated with all bone traits (beta = 0.144 to 0.180, p<0.001 to p=0.010) except MNW, whereas no statistically significant associations were found for sedentary or moderate-to-vigorous intensity activity (Table 4). The results did not change, when all hormone replacement therapy, bisphosphonate and oral glucocorticoid users were excluded: light activity remained significantly and positively associated with all bone parameters (p<0.001 to p=0.010, data not shown) except MNW when investigated as single physical activity variable in the model. When adjusted with other bands, the positive association with MNW became statistically significant, too (p=0.038, data not shown). Sedentary or moderate-to-vigorous activity were not associated with any bone parameter in the sensitivity analyses either.

Low, medium or high impacts were not associated with any bone trait when investigated in separate models (p>0.09 for all, Table 3). In the sensitivity analyses excluding all hormone replacement therapy, bisphosphonates and oral glucocorticoid users and only one impact intensity in the model at a time, low impacts were positively associated with total femur BMD (beta=0.130, p=0.048, data not shown). When adjusted with other impact intensity bands, low impacts were positively associated with femoral neck BMD (beta=0.186, p=0.025) and negatively with MNW (beta=-0.177, p=0.038), and this result was replicated in the sensitivity analyses (data not shown). Medium or high impacts were not associated with any bone trait in any model.

Osteogenic index was not associated with any bone trait (p>0.3 for all, Table 3), which did not change in the sensitivity analyses excluding all hormone replacement therapy, bisphosphonates and oral glucocorticoids users (data not shown). Associations of log-transformed number of impacts within each intensity band utilized to calculate osteogenic index with femoral neck BMC, BMD and SM are presented in Figure 2 (data for total femur BMC and BMD and MNW not shown). Impacts of any intensity were not associated with any bone variable, when the associations were adjusted for covariates.

4 Discussion

We examined the associations of physical activity with proximal femur bone traits among sedentary older men and women utilizing three different approaches to process the raw acceleration data. We found that light intensity physical activity was positively associated with femoral neck and total femur bone mineral content and density and with section modulus, which indicates femoral neck bending strength. In contrast, neither sedentary or moderate-to-vigorous activity nor any of the two impact peak-based methods were significantly associated with bone health. That is, high impacts or osteogenic index were not better predictors of bone health among sedentary older adults than other physical activity measures, in contrast to what was hypothesized.

We found that light intensity activity was consistently positively associated with all other proximal femur bone traits except femoral neck minimal width in all models, which is in contrast to the previous literature indicating relatively high-magnitude impact peaks [17, 18, 20] and moderate and vigorous activities [8, 9, 33] as positive predictors of proximal femur bone traits. Only a few previous studies have investigated the associations between light physical activity and proximal femur bone traits in older adults, with no significant associations found [8, 10, 33, 34]. Chastin and colleagues [35] have shown a significant positive association between light activity and femoral neck BMD in women in a general adult population including also older adults. In contrast, based on previous research [18–20, 22] we hypothesized that high impacts and osteogenic index would be beneficially associated with bone measures, but did not observe any relationship. Similarly to the present study, Hannam and colleagues [18] did not find any significant associations between impacts of any intensity and hip BMD among a comparable cohort of older women. In contrast, they found high impacts to be positively and low/medium impacts negatively associated with hip structural measures in some adjusted models, yet the observed significant associations were weak. This was presumed to be due to low amount of high impacts or the low threshold utilized to categorize high impacts [18]. In the present study, the mean daily amount of high impacts was tenfold compared to the study of Hannam et al [18]. It may thus be, that the intensity of high impacts classified as per Deere and colleagues [16] is not sufficient for osteogenesis, even though this amount could have been expected to be sufficient based on the findings by Stiles and colleagues [22]. They observed that the osteogenic threshold was lower among post- than among premenopausal women, which could have indicated even lower threshold among older adults [22].

In contrary to Hannam et al [18], we found that low impacts were positively associated with hip BMD. The association was, however, statistically significant only when adjusted for other impact intensities. On the other hand, the association between femoral neck width and low impacts was negative, when other impact bands were included in the model. These contrasting findings must be interpreted with caution due to high collinearity of impacts within different intensity bands. As for the femoral neck width, biological covariates, including sex, age and height, may determine the bone structure to the extent that associations with physical activity variables remain imperceptible.

Bone mass and strength decline with increasing age [36], and some researchers have proposed that lower impacts may create similar strains in older and weaker bones as higher impacts create in younger and stronger bones [16]. In contrast, we have observed a reversed trend between maximal performance and skeletal robustness in cross-sectional studies compared to the suggestion by Deere and colleagues [16], i.e. we found that younger men were able to produce higher maximal forces with respect to tibial robustness in jumping compared to older men [37], and that the relationship between jumping performance and tibial robustness was similar between pre- and postmenopausal women albeit the marked bone loss associated with menopause [38]. In addition to magnitude of the strains, another crucial element of bone loading physical activity is the frequency of the strains [39]. In the present study, the amount of impacts exceeding 4.9g, which has been considered sufficient to promote bone health in adolescents and younger adults [19, 21], was very low. It is thus plausible, that the impacts have not occurred as cycles with sufficient length and frequency to stimulate bone remodelling. However, it has also been proposed, that low-force exercises may cause sufficient strains to maintain the so-called conservation mode [40] and that habitual physical activity may influence the rate of age-related bone loss [41]. This is supported by a meta-analysis showing that long-term walking interventions prevent age-related bone loss [42]. Thus, it could be that continuous and large amounts of accelerometer-based light activity can create sufficient strains or micro damage to avoid dropping to disuse-mode with excessive bone resorption, and decelerate the age-related bone loss. It may be that sedentary older adults, who do not meet the physical activity recommendations, benefit from continuous loading in means of large amounts of habitual upright ambulatory activities that are classified as light physical activity.

Even though light intensity activity only explained approximately 2 % of variation in bone parameters, an increase of 10 minutes of light intensity activity per day was associated with 0.3 % higher hip BMD. This corresponds almost to the average yearly decline of 0.5 % in BMD in this age group [36]. Increasing light intensity physical activity might thus be a feasible way to prevent the age-related loss of bone among sedentary older adults. It is, however, important to bear in mind that the benefits of high intensity resistance exercise alone and combined with impact activity for older adults' bone health are well documented [4, 43]. Higher intensity activities should therefore be preferred, if possible and safe. Future longitudinal and intervention studies are required to confirm, if light intensity physical activity has positive effect on bone health among sedentary older adults.

This study has several limitations. The cross-sectional study design does not allow to draw any conclusions on the causal effects of habitual physical activity on bone health. In accordance with the inclusion criteria of the PASSWORD-study, the amount of high impacts was very small. It is therefore not possible to draw conclusions on, if greater amount of high impacts would be beneficially associated with bone health also in older age. In addition, the study sample was relatively small, which may have led to limited power to detect associations between small numbers of high impacts with bone traits. The study population was also relatively healthy but at most moderately physically active, thus the results cannot be generalized to all older adults. Furthermore, bone measurement was limited to DXA-scan of the femurs. Additional bone characterisations would have given a wider understanding of the associations between physical activity and bone properties. For example, any lumbar spine measurements were not obtained, and future studies are required to investigate if high impact activity is associated with lumbar spine health among older adults. Finally, many lifestyle and environmental factors during life-course, which determine bone health, could have affected the results. It may, for example, be that those participants who have earlier in their lives engaged in more intense physical activity and thus gained good bone health, have maintained higher level of lighter activity in old age. Healthy diet – especially sufficient intake of vitamin D and calcium – is crucial for bone health, but nutrient intake could not be controlled for in the present study. It has also been suggested that lean body mass mediates the association between physical activity and bone health [34] and it would have been worthwhile to adjust the models with body composition instead of body weight. Due to high collinearity between lean body mass and two important predictors of bone strength and structure, sex and height, this was not possible in the present study.

5 Conclusion

In summary, we found that light intensity physical activity was positively associated with bone health among sedentary older adults, whereas any measure of high intensity or high impact activity was not. In light of these results, older adults with sedentary lifestyles should be encouraged to replace sedentary time with light upright ambulatory activities to avoid bone disuse mode and prevent excessive bone loss, even though high intensity activities should be preferred when they are possible and safe to perform. However, longitudinal research is required to confirm our findings that light physical activity may ameliorate the age-related bone loss among older adults, who do not meet the physical activity recommendations in means of at least moderate intensity activity and strength training. In this population, the amount of high impact activity may be insufficient to stimulate bone remodelling. It would be worth testing, whether high-impact activity was effective in this population of at most moderately physically active, but relatively healthy community-dwelling older adults. In addition, associations of osteogenic index and impact intensities should be investigated in more active older populations and in physical activity intervention settings among older adults.

Acknowledgements

Funding. This research was supported by the Academy of Finland (296843 to SS), which funded the PASSWORD -study. This study was in part funded from the European Union’s Horizon 2020 Research and Innovation Programme under Marie Sklodowska-Curie Actions grant agreement No. 675003 to SS. TR was an Academy Research Fellow during the preparation of this manuscript (Academy of Finland grant numbers 321336 and 328818). The content of this article does not reflect the official opinion of the European Union. Responsibility for the information and views expressed in the article lies entirely with the authors.

Conflicts of interest. Authors declare no conflict of interest.

References

[1] Cosman F, de Beur SJ, LeBoff MS, Lewiecki EM, Tanner B, Randall S, Lindsay R (2014) Clinician’s guide to prevention and treatment of osteoporosis. Osteoporosis Int 25(10):2359-2381.

[2] Sözen T, Özışık L, Başaran NÇ (2017) An overview and management of osteoporosis. Eur J Rheumatol 4(1):46.

[3] Drake MT, Clarke BL, Lewiecki EM (2015) The pathophysiology and treatment of osteoporosis. Clin Ther 37(8):1837-1850.

[4] Gómez-Cabello A, Ara I, González-Agüero A, Casajús J, Vicente-Rodríguez G (2012) Effects of training on bone mass in older adults. Sports Med 42(4):301-325.

[5] Piercy KL, Troiano RP, Ballard RM, Carlson SA, Fulton JE, Galuska DA, George SM, Olson, RD (2018) The physical activity guidelines for Americans. JAMA 320(19):2020-2028.

[6] Pellikaan P, Giarmatzis G, Vander Sloten J, Verschueren S, Jonkers I (2018) Ranking of osteogenic potential of physical exercises in postmenopausal women based on femoral neck strains. PloS one 13(4):e0195463.

[7] Schrack JA, Cooper R, Koster A, Shiroma EJ, Murabito JM, Rejeski WJ, Ferrucci L, Harris TB (2016) Assessing daily physical activity in older adults: unraveling the complexity of monitors, measures, and methods. J Gerontol A Biol Sci Med Sci 71(8):1039-1048.

[8] Johansson J, Nordström A, Nordström P (2015) Objectively measured physical activity is associated with parameters of bone in 70-year-old men and women. Bone 81:72-79.

[9] Ng CA, McMillan LB, Beck B, Humbert L, Ebeling PR, Scott D (2020) Associations between physical activity and bone structure in older adults: does the use of self-reported versus objective assessments of physical activity influence the relationship? Osteoporos Int 31(3):493-503.

[10] Gába A, Kapuš O, Pelclová J, Riegerová J (2012) The relationship between accelerometer-determined physical activity (PA) and body composition and bone mineral density (BMD) in postmenopausal women. Arch Gerontol Geriatr 54(3):e315-321.

[11] Gerdhem P, Dencker M, Ringsberg K, Åkesson K (2008) Accelerometer-measured daily physical activity among octogenerians: results and associations to other indices of physical performance and bone density. Eur J Appl Physiol 102(2):173-180.

[12] Ahola R, Korpelainen R, Vainionpää A, Jämsä T (2010) Daily impact score in long-term acceleration measurements of exercise. J Biomech 43(10):1960-1964.

[13] Vähä- Ypyä H, Vasankari T, Husu P, Suni J, Sievänen H (2015) A universal, accurate intensity- based classification of different physical activities using raw data of accelerometer. Clin Physiol Funct Imaging 35(1):64-70.

[14] Turner CH (1998) Three rules for bone adaptation to mechanical stimuli. Bone 23(5):399-407.

[15] Turner CH, Robling AG (2003) Designing exercise regimens to increase bone strength. Exerc Sport Sci Rev 31(1):45-50.

[16] Deere KC, Hannam K, Coulson J, Ireland A, McPhee JS, Moss C, Edwards MH, Dennison E, Cooper C, Sayers A, Lipperts M, Grimm B, Tobias JH (2016) Quantifying habitual levels of physical activity according to impact in older people: accelerometry protocol for the VIBE study. J Aging Phys Act 24(2):290-295.

[17] Hannam K, Deere K, Hartley A, Clark EM, Coulson J, Ireland A, Moss C, Edwards MH, Dennison E, Gaysin T, Cooper R, Wong A, McPhee JS, Cooper C, Kuh D, Tobias JH (2017) A novel accelerometer-based method to describe day-to-day exposure to potentially osteogenic vertical impacts in older adults: findings from a multi-cohort study. Osteoporos Int 28(3):1001-1011.

[18] Hannam K, Deere K, Hartley A, Al-Sari U, Clark E, Fraser W, Tobias WH (2017) Habitual levels of higher, but not medium or low, impact physical activity are positively related to lower limb bone strength in older women: findings from a population-based study using accelerometers to classify impact magnitude. Osteoporos Int 28(10):2813-2822.

[19] Vainionpää A, Korpelainen R, Vihriälä E, Rinta–Paavola A, Leppäluoto J, Jämsä T (2006) Intensity of exercise is associated with bone density change in premenopausal women. Osteoporosis Int 17(3):455-463.

[20] Multanen J, Rantalainen T, Kautiainen H, Ahola R, Jämsä T, Nieminen MT, Lammentausta E, Häkkinen A, Kiviranta I, Heinonen A (2017) Effect of progressive high-impact exercise on femoral neck structural strength in postmenopausal women with mild knee osteoarthritis: a 12-month RCT. Osteoporosis Int 28(4):1323-1333.

[21] Deere K, Sayers A, Rittweger J, Tobias JH (2012) Habitual levels of high, but not moderate or low, impact activity are positively related to hip BMD and geometry: results from a population- based study of adolescents. J Bone Miner Res 27(9):1887-1895.

[22] Stiles VH, Metcalf BS, Knapp KM, Rowlands AV (2017) A small amount of precisely measured high-intensity habitual physical activity predicts bone health in pre- and post-menopausal women in UK Biobank. Int J Epidemiol 46(6):1847-1856.

[23] Tobias JH, Gould V, Brunton L, Deere K, Rittweger J, Lipperts M, Grimm B (2014) Physical activity and bone: may the force be with you. Front Endocrinol 5:20.

[24] Savikangas T, Tirkkonen A, Alen M, Rantanen T, Fielding RA, Rantalainen T, Sipilä S (2020) Associations of physical activity in detailed intensity ranges with body composition and physical function: a cross-sectional study among sedentary older adults. Eur Rev Aging Phys Act 17(1):4.

[25] Sipilä S, Tirkkonen A, Hänninen T, Laukkanen P, Alen M, Fielding RA, Kivipelto M, Kokko K, Kulmala J, Rantanen T, Sihvonen SE, Sillanpää E, Stigsdotter-Neely A, Törmäkangas T (2018) Promoting safe walking among older people: the effects of a physical and cognitive training intervention vs. physical training alone on mobility and falls among older community-dwelling men and women (the PASSWORD study): design and methods of a randomized controlled trial. BMC Geriatrics 18(1):215.

[26] Kanis JA (2002) Diagnosis of osteoporosis and assessment of fracture risk. The Lancet. 359(9321):1929-1936.

[27] Khoo BC, Beck TJ, Qiao QH, Parakh P, Semanick L, Prince RL, Singer KP & Price RI (2005). In vivo short-term precision of hip structure analysis variables in comparison with

bone mineral density using paired dual-energy X-ray absorptiometry scans from multi-center clinical trials. Bone 37(1), 112-121.

[28] Munukka M, Waller B, Multanen J, Rantalainen T, Häkkinen A, Nieminen MT, Lammentausta E, Kujala UM, Paloneva J, Kautiainen H & Kiviranta I (2014). Relationship between lower limb neuromuscular performanceand bone strength in postmenopausal women with mild knee osteoarthritis. J Musculoskelet Neuronal Interact 14(4), 418-424.

[29] Multanen J, Heinonen A, Häkkinen A, Kautiainen H, Kujala UM, Lammentausta E, Jämsä T, Kiviranta I & Nieminen MT (2015). Bone and cartilage characteristics in postmenopausal women with mild knee radiographic osteoarthritis and those without radiographic osteoarthritis. J Musculoskelet Neuronal Interact 15(1), 69-77.

[30] Vähä-Ypyä H, Vasankari T, Husu P, Mänttäri A, Vuorimaa T, Suni J, Sievänen H (2015). Validation of cut-points for evaluating the intensity of physical activity with accelerometry-based mean amplitude deviation (MAD). PLoS One 10(8):e0134813.

[31] Belavy DL, Quittner M, Ridgers ND, Ling Y, Connell D, Trudel G, Rantalainen T (2019) Beneficial intervertebral disc and muscle adaptations in high-volume road cyclists. Med Sci Sports Exerc 51(1):211-217.

[32] Guralnik JM, Simonsick EM, Ferrucci L, Glynn RJ, Berkman LF, Blazer DG, Scherr PA & Wallace RB (1994). A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. J Gerontol 49(2), M85-M94.

[33] Langsetmo L, Burghardt AJ, Schousboe JT, Cawthon PM, Cauley JA, Lane NE, Orwoll ES, Ensrud KE (2020). Objective measures of moderate to vigorous physical activity are associated with higher distal limb bone strength among elderly men. Bone 132: 115198.

[34] McMillan L, Aitken D, Ebeling P, Jones G, Scott D (2018) The relationship between objectively assessed physical activity and bone health in older adults differs by sex and is mediated by lean mass. Osteoporos Int 29(6):1379-1388.

[35] Chastin SFM, Mandrichenko O, Helbostadt JL, Skelton DA (2014) Associations between objectively-measured sedentary behaviour and physical activity with bone mineral density in adults and older adults, the NHANES study. Bone 64:254-262.

[36] Westbury LD, Syddall HE, Fuggle NR, Dennison EM, Cauley JA, Shiroma EJ, Fielding RA, Newman AB, Cooper C (2020) Long-term rates of change in musculoskeletal aging and body composition: findings from the Health, Aging and Body Composition Study. Calcif Tissue Int. https://doi.org/10.1007/s00223-020-00679-2.

[37] Rantalainen T, Sievänen H, Linnamo V, Hoffrén M, Ishikawa M, Kyröläinen H, Avela J, Selänne H, Komi PV, Heinonen A (2009) Bone rigidity to neuromuscular performance ratio in young and elderly men. Bone 45(5):956-963.

[38] Rantalainen T, Nikander R, Heinonen A, Multanen J, Häkkinen A, Jämsä T, Kiviranta I, Linnamo V, Komi PV, Sievänen H (2010) Neuromuscular performance and body mass as indices of bone loading in premenopausal and postmenopausal women. Bone 46(4):964-969.

[39] Robling AG, Castillo AB, Turner CH (2006) Biomechanical and molecular regulation of bone remodeling. Annu Rev Biomed Eng 8:455-498.

[40] Frost HM (1999) Why do bone strength and "mass" in aging adults become unresponsive to vigorous exercise? Insights of the Utah paradigm. J Bone Miner Metab 17(2):90-97.

[41] Kohrt WM, Bloomfield SA, Little KD, Nelson ME, Yingling VR (2004) Physical activity and bone health. Med Sci Sports Exerc 36(11):1985-1996.

[42] Ma D, Wu L, He Z (2013) Effects of walking on the preservation of bone mineral density in perimenopausal and postmenopausal women: a systematic review and meta-analysis. Menopause 20(11):1216-1226.

[43] Marques EA, Mota J & Carvalho J (2012). Exercise effects on bone mineral density in older adults: a meta-analysis of randomized controlled trials. Age 34(6), 1493-1515.

CRediT authorship contribution statement

Tiina Savikangas: Conceptualization, Formal analysis, Methodology, Investigation, Writing - Original Draft; **Sarianna Sipilä**: Conceptualization, Funding acquisition, Investigation, Writing - Review & Editing, Supervision; **Timo Rantalainen**: Conceptualization, Software, Writing - Review & Editing, Supervision

Fig. 1 Log-transformed number of mean daily impacts at each intensity band. Y-axis values stand for the lower limit of each intensity band, the values utilized to calculate osteogenic index

Fig. 2 Associations of mean daily number of impacts at each intensity band (x-axis) utilized to calculate osteogenic index with proximal femur bone traits, presented as partial correlation coefficient r (y-axis, black line) and 95 % confidence interval (CI, shaded area). a) for BMC (adjusted for weight, height and smoking status); b) for BMD (adjusted for weight, age, the SPPB score and use of hormone replacement therapy); and c) for section modulus (adjusted for weight, height, sex and smoking status)

Table 1. Descriptive statistics of study participants in the whole sample and according to sex (mean ± SD or n (%)).

	All (n=284)	Men (n=121)	Women (n=163)
Age, years	74.4 ± 3.8	74.3 ± 3.9	74.4 ± 3.7
Height, cm	166 ± 9	173 ± 6	161 ± 6
Weight, kg	76.9 ± 14.4	83.9 ± 12.4	71.7 ± 13.5
BMI, kg/m^2	27.9 ± 4.8	27.8 ± 3.6	27.9 ± 5.5
SPPB, total score [a]	10.3 ± 1.5	10.6 ± 1.5	10.0 ± 1.5
Smoking status, n (%)			
Never	175 (62)	55 (46)	120 (74)
Former	98 (35)	57 (47)	41 (25)
Current	11 (4)	9 (7)	2 (1)
Medication			
Hormone replacement therapy, n (%)	23 (8)	-	23 (14)
Bisphosphonates, n (%)	2 (1)	-	2 (1)
Glucocorticoid, n (%)	12 (4)	5 (4)	7 (4)
Femoral neck T-score			
≤ -1.0, n (%)	138 (49)	64 (53)	74 (45)
≤ -2.5, n (%)	11 (4)	7 (6)	4 (3)
Proximal femur bone traits			
Femoral neck BMC, g [b]	4.442 ± 0.995	4.967 ± 0.996	4.053 ± 0.798
Femoral neck BMD, g/cm^2 [c]	0.905 ± 0.132	0.932 ± 0.137	0.885 ± 0.124
Total femur BMC, g [b]	34.837 ± 7.002	39.429 ± 6.588	31.408 ± 5.056
Total femur BMD, g/cm^2 [c]	0.994 ± 0.150	1.037 ± 0.155	0.962 ± 0.138
SM, mm^3 [d]	664.6 ±182.7	807.5 ± 162.5	558.5 ± 110.4
MNW, mm [e]	32.7 ± 3.3	35.5 ± 2.7	30.7 ± 2.1
Accelerometer-based physical activity			
Days included	6.6 ± 0.8	6.7 ± 0.7	6.6 ± 0.8
Wear time, h/d	14.1 ± 1.3	14.3 ± 1.3	13.9 ± 1.2
Physical activity in intensity categories, min/d			
Sedentary activity	603 ± 82	627 ± 81	585 ±79
Light activity	210 ± 66	197 ± 61	219 ± 68
Moderate-to-vigorous activity	33 ± 20	33 ± 21	33 ± 20
Impacts, No.			
Low impacts	3937 ± 2426	4017 ± 2468	3877 ± 2400
Medium impacts	494 ± 463	479 ± 432	504 ± 487
High impacts	157 ± 154	165 ± 188	151 ± 122
Osteogenic index, score	173 ± 47	169 ± 47	176 ± 47

[a] Short Physical Performace Battery

[b] bone mineral content

[c] bone mineral density

[d] section modulus (Z)

[e] minimal neck width

Table 2. Pearson's correlation coefficients (r) between physical activity variables

	Light activity	Moderate-to-vigorous activity	Low impacts	Medium impacts	High impacts	Osteogenic index
Sedentary activity	-0.502***	-0.380***	-0.368***	-0.325***	-0.265***	-0.295***
Light activity		0.319***	0.441***	0.342***	0.296***	0.373***
Moderate-to-vigorous activity			0.873***	0.665***	0.491***	0.496***
Low impacts				0.724***	0.542***	0.547***
Medium impacts					0.765***	0.598***
High impacts						0.842***

*** $p < 0.001$

Table 3. Associations of accelerometer measured physical activity with proximal femur bone traits from multiple linear regression analysis adjusted with sex, age, weight, height, SPPB score, smoking status and use of hormone replacement therapy, bisphosphonates and oral glucocorticoids. Values are presented as standardized beta coefficients.

	Sedentary time		Light activity		Moderate-to-vigorous activity		Low impacts		Medium impacts		High impacts		Osteogenic index	
	beta	*p*	beta	*p*	beta	*p*	beta	*p*	beta	*p*	beta	*p*	beta	*p*
Femoral neck BMC ^{a}	-0.076	0.122	0.158	0.002	0.055	0.297	0.078	0.155	0.048	0.352	0.030	0.542	0.046	0.351
Femoral neck BMD ^{b}	-0.062	0.279	0.165	0.005	0.025	0.676	0.080	0.206	-0.039	0.512	-0.056	0.321	-0.009	0.875
Total femur BMC ^{a}	-0.070	0.112	0.148	0.001	0.040	0.392	0.080	0.097	0.039	0.394	0.007	0.870	0.040	0.349
Total femur BMD ^{b}	-0.083	0.137	0.182	0.001	0.026	0.663	0.102	0.094	0.026	0.736	-0.026	0.629	0.023	0.671
SM ^{c}	-0.034	0.414	0.147	<0.001	0.007	0.878	0.004	0.928	-0.033	0.441	-0.005	0.905	0.019	0.644
MNW ^{d}	0.022	0.458	0.053	0.194	0.002	0.968	-0.062	0.148	0.008	0.847	0.024	0.526	0.008	0.844

^{a} bone mineral content, g
^{b} bone mineral density, g/cm^2
^{c} section modulus (Z), mm^3
^{d} minimal neck width, mm

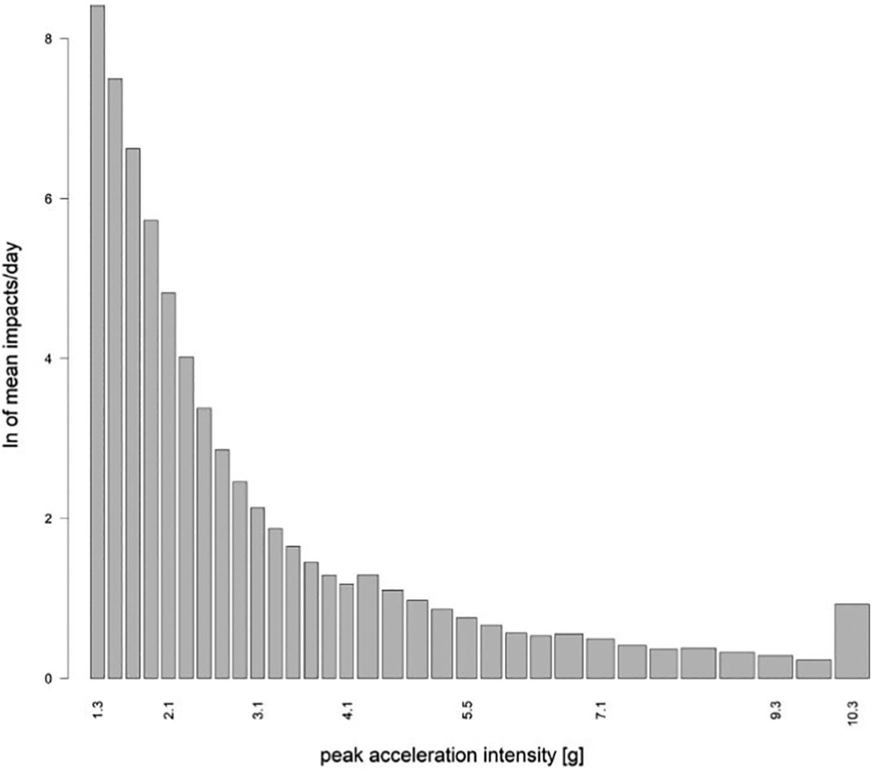
Table 4. Associations of accelerometer measured physical activity intensities (Model 1) and impact intensities (Model 2) with proximal femur bone traits from multiple linear regression analysis adjusted with sex, age, weight, height, SPPB score, smoking status and use of hormone replacement therapy, bisphosphonates and oral glucocorticoids. Values are presented as standardized beta coefficients.

					Model 1		Model 2					
	Sedentary time		Light activity		Moderate-to-vigorous activity		Low impacts		Medium impacts		High impacts	
	beta	*p*	beta	*p*	beta	*p*	beta	*p*	beta	*p*	beta	*p*
Femoral neck BMC ^{a}	-0.004	0.950	0.152	0.008	0.024	0.659	0.078	0.283	0.009	0.926	-0.010	0.890
Femoral neck BMD ^{b}	0.010	0.880	0.170	0.010	-0.004	0.952	0.186	0.025	-0.102	0.326	-0.065	0.448
Total femur BMC ^{a}	-0.005	0.928	0.144	0.004	0.011	0.814	0.093	0.145	0.020	0.799	-0.049	0.455
Total femur BMD ^{b}	-0.010	0.877	0.180	0.005	-0.011	0.859	0.157	0.053	-0.001	0.988	-0.095	0.250
SM ^{c}	0.034	0.477	0.165	<0.001	-0.013	0.774	0.047	0.434	-0.096	0.198	0.043	0.381
MNW ^{d}	0.068	0.138	0.082	0.070	0.010	0.811	-0.117	0.038	0.046	0.519	0.043	0.456

^{a} bone mineral content, g
^{b} bone mineral density, g/cm^2
^{c} section modulus (Z), mm^3
^{d} minimal neck width, mm

Highlights

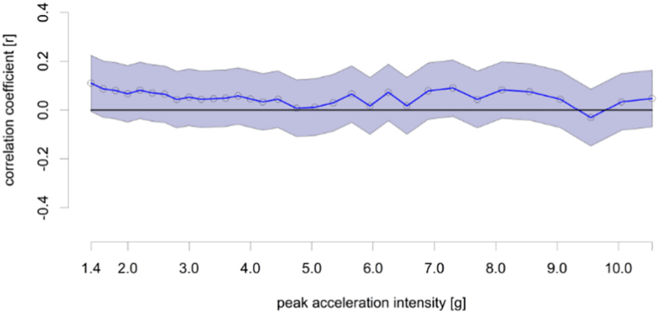
- Associations of physical activity with proximal femur bone traits were investigated.
- Three different accelerometer data processing approaches were utilized.
- Light activity was positively associated with bone density and strength of the hip.
- High intensity or impact-based activity were not associated with bone traits.
- Amount of high impacts may have been insufficient to benefit bone health.



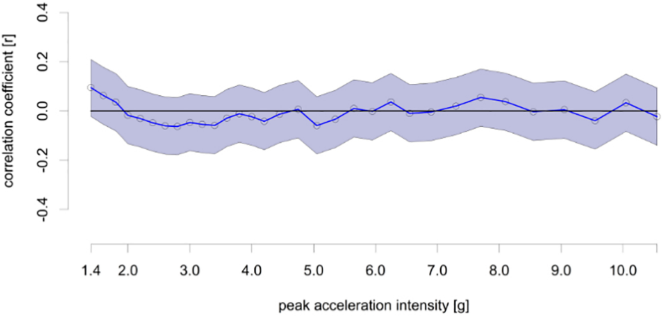
ln of mean impacts/day
0
2
4
6
8
1.3
2.1
3.1
4.1
5.5
7.1
9.3
10.3
peak acceleration intensity [g]

Figure 1

a. Femoral Neck BMC



b. Femoral Neck BMD



c. Section Modulus

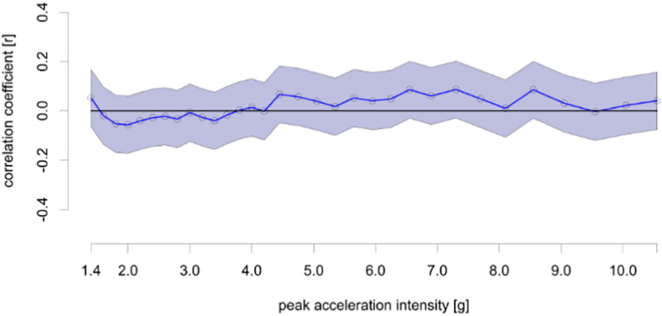


Figure 2