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Relationships among body weight, joint moments generated during functional activities, and hip bone mass in older adults

Man-Ying Wang^{b,*}, Sean P. Flanagan^a, Joo-Eun Song^b, Gail A. Greendale^c, and George J. Salem^b

^aDepartment of Kinesiology, California State University, Northridge, CA, USA

^bMusculoskeletal Biomechanics Research Laboratory, Department of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, CA, USA

^cUCLA School of Medicine, Division of Geriatrics, Los Angeles, CA, USA

Abstract

Objective—To investigate the relationships among hip joint moments produced during functional activities and hip bone mass in sedentary older adults.

Methods—Eight male and eight female older adults (70–85 yr) performed functional activities including walking, chair sit–stand–sit, and stair stepping at a self-selected pace while instrumented for biomechanical analysis. Bone mass at proximal femur, femoral neck, and greater trochanter were measured by dual-energy X-ray absorptiometry. Three-dimensional hip moments were obtained using a six-camera motion analysis system, force platforms, and inverse dynamics techniques. Pearson's correlation coefficients were employed to assess the relationships among hip bone mass, height, weight, age, and joint moments. Stepwise regression analyses were performed to determine the factors that significantly predicted bone mass using all significant variables identified in the correlation analysis.

Findings—Hip bone mass was not significantly correlated with moments during activities in men. Conversely, in women bone mass at all sites were significantly correlated with weight, moments generated with stepping, and moments generated with walking ($p < 0.05$ to $p < 0.001$). Regression analysis results further indicated that the overall moments during stepping independently predicted up to 93% of the variability in bone mass at femoral neck and proximal femur; whereas weight independently predicted up to 92% of the variability in bone mass at greater trochanter.

Interpretation—Submaximal loading events produced during functional activities were highly correlated with hip bone mass in sedentary older women, but not men. The findings may ultimately be used to modify exercise prescription for the preservation of bone mass.

Keywords

Bone mineral density; Functional activity; Hip; Joint moment; Submaximal loads

1. Introduction

Researchers have identified the *strains* induced during skeletal loading as important modulators of bone remodeling behavior (Burr, 1997). Studies using animal models suggest that loading histories involving dynamic strains with high magnitudes and rates, applied with unusual distribution patterns, are optimal for osteogenesis, and that these strain-loading histories play an important role in determining bone morphology (Carter et al., 1989; Lanyon and Rubin, 1984; O'Connor et al., 1982; Rubin and Lanyon, 1984; Rubin and Lanyon, 1985; Turner et al., 1995a,b). Nevertheless, the influences of the loadings on bone could be modified by factors such as age, gender, nutrition, and hormonal status (Maddalozzo and Snow, 2000; Prince et al., 1991; Turner et al., 1995a,b; Yeh et al., 1994). As a result, findings in studies investigating the effects of external loads on bone adaptation in humans have not been as consistent as those reported in animal studies (Snow et al., 1996). Identifying these relationships is complicated by the fact that dynamic loadings are more difficult to quantify in humans than in animals.

Muscles impart strains to the skeleton during physical activities by producing bone bending moments, as well as compressive and tensile forces, as they rotate and stabilize joints. Consequently, the relationships between bone mass and muscular strength in humans have been of interest to investigators for the past 20 years (Conroy et al., 1993; Di Monaco et al., 2000; Sinaki et al., 1986). These studies suggest a coupling between *maximum-effort* muscular activity and bone adaptation; however, they do not address the influence of more frequent, lower-intensity strains on bone mass. The dynamic loads associated with functional activities such as walking, sitting/standing from a chair, and stepping onto a stair, are noticeably less than maximum in healthy, independent, and ambulatory adults (Hughes et al., 1996). Nevertheless, it appears plausible that a life-time of functionally submaximal loadings might influence an individual's bone status, especially in those who have a sedentary lifestyle. Indeed, the hypothesis that strains are osteogenetic if only surpassing the minimum threshold has been recently challenged. Rubin and colleagues (2001) demonstrated that persistent, low-amplitude, high-frequency mechanical strains, which are similar to the strains imposed by muscular activities, were capable of increasing bone formation rates, mineralizing surfaces, bone density, and bone volume in animal models. Thus, low-amplitude strains, which predominantly occur during normal daily activities, were suggested to be as important as the *peak* impacts in bone remodeling (Fritton et al., 2000; Rubin et al., 2001). While this finding also conflicted with the animal studies demonstrating that the number of loading cycles was not a major determinant of osteogenetic responses (Rubin and Lanyon, 1984), investigations of the relationships between various loadings and bone adaptations are encouraged since bone may respond to different loading profiles via diverse mechanisms (Fritton et al., 2000). To date, the role of functionally submaximal loading events on bone adaptations in humans is uncertain.

Although it is not possible to directly measure bone strains or dynamic muscle forces using non-invasive procedures, motion-analysis systems and inverse-dynamic techniques, (which consider limb mass, inertia, acceleration, and reaction forces), may be used to calculate the relevant kinetic attributes of motion (e.g., net joint moments) related to muscle force and bone loading behaviors (Bergmann et al., 2001; Winter, 1990). During functional activities, external forces (e.g., ground reaction forces) acting on the body produce external torques or moments about the lower-extremity joints. These external moments must be met by internal moments (acting in the opposite direction) to lift the body's center of mass and/or prevent collapse of the lower extremity. These internal moments are generated via muscle activities and peri-articular forces (i.e., ligaments and capsules) crossing the lower-extremity joints. In addition to producing the internal moments required to successfully ambulate, these muscular and peri-articular forces also create repetitive bone strains. Therefore, joint

moments can be considered as a ‘first order approximation’ of muscular forces and bone loadings. These ‘approximations’ have been reported to correlate with bone distribution in normal adults and patients with hip osteoarthritis (Hurwitz et al., 1998a,b).

The purpose of this study was to investigate the relationships among hip bone mass and submaximal loadings estimated by participants’ hip net joint moments (HJMs) produced during walking, stair stepping, and chair sit–stand–sit activities in older adults. We hypothesized that HJMs generated during these functional activities would be significantly related to hip bone mineral density and bone mineral content.

2. Methods

2.1. Subjects

Eight male and eight female healthy older adults (70–85 yr), participating in a study examining the biomechanical effects of various exercise activities, were recruited from the greater Los Angeles area. The number of the subjects was determined by considering both precision and feasibility. The estimates of precision, defined as the distance from the upper or lower end of the 95% confidence interval to the observed mean, were obtained using our previously published HJMs data in 56 older adults (Salem et al., 2001). While increasing the sample size did not improve the precision proportionally, sample size was optimized to 16. Potential subjects were screened using medical-history and physical-activity questionnaires (Reuben et al., 1990). All participants were relatively healthy and independent. Subjects with neurological, musculoskeletal, and/or cardiovascular disorders were excluded from the study. Additionally, only sedentary subjects who did not participate in active sports (e.g., aerobics, jogging, tennis) or who did not walk more than a mile without resting three or more times per week, were included. Thus, confounding factors related to frequent or intensive exercise activities were eliminated. The study protocol was approved by the Health Sciences Institutional Review Board of University of Southern California and all subjects consented to participate.

2.2. Bone density measurement

Bone mineral density (BMD) and bone mineral content (BMC) were measured using dual-energy X-ray absorptiometry (DEXA, Hologic QDR1500, Waltham, MA, USA) by a licensed technician. The measurement sites included the dominant-limb proximal femur, femoral neck, and greater trochanter (Fig. 1). The accuracy and precision of DEXA measurements have been previously discussed (Orwoll et al., 1993; Sievanen et al., 1992). In our laboratory, a phantom scan method was performed daily to meet the manufacturer’s precision standard of less than 1.5% for the hip joint. Reproducibility of the measures ranged from 0.8% to 1.5% for the various scans performed within the last five years (Hawkins et al., 2003).

2.3. Biomechanical data collection

Participants were instrumented for biomechanical analysis at their second study visit, seven days later. Anthropometric data of each subject were measured before biomechanical data collection. Standing height was measured with a stadiometer and body weight was measured using a calibrated force platform (AMTI, Watertown, MA). Leg length between anterior superior iliac spine and lateral malleolus for each leg was taken by a tape measure. Distance between bilateral anterior superior iliac spines, knee width between bilateral femoral epicondyles and ankle width between bilateral malleoli were recorded using calipers and a ruler.

Fourteen reflective markers (2.5 cm spheres) were taped to the skin bilaterally over important lower-extremity bony landmarks in order to track the participant's limb positions and movements using a six-camera, motion analysis system (60 Hz sampling rate; Vicon 370, Oxford Metrics, Oxford, UK). The bony landmarks included heels, second and fifth metatarsal heads, lateral malleoli, lateral epicondyles of the femur, anterior superior iliac spines, and posterior superior iliac spines. Additionally, markers each on a 5-cm wand were placed over the lateral thighs and shanks. The segment coordinate system relative to the laboratory coordinate system was then established according to these marker positions. Hip joint centers were estimated based on the positions of anterior superior iliac spines, individual leg length, and intra-anterior superior iliac spine distance (Davis et al., 1991). Segment weight, length, and radius of gyration were calculated using published anthropometric data (Winter, 1990). Ground reaction forces were recorded from force platforms at 1200 Hz (Model #OR6-6-1, AMTI, Watertown, MA, USA). Three-dimensional kinematics and kinetics, including intersegmental forces and joint moments, were calculated using Newton–Euler equations of motion and previously reported inverse dynamics methods (Davis et al., 1991; Kadaba et al., 1987; Kadaba et al., 1990). Detail descriptions of the link segment models during various functional activities were reported in Bergmann's study (Bergmann et al., 2001). The same methodology was applied to both men and women. Data processing software, Workstation (Oxford Metrics, Oxford, UK) and Datapac 2000 (RUN Technologies Co., Laguna Hills, CA, USA) were utilized for all calculations.

Participants were instructed to perform three common activities of daily living—normal walking, chair sit–stand–sit, and stair stepping. Three continuous and successful trials were collected for each activity and the sequence of the activities was randomized. The number of the trials was determined based on our pilot data which demonstrated similar reliability of the measurement among three to five trials in five subjects. The Intraclass Correlation Coefficients for the three trials in the current study were greater than 0.85 for all HJMs. In order to reproduce the efforts associated with these activities in non-laboratory conditions, the participants were encouraged to perform the activities at a self-selected pace. The normal walking activity was performed on a six-meter walk way. During the chair sit–stand–sit and the stair-stepping activities, a safety bar was positioned in order to assist participants in the event that they lost their balance. They were instructed, however, not to use the bar to assist their movement. Our previous data suggest that the forces placed on the safety bar by the participants during these activities were minimal (Wang et al., 2003). During the chair sit–stand–sit activity, participants stood with their feet on separate force platforms. They were then instructed to sit back onto a firm armless chair (43.8 cm in height), pause briefly, and then rise from the chair. For the stepping activity, the participants stepped with their dominant limb onto a step (21 cm) with an embedded force platform. They then shifted their body weight to the lead leg and extended the knee and hip joints, before lifting their contralateral limb and stepping onto the force platform. After pausing briefly, subjects then descended the step while leading with the non-dominant limb. Rest periods were provided between activities and all participants were able to perform the activities without difficulty. By definition, the dominant limb was identified by the subjects as the limb that they would use to kick a ball.

2.4. Data and statistical analysis

Data from the entire movement cycle of each trial of the functional activities were used to identify the peak HJMs. Average peak HJMs were then calculated across the three trials for each functional activity (normal walking, sit–stand–sit, and stepping activities) in three dimensions, each with opposite directions. The moments included flexion/extension in the sagittal plane, abduction/adduction in the coronal plane, and internal/external rotation in the transverse plane. The absolute values of these average peak moments in six movement

directions were further summed up for each activity to generate individual measures of overall hip dynamic loading, i.e., sum of the hip joint moments for walking (SHJM *walk*), sit–stand–sit (SHJM *chair*), and stair stepping (SHJM *step*). All of the HJMs reported here are internal net joint moments and all analyses were conducted on data obtained from the participants' dominant limb. Bone related variables included BMD and BMC at the proximal femur, femoral neck, and greater trochanter.

Independent-samples *t*-tests were used to examine significant differences in the anthropometrics and bone variables between genders. Pearson's correlation coefficients were calculated to assess the linear relationships among participant characteristics (age, height, and body weight), hip BMD/BMC, and SHJM *walk*, SHJM *chair*, and SHJM *step*. Those variables that were significantly related to BMC and BMD at all measurements regions, were then entered into forward stepwise linear regression models in order to determine their relative contribution to hip bone mass. The criteria for the variable entry (p_{in}) and removal (p_{out}) of the regression models were $p < 0.05$ and $p > 0.1$, respectively. When statistically significant summation variables were identified in the regression model, a secondary forward stepwise regression analysis was then conducted using HJMs in the six *individual* movement directions to define the specific HJMs that predict hip bone mass. Linearity and normality were inspected by scatter plots and normal probability plots. All statistical procedures were employed using SPSS software version 10.0 (Chicago, IL, USA).

3. Results

Demographic and anthropometric characteristics of the study participants are provided in Table 1. There were no statistically significant differences in age or body weight between the men and women participants; however, the average height of the men was greater ($p < 0.05$). The majority of the participants were Caucasian (75%). No subjects were osteoporotic (Z score < -2.5). BMC and BMD at the femoral neck, greater trochanter, and proximal femur are reported in Table 2. There were statistically significant differences in BMC ($p < 0.01$) but not BMD between genders at all measurement sites. The peak internal HJMs generated with the normal walking, chair sit–stand–sit and stair-stepping activities are provided in Table 3. Among the three functional activities, stair stepping activity generated the greatest overall hip dynamic moments whereas the chair sit–stand–sit activity generated the lowest overall hip moments.

Pearson's correlation coefficients among the subjects' characteristics (age, height, and body weight), hip bone mass (BMC and BMD at femoral neck, greater trochanter, and proximal femur), and SHJMs are presented in Table 4. Scatter plots indicated that these variables were linearly related. An example is shown in Fig. 2 which illustrates the linear relationship between SHJM *step* and BMD at proximal femur. In men, only height was significantly related to BMC at greater trochanter ($r = 0.71$, $p < 0.05$). No other subject characteristics or SHJMs were significantly related to the BMC or BMD in the male participants.

Conversely, in women, hip BMD and BMC at *all* measurement regions were significantly correlated with SHJM *walk* and SHJM *step* ($p < 0.05$ to $p < 0.001$) (Table 4). The greatest correlation coefficients were indicated at proximal femoral BMC in relation to SHJM *step* ($r = 0.97$, $p < 0.001$) and SHJM *walk* ($r = 0.95$, $p < 0.001$). SHJM *chair* was significantly associated with bone mass at greater trochanter (BMC: $r = 0.92$, $p < 0.01$; BMD: $r = 0.77$, $p < 0.05$) and proximal femur (BMC: $r = 0.93$, $p < 0.01$; BMD: $r = 0.76$, $p < 0.05$). However, SHJM *chair* was not significantly correlated with bone mass at femoral neck. Among the SHJMs generated with the three activities, the stepping activity demonstrated the strongest significant correlations with the bone variables (r ranged from 0.80 to 0.97 for all measurement regions).

Additionally in women, body weight was significantly correlated with BMC and BMD at all hip subregions, where the greatest correlation coefficient was demonstrated at greater trochanteric BMC ($r = 0.96$; $p < 0.001$). In contrast, height only showed significant correlations with BMC at greater trochanter ($r = 0.90$, $p < 0.01$) and proximal femur ($r = 0.80$, $p < 0.05$), and BMD at greater trochanter ($r = 0.77$, $p < 0.05$).

Subsequently, body weight, SHJM *walk*, and SHJM *step* were then used in the forward stepwise linear regression analysis in order to assess their relative effects on hip bone mass in women. Results indicated that at the femoral neck, 71% of the variability in BMC ($p < 0.01$) and 64% of the variability in BMD ($p < 0.05$) were explained by SHJM *step* (Table 5). At proximal femur, SHJM *step* also significantly explained 93% and 73% of the variability in BMC and BMD ($p < 0.001$ and $p < 0.01$) respectively. Body weight independently predicted 92% of the variance in BMC ($p < 0.001$) and 83% of the variance in BMD ($p < 0.01$) at greater trochanter. SHJM *walk*, however, did not significantly predict hip bone mass while SHJM *step* or weight was entered to the regression models.

Since the overall dynamic hip muscular loadings produced with stepping activity independently predicted bone mass at femoral neck and proximal femur in women, direction-specific HJMs (flexion, extension, abduction, adduction, internal rotation, and external rotation moments) generated during the stepping activity were entered into stepwise regression models to predict BMC and BMD at both sites. Results demonstrated that the abduction moments generated during the stepping activity significantly explained the variance in BMC ($R^2 = 0.56$, $p < 0.05$) and BMD ($R^2 = 0.68$, $p < 0.05$) at femoral neck, as well as the BMD at proximal femur ($R^2 = 0.77$, $p < 0.01$) (Table 6). Moreover, 91% of the variability in BMC at proximal femur was predicted by a combination of abduction and extension moments produced during the stepping activity ($p < 0.05$). As a result, hip abduction moments associated with the stepping activity showed the greatest explanatory power to the variability in bone mass at femoral neck and proximal femur; while weight was the strongest predictor of bone mass at greater trochanter in women.

4. Discussion

This study investigated the associations among the HJMs produced during functional activities and hip bone mass (BMC and BMD) in sedentary older adults. Men and women demonstrated different results. Hip bone mass was not significantly correlated with SHJMs in men; however, body weight, SHJM *step*, and SHJM *walk* were significantly related to hip BMD and BMC at all measurement regions in women. The stepping activity demonstrated the greatest explanatory power of hip bone mass among the sum moments generated across the three activities. This strong relationship was primarily attributed to the abduction moments associated with the stepping activity. Findings in this study suggest that submaximal loading events produced during functional activities are strongly related to hip bone mass in older women, but not men.

Site-specific factors that correlate with bone mass, such as maximum-effort muscular strength and muscle mass, have been identified in the previous studies (Bevier et al., 1989; Di Monaco et al., 2000; Halle et al., 1990; Kyllonen et al., 1991; Madsen et al., 1993; Pocock et al., 1989; Sinaki et al., 1986; Sinaki et al., 1989; Zimmermann et al., 1990). Because muscular activities impose mechanical forces that drive bone-remodeling processes, it is not surprising that significant correlations among bone mass, muscle strength, and muscle mass exist. For example, there appears to be a moderate relationship between trunk muscle strength and lumbar BMD ($0.25 < r < 0.47$) in postmenopausal women (Halle et al., 1990; Kyllonen et al., 1991; Sinaki et al., 1986). There are also moderate linear correlations between hand grip strength and radial BMD ($0.30 < r < 0.57$) in

healthy adults older than 50 years of age (Bevier et al., 1989; Di Monaco et al., 2000; Sinaki et al., 1989). Additionally, hip muscular strength has been significantly associated with hip BMD in postmenopausal women (mean age = 55.4–58.3 yrs) ($0.20 < r < 0.42$) (Tan et al., 1998; Zimmermann et al., 1990) and quadriceps strength has been significantly related to BMD at the proximal tibia ($0.79 < r < 0.84$) in women aged 21–78 yrs (Madsen et al., 1993). To our knowledge, this is the highest value of association previously reported. Recently, submaximal muscular loadings, as estimated by dynamic joint moments, were reported to significantly predict bone mass (Moisio et al., 2004). Moisio's group demonstrated that 29–58% of the variability in hip BMC and BMD could be explained by HJMs generated during walking in healthy men and women, aged 30–49 yrs (Moisio et al., 2004). Hip joint moments generated during jogging also significantly predicted 13–32% of the variance in hip bone mass. In the present study, the correlation coefficients between the HJMs and hip bone mass ($r = 0.72–0.97$) were generally greater than those that have been previously reported in the studies investigating the relationships between bone density and muscle strength (Tan et al., 1998; Zimmermann et al., 1990), and the relationships between bone mass and joint moments (Hurwitz et al., 1998a,b; Moisio et al., 2004). We found that, in our sedentary older women, HJMs produced during submaximal functional tasks, particularly stair stepping, significantly explained up to 93% of the variance in BMC and BMD at femoral neck and proximal femur. Nevertheless, caution is suggested when comparing the present findings to previous studies investigating the relationships between *maximum effort* performance and bone mass since this study only addressed relationships between *submaximal efforts* (functional hip joint moments) and bone mass.

By employing a secondary stepwise analysis, incorporating three-dimensional HJMs generated during stepping, we found that the hip *abduction moments* explained up to 88% of the variance in BMC and BMD at femoral neck and proximal femur in women. Earlier investigations in our laboratory have indicated that hip abductor muscles are important modulators of the stepping activities in elders (Wang et al., 2003). This muscle group functions to prevent pelvis drop and to abduct the thigh. Muscles providing this internal joint moment include tensor fasciae latae, gluteus maximus, gluteus medius, gluteus minimus, piriformis, superior gemellus, obturator internus, inferior gemellus, and quadratus femoris. Because these muscles have multiple distal attachment sites and develop tensile and compressive forces in numerous directions, they are likely to generate complicated strain patterns on the irregular-shaped proximal femur. This may help explain why the HJMs significantly related to bone mass at femoral neck even though this site has no muscular attachments. It is also possible that the femoral neck was compressed as a whole during co-contractions of the surrounding muscles.

Body weight was significantly correlated to BMC and BMD at all hip subregions in women. Body weight also significantly independently predicted 83–92% of the variance in bone mass at greater trochanter. These findings are consistent with previous reports that body weight significantly predicts BMD at weight bearing sites, including the lumbar spine, proximal femur, greater trochanter and femoral neck in postmenopausal women (Bevier et al., 1989; Blain et al., 2001; Foley et al., 1999; Halle et al., 1990). However, when examining BMD and BMC at femoral neck and proximal femur in regression models, the significant prediction power of body weight no longer existed after SHJM *step* was entered into the models. The findings indicated that SHJM *step* was a stronger predictor of bone mass at femoral neck and proximal femur than body weight. Once the commonality was explained by SHJM *step*, body weight demonstrated very little contribution to the prediction of bone mass at femoral neck and proximal femur. SHJM *step* independently predicted up to 71% and 93% of the variability in bone mass at femoral neck and proximal femur, respectively. These results were similar to Moisio's report that dynamic hip moments significantly explained up to 58% of the variability in hip bone mass independent of weight

(Moisio et al., 2004). It is noteworthy that the predictive power of the hip joint moments was greater in the present study than those demonstrated in Moisio's study, where data from men and women were pooled. In men, neither body weight nor HJMs generated during functional activities were significantly related to hip bone mass in the current study. Similar findings of non-significant relationships between weight and BMD at weight-bearing sites in *men* have also been reported (Bevier et al., 1989; Snow-Harter et al., 1992).

Men and women demonstrated very different relationships between hip moments and bone mass in the present study. Similar discrepancies have also been reported in studies investigating the relationships among body composition, muscular strength, and bone mass (Baumgartner et al., 1996; Bevier et al., 1989; Reid et al., 1992). In general, there tends to be significantly moderate to strong relationships ($0.20 < r < 0.84$) in women (Di Monaco et al., 2000; Halle et al., 1990; Kyllonen et al., 1991; Madsen et al., 1993; Sinaki et al., 1986; Tan et al., 1998; Zimmermann et al., 1990); whereas, only moderate relationships ($0.19 < r < 0.55$) have been reported for men (Bevier et al., 1989; Hughes et al., 1995; Huuskonen et al., 2000; Snow-Harter et al., 1992). Moreover, it appears that fat mass may be more important determinant of bone mass in older women than men (Baumgartner et al., 1996; Reid et al., 1992). The gender effects identified in the present study can most likely be attributed to factors other than gravitational consequences since both genders had a similar average body weight. There were also no differences in body mass index, age or BMD between genders. Genetic distinctions, including sex hormones and other environmental and metabolic factors such as nutrition, growth hormone, and aerobic capacity may account for the different associations observed between genders (Bevier et al., 1989; Maddalozzo and Snow, 2000; Prince et al., 1991; Turner et al., 1995a,b; Yeh et al., 1994).

Interpretation of the results of this investigation should be made in light of the study's limitations. Errors associated with motion analysis such as marker placements, skin movements, and estimations of segment properties by published anthropometric data have been widely discussed (Winter, 1990). In the current study, the markers were placed by the same research associate, the high-frequency noises caused by skin movements were filtered, and individual anthropometric data were measured to minimize the errors related to biomechanical analysis. Another limitation of the present study is that the sample size was small and information related to participants' *long-term* activity patterns was not collected; consequently, caution is recommended when extrapolating these findings to other populations (e.g., master athletes). However, with a statistical power of less than 50%, strong relationships between the HJMs produced during functional activities and hip bone mass were identified and similar relationships were reported in the previous studies (Moisio et al., 2004). Additional studies, with greater sample sizes and with information related to long-term activity levels are encouraged. Finally, causal relationships between the functional activities and bone mass cannot be established from this study because of its cross-sectional design. Longitudinal intervention studies, examining the influence of increased functional activity performance on bone health, will be necessary to uncover these potential dose–effect relationships.

5. Conclusions

Data from this study demonstrated that HJMs generated with functional activities, particularly stair stepping, were significantly associated with hip bone mass in sedentary older women, but not men. The relationships were generally greater than those that have been reported in the literature. These cross-sectional findings suggest that submaximal muscular loading events, produced during activities of daily living, may influence hip strain history and thus correlate with bone morphology in postmenopausal women. Well-designed, longitudinal investigations, however, will be required to identify the causal relationships

between functional activity performance characteristics (e.g., type, duration, repetitions, and resistance) and bone health.

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Fig. 1.
DEXA measurement sites by Hologic software for hip joint. Proximal femur includes femoral neck, greater trochanter, and intertrochanteric regions.

Fig. 2.

A scatter plot of the relationship between BMD of the proximal femur and sum hip joint moments generated with the stepping activity in women (●) and men (Δ). The line of best fit for women was determined by linear regression analysis.

Table 1

Demographic and anthropometric characteristics of participants

Measurement	Overall	Women	Men
<i>N</i>	16	8	8
Age	74.7 (4.7)	74.1 (5.1)	75.3 (4.6)
Height, cm	166.3 (13.2)	158.3 (9.5)	174.4 (11.5) *
Weight, kg	71.8 (16.0)	67.8 (20.8)	75.8 (8.7)
Caucasian	75.0%	62.5%	87.5%

Values are mean (SD) or percent.

* Significantly different between men and women ($p < 0.05$).

Table 2

BMD and BMC at measurement sites

	All (n = 16)	Women (n = 8)	Men (n = 8)
<i>BMC, g</i>			
Femoral neck	4.116 (0.977)	3.471 (0.484)	4.760 (0.929) *
Greater trochanter	8.269 (2.759)	6.330 (2.061)	10.209 (1.860) *
Proximal femur	32.755 (8.159)	26.536 (6.313)	38.974 (3.795) *
<i>BMD, g/cm²</i>			
Femoral neck	0.708 (0.121)	0.668 (0.088)	0.747 (0.143)
Greater trochanter	0.683 (0.106)	0.651 (0.129)	0.714 (0.072)
Proximal femur	0.865 (0.123)	0.825 (0.134)	0.905 (0.104)

Values are mean (SD).

* Significantly different between men and women ($p < 0.01$).

Table 3Peak hip joint moments associated with three functional activities^a

Moment, Nm	All (n = 16)	Women (n = 8)	Men (n = 8)
<i>Normal walking</i>			
Extension	86.72 (27.84)	79.50 (31.73)	94.96 (22.02)
Flexion	29.66 (9.97)	28.92 (11.98)	30.52 (7.93)
Abduction	45.54 (20.82)	46.86 (26.13)	44.04 (14.50)
Adduction	18.14 (14.63)	13.26 (9.09)	23.71 (18.30)
External rotation	6.66 (3.90)	7.59 (5.10)	5.60 (1.62)
Internal rotation	10.77 (5.14)	8.06 (3.26)	13.86 (5.31)
<i>Chair sit–stand–sit</i>			
Extension	76.93 (31.30)	65.43 (28.30)	90.06 (31.22)
Flexion	17.60 (9.73)	21.08 (6.44)	13.61 (11.74)
Abduction	14.40 (20.54)	22.75 (25.39)	4.86 (5.75)
Adduction	18.65 (13.50)	7.88 (4.88)	30.97 (8.10)
External rotation	5.89 (5.84)	3.17 (2.66)	8.99 (7.08)
Internal rotation	5.27 (4.78)	5.67 (5.49)	4.83 (4.21)
<i>Stair stepping</i>			
Extension	93.21 (34.15)	84.60 (37.69)	101.81 (30.15)
Flexion	22.79 (15.58)	25.20 (21.15)	20.38 (7.72)
Abduction	57.72 (25.47)	57.40 (32.94)	58.05 (17.45)
Adduction	11.44 (8.50)	7.15 (4.93)	15.73 (9.41)
External rotation	3.15 (2.13)	3.78 (2.00)	2.52 (2.20)
Internal rotation	24.42 (11.41)	20.44 (11.79)	28.41 (10.20)

Values are mean (SD).

^aPeak hip joint moments (N m) were calculated by averaging the peak hip moments across the three trials per activity.

Table 4

Pearson's correlation coefficients among participants' characteristics, BMC, BMD, and SHJMs generated during three functional activities^a

	Age	Height	Weight	SHJM		
				Chair	Step	Walk
<i>Male</i>						
Femoral neck BMC	0.05	-0.30	0.22	0.19	-0.17	0.16
Greater trochanter BMC	-0.50	0.71 *	0.66	0.58	0.50	0.44
Proximal femur BMC	-0.05	0.11	0.61	0.44	0.17	0.45
Femoral neck BMD	0.40	-0.57	0.00	-0.09	-0.35	-0.13
Greater trochanter BMD	0.55	-0.33	0.26	0.12	-0.06	-0.02
Proximal femur BMD	0.53	-0.58	0.37	-0.23	-0.27	-0.20
<i>Female</i>						
Femoral neck BMC	-0.20	0.67	0.82 *	0.69	0.84 **	0.78 *
Greater trochanter BMC	-0.06	0.90 **	0.96 ***	0.92 **	0.94 ***	0.91 **
Proximal femur BMC	-0.06	0.80 *	0.94 **	0.93 **	0.97 ***	0.95 ***
Femoral neck BMD	-0.45	0.53	0.75 *	0.66	0.80 *	0.72 *
Greater trochanter BMD	-0.42	0.77 *	0.91 **	0.77 *	0.86 **	0.77 *
Proximal femur BMD	-0.46	0.64	0.84 **	0.76 *	0.85 **	0.75 *

BMC = bone mineral content, and BMD = bone mineral density.

^aSum of the hip joint moments (SHJMs) were calculated as the sum total of the peak hip joint moments across the three rotational planes (i.e., flexion/extension, abduction/adduction, and internal rotation/external rotation) for each activity.

* $p < 0.05$.
 ** $p < 0.01$.
 *** $p < 0.001$.

Table 5Results of BMC and BMD regressed on all significant variables indicated by correlation analysis^a

	Variables in	Standardized beta	Change in R^2	p -Value
<i>BMC</i>				
Femoral neck	SHJM <i>step</i>	0.842	0.709	0.009
Greater trochanter	Weight	0.959	0.920	0.000
Proximal femur	SHJM <i>step</i>	0.966	0.934	0.000
<i>BMD</i>				
Femoral neck	SHJM <i>step</i>	0.798	0.637	0.018
Greater trochanter	Weight	0.909	0.826	0.002
Proximal femur	SHJM <i>step</i>	0.853	0.728	0.007

SHJM = sum of the peak hip joint moments, BMC = bone mineral content, and BMD = bone mineral density.

^aResults are restricted to the women group. Variables entered into the stepwise regression models included body weight, SHJM *walk*, and SHJM *step* ($p_{in} = 0.05$, $p_{out} = 0.1$). These three independent variables were significantly related to BMC and BMD at all hip subregions indicated by correlation analysis.

Table 6

Results of BMC and BMD at femoral neck and proximal femur regressed on plane-specific hip joint moments generated during the stepping activity^a

	Variables in	Standardized beta	Change in R^2	p -Value
Femoral neck BM	Abd	0.751	0.564	0.032
Femoral neck BMD	Abd	0.822	0.676	0.012
Proximal femur BMC	Abd	0.604	0.764	0.014
	Ext	0.469	0.147	0.035
Proximal femur BMD	Abd	0.875	0.766	0.004

BMC = bone mineral content, and BMD = bone mineral density.

^aResults are restricted to the women group. Variables entered into the stepwise regression models were the plane-specific hip joint moments (N m) including flexion (Flex), extension (Ext), abduction (Abd), adduction (Add), internal rotation (IR), and external rotation (ER) moments generated during the stepping activity ($p_{in} = 0.05$, $p_{out} = 0.1$).