

# Relationships between self-reported lifetime physical activity, estimates of current physical fitness, and aBMD in adult premenopausal women

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## Abstract

**Summary** Osteoporosis is common, and physical activity is important in its prevention and treatment. Of the categories of historical physical activity (PA) examined, we found that weight-bearing and very hard physical activity had the strongest relationships with areal bone mineral density (aBMD) throughout growth and into adulthood, while for measures of strength, only grip strength proved to be an independent predictor of aBMD.

**Purpose/introduction** To examine relationships between aBMD (total body, lumbar spine, proximal femur, tibial shaft, distal radius) and estimates of historical PA, current strength, and cardiovascular fitness in adult premenopausal women.

**Methods** One hundred fifty-two adult premenopausal women (40±9.6 years) undertook aBMD (dual-energy X-ray absorptiometry (DXA)) and completed surveys to estimate historical physical activity representative of three decades (Kriska et al. [1]), while subsets underwent functional tests of isokinetic strength (hamstrings and quadriceps), grip strength (hand dynamometer), and maximum oxygen uptake (MaxV<sub>O</sub><sub>2</sub>; cycle ergometer). Historical PA was characterized by demand (metabolic equivalents, PA>3 METS; PA>7 METS) and type (weight-bearing; high impact).

**Results** Significant positive independent predictors varied by decade and site, with weight-bearing exercise and PA>3 METS significant for the tibial shaft (10–19 decade) and only PA>7 METS significant for the final two decades (20–29 and

30–39 years; total body and total hip). A significant negative correlation between high impact activity and tibial shaft aBMD appeared for the final decade. For strength measures, only grip strength was an independent predictor (total body, total hip), while MaxV<sub>O</sub><sub>2</sub> provided a significant independent prediction for the tibial shaft.

**Conclusions** Past PA>7 METS was positively associated with aBMD, and such activity should probably constitute a relatively high proportion of all weekly PA to positively affect aBMD. The findings warrant more detailed investigations in a prospective study, specifically also investigating the potentially negative effects of high impact PA on tibial aBMD.

**Keywords** Osteoporosis · Historical physical activity · Premenopausal women

## Abbreviations

aBMD	Areal bone mineral density
BMC	Bone mineral content
BMI	Body mass index
CFQ	Calcium frequency questionnaire
DXA	Dual-energy X-ray absorptiometry
GRF	Ground reaction forces
HLAQ	Historical Leisure Activity Questionnaire
MaxV <sub>O</sub> <sub>2</sub>	Maximum oxygen uptake
METS	Metabolic equivalents
OI	Osteogenic index

## Introduction

Bone mass is mainly determined by the interplay of genetic factors (range 50–90 %) with the magnitude of the contribution somewhat different for different parts of the skeleton [2].

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Physical activity (PA) and diet appear to be the “major players” among the modifiable lifestyle factors that contribute to the remaining variance. In terms of PA, those forms which feature impact loading and/or strong muscular contractions appear to have the greatest positive influence [3]. An age/exercise interaction has also been adduced with the “growing years” purported to provide the most exercise-amenable skeleton with peak bone mass (PBM) usually attained at or not long after puberty [4, 5] but potentially deferred until early in the third decade [6]. Given the prevalence and morbidity associated with osteoporosis, particularly in postmenopausal women, it is important to determine whether any bone gains made in response to exercise during the years preceding menopause are preserved, providing a reserve against which to draw. Studies of retired athletes support retention [7–9] though not universally [10]. Retrospective studies of the link between life span PA and bone mass have targeted postmenopausal women [11, 12], adult premenopausal women [13–15], and “older” men [11, 15, 16] subdividing the life span in a variety of ways and using different descriptors of the type and demand of PA including “mild to strenuous” [11], weight-bearing [12–14], metabolic equivalents (METs) [17], and strain rate/ground reaction forces (GRFs) [16, 18]. These generally support a retained positive effect of weight-bearing activity, particularly that engendering high GRF, though one study [19] reported that distance walked to and from school (low impact/low metabolic cost) between 9 and 11 years made a significant independent contribution to femoral bone mass in perimenopausal women. Although adolescence is commonly posited as a “window of opportunity” for maximizing the exercise/bone response [20], Daly and Bass [16] found no relationship between adolescent PA (classified by an osteogenic index (OI)) and bone mass in older men. However, they did find significantly higher indices of femoral shaft bone strength when comparing the highest and lowest tertiles for adolescent weight-bearing impact PA. In the current work, relationships between aBMD and historical PA were explored in adult premenopausal women using data from three decades encompassing the “growing” years, young adulthood, and the period immediately following the attainment of PBM. Historical PA was characterized by MET value as “moderate plus” (all PA > 3 METs) and very hard (all PA > 7 METs); “weight-bearing” and “high impact.” Relationships between aBMD and body composition/anthropometric variables were assessed to inform the selection of covariates for regression analyses examining aBMD/activity relationships [21]. To more common assessment sites (total body, lumbar spine, total hip, distal radius), the tibial shaft ( $n=88$ ) was added to explore how this primary cortical weight-bearing site might reflect PA. Finally, subgroups underwent assessments of strength and aerobic capacity to provide data on relationships between “functional” measures and current aBMD. Given the variable results of studies into the influence of lifetime PA on bone mass

in later life, our main aim was similar to previous work in attempting to elucidate what types of PA carried out in the past might have lasting positive effects on the skeleton, thereby informing exercise prescription at different ages.

## Methods

### Participants

Five hundred twenty-one community dwelling women initially responded to advertisements in local newspapers, local community fitness centers, and the Victorian members’ database of Australian Union of Senior Swimmers International (AUSSI). The latter were approached in relation to a study of the influence of swimming on bone mass which indicated no negative effect [22]. Exclusion criteria were menstrual status (fewer than nine normal menses in the previous 12 months), age (<25 years), use of medications known to effect bone mass, and gynaecological/medical conditions (e.g., hysterectomy, ovariectomy, polycystic ovarian disease, thyroid conditions, history of low trauma fracture). After the application of the exclusion criteria, data from 152 participants were included. The reasons for exclusion were failure to complete health and physical activity surveys ( $n=209$ ) and a combination of gynecological abnormalities, postmenopausal status, and/or use of inappropriate medications ( $n=160$ ). Of the 152 eligible participants, subsets participated in tests to examine relationships between current aBMD and muscular strength ( $n=59$ ) and/or maximum oxygen uptake ( $\text{MaxV}\text{O}_2$ ,  $n=66$ ). All procedures were approved by the RMIT University Human Ethics Committee, and written informed consent obtained from all participants in the study.

### Anthropometry and body composition

Height was measured using a calibrated wall-mounted stadiometer (Tanita, Japan) to the nearest 0.1 cm with the subject lightly clad and wearing no shoes. Weight was determined using calibrated electronic digital scales (SECA, Germany) to the nearest 0.1 kg and BMI calculated ( $\text{kg}/\text{m}^2$ ). Total body lean mass (kg) and fat mass (kg) were derived from dual-energy X-ray absorptiometry (DXA) total body scans (Lunar DPX-IQ, GE Medical Systems, Madison, WI).

### Medical history and menstrual status

Medical history was assessed by completion of a questionnaire that solicited information on general health, medication use, specific illnesses (emphasis on gynecological issues), surgical procedures, and previous fractures including any produced by low trauma. A separate section elicited frequency of menses in the preceding 12 months and the occurrence of

changes typical of menopausal onset (e.g., fluid retention, hot flushes, night sweats).

### Calcium intake

Daily calcium intake was approximated retrospectively through completion of a 12-month calcium frequency questionnaire (CFQ [1]) containing 22 food items for which participants were asked to specify the number of serves consumed per day or per week or per month with a standard serving size specified for each item. Information from the CFQ was analyzed using “Foodworks 2005” (Xyris Software, Brisbane, Australia) by a dietician.

### Historical physical activity

To estimate historical PA, the previously validated Historical Leisure Activity Questionnaire (HLAQ) originally designed by Kriska and colleagues [23] was modified and self-administered. Participants were asked to complete a table listing 44 physical activities (including sport, occupational, domestic, and leisure activities). The list of activities was expanded to take into account the Australian context (e.g., squash, netball, hockey). Participants were asked to indicate if they had ever performed a listed activity and if so, for how many years, at what ages, whether they currently performed the activity, and finally, on average, the number of weeks/days and duration (hours) of participation. They were also asked to add activities whenever they considered them appropriate with a particular emphasis on reporting any strength-based activities like weight training. The data were subsequently compiled under the headings stated previously to reflect type and demand with MET values based upon the work of Ainsworth and colleagues [24]:

- Weight-bearing: PA performed upright with body weight supported on the feet, e.g., walking, running, tennis, net ball.
- High impact: PA dominated by jumping and landing with GRFs generally considered >3 BW and rapidly absorbed, e.g., basketball, gymnastics, netball, ballet.
- Moderate plus: PA >3 METS, e.g., brisk walking >6 kph, jogging, leisurely cycling <10 kph.
- Very hard: PA >7 MET, e.g., hill climbing, running  $\geq 10$  kph, circuit training.

Activities reported by participants were matched to those provided by Ainsworth et al. [24] wherever possible and the best match made in other circumstances.

The moderate plus category (all PA >3 METS) was considered a gauge of total PA and used to express the proportions (%) contributed by each of the other PA categories. Similarly, the weight-bearing category was used as a baseline for

estimating the proportion of high impact PA experienced. The data were subsequently assigned to three decades: 10–19 years (rapid bone formation; transition through puberty), 20–29 years (young adulthood including the attainment of PBM), and 30–39 years (normally characterized by maintenance of bone mass).

### DXA measurements

aBMD was measured by DXA (Lunar DPX-IQ, GE Medical systems, Madison, WI) at the total body, total hip, lumbar spine (L2–L4), tibial shaft, and ultradistal radius (left side for all extremities). Short-term operator in vivo precision was assessed by calculating coefficients of variation for duplicate measurements over a 2-week period in 30 adult volunteers (mean age 35 years) in a separate university-approved pilot study (range 1.1–3.5 %). In addition, weight for each participant was compared with the sum of their total bone, lean, and fat masses (mean difference  $-680$  gm,  $r=0.99$ ). The left tibial shaft was examined in 88 participants using the manufacturer’s AP spine software with the subject supine and the leg surrounded by rice bags and scanned from ankle to knee. Edge markers were used to isolate the tibia then the “ruler” facility employed to divide the tibia into proximal, middle, and distal thirds with the middle third used to represent the shaft. Different *ns* for DXA scans appearing in the various tables that follow were the result of the age range of the participants (particularly in the 30–39 decade) and missing scans resulting from scheduling difficulties particularly for tibial scans which required an additional visit to the laboratory.

### Functional measurements

Maximum voluntary concentric and eccentric contractions of the quadriceps and hamstring muscle groups were performed on a calibrated Kin Com isokinetic muscle testing device (Isokinetic International, Chattanooga, USA) at 30° per second. Grip strength was measured in both limbs using a calibrated hand dynamometer (Smedley, Tokyo) performed in a standing position. Cardiovascular fitness was assessed by determining MaxVO<sub>2</sub> (ml/min and ml/kg/min) and peak power output (PPO, watts) using a calibrated electronically braked cycle ergometer (Lode Excalibur Sport, Netherlands) and automated expired gas analysis apparatus (Medgraphics, USA) using a ramp protocol. Briefly, participants pedaled at an initial load equivalent to their body weight (expressed in watts) for 2 min, and the load increased by 25 or 100 W (based upon individual fitness levels) for a further 2 min until unable to continue (cadence 60–80 cpm).

## Statistical analysis

Pearson correlations were calculated to indicate the strength of relationships for aBMD at the various sites while the major analysis involved a series of hierarchical multiple regressions using age, weight, BMI, lean mass, and percent fat mass as covariates (constants) to identify independent predictors of bone mass among the PA variables. The covariates were chosen on the basis of previously published work [25–28] and our own analysis (partial correlations with age as covariate) and were entered as a block in the first step of the regression analysis with one activity variable added at the second step. Separate analyses were applied to historical physical activity, isokinetic strength, grip strength, and aerobic fitness. Alpha was set at  $p < 0.01$  to detect significant correlations in all hierarchical regression analyses of historical physical activity. This alpha level was selected to provide a more stringent criterion in the face of multiple correlation calculations and the concomitant increased likelihood of type 1 errors. For all other analyses,  $p < 0.05$  was accepted for significance. All tests were performed using PASW version 18 for Windows.

## Results

### Participant characteristics

Table 1 summarizes general physical social characteristics, aBMD, and calcium intake for the participants. Calcium intake was low, averaging 66 % of the RDI. Mean *T*- and *Z*-scores were above average for aBMD at all sites with the exception of the distal radius where the averages were negative. All were premenopausal on the basis of nine or more normal menstrual cycles reported in the previous 12 months and the absence of any current menopausal symptoms (data not shown).

### Relationships between different BMD sites

Correlations between the different sites have been summarized briefly here where we report the ranges of *r* for each site, the sites of the weakest and strongest correlations, and *p* values:

- Lumbar spine 0.45–0.79 (tibia weakest, total body strongest, all  $p < 0.01$ ).
- Total hip 0.51–0.81 (tibia weakest, total body strongest, all  $p < 0.01$ ).
- Radius 0.24–0.65 (tibia weakest, total body strongest,  $0.05 > p < 0.01$ ).
- Tibial shaft 0.24–0.59 (radius weakest, total body strongest,  $0.05 > p < 0.01$ ).
- Total body 0.59–0.81 (tibia weakest, total hip strongest, all  $p < 0.01$ ).

**Table 1** Characteristics of participants

Descriptive statistics			
	<i>N</i>	Mean	SD
Age (years)	152	40.0	9.6
Anthropometry			
Height (m)	152	1.648	0.064
Weight (kg)		67.3	12.8
BMI		24.8	4.5
Total body aBMD (g/cm <sup>2</sup> )	152	1.207	0.078
<i>T</i> -score		1.03	0.97
<i>Z</i> -score		1.02	0.99
UD radius aBMD (g/cm <sup>2</sup> )	142	0.350	0.047
<i>T</i> -score		−0.67	1.31
<i>Z</i> -score		−0.67	1.31
AP spine aBMD (g/cm <sup>2</sup> )	148	1.255	0.153
<i>T</i> -score		0.46	1.28
<i>Z</i> -score		0.51	1.29
Total hip aBMD (g/cm <sup>2</sup> )	147	1.033	0.148
<i>T</i> -score		0.29	0.23
<i>Z</i> -score		0.37	1.16
Tibial shaft aBMD (g/cm <sup>2</sup> )	8	1.742	0.20
Body composition			
Lean (kg)	152	41.9	4.9
Fat (kg)		22.1	10.7
Total BMC (g)		2582	335
%Fat		37.1	10
Calcium			
Intake (mg)	146	688.0	439.3
%RDI		66.3	42.9
Obstetrical			
Years of OCP	152	7.0	7.1
Number of pregnancies		1.6	1.6
Ethnicity (%)			
	152		
	Caucasian	93	
	Asian	3.5	
	Other	3.5	
Education			
(highest level attained %)	152		
	≤Primary school	5	
	High school	26	
	Tertiary	69	

*BMI* body mass index, *UD* ultradistal, *RDI* recommended daily intake, *BMC* bone mineral content, *OCP* oral contraceptive pill

### Relationships between measures of body composition/anthropometry and aBMD

Partial correlations (covariate=age) were used to explore relationships between aBMD and height, weight, BMI, total lean mass, total fat mass, and percent fat. For total body aBMD, the strongest significant correlations were provided



by total lean mass ( $r=0.32$ ;  $p<0.001$ ), body weight ( $r=0.25$ ;  $p<0.01$ ), and BMI ( $r=0.20$ ;  $p<0.05$ ). None of the variables correlated significantly with aBMD at the ultradistal radius, and only two were significantly related to lumbar spine aBMD (total lean mass and height,  $r=0.28$  and  $0.16$ ;  $p<0.001$  and  $0.05$ , respectively). Total hip aBMD correlated significantly with each of the independent variables with the exception of height ( $r=0.17$  to  $0.34$ ;  $0.05>p<0.001$ ). Overall, the magnitudes of the significant correlations were comparable for total lean mass, weight, and BMI. The tibial shaft correlated significantly with weight, BMI, and total lean mass but with neither measure of fat or height (range  $r=0.22$  to  $0.32$ ;  $0.05<p<0.01$ ). Total lean mass, BMI, and %Fat were subsequently used as covariates in analyzing the relationships between PA and aBMD.

### Historical physical activity

Tables 2 to 4 present the results of hierarchical multiple regression analyses exploring the relationships between historical PA and the various measures of aBMD. Each decade is represented by one table with dependent variables (aBMD at each site) displayed on the left, categories of lifetime PA and their unadjusted simple correlations with aBMD appear next, followed by the “model summary” which shows the correlation ( $R$ ) and variance explained ( $R^2$ ) by the combination of covariates (age, lean mass, BMI, %Fat) and any significant activity variable. The final columns display the additional variance explained by PA (change  $R^2$ ) and whether the addition is significant ( $p$ ) followed in such cases, by the standardized beta coefficient and 95 % confidence intervals.

#### 10–19 years

For the earliest decade (Table 2), two significant positive correlations were detected, both at the tibial shaft: one with weight-bearing PA and the other with moderate plus PA ( $r=0.27$  and  $0.28$ , respectively; both  $p<0.01$ ). The prediction of aBMD based upon the combination of covariates and PA (model summary) explained between 14.5 and 18.9 % of the variance with weight-bearing and moderate plus PA both adding significant levels of unique predictive variance (4.5 and 4.7 %, respectively, both  $p<0.05$ ;  $\beta$  both 0.22, both  $p<0.05$ ). In summary, mean hours of moderate plus PA were approximately 1 h per week with very hard and high impact PA contributing 27 and ~6 %, respectively, while high impact activity constituted ~3 % of weight-bearing activity.

#### 20–29 years

In this decade (Table 3), there were two significant positive correlations for very hard PA (total body and total hip,  $r=0.29$  and  $0.31$ , respectively; both  $p<0.01$ ), while both weight-

bearing and moderate plus PA (portraying total PA) were related to aBMD at the tibial shaft ( $r=0.29$  and  $0.27$ , respectively; both  $p<0.01$ ). After “adding” PA to the covariates, only very hard PA added significantly to the prediction of aBMD and only for total body and total hip adding 5.0 and 6.0 %, respectively ( $\beta$  0.24 and 0.27, respectively, both  $p<0.01$ ). In terms of total time spent engaged in PA, moderate plus PA had risen to an average of 1.75 h per week with very hard and high impact activities contributing 12.5 and ~6 %, respectively, while the proportion of weight-bearing activity contributed by high impact PA averaged ~3.0 %.

#### 30–39 years

Table 4 reveals that only very hard PA generated significant positive relationships at any site (total body, radius, and total hip  $r=0.25$  to  $0.37$ , all  $p<0.01$ ). There were no relationships between lumbar spine aBMD and any activity variable, but a significant negative correlation between high impact activity and the tibial shaft was detected ( $-0.40$ ;  $p<0.001$ ). Independent contributions to the covariate model were provided by very hard PA for total body and total hip (8.0 and 7.0 % additions,  $p<0.01$ ;  $\beta$  0.30 and 0.28, respectively, both  $p<0.01$ ), while the negative relationship between high impact PA and the tibial shaft added a considerable 28 % to the prediction offered by the covariate model ( $p<0.001$ ;  $\beta$   $-0.55$ ,  $p<0.0001$ ). Mean reported moderate plus PA was very similar to the previous decade (~1.75 h per week) with very hard and high impact activities now contributing 21 and ~3 %, respectively; however, the proportion of weight-bearing PA made up of high impact PA was less than 1.5 %.

### Consistency of reporting

Bivariate correlations calculated for each category of PA for each decade (data not shown) suggested that participants had been consistent in their reporting and appeared to have largely maintained their individual PA patterns. For moderate plus PA,  $r$  ranged between 0.73 and 0.88, for very hard PA 0.65 to 0.87, for high impact 0.28 to 0.62, and for weight-bearing PA 0.72 to 0.85 (all  $p<0.0001$  with the exception of  $r=0.28$ ,  $p=0.006$ ). With one exception, the strength of the relationship was least between the first and last decades while for high impact PA, the weakest correlation was found between the 20–29 and 30–39 decades ( $r=0.28$ ).

### Bone mass and functional measures

#### Strength

Isokinetic strength testing of the quadriceps and hamstring muscle groups revealed the expected greater mean magnitudes for the eccentric form (quadriceps 131 vs. 114; hamstrings 59

**Table 2** Relationships between physical activity and bone mass for the 10–19 decades

Historical activity 10–19																	
Weight-bearing, high impact, moderate+, very hard										Constant: age, lean, BMI, %Fat							
Dependent: BMD (g/cm <sup>2</sup> )					Predictor			Correlation		Model summary				Change			
Bone site	<i>N</i>	Age	Mean	SD	Mean	SD	<i>r</i>	<i>p</i>	<i>R</i>	<i>R</i> <sup>2</sup>	Adj. <i>R</i> <sup>2</sup>	<i>R</i> <sup>2</sup>	<i>F</i>	<i>p</i>	Beta	95 % Confidence	
Total body	148	40	1.207	0.079	Wt B	2.2	2.4	0.03	0.693	0.381	0.145	0.115	0.016	2.73	0.101		
					Hi imp	0.07	0.15	0.17	0.021								
					Mod+	1.1	1.3	0.11	0.149								
					V hard	0.3	0.4	0.08	0.286								
UD radius	138	40	0.350	0.047	Wt B	2.2	2.4	-0.01	0.892								
					Hi imp	0.07	0.42	0.08	0.556								
					Mod+	1.1	1.3	0.11	0.210								
					V hard	0.3	0.4	0.01	0.976								
AP spine	144	40	1.257	0.154	Wt B	2.2	2.5	-0.05	0.278								
					Hi imp	0.07	0.16	0.11	0.096								
					Mod+	1.1	1.3	0.04	0.311								
					V hard	0.3	0.4	0.04	0.320								
Total hip	143	40	1.031	0.148	Wt B	2.3	2.5	0.06	0.230	0.420	0.177	0.147	0.010	1.67	0.198		
					Hi imp	0.07	0.16	0.12	0.074								
					Mod+	1.1	1.3	0.15	0.033								
					V hard	0.3	0.4	0.19	0.012								
Tibial shaft	85	40	1.742	0.200	Wt B	2.3	2.7	<b>0.27</b>	0.006	0.411	0.169	0.116	0.045	4.28	<b>0.042</b>	0.22*	0.001 to 0.031
					Hi imp	0.07	0.15	0.09	0.195								
					Mod+	1.2	1.5	<b>0.28</b>	0.005								
					V hard	0.3	0.5	0.07	0.275								

Significant correlations bold. All activity expressed in hours per week

*Wt B* weight-bearing, *Hi imp* high impact, *Mod+* moderate plus, *V* very, *UD* ultradistal, *AP* anteroposterior, *Change R*<sup>2</sup> additional variance explained by any significant activity variable, *Adj. R*<sup>2</sup> variance explained after adjusting for the number of independent variables, *Constant* covariates, *Beta* standardized coefficient

*p*<0.05

vs. 52 nm, respectively). For the quadriceps, both concentric and eccentric maximum strength correlated significantly with aBMD at the total body, spine, and total hip (range 0.23–0.35; 0.05>*p*<0.001), while the hamstring group produced only two significant positive correlations, both for the concentric mode with total body and total hip (*r*=0.24 and 0.25; *p*<0.05). However, no isokinetic measurement for either muscle group was an independent predictor of aBMD at any site. Grip strength (Table 5) also produced a number of significant simple correlations at various sites but none with the radius or tibial shaft. Significant correlations were lowest at the lumbar spine (*r*=0.28) and highest at the total body (*r*=0.41). In contrast with the lower limb strength measurements, grip strength added significant independent predictions to the covariate model for the total body and total hip adding an average (left and right sides) of 15.1 and 10.7 %, respectively (mean  $\beta$  0.22, 0.36, respectively, both *p*<0.01).

### Cardiovascular fitness

The results for the cardiovascular tests are summarized in Table 6. Before addition to the covariate model, absolute MaxVO<sub>2</sub> (ml/min) provided the strongest and most frequent significant relationships with aBMD, producing positive correlations with all but the distal radius (*r*=0.26 to 0.46). The weakest of these was at the lumbar spine, where it was, however, the only variable to produce a significant correlation (*r*=0.26). Adjusting for body weight (MaxVO<sub>2</sub> ml/kg/min) did not produce stronger correlations than the absolute measure. Indeed, the correlations produced were always weaker than those generated by absolute MaxVO<sub>2</sub> at the same site. PPO correlated significantly only with the tibial shaft (*r*=0.33). Significant independent predictions of aBMD were only detected at the tibial shaft where both absolute and relative MaxVO<sub>2</sub> added 10 and 9 %, respectively, to the covariate model ( $\beta$  0.57, 0.55, respectively, both *p*<0.05).

**Table 3** Relationships between physical activity and bone mass for the 20–29 decade

Historical activity: 20–29 years																
Weight-bearing, high impact, moderate+, very hard							Constant: age, lean, BMI, %Fat									
Dependent: BMD (g/cm <sup>2</sup> )				Predictor			Correlation		Model summary				Change			
Bone site	<i>N</i>	Age	Mean	SD	Mean	SD	<i>r</i>	<i>p</i>	<i>R</i>	<i>R</i> <sup>2</sup>	Adj. <i>R</i> <sup>2</sup>	<i>R</i> <sup>2</sup>	<i>F</i>	<i>p</i>	Beta	95 % Confidence
Total body	126	43	1.208	0.082	Wt B	3.56	3.33	0.04	0.566							
					Hi imp	0.10	0.30	0.01	0.750							
					Mod+	1.76	1.80	0.09	0.238							
					V hard	0.22	0.41	<b>0.29</b>	0.001	0.46	0.21	0.18	0.05	7.47	<b>0.007</b>	0.24**
UD radius	119	43	0.348	0.048	Wt B	3.64	3.37	0.00	0.494							
					Hi imp	0.10	0.31	−0.091	0.282							
					Mod+	1.77	1.84	0.12	0.089							
					V hard	0.22	0.41	0.19	0.022	0.31	0.10	0.06	0.01	1.47	0.229	
AP spine	122	43	1.260	0.159	Wt B	3.60	3.35	−0.04	0.34							
					Hi imp	0.10	0.30	−0.02	0.412							
					Mod+	1.78	1.82	0.01	0.453							
					V hard	0.23	0.41	0.19	0.017	0.35	0.13	0.09	0.02	2.50	0.116	
Total hip	121	43	1.022	0.153	Wt B	3.60	3.34	0.09	0.176							
					Hi imp	0.10	0.30	0.00	0.493							
					Mod+	1.80	1.82	0.16	0.045	0.44	0.19	0.16	0.01	0.71	0.402	
					V hard	0.23	0.42	<b>0.31</b>	0.000	0.50	0.25	0.22	0.06	9.89	<b>0.002</b>	0.27**
Tibial shaft	76	42	1.739	0.206	Wt B	3.76	3.54	<b>0.29</b>	0.005	0.42	0.18	0.12	0.04	3.00	0.088	
					Hi imp	0.07	0.25	0.12	0.155							
					Mod+	1.75	1.90	<b>0.27</b>	0.009	0.41	0.17	0.11	0.03	2.56	0.114	
					V hard	0.23	0.40	0.08	0.258							

Significant correlations bold. All activity expressed in hours per week

*Wt B* weight-bearing, *Hi imp* high impact, *Mod+* moderate plus, *V* very, *UD* ultradistal, *AP* anteroposterior, *Change R*<sup>2</sup> additional variance explained by any significant activity variable, *Adj. R*<sup>2</sup> variance explained after adjusting for the number of independent variables, *Constant* covariates, *Beta* standardized coefficient

\*\**p*<0.01

## Discussion

### Body composition, anthropometry, and aBMD

The results of the current investigation revealed a number of age-adjusted significant positive correlations between measures of body composition, anthropometry, and aBMD at various sites but none for the distal radius in concert with previous work [29, 30]. That height produced only a single small significant correlation (with the spine) agrees with the work of Lu et al. [25] who found no correlations between height and total hip BMD but a significant positive correlation with spine aBMD albeit about double the size of the one found in the present work (*r*=0.31 vs. 0.16). In the current work, the magnitudes of the correlations produced by lean mass, body weight, and BMI were comparable at all sites other than the spine where only lean mass and height produced significant positive correlations. When fat and lean mass were compared,

the latter consistently produced higher correlations, in agreement with previous work supporting a greater influence of lean mass on bone [21, 25, 26] though for total body aBMD, the correlation was only about half the magnitude found previously when total body BMC was used as the dependent variable [21, 27]. In connection with this result, it has been suggested that when bone mass is represented by BMC (a variable uncontrolled for body size), the relationship between bone and lean mass is strongest but diminishes with a concomitant increase in the variance explained by fat mass when body size is accounted for in some way (e.g., using aBMD or volumetric BMD [28]), and this might account for the smaller correlations found compared with previous works [21]. Despite the use of aBMD in the current work, the correlations identified for fat mass were smaller at all sites than those recorded for lean mass, weight, and BMI, a finding in agreement with Wang et al. [26] who reported similar findings and magnitudes for these relationships in a large group of younger

**Table 4** Relationships between physical activity and bone mass for the 30–39 decade

Historical activity: 30–39 years																	
Weight-bearing, high impact, moderate+, very hard										Constant: age, lean, BMI, %Fat							
Dependent: BMD (g/cm <sup>2</sup> )				Predictor		Correlation		Model summary			Change						
Bone site	<i>N</i>	Age	Mean	SD	Mean	SD	<i>r</i>	<i>p</i>	<i>R</i>	<i>R</i> <sup>2</sup>	Adj. <i>R</i> <sup>2</sup>	<i>R</i> <sup>2</sup>	<i>F</i>	<i>p</i>	Beta	95 % Confidence	
Total body	96	46	1.215	0.083	Wt B	3.77	3.68	0.01	0.921								
					Hi imp	0.05	0.18	0.07	0.481								
					Mod+	1.76	1.88	0.14	0.186								
					V hard	0.18	0.36	<b>0.37</b>	0.000	0.47	0.22	0.18	0.08	9.60	<b>0.003</b>	0.30**	0.025 to 0.114
UD radius	93	46	0.349	0.048	Wt B	3.81	3.72	−0.02	0.787								
					Hi imp	0.05	0.19	−0.06	0.641								
					Mod+	1.74	1.89	0.13	0.244								
					V hard	0.17	0.35	<b>0.25</b>	0.007	0.33	0.11	0.05	0.04	3.69	0.058		
AP spine	95	46	1.271	0.164	Wt B	3.80	3.69	−0.06	0.299								
					Hi imp	0.05	0.18	0.03	0.402								
					Mod+	1.77	1.89	0.04	0.356								
					V hard	0.18	0.36	0.17	0.050								
Total hip	93	46	1.035	0.156	Wt B	3.83	3.72	0.06	0.296								
					Hi imp	0.05	0.18										
					Mod+	1.79	1.90	0.15	0.075								
					V hard	0.18	0.36	<b>0.36</b>	0.000	0.52	0.27	0.23	0.07	8.46	<b>0.005</b>	0.28**	0.038 to 0.200
Tibial shaft	57	46	1.731	0.217	Wt B	3.78	3.62	0.18	0.089								
					Hi imp	0.05	0.19	<b>−0.40</b>	0.001	0.62	0.39	0.33	0.28	23.20	<b>0.000</b>	−0.55***	−0.828 to −0.341
					Mod+	1.71	2.01	0.14	0.145								
					V hard	0.15	0.26	0.10	0.238								

Significant correlations bold. All activity expressed in hours per week

*Wt B* weight-bearing, *Hi imp* high impact, *Mod+* moderate plus, *V* very, *UD* ultradistal, *AP* anteroposterior, *Change R*<sup>2</sup> additional variance explained by any significant activity variable, *Adj. R*<sup>2</sup> variance explained after adjusting for the number of independent variables, *Constant* covariates, *Beta* standardized coefficient

\*\**p*<0.01, \*\*\**p*<0.001

women (*N*=921, 20–25 years of age). With regard to aBMD alone, the different sites were moderately to very strongly correlated, with the exception of the relationship between the tibial shaft and the distal radius (*r*=0.24). In fact, in all cases, the weakest relationships were found for the tibial shaft (*r*=0.24 to 0.59), a logical finding given that it was the only cortical site measured.

### Historical physical activity and bone mass

#### 10–19 years

For the first decade surveyed, only weight-bearing and moderate plus PA were independent predictors of aBMD and only for the tibial shaft (~4.5 % addition to the covariate model by each). Others have reported positive independent effects of weight-bearing activity graded by GRF during adolescence on bone mass in later life, though at different sites [16, 17].

In terms of the moderate plus category, Rideout et al. [12] also reported that a measure of total PA during a similar period (12–18 years) was a significant independent predictor of aBMD (total hip) in postmenopausal women. In contrast, Daly and Bass [16] found that an estimate of total PA for the periods 13 to 50+ years (“lifetime”) and 19 to 50 years (“mid-adulthood”) was not related to aBMD at any site. Similarly, Van Langendonck et al. [18] reported that only an “impact score” (based upon estimates of GRFs) achieved during adulthood provided a significant independent predictor of total body and lumbar spine BMD in men after a follow-up of 27 years. Interestingly, very hard PA constituted a reasonably large proportion of moderate plus PA in this decade (27 %) which may account for its positive association with tibial shaft aBMD. There would appear to be few studies where the tibia has been investigated separately, and therefore, few data are available for comparison; however, our results agree to some extent with Sayers et al. [31] who studied the middle tibia by pQCT



**Table 5** Relationships between grip strength and bone mass

Isotonic																		
Left and right grip strength										Constant: age, lean, BMI, %fat								
Dependent: BMD (g/cm <sup>2</sup> )					Predictor				Correlation		Model summary			Change				
Bone site	N	Age	Mean	SD	Grip mean	SD	Mean	SD	r	p	R	R <sup>2</sup>	Adj. R <sup>2</sup>	R <sup>2</sup>	F	p	Beta	95 % Confidence
Total body	59	41	1.204	0.078	Left	27.7	6.9		<b>0.39</b>	0.001	0.496	0.246	0.175	0.136	9.56	<b>0.003</b>	0.40**	0.002 to 0.007
					Right	29.7	6.0		<b>0.41</b>	0.001	0.526	0.276	0.208	0.166	12.15	<b>0.001</b>	0.44**	0.002 to 0.009
UD radius	55	41	0.346	0.040	Left	27.6	7.0		0.21	0.198								
					Right	29.6	6.1		0.21	0.253								
AP spine	57	41	1.253	0.148	Left	27.9	7.0		<b>0.32</b>	0.007	0.431	0.186	0.106	0.055	3.463.46	0.069		
					Right	29.7	6.1		<b>0.28</b>	0.018	0.415	0.172	0.091	0.042	2.58	0.114		
Total hip	57	41	1.013	0.128	Left	27.8	7.0		<b>0.33</b>	0.006	0.501	0.251	0.178	0.104	7.10	<b>0.010</b>	0.35**	0.002 to 0.011
					Right	29.7	6.1		<b>0.33</b>	0.006	0.506	0.256	0.184	0.110	7.52	<b>0.008</b>	0.36**	0.002 to 0.013
Tibial shaft	47	40	1.739	0.197	Left	27.3	6.9		0.15	0.162								
					Right	29.3	6.2		0.12	0.209								

Significant correlations bold; grip strength in kilograms

UD ultradistal, AP anteroposterior, Change R<sup>2</sup> additional variance explained by any significant activity variable, Adj. R<sup>2</sup> variance explained after adjusting for the number of independent variables, Constant covariates, Beta standardized coefficient

\*\* $p < 0.01$

in a large cross-sectional study of bone mass and habitual physical activity in boys and girls (mean age 15.5 years). They found that only vigorous activity (6 METS) was positively related to cortical bone mineral content and geometry. The failure of high impact exercise to leave an “impression” in the current study might simply be due to too little of this form of activity being performed. High impact PA expressed as a percentage of moderate plus and weight-bearing exercise provided figures of 7 and 3 %, respectively, for this decade. Hence, the strain and strain rates evoked by this volume of exercise may have been insufficient to stimulate modeling.

### 20–29 years

Examination of the results from the second decade highlights the potential importance of strenuous physical activity to aBMD with very hard PA as the only independent predictor (total hip; total body). For this period, the proportion of moderate plus activity contributed by very hard activity was ~13 %, about half of its contribution in the 10–19 decade. Hence, though moderate plus activity had increased (from 1.1 to ~1.75 h per week), it appears that only the more demanding components were associated with an osteogenic affect since moderate plus activity by itself produced no significant correlations with aBMD. This time, there were no independent predictors for the tibial shaft, perhaps indicative of a greater responsiveness at this site during the growing years [20]. High impact activities had dropped to around 6 and 3.4 % of moderate plus and weight-bearing PA, respectively,

and were therefore likely too few to produce any detectable relationship with aBMD.

### 30–39 years

Very hard activity continued to dominate in the final decade, continuing to produce highly significant independent contributions at the total hip (7 % addition) and total body (8 % addition), reinforcing the notion that some degree of arduous physical activity is needed to produce and/or maintain a positive adaptation in bone. In this case, that proportion was around 20 % (very hard activity as a proportion of moderate plus PA). The relatively strong negative correlation between high impact PA and tibial shaft aBMD is counterintuitive given that this form of exercise constituted only about 3 % of the weekly hours reported for moderate plus activity and even less of the of weight-bearing activity (1.3 %). Perhaps the tibial shaft is less able to mount a positive response (e.g., increased intracortical resorption coupled with perosteal deposition) when presented with high impact PA on an inconsistent basis after the age of PBM. Lending some support to this notion, Shedd et al. [32] found that a peak strain score (based upon GRFs) calculated for PA over 12 months in postmenopausal women was negatively related to indices of bone strength (polar moment of inertia; strength-strain index) though the measurement site was the distal tibia.

Some degree of consistency in the relationship between historical PA and aBMD was found for both bone site and type of PA with very hard PA adding significant contributions to the prediction of aBMD at both total body and total hip in

each of the final two decades. The tibial shaft featured in both the first and last decades but with different types of PA generating positive independent contributions to the covariate model for weight-bearing and moderate plus PA during the first decade and a large negative contribution in the final decade with high impact PA.

As previously alluded to (Statistical analysis section), calculating a large number of correlations increases the risk of detecting significant correlations that are not “real.” Adjusting the alpha level using the Bonferroni approach would have provided a much more stringent “test,” but we considered the resulting alpha level ( $p < 0.0008$ ) overly conservative.

**Strength and bone mass**

*Isokinetic*

In the current work, concentric quadriceps torque failed to provide any independent predictions of aBMD at any site, findings congruent with some previous work using both younger and older participants [30, 33] and divergent with others [34]. In one study employing isometric dynamometry in older men and women [35], initial significant unadjusted correlations of 0.395 and 0.353 for knee extension and flexion,

respectively, “disappeared” after normalization for height and weight, prompting the suggestion that in older adults, body size is responsible for the relationship between aBMD of the proximal femur and maximum isometric strength. Interestingly, the tibia has been the target of a number of studies into bone mass/strength relationships. In early work, Madsen et al. [36] found strong positive correlations between quadricep isokinetic strength and proximal tibial bone mass in a group of 66 women (21–78 years of age) and concluded that quadricep strength was a better predictor of tibial BMD than age, height, or weight. Similarly, Vico et al. [37] found that isokinetic thigh muscle torques (flexion and extension) were the best predictors of tibial cortical bone (QCT) in 55 postmenopausal women. In contrast, Sööt et al. [38], employing both isokinetic and isometric measures of quadricep strength in 129 women (17–40 years), found that BMI and lean body mass were the strongest predictors of “leg” bone mass with strength the best predictor only for those classed as overweight. It is difficult to draw conclusions from the foregoing discussion given the varying populations and measurement sites; however, on the basis of the current and previous research, it is reasonable to suggest that there is no advantage provided by testing both maximum eccentric and concentric quadricep isokinetic strength to predict proximal

**Table 6** Relationships between bone mass and measures of cardiovascular fitness

Cardiovascular fitness										Constant: age, lean, BMI, %Fat									
Maximal oxygen uptake, peak power output										Model summary									
Dependent: BMD (g/cm <sup>2</sup> )					Predictor					Correlation		Change				95 % Confidence			
Bone site	N	Age	Mean	SD		Mean	SD	r	p	R	R <sup>2</sup>	Adj. R <sup>2</sup>	R <sup>2</sup>	F	p	Beta	95 % Confidence		
Total body	66	41	1.207	0.076	MaxVO <sub>2</sub>	2032	568	<b>0.34</b>	0.003	0.37	0.14	0.07	0.04	2.83	0.097				
					MaxVO <sub>2</sub> /kg	32	10	<b>0.23</b>	0.033	0.36	0.13	0.06	0.04	2.46	0.122				
					PPO (watts)	167	50	0.17	0.085										
UD radius	61	41	0.353	0.045	MaxVO <sub>2</sub>	2036	584	0.25	0.205										
					MaxVO <sub>2</sub> /kg	32	10	0.24	0.305										
					PPO (watts)	168	52	0.14	0.768										
AP spine	62	41	1.262	0.144	MaxVO <sub>2</sub>	2036	584	<b>0.26</b>	0.022	0.32	0.11	0.03	0.00	0.19	0.668				
					MaxVO <sub>2</sub> /kg	32	10	0.19	0.073										
					PPO (watts)	167	52	0.13	0.159										
Total hip	62	41	1.017	0.133	MaxVO <sub>2</sub>	2046	582	<b>0.30</b>	0.010	0.33	0.11	0.33	0.11	0.03	0.02	1.51			
					MaxVO <sub>2</sub> /kg	32	10	0.20	0.060										
					PPO (watts)	168	52	0.16	0.110										
Tibial shaft	55	40	1.752	0.173	MaxVO <sub>2</sub>	2044	599	<b>0.46</b>	0.000	0.53	0.28	0.20	0.10	7.08	0.011	0.57*	0.000 to 0.000		
					MaxVO <sub>2</sub> /kg	32	10	<b>0.29</b>	0.017	0.51	0.27	0.19	0.09	6.10	0.017	0.55*	0.002 to 0.017		
					PPO (watts)	169	53	<b>0.33</b>	0.007	0.45	0.20	0.12	0.03	1.89	0.176				

Significant correlations bold

MaxVO<sub>2</sub> maximum oxygen uptake (ml/min), PPO peak power output, MaxVO<sub>2</sub>/kg maximum oxygen uptake (ml/kg/min), UD ultradistal, AP anteroposterior, Change R<sup>2</sup> additional variance explained by any significant activity variable, Constant covariates, Beta standardized coefficient

\* $p < 0.05$

femoral bone mass despite the fact that maximum eccentric strength exceeds maximum concentric strength. Maximum isokinetic strength of the hamstring muscle group did not appear to provide a useful indicator of femoral or tibial bone mass. It should be said that none of the correlations detected in the current work were more than moderate at best and even the covariate model explained a maximum of 22.8 % of the variance for the total hip. However, in the current work, concentric isokinetic quadriceps strength provided correlations that were at least as strong at the total hip as those provided by each of the individual covariates and being a functional measurement, provides information pertinent to fall prevention in addition to any relationships with bone mass.

### *Grip strength*

In the current work, grip strength was an independent predictor of aBMD at both total body and total hip adding about 15 and 11 %, respectively, to the variance explained by the covariates. Moderate significant positive correlations between grip strength and both mid-radial and lumbar spine aBMD have been reported in older subjects (age range 61–84 years) in early work [39] with the magnitude of the correlation at the spine comparable to that found in the current study ( $r=0.37$  vs. 0.32 current). Discordant findings for the forearm itself are logically explained by the use of different measurement sites (mid-radius [39], ultradistal radius current). Kritiz-Silverstein and Barrett-Connor [40] concluded that grip strength was a marker of “overall” bone fragility in a large group of postmenopausal women ( $n=649$ ), a proposition extended to children by Chan et al. [41] who studied over 300, 11–12-year-old boys and girls finding grip strength to be an independent predictor for spine and total body bone mass in boys and for spine and hip in girls after controlling for weight, height, pubertal development, weight-bearing activity, and calcium intake. Hence, there is support for grip strength as a general indicator of bone “strength” with the present work indicating that grip strength in combination with age, BMI, lean mass, and %Fat explained ~25 % of the variance in aBMD at the total hip and the total body. The fact that each of the body composition variables produced correlations of similar magnitude suggests that using a simple measure like BMI in combination with grip strength would be useful in screening for low bone mass at these two sites. Somewhat paradoxically, grip strength did not reflect aBMD in the distal radius itself, possibly due to the small number and size of muscles directly inserting here (two) and a general lack of impact loading. In contrast, Di Monaco et al. [42] found grip strength to be the strongest independent predictor of distal radial BMD in a group of postmenopausal women after controlling for a large number of covariates (age, weight, height, BMI, calcium intake, years since menopause) a finding at odds with the present results and that of several others [14, 33, 43] with none finding a significant relationship

between grip strength and aBMD or “bone strength” at this site whether measured isometrically or isokinetically.

### **Cardiovascular**

Early work suggested a link between aerobic capacity and aBMD in both premenopausal and postmenopausal women with significant independent relationships found between aBMD of subregions of the proximal femur and both predicted (submaximal effort) MaxVO<sub>2</sub> [44] and MaxVO<sub>2</sub> (ml/min) based upon maximal effort [37]. Indeed, absolute MaxVO<sub>2</sub> (ml/min) was the best predictor of aBMD in postmenopausal women explaining between 10.8 and 18.3 % of the variance at proximal femoral sites [37], while for lumbar spine, both positive [44] and negative [39] findings have been reported in this population. In the current work, both measures of MaxVO<sub>2</sub> were significantly positively correlated with aBMD at the total body and tibial shaft, while the absolute measure also correlated significantly with aBMD at the lumbar spine and total hip. However, they were independent predictors only for the tibial shaft, each adding about 10 % to the covariate model. The tibial shaft was also the only site where PPO produced a significant correlation though it made no independent contribution. These results should focus interest on the tibial shaft as a site for further investigation considering that it appeared to “reflect” some aspects of both historical PA and current aerobic status. The fact that unadjusted MaxVO<sub>2</sub> was a better predictor than the weight-adjusted value probably reflects the positive relationship between body weight and bone mass in general. Improving aerobic capacity may not necessarily lead to improvement in lower extremity bone mass even when combined with strength training in older adults [45] which suggests a need to use higher impact style exercises when seeking to improve aerobic capacity and bone mass simultaneously (using weighted vests during walking/running) particularly in light of work finding that endurance running may be associated with low bone mass despite the associated multiple moderate impacts [46].

### **Summary**

Before summarizing the findings, two important limitations are acknowledged: First the ability to accurately recall physical activity patterns over many years is an obvious limitation; however, the tool applied in the current work was based upon the HLAQ designed by Kriska et al. [1] which has proven reliability; second, aBMD as measured in the current work, does not “capture” the geometric features of bone that contribute to bone strength so that aBMD is an incomplete surrogate for the latter [e.g., [47]]. With these factors in mind, we found that the relationship between historical PA and aBMD varied by type and site across three decades with only the tibial shaft

“reflecting” positive effects of weight-bearing PA and PA > 3 METS (moderate plus) during adolescence (10–19 years) then “switching” to very hard PA at the total hip and total body over the last two decades (20–29 and 30–39 years). In general, PA > 7 METS was positively associated with aBMD, and therefore, we speculate that total PA should have a relatively high contribution from strenuous PA (e.g., netball, squash, running ~10 km/h, hiking with a pack). Similarly, it would appear that weight-bearing PA requires a relatively higher contribution from high impact PA ( $\geq 4BW$ ) than found in the current work though it might have a negative effect on the tibia after the attainment of PBM perhaps due to a reduced ability to adapt to this form of loading. The fact that tibial shaft aBMD was related to aspects of both historical PA and current aerobic status (MaxVO<sub>2</sub>) suggests a need for further investigation into the tibia as a potential “barometer” of the bone/PA relationship. Clearly, all of these suggestions should be tested in prospective studies.

With regard to relationships between functional measures and current aBMD, we found no value accrued to the prediction of bone mass by measuring maximum isokinetic strength in the quadriceps and hamstrings; hence, the utility of making such measures is related more to their association with both fall prevention and femoral bone mass combined. In contrast, we found that grip strength provided significant independent additions to the predictions of aBMD at the total body and total hip thereby supporting the notion that this simple measure is a useful indicator of aBMD/bone strength particularly when combined with a body composition indicator such as BMI.

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#### Compliance with ethical standards

**Conflict of interest** Kathleen Greenway, Jeff Walkley, and Peter Rich declare that they have no conflict of interest.

**Ethical approval** All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

All procedures were approved by the RMIT University Human Ethics Committee, and written informed consent obtained from all participants in the study.

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