Osteoporos Int (2008) 19:1485–1495
DOI 10.1007/s00198-008-0595-1

ORIGINAL ARTICLE

Relationship between grip strength and bone mineral density in healthy Hong Kong adolescents

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Received: 3 July 2007 / Accepted: 8 January 2008 / Published online: 29 March 2008

Abstract
Summary This study evaluated the magnitude of the correlations among grip strength, bone mineral density (BMD) and bone mineral content (BMC), after controlling for weight, height, pubertal development, weight-bearing activities and calcium intake. The results lead to the conclusion that grip strength is an independent predictor of bone mass in both sexes. The relationship between muscle strength and bone mass is systemic.
Introduction Previous studies had shown a site-specific relationship between muscle strength and bone in pubertal children. This study evaluated the magnitude of the correlations among grip strength, bone mineral density (BMD) and bone mineral content (BMC) at distant bone.
Methods Cross-sectional data of 169 11- to 12-year-old boys and 173 10- to 11-year-old girls came from the baseline result of a cohort study. Grip strength, BMD, BMC, weight, height, pubertal development, weight-bearing activities and calcium intake were measured. Pearson correlations and multiple regressions were used to calculate univariate and adjusted associations among grip strength and bone mass at distant bone.
Results Significant correlations were shown between grip strength and bone mass at hip, spine and whole body (boys: BMC:0.72–0.74, BMD:0.38–0.60; girls: BMC:0.71–0.72, BMD:0.44–0.63; $p < 0.0001$). Multiple regressions with all covariates showed that about 70% and 50%, respectively, of the variations in BMC and BMD could be explained but not for whole body BMD. Grip strength was an independent predictor of bone mass, except hip BMD in boys and whole body BMD in girls. Stepwise regression showed that grip strength was a robust predictor in both sexes. Prediction models by grip strength and weight explained about 60% and 40% of the variations in BMC of different sites and in BMD of hip and spine, respectively.
Conclusions We found that grip strength is an independent predictor of bone mass in both sexes. The relationship between muscle strength and bone mass is systemic.

Keywords Adolescents · Bone mineral density · Grip strength · Hong Kong

Introduction

Osteoporosis is widely recognized as a major health problem in aging men and women. In Hong Kong, the prevalence of osteoporosis among Chinese women and men aged 50 years old or above were 37% and 7% at the spine and 16% and 6% at total hip, respectively [1]. The risk of osteoporosis is determined by two main factors: the peak bone mass in adulthood and the rate of bone loss with aging. Much research has been conducted on bone loss in the elderly; however, little is known about bone accretion in adolescents.

During childhood and adolescence, bone mineral density (BMD) increases until peak bone mass is reached. Those

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who achieve a higher peak bone mass are less at risk of having an osteoporotic fracture later in life [2]. To prevent future osteoporosis, intervention carried out in the adolescent years is the most effective approach as individuals gain much of their peak bone mass by the end of adolescence [3].

The site-specific relationship between muscle strength and bone mass previously has been demonstrated in grip strength and forearm bone density in adults and elderly [4, 5]. Moreover, some studies concluded that the relationship between grip strength and bone mass is not only site specific but also systemic [6–9]. There is a relationship between low grip strength and reduced BMD on both spine and femoral neck, as well as an increased risk of incident vertebral fracture in women [9]. Axial bone loss associates robustly with the improved age-grouped grip strength quartile among postmenopausal women [10].

Positive results for grip strength and site specific bone mass are found in adolescents [11–14]. The systemic relationships between grip strength and other muscle strength such as leg power, and distant bone are also demonstrated in adolescents [15–17].

However, only a few studies have been conducted on the evaluation of the possible role of confounding variables, which may be substantially related to both BMD and muscle strength. Physical activities, calcium intake, anthropometric parameters and pubertal stages have long been recognized as main determinants of bone accretion in adolescents [18–22]. Confounding variables such as anthropometric variables may contribute to the disputing results concerning the relationship between grip strength and BMD [23]. The problem of confounding factors is more serious in adolescents because of the large variability in body size due to varying degrees of pubertal development.

Moreover, a majority of the studies were conducted in white adolescents to establish the association between muscle strength and bone mass. There is uncertainty when extrapolating from these studies to Asian adolescents because of substantial differences in peak bone mass and body size in Caucasians when compared with their Asian peers [24].

Therefore, the focus of this study was to evaluate the magnitude of the correlation between grip strength and bone mass at distant bone in Hong Kong adolescents. Potential confounders such as weight, height, pubertal development, weight-bearing activities and calcium intake were controlled in the statistical analysis.

Subjects

This cross-sectional study was part of a longitudinal study (The Hong Kong Adolescent Bone Health Cohort Study) conducted by Jockey Club Centre for Osteoporosis Care and Control, the Chinese University of Hong Kong. Baseline measurements taken from November 2003 to October 2004 were reported in this study. Hong Kong Chinese adolescents, 11- to 12-year-old boys and 10- to 11-year-old girls were included. The choice of age group was planned to capture early puberty adolescent. A total of 169 boys and 173 girls were recruited from nine primary schools geographically spread throughout Hong Kong. All subjects were normally growing adolescents who were free from chronic disease and had received no prior therapy with a known effect on bone metabolism. The study was approved by the Ethics Committee of the Chinese University of Hong Kong, with informed parental consent and subject assent of all participants.

Methods

Anthropometric and bone mass measurement

Weight (kg) and height (cm) were measured before bone mass measurement. Using the Physician Balance Beam Scale (Healthometer, Illinois, USA), we measured body weight to the nearest 0.1 kg, with subjects wearing a light gown. Height was measured to the nearest 0.1 cm with subjects barefoot by Holtain Harpenden stadiometer (Holtain Ltd, Crosswell, UK). Weight and height were used instead of body mass index (BMI) as they have stronger effect in the calculations.

Bone mineral density (BMD, g/cm^2) and bone mineral content (BMC, g) at the total hip of left side (femoral neck, intertrochanteric area and Ward's triangle), spine (L1–L4) and whole body were measured by dual X-ray densitometry (DEXA) (QDR Model 4500W, Hologic Inc, Waltham, MA). Phantom calibration was done everyday. Using the low density mode, we had considerable experience with the assessment of BMD in adolescents [25]. In our laboratory, the CV for BMD measurements were within 1.5% at all sites with subject repositioning.

Bone mineral content and bone mineral density are areal measurements, which are highly influenced by somatic growth and bone size of the scanned sites. Longitudinal studies for growing adolescents use BMC as outcome measures because subjects' body size changes during the rapid growth period [26, 27]. For cross-sectional studies, BMD can be used since it is not required to consider the individual change in body size. However, short adolescents with or without normal bones will have a lower BMC than other healthy age-matched peers. It is also difficult to interpret areal BMD for adolescents with short stature as the similar situation of BMC. Areal BMD calculated as BMC/(bone area) is measured with anterior-posterior osteodensitometry represents a mixture of areal density and skeletal size. Because BMD does not correct for the thickness of bone, there may be an underestimation of areal bone mineral in smaller individuals and an overestimation in larger subjects [28]. So the problem of size effect in bone densitometry on adolescents should be considered. An appropriate way to correct results for body size is to use multiple regression analysis simultaneously to adjust BMC for weight, height, and other relevant factors such as age, pubertal status, and calcium intake [29]. By including body parameters, for examples, weight and height in the prediction equations, the prediction of BMC and BMD can be significantly improved [30]. As a result, our study design can reduce the effect of bone size on bone measurement.

Handgrip strength measurement

Handgrip strength was measured by Jamar Hard dynameter (Sammons Preston, Canada), and the results were expressed in kilograms. The measurements were made with the subjects sitting and their arms placed straight by their side. Subjects should grip dynamometer as hard as possible for 3 seconds. At the same time, they should not press the instrument against their bodies or bend at the elbow [31]. The subjects were given verbal support to generate maximal effort. The peak force recorded by the dynamometer was used to represent each subject's maximum handgrip strength. Both hands were tested three times and the highest value was used. In order to identify the dominant hand of the subjects, they were asked to indicate which hand they use for writing.

Assessment of pubertal status

The Tanner grading system was used to assess sexual development by the researcher of the same sex [32]. For accurate Tanner ratings, it is suggested that they are carried out by health professionals [33]. With the application of the method of Tanner, pubertal development was evaluated by researchers' assessment of breast and pubic hair stage in girls and genitalia and pubic hair stage in boys. Researchers were given pictures and written descriptions best reflecting the subjects' appearance. When there were discrepancies among criteria, greater emphasis would be placed on the degree of breast development in girls and, testicular and penile size in boys in determining the Tanner stage.

Calcium intake assessment

Each subject was interviewed separately by an experienced dietitian. Some of their parents assisted in answering since subject's meals were prepared by them. A food frequency method was used for dietary assessment of average daily calcium intake in a year. The validity of the method was examined [34]. We had extensive experience with the application of this method in Chinese adolescents [35]. The food processor nutrition analysis and fitness software V8.0 (Esna Research, Salem, USA) was used to analyze the data. We adapted this to local use by adding the composition of

Table 1 Mean, standard deviation and range of all studied variables in boys and girls

	Boy (*n*=169)			Girl (*n*=173)		
	mean	sd	range	mean	sd	range
Age (yr)	11.65	0.37	11.00–12.76	10.68	0.37	10.02–11.96
Grip strength (kg)- dominant hand	18.80	4.80	10–38	15.46	4.32	8–28
Grip strength (kg) - non-dominant hand	17.29	4.80	8–34	14.44	4.24	6–26
Hip BMC (g)	19.49	4.34	10.96–33.53	17.08	4.07	8.67–29.93
Spine BMC (g)	27.60	6.05	16.63–54.13	27.54	7.30	13.06–53.13
Whole body BMC (g)	1161.43	215.28	733.13–1892.70	1065.69	222.66	562.76–1726.17
Hip BMD (g/cm^2)	0.7131	0.0783	0.5495–0.8947	0.6728	0.0899	0.4827–0.9990
Spine BMD (g/cm^2)	0.5779	0.0709	0.4192–0.8382	0.6031	0.0879	0.4337–0.9004
Whole body BMD (g/cm^2)	0.8413	0.0549	0.7102–1.0027	0.8286	0.0544	0.6818–1.0101
Weight (kg)	41.17	9.21	24.1–66.5	36.27	8.27	21.2–61.9
Height (cm)	148.13	7.95	132.5–169.4	143.60	7.90	123.9–161.5
MECHPA	1.30	1.68	0–9	1.02	1.88	0–11
Calcium (mg)	619.51	242.78	167.52–1384.46	569.07	274.16	188.19–2906.54
Pubertal stage	Frequency		%	Frequency		%
1	43		25.44	95		55.23
2	101		59.76	57		33.14
3	25		14.79	18		10.47
4	0		0	2		1.16

local food to the list, using the relevant food composition tables [36].

Weight-bearing exercise assessment

Participants were required to make a list of different organized sport teams which they had joined within past year. All sport teams were classified to the four categories: (1) the physical activities with GRF greater than four times body weight (score 3); (2) those with GRF values between 2 and 4 (score 2); (3) those with GRF values between 1 and 2 (score 1); and (4) those with GRF values of 1 (score 0); which were based on ground reaction forces (GRF) to determine the mechanical component of sport team [37]. Those subjects who reported no participation on any sport teams were assigned a zero. Mechanical components of physical activities (MECHPA) were then obtained by putting all scores altogether. It was unrelated to the duration, frequency and metabolic intensity as supported by Van Langendonck [38]. Van Langendonck suggested that the type of sport participation is more important than the duration of the participation of sports. Calculation of weight-bearing activities by MECHPA was validated, showing an association between self-reported weight-bearing physical activities and lumbar BMD in adolescents [39].

Statistical methods

Statistical analyses were performed separately for the two sexes to allow for sex differences and different measures of the pubertal stages. Pearson correlation coefficients were used to evaluate univariate relationships between bone mass parameters at different sites and other continuous variables. Spearman correlation coefficients were calculated for pubertal stages. To investigate the independent predictors of bone mass, BMC and BMD of each site were used as a dependent variable among the explanatory variables using multiple regression models. Ordinal variables were used for pubertal stage, each measuring the change from one pubertal stage to the next. Only one ordinal variable was used as linear trend of pubertal stages against bone mass was found. The predictors of BMC and BMD were quantified by linear stepwise regression analysis. Two-tailed p-values at level of 0.05 or less were considered to be of statistical significance. The SAS 9.1 was used.

Results

Table 1 describes the main features of the considered variables in boys and girls. For each variable, the mean, standard deviation and range are presented. All continuous variables of boys were significantly greater than those of girls, at the same time, more boys had advance pubertal stages ($p<0.05$).

The positive correlations between BMC of different sites and grip strength are shown in Fig. 1. The correlations of BMC and BMD at hip, spine and whole body with various measures in boys and girls are shown in Table 2. The results were similar for both sexes and the correlation coefficients for BMD were less than BMC at all sites. There were significant correlations between grip strength and bone mass at different sites (boys: BMC: hip=0.74, spine=0.72 and whole body=0.73; BMD: hip=0.48 and spine=0.60; girls: BMC: hip=0.72, spine=0.71 and whole body=0.72; BMD: hip=0.61 and spine=0.63; $p<0.0001$). However, grip strength was less correlated to the BMD of whole body (boys : 0.38; girls: 0.44; $p<0.0001$). The coefficients between grip strength and BMC were

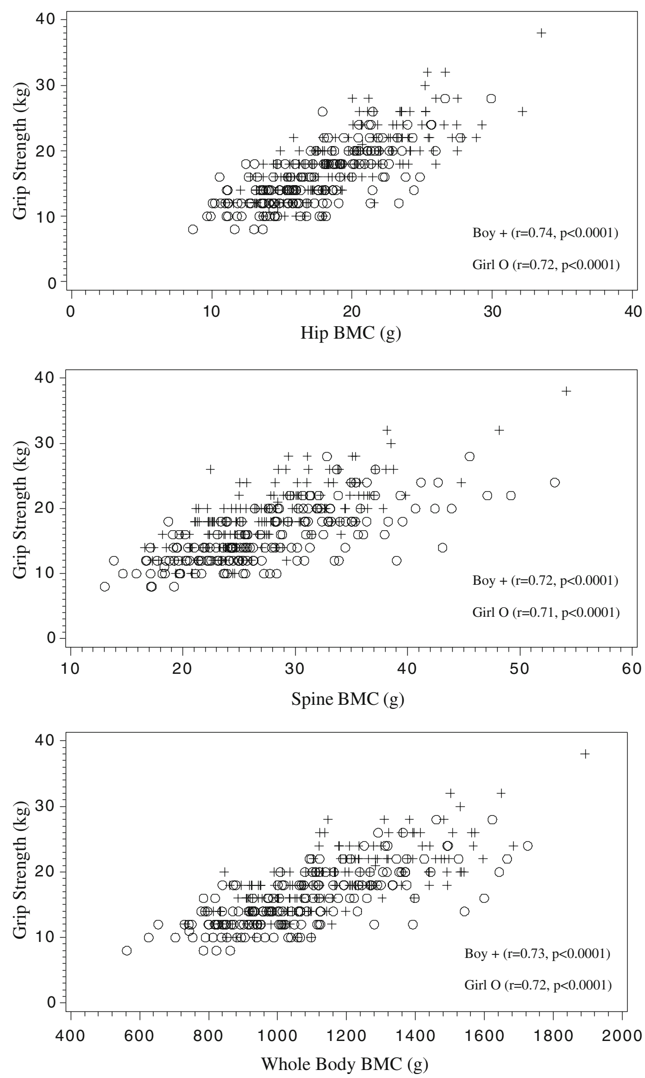

Fig. 1 Relationship between grip strength and BMC results in different sites. Plus indicate results for boys, circles are results for girls

Table 2 Pearson's correlation coefficients of BMC and BMD at hip, spine and whole body with various measures

Boys	Hip BMC		Spine BMC		Whole body BMC		Hip BMD		Spine BMD		Whole body BMD	
	r	*p*-value	*r*	*p*-value	*r*	*p*-value	*r*	*p*-value	*r*	*p*-value	*r*	*p*-value
Grip strength (kg) - dominant hand	0.74	<0.0001	0.72	<0.0001	0.73	<0.0001	0.48	<0.0001	0.60	<0.0001	0.38	<0.0001
Grip strength (kg) - non-dominant hand	0.73	<0.0001	0.72	<0.0001	0.72	<0.0001	0.50	<0.0001	0.61	<0.0001	0.37	<0.0001
Weight (kg)	0.72	<0.0001	0.66	<0.0001	0.80	<0.0001	0.59	<0.0001	0.57	<0.0001	0.31	<0.0001
Height (cm)	0.75	<0.0001	0.73	<0.0001	0.74	<0.0001	0.39	<0.0001	0.50	<0.0001	0.29	0.0001
MECHPA	0.35	<0.0001	0.33	<0.0001	0.27	0.0004	0.31	<0.0001	0.32	<0.0001	0.23	0.0026
Calcium (mg)	0.19	0.0153	0.14	0.0642	0.07	0.3781	0.17	0.0271	0.10	0.1849	0.08	0.3058
Pubertal stage[1]	0.45	<0.0001	0.49	<0.0001	0.45	<0.0001	0.27	0.0004	0.43	<0.0001	0.21	0.0051
Girls												
Grip strength (kg) - dominant hand	0.72	<0.0001	0.71	<0.0001	0.72	<0.0001	0.61	<0.0001	0.63	<0.0001	0.44	<0.0001
Grip strength (kg) - non-dominant hand	0.67	<0.0001	0.65	<0.0001	0.65	<0.0001	0.54	<0.0001	0.59	<0.0001	0.40	<0.0001
Weight (kg)	0.75	<0.0001	0.71	<0.0001	0.82	<0.0001	0.65	<0.0001	0.67	<0.0001	0.46	<0.0001
Height (cm)	0.75	<0.0001	0.74	<0.0001	0.76	<0.0001	0.54	<0.0001	0.61	<0.0001	0.40	<0.0001
MECHPA	0.22	0.0044	0.25	0.0011	0.18	0.0193	0.18	0.0211	0.25	0.0008	0.08	0.3213
Calcium (mg)	0.15	0.0473	0.15	0.0562	0.15	0.0495	0.11	0.1677	0.13	0.0901	0.13	0.0911
Pubertal stage[1]	0.60	<0.0001	0.67	<0.0001	0.62	<0.0001	0.50	<0.0001	0.56	<0.0001	0.39	<0.0001

[1] Spearman correlation coefficient

markedly higher than those of BMD. The results of weight and height were similar to that of grip strength in both sexes. Pubertal stages were significantly related to bone mass but there were small correlation with hip and whole body BMD in boys (boys : BMC=0.45–0.49; p<0.0001; BMD at hip, spine and whole body=0.27, 0.43 and 0.21; p<0.01; girls: BMC=0.60–0.67, BMD=0.39–0.56; p<0.0001). Weight-bearing activities of boys correlated significantly in moderate magnitude, the results were consistent with BMC and BMD (r=0.27–0.35; p=0.0001–

Table 3 Multivariate analysis of dominant handgrip strength with the determinants of BMC and BMD at hip, spine and whole body in boys

	Hip BMC		Spine BMC		Whole body BMC	
	β	*p*-value	β	*p*-value	β	*p*-value
Grip strength (kg) - dominant hand	0.24	<0.0001*	0.35	<0.0001*	11.31	<0.0001*
Weight (kg)	0.16	<0.0001*	0.16	0.0002*	11.23	<0.0001*
Height (cm)	0.15	<0.0001*	0.23	<0.0001*	5.74	0.0002*
MECHPA	0.41	0.0001*	0.47	0.0053*	10.81	0.0324*
Calcium (mg)	0.002	0.0153*	0.001	0.3939	−0.006	0.8517
Pubertal stage	0.45	0.1574	1.26	0.0137*	23.32	0.1232
Constant	−16.83		−22.56		−417.93	
Adjusted R^2	0.7469		0.6756		0.7713	
	Hip BMD		Spine BMD		Whole body BMD	
	β	*p*-value	β	*p*-value	β	*p*-value
Grip strength (kg) - dominant hand	0.002	0.1920	0.004	0.0020*	0.003	0.0240*
Weight (kg)	0.005	<0.0001*	0.003	<0.0001*	0.0008	0.1743
Height (cm)	−0.002	0.0738	−0.0003	0.7085	0.00009	0.9073
MECHPA	0.01	0.0005*	0.007	0.0040*	0.004	0.0828
Calcium (mg)	0.00005	0.0119*	0.000008	0.6515	0.000007	0.6627
Pubertal stage	0.007	0.4204	0.02	0.0117*	0.0004	0.9590
Constant	0.65		0.38		0.73	
Adjusted R^2	0.4263		0.4652		0.1421	

* *p*-value<0.05

Table 4 Multivariate analysis of dominant handgrip strength with the determinants of BMC and BMD at hip, spine and whole body in girls

	Hip BMC		Spine BMC		Whole body BMC	
	β	*p*-value	β	*p*-value	β	*p*-value
Grip strength (kg) - dominant hand	0.21	0.0010*	0.31	0.0072*	8.57	0.0046*
Weight (kg)	0.16	<0.0001*	0.20	0.0008*	13.10	<0.0001*
Height (cm)	0.16	<0.0001*	0.28	<0.0001*	6.41	0.0003*
MECHPA	0.13	0.1849	0.37	0.0311*	2.86	0.5306
Calcium (mg)	0.0006	0.3349	0.0007	0.5248	0.04	0.2070
Pubertal stage	0.49	0.1317	2.26	0.0001*	31.67	0.0424
Constant	−16.10		−29.52		−535.50	
Adjusted R^2	0.6959		0.6893		0.7637	
	Hip BMD		Spine BMD		Whole body BMD	
	β	*p*-value	β	*p*-value	β	*p*-value
Grip strength (kg) - dominant hand	0.005	0.0040*	0.004	0.0319*	0.002	0.1204
Weight (kg)	0.005	<0.0001*	0.004	<0.0001*	0.002	0.0166*
Height (cm)	−0.0005	0.6453	0.001	0.2213	0.0002	0.7861
MECHPA	0.002	0.3782	0.006	0.0212*	−0.0006	0.7678
Calcium (mg)	0.00001	0.6010	0.00001	0.5053	0.00001	0.2934
Pubertal stage	0.02	0.0696	0.02	0.0123*	0.01	0.1706
Constant	0.46		0.19		0.68	
Adjusted R^2	0.4752		0.5422		0.2318	

* *p*-value<0.05

0.0026). For girls, there were lower correlations and an insignificant association with whole body BMD (r=0.18–0.25; p=0.0008–0.0211; whole body=0.08; p=0.3213). The correlations between weight bearing activities and grip strength for boys and girls were 0.3205 and 0.2476, respectively (p<0.01). Small correlations for calcium intake with bone mass at all sites were found in both sexes (r=0.07–0.19; p=0.0271–0.3781).

BMC and BMD of each site were used as dependent variables with grip strength among the predictors to figure out the independent predictors of bone mass. The estimations were along with weight, height, weight-bearing activities, calcium intake and pubertal stages via the approach of a multiple regression model. The results of multiple regression analysis are shown in Tables 3 and 4. Six factors explained about 70% and 50% of the variations in BMC and BMD at all sites, respectively, except for whole body BMD. Grip strength was an independent predictor of bone mass except hip BMD in boys and whole body BMD in girls. For boys, weight and weight-bearing activities were independent predictors of bone mass except whole body BMD. Height was significant in BMC but not in BMD. The results of girls were similar to those of boys, except the independent role of weight-bearing activities was significant at spine only.

Stepwise regression model (Table 5) showed that grip strength was a robust predictor of bone mass in both sexes with an exception for hip BMD in boys. Table 6 shows the prediction model of bone mass by grip strength and weight. For both sexes, grip strength and weight could be used to explain approximately 60% of the variations in BMC of different sites and 40% in BMD of hip and spine.

Discussion

Strong positive correlations were shown between grip strength and bone mass at various sites of adolescents in the present study. Multiple regression analysis showed that grip strength was a strong independent predictor of BMC and BMD at hip, spine and whole body.

The results supported the mechanostat theory that muscle strength is related to bone mass during youth. It postulates that developmental changes in bone strength are secondary to the increasing loads imposed by larger muscle forces [40, 41]. It predicts that the increasing muscle mass during development creates the stimulus for the increase in bone mass. Muscle force during development varies directly with bone strength, then the increase in muscle development must come before and should determine the increase in bone mass.

Unfortunately, the analysis of both site-specific and systemic relationship in the current study was not allowed as the radius bone density measurement was absent. However, the aforementioned association between grip

Table 5 Stepwise regression model of dominant grip strength with the determinants of BMC and BMD at hip, spine and whole body

	Hip BMC	Spine BMC	WB BMC	Hip BMD	Spine BMD	WB BMD
Boys						
Grip strength	0.2601 [c]	0.3626 [c]	12.38 [c]		0.0038 [b]	0.0044 [c]
	(0.0503)	(0.0816)	(2.33)		(0.0012)	(0.0008)
Weight	0.1566 [c]	0.1504 [c]	11.11 [c]	0.0048 [c]	0.0027 [c]	
	(0.0262)	(0.0409)	(1.22)	(0.0005)	(0.0005)	
Height	0.1637 [c]	0.2280 [c]	6.24 [c]			
	(0.0317)	(0.0510)	(1.49)			
MECHPA	0.4118 [c]	0.4699 [b]	10.72 [a]	0.0110 [c]	0.0073 [b]	
	(0.1066)	(0.1676)	(5.01)	(0.0028)	(0.0025)	
Calcium	0.0019 [b]			0.00005 [b]		
	(0.0007)			(0.00002)		
Pubertal stage		1.3039 [a]			0.0191 [b]	
		(0.5006)			(0.0073)	
Constant	−17.78 [c]	−22.26 [c]	−466.71 [a]	0.4690 [c]	0.3502 [c]	0.7593 [c]
	(3.90)	(6.22)	(183.41)	(0.0242)	(0.0199)	(0.0159)
Adjusted R^2	0.7454	0.6761	0.7707	0.4210	0.4707	0.1406
Girls						
Grip strength	0.2567 [c]	0.3082 [b]	9.16 [b]	0.0067 [c]	0.0041 [b]	0.0030 [b]
	(0.0578)	(0.1118)	(2.92)	(0.0016)	(0.0016)	(0.0011)
Weight	0.1583 [c]	0.2016 [c]	12.89 [c]	0.0048 [c]	0.0044 [c]	0.0020 [b]
	(0.0329)	(0.0593)	(1.58)	(0.0008)	(0.0008)	(0.0006)
Height	0.1772 [c]	0.2866 [c]	6.66 [c]			
	(0.0351)	(0.0647)	(1.73)			
MECHPA		0.3763 [a]			0.0060 [a]	
		(0.17043)			(0.0025)	
Calcium						
Pubertal stage		2.2768 [c]	31.71 [a]		0.0242 [b]	
		(0.5799)	(15.44)		(0.0083)	
Constant	−18.06 [c]	−29.62 [c]	−547.80 [b]	0.3969 [c]	0.3366 [c]	0.7106 [c]
	(4.16)	(7.73)	(205.90)	(0.0229)	(0.0211)	(0.0167)
Adjusted R^2	0.6924	0.6904	0.7636	0.4743	0.5419	0.2330

The numbers within a column are regression coefficients (standard error), WB: whole body

[a] p-value<0.05

[b] p-value<0.01

[c] p-value<0.001

strength and bone mass at radius might suggest the relationship between grip strength and bone mass was both site specific and systemic.

It was interesting to find that grip strength was related to bone mass at all sites measured. During normal activity, large joint reaction forces are produced by skeletal muscle contraction forces. Therefore, the above-mentioned relationship between muscle strength and bone mineral density of nearby skeletal structures should not be surprising. This study had reported the significant relationship between grip strength and BMD of distant skeletal sites. This indicated a more perplexing relationship between muscle strength and bone mass than that of direct force by muscles on bone. Several explanations of systemic relationship between grip strength and bone mass at distant skeletal sites were formulated. Firstly, a similar finding had been found in young women in whom dominant grip strength had acted as an independent predictor of spine BMD [7]. This relationship, which was inferred by arm activity, had been linked to the simultaneous contraction of trunk-stabilizing muscles that directly exerted forces on the spine. Also, Bevier explained that the results of his study that grip strength significantly predicted spine bone density in women because grip strength and back strength themselves were significantly correlated [6].

However, the role of grip strength as an independent predictor of bone mass still existed in the non-dominant hand in the present study, even though there were significant differences in grip strength between dominant and non-dominant hands (p<0.0001 in paired t-test). The result showed that the relationship between muscle strength and BMD was independent of regular activities by the dominant hand. It signified a general association rather than a local cause-and-effect relationship. In the studies of middle-aged men [42], the

Table 6 Multivariate analysis of dominant grip strength and weight of BMC and BMD at hip, spine and whole body

	β	*p*-value	β	*p*-value	β	*p*-value
Boys	Hip BMC		Spine BMC		Whole body BMC	
Grip strength (kg) - dominant hand	0.44	<0.0001	0.65	<0.0001	17.71	<0.0001
Weight (kg)	0.20	<0.0001	0.23	<0.0001	13.35	<0.0001
Constant	2.74		5.77		278.84	
Adjusted R^2	0.6719		0.6002		0.7421	
	Hip BMD		Spine BMD		Whole body BMD	
Grip strength (kg) - dominant hand	0.003	0.0073	0.006	<0.0001	0.004	0.0006
Weight (kg)	0.004	<0.0001	0.003	<0.0001	0.0007	0.1533
Constant	0.49		0.36		0.74	
Adjusted R^2	0.3657		0.4287		0.1460	
Girls	Hip BMC		Spine BMC		Whole body BMC	
Grip strength (kg) - dominant hand	0.37	<0.0001	0.72	<0.0001	16.00	<0.0001
Weight (kg)	0.24	<0.0001	0.38	<0.0001	16.67	<0.0001
Constant	2.56		2.65		213.51	
Adjusted R^2	0.6476		0.6034		0.7311	
	Hip BMD		Spine BMD		Whole body BMD	
Grip strength (kg) - dominant hand	0.007	<0.0001	0.007	<0.0001	0.003	0.0077
Weight (kg)	0.005	<0.0001	0.005	<0.0001	0.002	0.0010
Constant	0.40		0.32		0.71	
Adjusted R^2	0.4743		0.5086		0.2330	

systemic association between muscle strength and bone mass was due to the more favorable biochemical profile of the subjects with good physical fitness, including low levels of parathyroid hormone [43]. A general relationship between muscle strength and BMD is possibly grounded in a simultaneous and equivalent increase in these two parameters in adolescents with a relatively low level of physical activity [17].

Lastly, because of the indication of twin studies, genetic factors may be said to decide the muscle mass and bone [44]. The growth of muscle and bone were hypothesized to be determined independently by genetic mechanisms. It may be acknowledged that the present data did not establish a direct cause-and-effect relationship between muscle force and bone mass, i.e., whether the relationship between muscle strength and bone density were due to common genes or a proportional gain in bone density caused by improved strength. In this view, prospective studies should be implemented in order to assess the changes of bone mass during strength training.

The correlation coefficients between grip strength and BMC were markedly higher than those of BMD. In growing girls, a greater muscle area was associated with a greater bone cross-sectional area [13]. The correlation coefficients for BMD were less than those of BMC as bone area was adjusted as a result of the close relationship between muscle strength and muscle area. The higher values of correlation in BMC were similar to those of another studies in girls [11,16].

For boys, our results showed that weight-bearing activities were independent predictors of bone mass except whole body BMD. But the independent role was only significant at spine for girls in multivariate analysis. It might be due to lower participation in weight-bearing exercise in girls. The systemic association between weight-bearing exercise and bone mass suggests that there is a mediated effect throughout the skeleton. Bone metabolism assessed by serum markers demonstrated favorable systemic effects of physical exercise [43]. Therefore, because of the physical stress, localized enhancement of bone formation can probably lead to favorable effects on bone metabolism in the rest of the skeleton.

The small values of univariate correlation in calcium intake were similar to those of other observational study in adolescents [22]. Calcium supplement would have more effect for intervention studies when considering BMD change [19]. Non-significant result in multivariate analysis of this study might due to the effect of calcium intake was not strong enough after adjusting other covariates such as weight and grip strength. Moreover, weak association might due to narrow distribution and low consumption of calcium intake as the true influence of calcium in bone could not be shown from those adolescents. Mean calcium intake was 619.51±242.78 mg/day and 569.07±274.16 mg/day among boys and girls, respectively, in this study. Subjects had low calcium intake compared to recommendation of 800–1000 mg per day [45]. That may due to the non-milk drinking habit in Chinese. The beneficial effect may be established if sufficient calcium intake is available. On the other hand, recall bias might exist because adolescents were required to report their dietary intake in the past year.

Pubertal development is a key determinant of bone accretion in adolescents. However, the correlations among pubertal stages and bone parameters were moderate and only significant in spine, but not in hip and whole body in multiple regression analysis. The reason might be the narrow range of pubertal stages in our subjects, as most of them were early puberty.

Our results were consistent with the majority of those from previous studies showing body weight was a strong independent predictor of bone mass in adolescents. Analysis of association between bone mass and any variable without adjusting weight will be hampered by it. From our results, grip strength was still a significant predictor of bone mass after adjusting weight, meaning that grip strength was a robust and strong predictor for bone mass. Height was significant in BMC but not in BMD because BMD was already adjusted by body stature.

Since grip strength and weight were the most important predictors for bone mass, a combination of those parameters may provide high predictive power for bone mass. For both sexes, grip strength and weight could be used to explain about 60% of the variance in BMC of different sites and 40% in hip and spine BMD. The result showed that it might be sufficiently strong to permit measurement of grip strength plus weight to be used for prediction of the bone mass in early puberty period. It was preliminary analysis hence further diagnostic studies by receiver operating characteristic (ROC) curve were required in future.

Based on the fact that adolescence is the critical life period for bone mineral accrual, the method to identify pediatric patients with skeletal compromise should be reliable and essential for the development of prevention strategies. The ideal measurement of the pediatric bone mass should be safe and readily available. It is also easy to perform with adolescents of all ages. DEXA is patient-friendly, highly precise, and involves only minimal radiation exposure, but it is bulky and expensive. Measurement of grip strength is simple, neither expensive nor invasive. Although the actual uncertainty is about its basis, significantly correlated grip strength among different sites of bone mass may be considered as an additional factor to the factor "weight" to be a predictive method for detecting bone structure in early puberty period. Even it is not an adequate substitute for bone densitometry, the risk groups at which to direct bone density measurement can be identified. Intervention such as weight-bearing exercise and calcium supplement can be introduced earlier in order to let adolescents increase bone mass optimally before bone growth spurt.

This study is cross-sectional with all its limitations which reflects associations but not reveals causes and effects. Recall bias might exist in calcium assessment because adolescents were required to report their dietary intake in the past year.

Conclusion

We conclude that grip strength is an independent predictor of bone mineral density in both sexes. Relationship of muscle strength to bone mass is not only site specific but also systemic. Prediction model by grip strength and weight may be used for prediction of the bone mass in early puberty period.

Acknowledgements This study was supported by the Jockey Club Center for Osteoporosis Care and Control, the Chinese University of Hong Kong. We thank Dr. Edith Lau and Dr. Dicky Choy for their earlier contributions to the initial design of The Hong Kong Adolescent Bone Health Cohort Study. We gratefully acknowledge the invaluable assistance of Ms Wong Wing Man with subject recruitment, and Ms Winny Lau with dietary assessment. Special thanks to our subjects and families for their generous cooperation.

Conflicts of interest statement None.

Appendix

Table 7 Multivariate analysis of non-dominant handgrip strength with the determinants of BMC and BMD at hip, spine and whole body in boys

	Hip BMC		Spine BMC		Whole body BMC	
	β	*p*-value	β	*p*-value	β	*p*-value
Grip strength (kg) - non-dominant hand	0.25	<0.0001*	0.37	<0.0001*	12.75	<0.0001*
Weight (kg)	0.16	<0.0001*	0.16	0.0001*	11.24	<0.0001*
Height (cm)	0.15	<0.0001*	0.22	<0.0001*	5.48	0.0003*
MECHPA	0.40	0.0002*	0.45	0.0069*	9.67	0.0497*
Calcium (mg)	0.002	0.0155*	0.0009	0.4107	−0.009	0.7746
Pubertal stage	0.46	0.1417	1.26	0.0119*	21.97	0.1336
Constant	−16.53		−21.97		−381.21	
Adjusted R^2	0.7517		0.6827		0.7826	

Table 7 (continued)

	Hip BMC		Spine BMC		Whole body BMC	
	β	*p*-value	β	*p*-value	β	*p*-value
	Hip BMD		Spine BMD		Whole body BMD	
	β	*p*-value	β	*p*-value	β	*p*-value
Grip strength (kg) - non-dominant hand	0.003	0.0268*	0.004	0.0003*	0.003	0.0273*
Weight (kg)	0.004	<0.0001*	0.003	<0.0001*	0.0009	0.1353
Height (cm)	−0.002	0.0406*	−0.0004	0.6299	0.0001	0.8763
MECHPA	0.01	0.0011*	0.007	0.0056*	0.004	0.0818
Calcium (mg)	0.00005	0.0152*	0.000007	0.6887	0.000008	0.6527
Pubertal stage	0.005	0.5362	0.02	0.0118*	0.0009	0.9031
Constant	0.67		0.39		0.73	
Adjusted R^2	0.4376		0.4762		0.1409	

* *p*-value<0.05

Table 8 Multivariate analysis of non-dominant handgrip strength with the determinants of BMC and BMD at hip, spine and whole body in girls

	Hip BMC		Spine BMC		Whole body BMC	
	β	*p*-value	β	*p*-value	β	*p*-value
Grip strength (kg) - non-dominant hand	0.17	0.0032*	0.21	0.0495*	5.00	0.0794
Weight (kg)	0.17	<0.0001*	0.23	0.0002*	13.84	<0.0001*
Height (cm)	0.17	<0.0001*	0.30	<0.0001*	6.97	0.0001*
MECHPA	0.15	0.1118	0.42	0.0154*	4.37	0.3399
Calcium (mg)	0.0005	0.4328	0.0006	0.5922	0.04	0.2399
Pubertal stage	0.53	0.1017	2.41	<0.0001*	37.29	0.0185*
Constant	−16.78		−31.11		−591.70	
Adjusted R^2	0.6919		0.6829		0.7565	
	Hip BMD		Spine BMD		Whole body BMD	
	β	*p*-value	β	*p*-value	β	*p*-value
Grip strength (kg) - non-dominant hand	0.003	0.0528	0.003	0.0661	0.002	0.2211
Weight (kg)	0.005	<0.0001*	0.004	<0.0001*	0.002	0.0082*
Height (cm)	−0.0002	0.8686	0.001	0.1740	0.0003	0.6948
MECHPA	0.003	0.2332	0.006	0.0126*	−0.0003	0.8792
Calcium (mg)	0.000008	0.6646	0.00001	0.5756	0.00001	0.3263
Pubertal stage	0.02	0.0352*	0.02	0.0090*	0.01	0.1374
Constant	0.43		0.18		0.67	
Adjusted R^2	0.4606		0.5388		0.2275	

* *p*-value<0.05

References

1. Lynn HS, Lau EM, Au B, Leung PC (2005) Bone mineral density reference norms for Hong Kong Chinese. Osteoporosis Int 16 (12):1663–1668
2. Matkovic V, Jelic T, Wardlaw GM, Ilich JZ, Goel PK, Wright JK, Andon MB, Smith KT, Heaney RP (1994) Timing of peak bone mass in Caucasian females and its implication for the prevention of osteoporosis. Inference from a cross-sectional model. J Clin Invest 93(2):799–808
3. Forwood MR, Baxter-Jones AD, Beck TJ, Mirwald RL, Howard A, Bailey DA (2006) Physical activity and strength of the femoral neck during the adolescent growth spurt: a longitudinal analysis. Bone 38 (4):576–583
4. Ozgocmen S, Karaoglan B, Cimen OB, Yorgancioglu ZR (2000) Relation between grip strength and hand bone mineral density in healthy women aged 30–70. Singap Med J 41(6):268–270
5. Di Monaco M, Di Monaco R, Manca M, Cavanna A (2000) Handgrip strength is an independent predictor of distal radius bone mineral density in postmenopausal women. Clin Rheumatol 19(6):473–476
6. Bevier WC, Wiswell RA, Pyka G, Kozak KC, Newhall KM, Marcus R (1989) Relationship of body composition, muscle strength, and aerobic capacity to bone mineral density in older men and women. J Bone Miner Res 4(3):421–432
7. Snow-Harter C, Bouxsein M, Lewis B, Charette S, Weinstein P, Marcus R (1990) Muscle strength as a predictor of bone mineral density in young women. J Bone Miner Res 5(6):589–595
8. Sahin G, Duce MN, Milcan A, Bagis S, Cimen OB, Cimen B, Erdogan C (2002) Bone mineral density and grip strength in

postmenopausal Turkish women with osteoporosis: site specific or systemic? Int J Fert Women's Med 47(5):236–239
9. Dixon WG, Lunt M, Pye SR, Reeve J, Felsenberg D, Silman AJ, O'Neill TW (2005) European Prospective Osteoporosis Study Group. Low grip strength is associated with bone mineral density and vertebral fracture in women. Rheumatology 44(5):642–646
10. Sirola J, Tuppurainen M, Honkanen R, Jurvelin JS, Kroger H (2005) Associations between grip strength change and axial postmenopausal bone loss - a 10-year population-based follow-up study. Osteoporosis Int 16(12):1841–1848
11. Kristinsson JO, Valdimarsson O, Steingrimsdottir L, Sigurdsson G (1994) Relation between calcium intake, grip strength and bone mineral density in the forearms of girls aged 13 and 15. J Intern Med 236(4):385–390
12. Tsuji S, Tsunoda N, Yata H, Katsukawa F, Onishi S, Yamazaki H (1995) Relation between grip strength and radial bone mineral density in young athletes. Arch Phys Med Rehabil 76(3):234–238
13. Heinonen A, McKay HA, Whittall KP, Forster BB, Khan KM (2001) Muscle cross-sectional area is associated with specific site of bone in prepubertal girls: a quantitative magnetic resonance imaging study. Bone 29(4):388–392
14. Afghani A, Xie B, Wiswell RA, Gong J, Li Y, Anderson Johnson C (2003) Bone mass of Asian adolescents in China: influence of physical activity and smoking. Med Sci Sports Exerc 35(5):720–729
15. Ginty F, Rennie KL, Mills L, Stear S, Jones S, Prentice A (2005) Positive, site-specific associations between bone mineral status, fitness, and time spent at high-impact activities in 16- to 18-year-old boys. Bone 36(1):101–110
16. Valdimarsson O, Kristinsson JO, Stefansson SO, Valdimarsson S, Sigurdsson G (1999) Lean mass and physical activity as predictors of bone mineral density in 16–20-year old women. J Intern Med 245(5):489–496
17. Nordstrom P, Thorsen K, Nordstrom G, Bergstrom E, Lorentzon R (1995) Bone mass, muscle strength, and different body constitutional parameters in adolescent boys with a low or moderate exercise level. Bone 17(4):351–356
18. Kemper HCG, Twisk JWR, Van Mechelen W, Post GB, Roos JC, Lips P (2000) A fifteen-year longitudinal study in young adults on the relation of physical activity and fitness with the development of the bone mass: the Amsterdam growth and health longitudinal study. Bone 27(6):847–853
19. Cadogan J, Eastell R, Jones N, Barker M (1997) Milk intake and bone mineral acquisition in adolescent girls: randomised, controlled intervention trial. BMJ. Br Med J 315:1225–1260
20. Bailey DA, Martin AD, McKay HA, Whiting S, Mirwald R (2000) Calcium accretion in girls and boys during puberty: a longitudinal analysis. J Bone Miner Res 15(11):2245–2250
21. Lee WT, Cheung AY, Lau J, Lee SK, Qin L, Cheng JC (2004) Bone densitometry: which skeletal sites are best predicted by bone mass determinants? J Bone Miner Metab 22(5):447–455
22. Cheng JCY, Leung SSSF, Lee WTK et al (1999) Axial and peripheral bone mineral acquisition: a 3-year longitudinal study in Chinese adolescents. Eur J Pediatr 158:506–512
23. Foley KT, Owings TM, Pavol MJ, Grabiner MD (1999) Maximum grip strength is not related to bone mineral density of the proximal femur in older adults. Calcif Tissue Int 64(4):291–294
24. Wu XP, Liao EY, Huang G, Dai RC, Zhang H (2003) A comparison study of the reference curves of bone mineral density at different skeletal sites in native Chinese, Japanese, and American Caucasian women. Calcif Tissue Int 73(2):122–132
25. Cheng JCY, Leung SSSF, Lee WTK et al (1998) Determinants of axial and peripherial bone mass in Chinese adolescents. Arch Dis Child 78(6):524–530
26. Van Coeverden SC, De Ridder CM, Roos JC, Van't Hof MA, Netelenbos JC, Delemarre-Van de Waal HA (2001) Pubertal maturation characteristics and the rate of bone mass development longitudinally toward menarche. J Bone Miner Res 16(4):774–781
27. MacKelvie KJ, Petit MA, Khan KM, Beck TJ, McKay HA (2004) Bone mass and structure are enhanced following a 2-year randomized controlled trial of exercise in prepubertal boys. Bone 34(4):755–764
28. Horlick M, Wang J, Pierson RN Jr, Thornton JC (2004) Prediction models for evaluation of total-body bone mass with dual-energy X-ray absorptiometry among children and adolescents.. Pediatrics 114(3):e337–e345
29. Fewtrell MS, British Paediatric & Adolescent Bone Group (2003) Bone densitometry in children assessed by dual x ray absorptiometry: uses and pitfalls.. Arch Dis Child 88(9):795–798
30. Hannan WJ, Cowen SJ, Wrate RM, Barton J (1995) Improved prediction of bone mineral content and density. Arch Dis Child 72 (2):147–149
31. Spijkerman DCM, Snijders CJ, Stijnen T, Lankhorst GJ (1991) Standardization of grip strength measurements. Scand J Rehab Med 23:203–206
32. Tanner JM (1978) Physical growth and development. In: Forfar JO, Arnell CC (eds) Textbook of Pediatrics. 2nd edn. Churchill LivingStone, Scotland, pp 249–303
33. Herman-Giddens ME, Slora EJ, Wasserman RC, Bourdony CJ, Bhapkar MV, Koch GG, Hasemeier CM (1997) Secondary sexual characteristics and menses in young girls seen in office practice: a study from the Pediatric Research in Office Settings network. Pediatrics 99(4):505–512
34. Woo J, Leung SSF, Ho SC, Lam TH, Janus ED (1997) A food frequency questionnaire for use in the Chinese population in Hong Kong: description and examination of validity. Nutr Res 17:1633–1641
35. Lee WTK, Cheung CSK, Tse YK, Guo X, Qin L, Ho SC, Lau J, Cheng JCY (2005) Generalized low bone mass of girls with adolescent idiopathic scoliosis is related to inadequate calcium intake and weight bearing physical activity in peripubertal period. Osteoporos Int 16:1024–1035
36. Institute of Nutrition and Food Safety, China CDC (2002) China Food Composition. Peking University Medical Press
37. Groothausen J, Siemer H, Kemper HCG, Twisk J, Welten DC (1997) Influence of peak strain on lumbar bone mineral density: An analysis of 15-year physical activity in young males and females. Pediatr Exerc Sci 9:159–173
38. Van Langendonck L, Lefevre J, Claessens AL, Thomis M, Philippaerts R, Delvaux K, Lysens R, Renson R, Vanreusel B, Vanden Eynde B, Dequeker J, Beunen G (2003) Influence of participation in high-impact sports during adolescence and adulthood on bone mineral density in middle-aged men: a 27-year follow-up study. Am J Epidemiol 158(6):525–533
39. Kemper HC, Bakker I, Twisk JW, van Mechelen W (2002) Validation of a physical activity questionnaire to measure the effect of mechanical strain on bone mass. Bone 30(5):799–804
40. Frost HM (2000) Muscle, bone, and the Utah paradigm: a 1999 overview. Med Sci Sports Exerc 32(5):911–917
41. Rauch F, Bailey DA, Baxter-Jones A, Mirwald R, Faulkner R (2004) The 'muscle-bone unit' during the pubertal growth spurt. Bone 34(5):771–775
42. Huuskonen J, Vaisanen SB, Kroger H, Jurvelin C, Bouchard C, Alhava E, Rauramaa R (2000) Determinants of bone mineral density in middle aged men: a population-based study. Osteoporosis Int 11(8):702–708
43. Brahm H, Piehl-Aulin K, Ljunghall S (1997) Bone metabolism during exercise and recovery: the influence of plasma volume and physical fitness. Calcif Tissue Int 61(3):192–198
44. Seeman E, Hopper JL, Young NR, Formica C, Goss P, Tsalamandris C (1996) Do genetic factors explain associations between muscle strength, lean mass, and bone density? A twin study. Am J Physiol 270(2 Pt 1):E320–E327
45. Chinese Nutrition Society (2000) The Chinese Dietary Reference Intakes (DRIs)