Cross-sectional associations between accelerometer-measured physical activity and hip bone mineral density. The Tromsø Study 2015–2016

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Abstract

Positive associations between physical activity and bone health have been found in population-based studies, however, mostly based on self-reported physical activity. Therefore, we investigated the association between accelerometer-measured physical activity, measured in steps per day and minutes of moderate to vigorous physical activity (MVPA) per day, and total hip areal bone mineral density (aBMD) measured by dual-energy X-ray absorptiometry in a general population, utilizing multiple regression models. The study participants, 1560 women and 1177 men aged 40–84 years, were part of the seventh survey of the Tromsø Study (2015–2016).

In both genders, we found a positive association between the number of daily steps and aBMD adjusted for age, body mass index (BMI), and smoking status ($p < .001$). In women, an increase of 1000 steps per day was associated with 0.005

g/cm2 higher aBMD. For men, a polynomial curve indicated a positive association with aBMD up to 5000 steps per day, plateauing between 5000 and 14000 steps, and then increasing again. Additionally, MVPA duration was positively associated with aBMD in both women ($p < .001$) and men ($p = .004$) when adjusted for age, BMI, and smoking status. Specifically, each 60-minute increase in daily MVPA was associated with 0.028 g/cm2 and 0.023 g/cm2 higher aBMD in women and men, respectively.

Despite positive associations, the clinical impact of physical activity on aBMD in this general population of adults and older adults was relatively small, and a large increase in daily MVPA might not be achievable for most individuals. Therefore, further longitudinal population-based studies, incorporating device-based measures of physical activity could add more clarity to these relationships.

Lay abstract

Physical activity is known to support bone health by keeping bones strong and reducing the risk of fractures. Previous studies have shown a positive association between physical activity and bone health, indicating that increased physical activity leads to better bone density. However, many of these studies have relied on self-reported data from questionnaires.

In our study, we aimed to investigate this association using a hip-worn device to accurately measure physical activity. We measured participants' daily steps and minutes of moderate to high-intensity physical activity over four days in 1560 women and 1177 men aged 40–84 years. Additionally, we assessed bone density in the hip to understand the relationship between physical activity and bone health.

Our findings revealed a modest yet significant association between physical activity levels and bone density in both men and women across different age groups, including adults and older adults. These results suggest that maintaining regular physical activity levels can contribute to maintaining optimal bone health over time.

Keywords

DXA; General population studies; Exercise; Osteoporosis

Introduction

Bone mineral density (BMD) is a strong predictor of hip fracture, the most severe among fragility fractures, which often lead to reduced quality of life, severe morbidity and increased mortality (1-4). Furthermore, hip fractures contribute to substantial economic burden in form of hospitalization and rehabilitation (3). Physical inactivity is known to be an important risk factor for bone health (5) and previous studies suggest that physical activity improves BMD, by mechanically stimulating bone cells and leading to formation and bone gain, and reduces fall incidence, thereby reducing the risk of hip fractures (5-7).

A recent systematic review of randomized controlled trials with participants aged 65 years and older shows a small but significant effect of physical activity on BMD (8), although it is unclear how generalizable these findings are to the general population. Findings from population-based observational studies can complement intervention studies (8), and show positive associations between self-reported physical activity and hip BMD in various populations (9-12).

However, self-report measures is often more prone to recall and response biases, in comparison with objective measures (13). Accelerometers have been available as objective measure of physical activity for decades (14). However studies of the association between accelerometer-measured physical activity and BMD are scarce and limited to samples of small size (15-17), women only (15, 18) or children and adolescents (11, 19-21). When comparing low duration physical activity, less than 5 minutes daily, to moderate and vigorous physical activity (MVPA), positive association between accelerometer-measured high duration, at least 20 minutes daily, of and hip BMD were observed in a large cohort of women and men aged 50 years and older, but not in those under 50 years. In women, the association was also found when the duration was intermediate (22). Based on the same national survey, positive associations between light PA and MVPA, and hip BMD were found also in a large cohort of 23-90+ year old women and men, respectively (23). Furthermore, positive associations between accelerometer-measured MVPA and hip BMD were demonstrated in a large cohort of 70-year-old men and women (24), while in another study only in men 65 years and older, and not in similar aged women (25). These equivocal findings need to be further elucidated including both sexes. Therefore, the aim of this cross-sectional study was to investigate the associations between accelerometer-measured physical activity, and total hip areal BMD (aBMD) in a large population-based sample of adult and older adult women and men study.

Methods

Design, sample, and ethical approval

The Tromsø Study is an ongoing population-based study (26) including seven surveys to date (1974–2016, Tromsø1–Tromsø7). Consisting of urban and rural living areas, the study is conducted in the municipality of Tromsø, Norway, which is similar to the general Norwegian population according to age (27) and gender (27). The present study includes data from Tromsø7 (2015–2016) (28), to which all inhabitants ≥40 years were invited (N = 32591) to visit 1. Visit 1 included questionnaires, biological sampling, and clinical examinations. A subsample (N = 13028) consisting of a random sample of 20% aged 40–59 years and 50% aged 60–84 years (n = 9925) as well as previous participants attending dual-energy X-ray absorptiometry (DXA), echocardiography and/or eye examinations in Tromsø6 (n = 3103) was pre-marked to visit 2 approximately 3–4 weeks later. Visit 2 included extended clinical examinations, including DXA and accelerometer measurements. Invitation to visit 2 required attendance at visit 1. In total 21083 (participation 65%) attended the first visit (Figure 1). Of these, 9253 were pre-marked for visit 2 invitations. In total 8346 attended visit 2 (comprising 64% the originally pre-marked visit 2 sample, 90% of those attending visit 1). The present study included 2737 participants; 1560 women and 1177 men aged 40–84 years who attended both DXA-scanning and wore accelerometers, and with valid data on confounders. All participants provided written informed consent prior to inclusion. Tromsø7 was approved by the Data Inspectorate of Norway and the Regional Committee of Medical and Health Research Ethics, North Norway (2014/940).

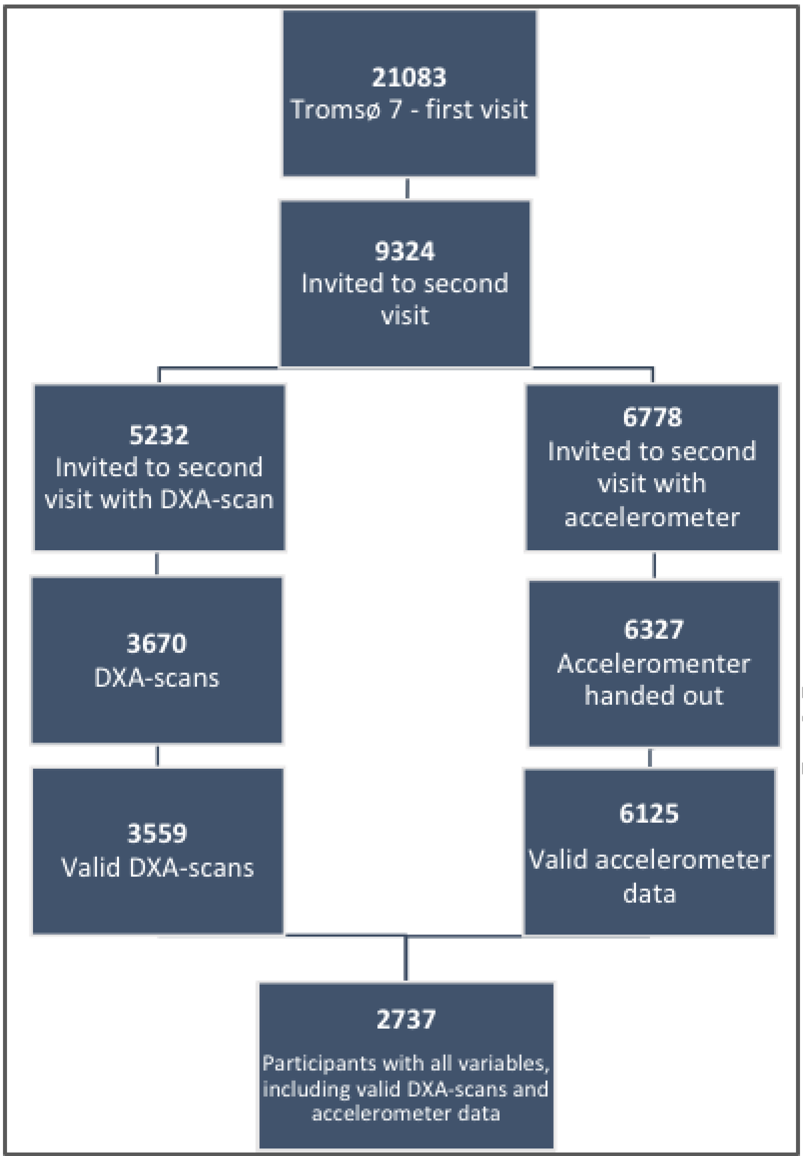

Figure 1 Flowchart illustrating the procedure for selection of participants.

Assessment of physical activity

Objective data on physical activity were assessed by an ActiGraph wGT3X-BT accelerometer (ActiGraph, LLC, Pensacola, United States) and expressed as steps per valid day and as minutes of MVPA per valid day. A valid day comprised of the wear time of four days, at least 10 hours per day. Trained technicians instructed participants to wear the accelerometer 24 hours a day for eight consecutive days prior to attaching the device to the participants' right hip at the examination site.

The device was programmed to start the data collection at 00:00 the next day and measure continuously for seven days. Removing the device was advised during water contact, e.g. when showering / bathing / swimming, and during contact sports. Raw acceleration data were collected with a sampling rate of 100 Hertz. The step count of the accelerometer was derived from the axial plane, based on a manufacturer's algorithm. The triaxial vector magnitude (VM) counts per minute (CPM) cut-points for different intensities were determined as follows: sedentary behavior: <150, light physical activity: 150–2689, and MVPA: ≥2690 VM CPM. More details of the data processing are described in Sagelv et al. (29, 30).

Measurement of bone mineral density

aBMD was measured using a DXA device (Lunar Prodigy, GE Medical Systems, Madison, WI, USA). All scans were performed according to standard procedures set by GE Medical Systems. The DXA device was calibrated daily using a standard phantom. Trained technicians performed the scanning according to a standardized protocol, and one of them performed quality assessment by visually reviewing each scan of the total sample afterwards. In a validation study, the short-term in vivo precision error for the Lunar Prodigy was 1.7% and 1.2% for the femoral neck and total hip measurements, respectively (31). Left total hip scans which include the femoral neck, trochanter and shaft regions were used for all our analyses (32).

Additional measurements

Participants' height and weight were measured with light clothing and no shoes to nearest centimeter and half-kilogram respectively, using a Jenix DS-102 scale

(DongSahn Jenix, Seoul, Korea). Body mass index (BMI) was calculated from weight and height (kg/m^2). Smoking (current, previous or never) was self-reported.

Statistical analyses

Multiple linear and non-linear regression models were used to analyze associations between objectively measured physical activity (per 1000 steps and per minute of MVPA per day) and hip bone aBMD separately for men and women, controlling for BMI, age and smoking status. Choice of adjustment variables is based on previous literature (33), and thus include variables that are commonly known to affect bone health (34) and available in the Tromsø study data. Analyses were performed separately for each activity variable. Effect sizes were reported as partial eta squared (η_p^2). We assessed the degree of plateauing effect for the number of steps and for the number of daily minutes with moderate and vigorous activity by the curve estimation procedure in SPSS. In the regression analysis the activity variables were centered. We checked the linearity, homogeneity and normal distribution assumptions, and whether there were influential observations using regression diagnostics (mainly by assessing residual plots and outlier statistics).

We used a significance level of .01 in all tests. SPSS Statistics for Windows v. 28 (IBM Corp. Released 2021. Armonk, NY, US) was used for the analyses.

Results

Sample characteristics

Table 1 displays sample characteristics for women and men separately. Both women and men had an age range of 40–84 years and a BMI of 13.7–50.6 kg/m^2 and 17.0–42.6 kg/m^2, respectively. The proportion reporting current or previous smoking was larger among men (63.7%) than among women (58.7%). In addition, a majority of men and women (>65%) achieved the WHO´s recommendations for physical activity, i.e., at least 150–300 minutes of moderate-intensity aerobic physical activity, or at least 75–150 minutes of vigorous-intensity aerobic physical activity or an equivalent combination of moderate- and vigorous-intensity activity throughout the week (35). (Table 1).

Table 1. Sample characteristics per sex. The Tromsø Study 2015–2016.

	Women (n=1560)	**Men (n=1177)**
Age (years)	66.2 (8.7)	66.4 (8.7)
Height (m)	1.63 (0.06)	1.76 (0.07)
Weight (kg)	71.0 (12.7)	85.9 (13.2)
BMI (kg/m2)	26.7 (4.7)	27.5 (3.7)
Smoking daily (%) (n)		
Never (%) (n)	41.3 (645)	36.3 (427)
Current (%) (n)	11.5 (179)	9.0 (106)
Previous (%) (n)	47.2 (736)	54.7 (644)
Left hip total BMD (g/cm2)	0.91 (0.13)	1.04 (0.14)
Accelerometer wear (valid days)	6.8 (0.5)	6.8 (0.5)
Accelerometer wear, time per valid day (h)	17.2 (1.7)	17.2 (2.0)
Steps per valid day[1] (steps/day)	6840 (2928)	6814 (2865)
Min in MVPA/day[2, 3]	36.7 (27.5)	43.1 (32.1)

MVPA ≥ 150 min/week (%) (n)	65.3 (1018)	71.1 (838)

Numbers are mean (SD) or percentage (n). [1]Hecht, 2009 (36), [2]Moderate and vigorous physical activity minutes per valid day; [3]Sasaki (37) and Kozey-Keadle (38).

The degree of plateauing of the effect of objectively measured activity on aBMD

We checked whether a linear model was sufficient to study the association between the number of daily steps or minutes MVPA per day and aBMD by testing whether parameters associated with quadratic and cubic terms were significantly different from zero. For men, adding a quadratic and cubic term for the number of daily steps variable improved the fit of the curve, and consequently a quadratic and a cubic term for the steps variable were included in the model (Figure 2). For the variable number of minutes in MVPA, no quadratic or cubic term was significant in the final regression analysis for men. For women, no quadratic or cubic terms were added because these were not significant (Figure 3).

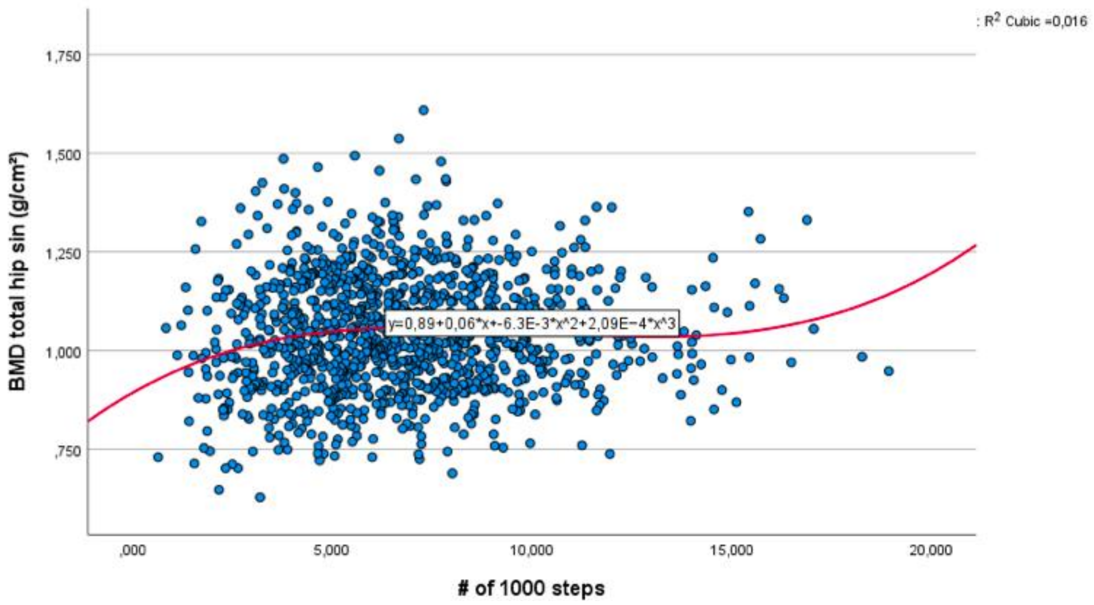

Figure 2. Curve-fit for a cubic model for the association between aBMD and the daily number of steps (in thousands) for men *n*= 1177. The Tromsø Study 2015–2016.

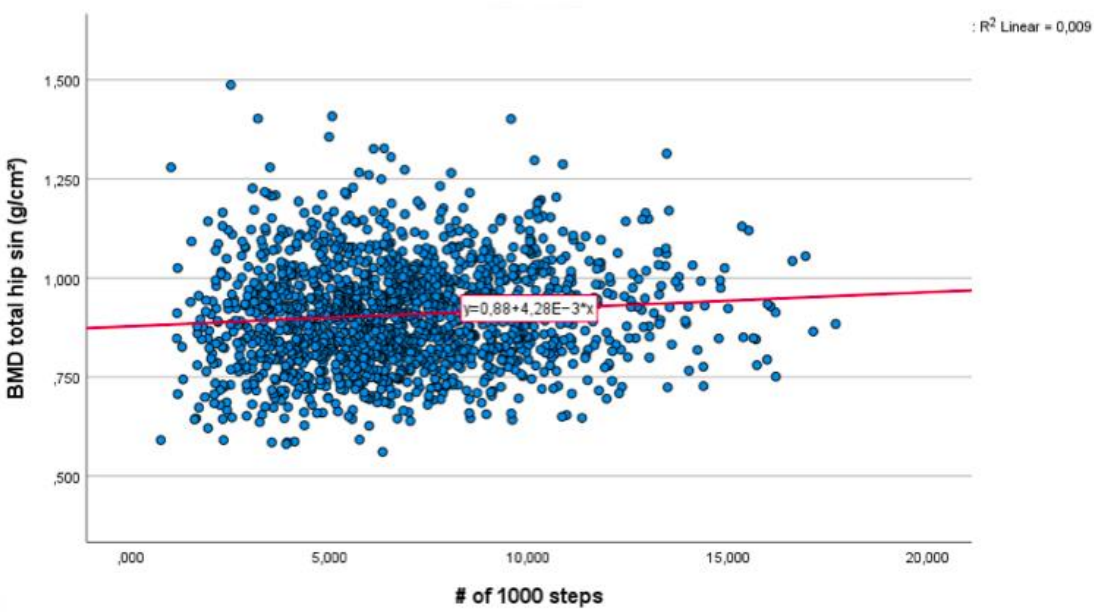

Figure 3 Curve-fit for a linear model for the association between aBMD and the daily number of steps (in thousands) for women *n* = 1560. The Tromsø Study 2015–2016.

Association between number of daily steps and aBMD

Women

The association between number of daily steps and aBMD for women are shown in Figure 3. Adding number of daily steps to a model containing age, BMI and smoking status, the proportion of total variance in aBMD (R^2) increased from 0.264 to 0.274. This small change in explained variance was significantly different from zero ($t_{(1555)} = 4.73$; $p < .001$; partial regression coefficient = 0.005), i.e., an increase of 1000 steps was associated with 0.005 g/cm^2 higher aBMD. To put the association of number of daily steps with aBMD into perspective we report effect size (partial eta squared, η_p^2) for all the independent variables: Number of steps: $\eta_p^2 = 0.014$; BMI: $\eta_p^2 = 0.206$; Age: $\eta_p^2 = 0.075$; Smoking status: $\eta_p^2 = 0.006$.

Men

Because the curve estimation procedure indicated a slightly curved association between the number of daily steps and aBMD, with significant quadratic and cubic terms, the activity variable was represented with a linear, a quadratic and a cubic term in the model. The polynomial curve fitted shows an initial positive association between aBMD and up to 5000 steps (Figure 2). The curve plateaued between approximately 5000 and 14000 steps and shows a small positive effect above 14000 steps. R^2- increased 0.015 (R^2 from 0.123 to 0.138) when adding the number of daily steps terms to a model containing the control variables. This increase was significantly different from zero ($F_{(3, 1169)} = 6.91$; $p < .001$.) Effect sizes for independent variables in the model (η_p^2) were: Steps: linear term: 0.0005, quadratic term: 0.011, cubic term: 0.008; BMI: 0.088; age: 0.009; Smoking status: 0.013.

Association between minutes MVPA per day on aBMD

Women

Adding minutes in MVPA to a model containing age, BMI, and smoking status, R^2 increased from 0.264 to 0.271, indicating a small, but significant association between minutes in MVPA and aBMD (R^2 change = .008; $t_{(1555)} = 4.02$; $p < .001$; partial regression coefficient = 0.000462). Each 60-minute increase in MVPA was associated with 0.028 g/cm^2 higher aBMD. Effect sizes for the independent variables in the model (η_p^2) were as follows: Minutes MVPA: 0.010; BMI: 0.204; Age: 0.084; Smoking status: 0.006.

The results of the two separate analyses; steps and MVPA for women were fairly similar, and the two activity variables, steps and MVPA, were highly correlated (r = 0.89).

Men

Adding minutes in MVPA to a model containing age, BMI and smoking status, R^2 increased from 0.123 to 0.129. The R^2 change of 0.006 was significantly different from zero (t = 2.89; p = .004; partial regression coefficient = 0.000381). Each 60-minute daily increase in MVPA was associated with 0.023 g/cm^2 higher aBMD. Effect sizes for independent variables in the model (η_p^2) were: MVPA: 0.007; BMI: 0.086; age: 0.013; Smoking status: 0.012. As for women, steps and MVPA were highly correlated (r = 0.86).

Discussion

In this cross-sectional study including 40–84-year-old women and men from a general population, objectively measured physical activity was positively associated with hip aBMD, although the association is weak. Keeping that in mind, the main findings of this study were: 1) In women and men, the number of daily steps was positively associated with hip aBMD; 2) In men, a slightly curved positive association between the number of daily steps and aBMD was indicated (the curve plateaued between 5000 and 14000 steps), while in women this association was linear; and 3) In women and men, MVPA was positively associated with hip aBMD. These findings were independent of age, BMI and smoking status.

The estimated 60-minute increase in MVPA per day was associated with 0.023 g/cm^2 and 0.028 g/cm^2 higher aBMD in men and women, respectively. To be noted here is, however, that an increase in physical activity level of this magnitude may be a lot for most individuals. The effect sizes were small, as even as much as 60-minute increase in MVPA per day was associated with a small estimated increase in aBMD in both men and women. Yet, even a small effect on BMD may be relevant for fracture risk (1), and given that the physical activity levels were measured over a relatively short period of one week and the cross-sectional design of this study, longitudinal studies with objectively measured physical activity are warranted.

While our study has identified a significant and yet small positive association between an increase in MVPA and hip aBMD, it is important to interpret these findings within the context of our study's cross-sectional design. Despite the inherent limitations in establishing causality, the association we have documented is consistent with a systematic review by Mohebbi et al.(39), suggesting a potential causal link between physical activity and BMD. Additionally, research by Soares et al.(40) supports the notion that an active lifestyle may contribute to a reduced risk of falls among older adults, which is an important consideration for bone health. Since a decrease of one standard deviation in BMD at the hip, spine or wrist is associated with a doubling in fracture risk (1), any preventive measure connected to reduction of bone loss is important.

Physical inactivity is known to be an important risk factor for bone health (5), often indicated through lower bone mineral density and higher risk of osteoporotic fractures (1, 41). Positive associations between physical activity and hip BMD in different populations are well documented in cross-sectional studies (9-12, 21) although study designs are largely based on self-reported physical activity, like Hauger et al. (10) who studied associations between self-reported physical activity and hip aBMD using data from Tromsø7, i.e. the same population as in our analysis. In their study, active women (physical activity level 2–4) had 4.1–10.2% higher aBMD than inactive (physical activity level 1) women. Men at physical activity level 3 had 4.3% higher aBMD compared to level 1, and men >65 years had 3.1–4.3% (physical activity level 2–3) higher aBMD compared to level 1. Despite measuring physical activity by questionnaire, these findings indicate similar positive associations between physical activity and aBMD as observed in our study. The plateauing of the daily steps seen among men in our study might explain the non-significantly higher aBMD among men in physical activity level 4 compared to level 1 in the study of Hauger et al. (10), even though we cannot explicitly point out the plateau on the level 1 to level 4 scale in our analyses.

Few previous studies have investigated objectively measured physical activity and bone health with a reasonably large study sample, which provides statistical power for stratified analyses such as comparing men and women. Similar to the current study, Johansson et al. (24) found positive associations between MVPA and hip aBMD. Although their findings are only generalizable to 70-year-olds and there were no stratified analyses showing results for women and men separately. In a sample of 2114 women and men aged 23–90+, Chastin et al. (23) , found that time spent in MVPA was associated with higher hip BMD in men. In women, sedentary behavior was negatively and light physical activity positively associated with hip BMD. Interestingly, and in contrast to our findings, Chastin et al. (23) did not find any associations between MVPA and BMD in women. In a similar study population, intermediate and high durations of MVPA were associated with hip BMD in women aged 50 years and above, and high duration MVPA was associated with hip BMD in men aged 50 years and above (22). Furthermore, in a smaller study (n=214), Hind et al. (16) found higher volumes of light physical activity but not MVPA to be positively associated with bone mineral density. Gaba et al. (15) and McMillan et al. (17) found body composition to be a stronger predictor of BMD than physical activity variables, which is also seen in our analyses, showing that BMI together with age and smoking status were stronger predictors for BMD than physical activity. One of the relatively strong effects of BMI on BMD is most likely related to the load placed upon weight-bearing bones, since, in general, greater body weight increases the effects of weight-bearing activity on bone adaptation (42). However, physical activity reach evidence grading A and B, respectively, in the position statement by Weaver et al. (42) for its effects on bone mass and density, and bone structural outcomes. Since we in our study found BMI (together with age and smoking status) to be a stronger predictor for BMD than physical activity, it is possible that our older subjects may not have engaged in physical activity intense enough to trigger an osteogenic response. It is known that for example repetitive low-magnitude loads, which may be a characteristic of the activities chosen by our study participants, are not osteogenic (42-44). Also, an animal trial suggests that the osteogenic response is weaker in ageing skeleton compared to a young one (45). However, according to Weaver et al. (42), our understanding of the specific dimensions of physical activity that are osteogenic is incomplete. Hence, further research should focus on what frequency, intensity, time, and type of physical activity is needed to optimize bone structural outcomes in different age segments in men and women.

Strengths and limitations

To our knowledge, our study is one of the largest studies investigating the association between objective measures of physical activity and BMD in a general population with a wide age range. Due to the cross-sectional design, we cannot establish causal relations. Furthermore, due to fairly slow bone density development, repeated measurements could have strengthened our study by allowing us to study possible changes over time, but no follow-up data with accelerometer-measured physical activity are yet available. Moreover, we did not study type of physical activity, only volume and intensity. Weight bearing exercises are found to be particularly beneficial (5), whereas cycling does not seem to contribute as much to the osteogenic stimulus that is needed for improving bone health (46). Activities such as cycling, resistance training, and swimming may be underestimated in our study due to the accelerometer's reduced validity in measuring those activities (47). Therefore, being able to identify the type of physical activity participants engaged in would help us to gain more detailed knowledge on associations between physical activity and bone mineral density. We followed WHO's recommendations for physical activity, i.e., MVPA (35), and therefore we have chosen not to include light physical activity in our study, which may not imply weight-bearing activities to the same degree as

MVPA. Moreover, our analysis did not account for additional confounders such as dietary factors or general health status.

Conclusion

In this cross-sectional study of women and men from a general population, accelerometer-measured physical activity was positively associated with total hip aBMD, after controlling for age, BMI and smoking status. Furthermore, the pattern of association varied by sex, as the prediction curve for men plateaued between 5000 and 14000 steps indicating a curved association. Further longitudinal population-based studies using objective measures of physical activity are warranted to confirm both the magnitude and the direction of these associations, although our findings indicate that maintaining physical activity levels means maintaining bone health in the general population.

List of abbreviations

aBMD Areal bone mineral density

BMD Bone mineral density

BMI Body mass index

DXA Dual-energy X-ray absorptiometry

η_p^2 Partial eta squared, effect size

g/cm2 Gram per square centimeter

h Hour

kg/m2 Kilogram per square meter

kg Kilogram

m Meter

min Minute

MVPA Moderate and vigorous physical activity

R^2 R squared, the proportion of total variance

SPSS IBM SPSS Statistics software

Tromsø1 The first survey of the Tromsø Study

Tromsø7 The seventh survey of the Tromsø Study

WHO World Health Organization

Declarations

Ethics approval and consent to participate

As described under the method section.

Consent for publications

Not applicable

Availability of data and materials

The legal restriction on data availability are set by the Tromsø Study Data and Publication Committee in order to control for data sharing, including publication of datasets with the potential of reverse identification of de-identified sensitive participant information. The data can however be made available from the Tromsø Study upon application to the Tromsø Study Data and Publication Committee. Contact information: The Tromsø Study, Department of Community Medicine, Faculty of Health Sciences, UiT The Arctic University of Norway; e-mail: tromsous@uit.no

Competing interest

The authors declare that they have no competing interests.

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Authors' contributions

SM; Conceptualization, Funding acquisition, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing

BHH Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

JJ; Writing – original draft, Writing – review & editing

LAH Conceptualization, Investigation, Methodology, Resources, Writing – original draft , Writing – review & editing

RT; Writing – original draft, Writing – review & editing

NE; Conceptualization, Investigation, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing.

BM; Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing.

BW; Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing.

All authors read and approved the final manuscript.

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