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ORIGINAL ARTICLE

Higher healthy lifestyle scores are associated with greater bone mineral density in middle-aged and elderly Chinese adults

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Abstract
Summary This study examined the association between healthy lifestyle score (HLS), which contained 7 items (smoking, BMI, physical activity, diet, alcohol, sleep and anxiety) and BMD. Results showed HLS was positively associated with BMD at all studied sites, suggesting that healthier lifestyle patterns might be beneficial to bone health.

Purpose Previous studies have reported favourable associations of individual healthy lifestyle factors with bone mineral density (BMD), but limited evidence showed the relationship of a combined healthy lifestyle score (HLS) with BMD. This study examined the association between the HLS and BMD.

Methods This community-based cross-sectional study included 3051 participants aged 40–75 years. The HLS contained 7 items (smoking, BMI, physical activity, diet quality, alcohol intake, sleep and anxiety). BMD values of whole body (WB), lumbar spine 1–4 (L_{1-4}), total hip (TH) and femur neck (FN) were measured using dual-energy X-ray absorptiometry.

Results After adjusting for potential covariates, HLS was positively associated with BMD at all studied sites (P-trend < 0.01). The mean BMDs were 2.69% (WB), 5.62% (L_{1-4}), 6.13% (TH) and 5.71% (FN) higher in participants with HLS of 6–7 points than in those with HLS of 0–2 points. The per 1 of 7 unit increase in the HLS was associated with increases of 7.63 (WB)–13.4 (TH) mg/cm^2 BMD levels at all sites. These favourable associations tended to be more pronounced in men than in women. Among the 7 items, physical activity contributed most to the favourable associations, followed by BMI, non-smoking and diet; the other three items played little roles. Sensitivity analyses showed that the significant associations remained after excluding any one of the 7 components or excluding fracture subjects at all sites.

Conclusion Higher HLS was associated with greater BMD in middle-aged and elderly Chinese, suggesting that healthier lifestyle patterns might be beneficial to bone health.

Keywords Lifestyle · Healthy lifestyle score · Bone mineral density · Chinese

Yun-yang Deng and Yu-ping Liu contributed equally to this work.

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Abbreviations

OP	Osteoporosis
HLS	Healthy lifestyle score
CVD	Cardiovascular disease
BMI	Body mass index
AHA-DLS	American Heart Association Diet and Lifestyle Score
GNHS	Guangzhou Nutrition and Health Study
DXA	Dual-energy X-ray absorptiometry
aMed	Alternate Mediterranean diet
MUFA	Monounsaturated fatty acid
SFA	Saturated fatty acid
SAS	Self-Rating Anxiety Scale
WB	Whole body
L_{1-4}	Lumbar spine 1–4
TH	Total hip
FN	Femur neck

Introduction

Osteoporosis (OP) is a systemic skeletal disease characterized by low bone mass and microarchitectural deterioration. It is the world's third most incident chronic disease after cardiovascular disease (CVD) and diabetes [1]. There were approximately 200 million (6.96%) OP patients around the globe in 2008 [1, 2]. In China, the prevalence of osteoporosis in those over the age of 50 was 23.9% and 12.5% in women and 3.2% and 5.3% in men, respectively, at the lumbar spine and femur neck [3]. Lifestyle played an indispensable role in various chronic diseases, including OP. Many studies have indicated favourable associations of some individual healthy lifestyle factors, such as non-smoking [4], proper body weight [5], moderate physical activity [6], healthy diet [7, 8], moderate alcohol intake [9], good sleep [10] and low anxiety levels [11], with bone health. However, each specific healthy behaviour was able to coexist with the others, and these behaviours may synergistically influence people's health [12, 13]. Combining these relevant behaviours into one single measure of the whole lifestyle, such as the healthy lifestyle score (HLS), may be useful in assessing synergistic associations than using each individual behaviour.

A variety of studies have calculated the HLS and showed associations of higher HLS with lower incidence or mortality of CVD [14–18], some cancers [19–22] and some other diseases [23, 24]. In these studies, the HLS was typically composed of the following factors: smoking, body weight or body mass index (BMI), physical activity, diet, alcohol consumption, sleep, etc. To date, few studies have examined the association between HLS and bone health. Only two studies investigated an alternative HLS known as the American Heart Association Diet and Lifestyle Score (AHA-DLS), which combines BMI, physical activity, diet and alcohol intake, and showed significant protective associations with BMD [25, 26]. However, the AHA-DLS does not include smoking, mental stress and sleeping variables, and this measure was designed mainly for use in studies focused on the prevention of CVD. Therefore, the AHA-DLS measure might not be appropriate for bone health; it might be less specific in describing the association between lifestyle and BMD. Moreover, each individual component was given the same weight in the HLS calculations in most previous studies, although the strengths of the associations may differ for the different component lifestyle factors [20, 27].

To address these issues, this cross-sectional study examined the association between an HLS containing 7 lifestyle factors and BMD in the whole body, lumbar spine, total hip and femur neck in a middle-aged and elderly Chinese population and explored the optimal weight for each item based on a regression model.

Methods

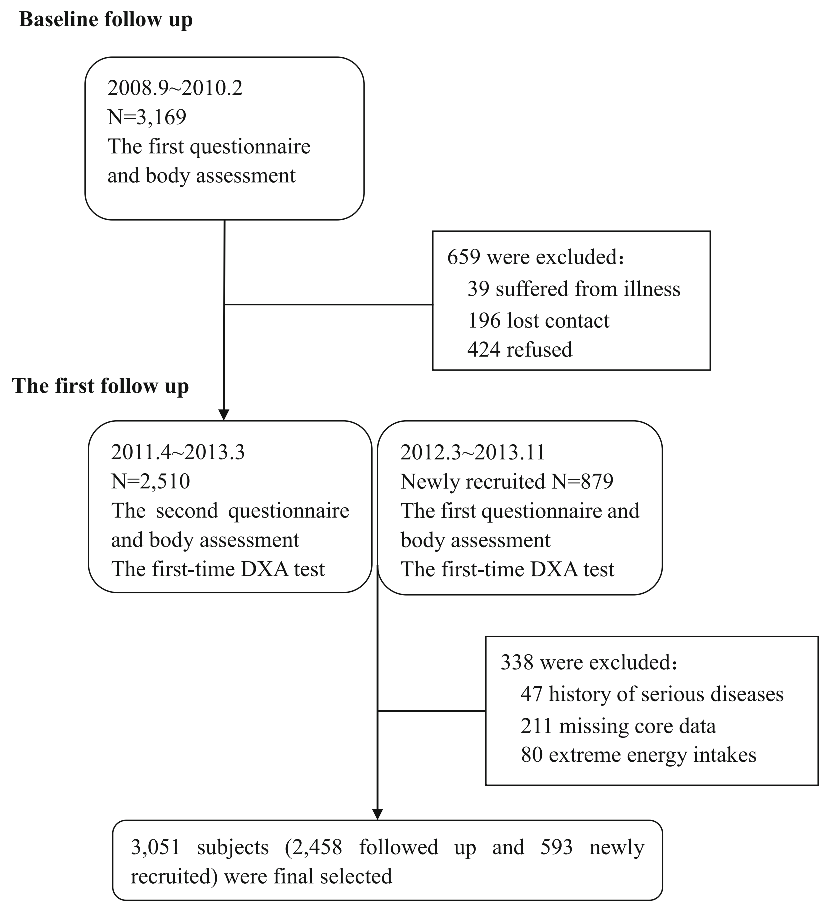
Study participants

The study was based on the Guangzhou Nutrition and Health Study (GNHS), in which 4048 participants aged 40–75 and have lived in urban Guangzhou (South China) for more than 5 years were recruited from 2008 to 2010 ($n = 3169$) and in 2013 ($n = 879$). Of the first bunch of 3169 participants (2008–2010), 659 subjects were lost to follow-up in 2011–2013. Among 3389 participants who attended the survey during 2011–2013, 338 subjects were further excluded due to the following conditions: (1) history of serious diseases ($n = 47$), such as malignancy or hyperthyroidism; (2) missing core data ($n = 211$); and (3) extreme energy intakes (< 800 or > 4200 kcal/d for men and < 600 or > 3500 kcal/d for women) ($n = 80$). Finally, 3051 subjects (including 2065 women and 986 men; 2458 followed up and 593 newly recruited) who completed at least one round of questionnaires and bone scanning by dual-energy X-ray absorptiometry (DXA) in 2011–2013 were included in this cross-sectional analysis (Fig. 1). Informed consent was obtained from all individual participants included in the study. The study was conducted under the guidance and regulations of the Ethics Committee of the School of Public Health at the Sun Yat-Sen University.

Assessment of lifestyle behaviours and other covariates

Subjects were invited to the School of Public Health at the Sun Yat-sen University for face-to-face interviews and body assessments, and the following information was collected: demographic characteristics (e.g. age, sex, education, marital status and household income), habitual diet, sleep conditions,

Fig. 1 The flow chart of the study



anxiety neurosis, history of diseases, use of supplements (e.g. multiple vitamins, calcium supplements and oral oestrogens) and other lifestyle factors (e.g. smoking, drinking and physical activity).

Smoking involved both active and passive smoking. Active smoking was defined as smoking more than 5 packs of cigarettes (100 cigarettes) in the past year. Passive smoking was defined as exposure to more than 1 cigarette or 5 min of indoor smoking every day in the past year. Physical activity included moderate and vigorous activities during work, leisure time and household chores. BMI values were calculated by measuring subjects' heights and weights. Sleep conditions were obtained by asking subjects whether they had insomnia for more than half a year. The Self-Rating Anxiety Scale (SAS) was used to evaluate the subjects' level of anxiety neurosis [28]. It consists of 20 items and a full score of 100 points.

Modified alternate Mediterranean diet score

A pre-validated 79-item food-frequency questionnaire [29] was used to collect the subjects' dietary information. The diet component of HLS was defined by using the alternate Mediterranean diet (aMed) score [30, 31]. We further modified the aMed score by removing alcohol intake because it was used as a separate factor in the HLS [31]. The final modified aMed score (0–8 points) included 8 items assigned a value of 0/1 for each component [30]: energy-adjusted whole grains, vegetables (excluding potatoes), fruit (including juices), legumes, nuts, fish, ratio of monounsaturated fatty acid (MUFA) to saturated fatty acid (SFA) and red or processed meats.

Healthy lifestyle score (HLS)

The definition of the HLS varies among studies [19, 27]. In this analysis, seven lifestyle-related components were selected: smoking, physical activity, BMI, modified aMed score, alcohol intake, sleep and anxiety. Each component was dichotomized as healthy or unhealthy. One point was given to each item representing a healthy condition according to the following criteria [16, 32]: (1) non-smoking, (2) physically active ($\geq$ 150 min/week of moderate or vigorous physical activity), (3) standard BMI (18.5 to 23.9 kg/m^2), (4) healthy diet (5–8 points of modified aMed Score), (5) moderate alcohol intake (men, 10–50 g/d; women, 5–25 g/d), (6) good sleep (no insomnia for < 6 months) and (7) no anxiety neurosis (SAS < 50). The total points ranged from 0 (least healthy) to 7 (most healthy). Specific information about these HLS criteria can be found in Supplementary Table 1.

BMD assessment

BMD (g/cm^2) was measured by dual-energy X-ray absorptiometry (DXA) (Discovery W, Hologic Inc., Waltham, MA, USA) and analysed with Hologic Discovery software version 3.2 during 2011–2013. The measured skeletal sites were whole body (WB), lumbar spine 1–4 (L_{1-4}), total hip (TH) and femur neck (FN). The in vivo coefficients of variation (CV) of the duplicated BMD measurements in 30 subjects after repositioning were 1.18% (WB), 0.87% (LS), 1.02% (TH) and 1.92% (FN), respectively. The long-term CV of the measurements was 0.26%, a value found by testing the phantom daily between March 2011 and May 2015 [33].

Statistical analysis

Baseline characteristics were presented as mean (standard deviation, SD) or frequencies (percent), and the ANOVA and chi-square analyses were used to examine differences among the HLS groups, for the continuous or categorical variables, respectively.

Multivariate analysis of covariance (ANCOVA) was used to compare the mean BMD values among the five HLS groups. Model I was adjusted for age and sex. In model II, we further adjusted for marital status, education status, household income, calcium supplement use, multivitamin use and daily energy intake. A Bonferroni test was conducted to make multiple comparisons. Liner regression was also used to obtain the coefficients (β), standardized error (SE) and standardized β (sβ) of the HLS.

A stratified analysis was performed with the use of ANCOVA and linear regression according to sex under model II; years since menopause and use of oestrogen were further adjusted for in the analysis limited to females. We also evaluated the association of each binary lifestyle factor with BMD under model II and further adjusted for the other factors in the HLS except the one being analysed.

We conducted the following sensitivity analyses: (1) the stability of the HLS: we excluded each component in turn and excluded subjects with a history of fractures. (2) The associations were reanalysed by weighting the HLS according to the corresponding sβ values of the 7 factors ($weight_i = [s\beta_i/(\sum s\beta_i)] \times 7$); and (3) the contribution of the current HLS was compared with the modified AHA-DLR [25, 26]. All analyses were performed with SPSS 22.0 for Windows (SPSS, Inc., NY, USA). A two-sided P value < 0.05 was considered statistically significant.

Results

A total of 3051 subjects (2065 women and 986 men) were included in this study. As HLS increased, subjects had higher levels of household incomes, education, physical activity, energy intake and dietary intakes of whole grain, vegetables, fruits, legumes, nuts and fish; subjects with increased HLS also had higher proportion of calcium and multivitamin supplement use but lower levels of body weight and BMI and fewer subjects with current smoking, insomnia and anxiety. There were no significant associations with HLS for other factors in Table 1 (P values ≥ 0.05).

In all subjects (Table 2), higher HLS was significantly associated with higher BMD at most bone sites (except L_{1-4}) after adjusting for age and sex in model I. The BMDs in the highest HLS (6–7 points) group were 2.87 (WB)–6.42% (FN) higher than those in the lowest HLS (0–2 points) group (all P values < 0.01). The association between HLS and BMD was strengthened after further adjusting for multiple covariates in model II. The percentage mean BMD differences between the extreme groups were 2.69% (WB), 5.62% (L_{1-4}), 6.13% (TH) and 5.71% (FN). The changes in BMD (mg/cm^2) associated with per 1 of 7 unit increase in HLS were 7.63 (WB), 12.2 (L_{1-4}), 13.4 (TH) and 11.6 (FN) (all P values < 0.01) (Table 2). In the sex-stratified analysis in model II, the favourable associations tended to be relatively more pronounced in men than in women, although significant associations were observed at all studied sites in men and in women (Table 3).

We compared mean BMD differences between binary groups classified by each HLS component (Table 4). Among the 7 components of the HLS, physical activity played a leading role in the favourable association between HLS and BMD, followed by smoking, BMI and the aMed score. The BMDs were 1.19% (WB) to 2.36% (FN) higher in subjects with higher (vs. lower) physical activity (all P values < 0.001). No significant differences in BMD for the other three components (alcohol intake, sleep and anxiety) were observed at any studied site.

The sensitivity analyses showed that significant associations remained after excluding either one of the 7 components or those with a history of fractures. After adjusting AHA-DLS, the favourable associations of HLS with BMD remained significant at all studied sites (Supplementary Table 3).

Discussion

In this community-based cross-sectional study, the score of this 7-item HLS was positively associated with BMD in this middle-aged and elderly Chinese population, which suggested that subjects with better adherence to a healthy lifestyle pattern (standard BMI, non-smoking, moderate exercise, healthy diet, moderate alcohol intake, good sleep and no anxiety) might have better bone health.

HLS and bone health

Although many studies have examined each component of the 7-item HLS with BMD [4–11], few studies have reported

Table 1 Characteristics of study participants by healthy lifestyle score (HLS)

	HLS					*P* value
	0–2	3	4	5	6–7	
n = 3051	244	728	1004	764	311	
Gender, *N*(%)						*< 0.001*
Men (986)	38 (15.6)	241 (33.1)	352 (35.1)	240 (31.4)	115 (37.0)	
Women (*n* = 2065)	206 (84.4)	487 (66.9)	652 (64.9)	524 (68.6)	196 (63.0)	
Age, year	60.3 (6.58)	60.8 (6.17)	60.8 (6.11)	60.4 (5.58)	60.3 (5.33)	0.413
Body weight, kg	59.1 (8.01)	60.2 (9.65)	59.4 (9.93)	58.4 (9.57)	58.4 (8.97)	*0.003*
Body mass index, kg/m^2	24.8 (2.83)	24.2 (3.01)	23.5 (2.98)	22.8 (2.75)	22.3 (2.40)	*< 0.001*
Household income, *N* (%)						*< 0.001*
<2000 Yuan/month/person	61 (25.0)	128 (17.6)	153 (15.2)	110 (14.4)	46 (14.8)	
2000–3000 Yuan/month/person	103 (42.2)	254 (34.9)	423 (42.1)	299 (39.1)	123 (39.5)	
> 3000 Yuan/month/person	80 (32.8)	346 (47.5)	428 (42.6)	355 (46.5)	142 (45.7)	
Education (year), *N*(%)						*< 0.001*
< 9	106 (43.4)	241 (33.1)	267 (26.6)	168 (22.0)	55 (17.7)	
9–12	108 (44.3)	343 (47.1)	474 (47.2)	375 (49.1)	162 (52.1)	
> 12	30 (12.3)	144 (19.8)	263 (26.2)	221 (28.9)	94 (30.2)	
Married, *N* (%)	207 (84.8)	651 (89.4)	892 (88.8)	674 (88.2)	273 (87.8)	0.393
Calcium supplement user, *N* (%)	67 (27.5)	186 (25.5)	309 (30.8)	246 (32.2)	102 (32.8)	*0.029*
Multivitamin regular user, *N* (%)	33 (13.5)	114 (15.7)	202 (20.1)	156 (20.4)	75 (24.1)	*0.002*
Smoker [a], *N* (%)	175 (71.7)	402 (55.2)	302 (30.1)	106 (13.9)	3 (1.0)	*< 0.001*
Physical activity [b], min/week	19.7 (38.0)	76.9 (174)	186 (243)	310 (259)	453 (248)	*< 0.001*
Energy intake, kcal/d	1.43 (0.39)	1.52 (0.42)	1.58 (0.47)	1.66 (0.46)	1.80 (0.47)	*<0.001*
Components of modified aMed score						
Whole grains [c], g/d	2.90 (3.14)	4.67 (13.6)	5.46 (15.6)	5.41 (5.92)	6.52 (5.62)	*0.004*
Vegetables (excluded potatoes), g/d	22.9 (8.17)	24.7 (10.9)	26.8 (11.8)	30.7 (12.1)	34.9 (13.6)	*<0.001*
Fruits (included juices), g/d	17.1 (11.0)	19.1 (18.5)	21.7 (28.8)	25.5 (13.9)	29.2 (14.1)	*<0.001*
Legumes [d], g/d	3.70 (4.32)	4.03 (4.16)	5.12 (6.58)	5.71 (5.86)	7.11 (5.83)	*<0.001*
Nuts, g/d	2.44 (5.73)	.39 (3.08)	2.93 (3.88)	3.79 (3.87)	5.12 (4.59)	*< 0.001*
Fish, g/d	10.7 (21.7)	0.4 (7.57)	12.1 (18.9)	13.2 (10.3)	16.6 (14.3)	*< 0.001*
Monounsaturated to saturated fatty acid ratio	1.388 (0.17)	1.386 (0.18)	1.380 (0.16)	1.380 (0.16)	1.371 (0.16)	0.787
Red and processed meats, g/d	30.0 (25.3)	29.8 (16.8)	30.3 (16.8)	29.8 (19.4)	28.9 (16.)	0.841
High adherence of modified aMed (range 0-8), N (%)	17 (7.00)	103 (14.1)	329 (32.8)	489 (64.0)	307 (98.7)	*< 0.001*
Moderate alcohol intake, *N* (%)	1 (0.40)	2 (0.30)	17 (1.70)	21 (2.70)	30 (9.60)	*< 0.001*
Insomnia [e], *N* (%)	71 (29.1)	57 (7.80)	39 (3.90)	13 (1.70)	0 (0.00)	*< 0.001*
Anxiety neurosis [f], *N* (%)	120 (49.2)	105 (14.4)	75 (7.50)	12 (1.60)	3 (1.00)	*< 0.001*
Women						
Menopause age, year	49.7 (4.01)	49.6 (4.26)	49.9 (3.53)	50.0 (3.28)	50.2 (3.41)	*< 0.001*
Oestrogen user, *N* (%)	10 (5.10)	20 (4.20)	45 (7.10)	38 (7.40)	20 (10.4)	*0.031*

We presented continuous variables as mean (SD) while categorical variables as frequencies (percentage). The differences among HLS group were tested by one-way ANOVA or Chi-square tests as appropriate

[a] Smoking involved both active (smoking more than 5 packs of cigarettes in the past year) and passive (more than 1 cigarette or 5 minutes indoor smoking around you every day in the past year) smoking

[b] Physical activities included middle and vigorous activities in occupation and leisure time, and household chores was calculated

[c] Refers to non-refined cereals, such as graham bread, oats, cereal flakes, etc., calculated as dry weight

[d] Values were calculated and expressed as proteins

[e] Subjects who had insomnia for more than half a year

[f] Subjects whose Self-Rating Anxiety Scale (SAS) ≥ 50

synergistic associations between lifestyle score and bone health. Two cross-sectional studies examined the association of the AHA-DLS, which contains 4 lifestyle factors (BMI, physical activity, diet and alcohol intake), with BMD or osteoporosis [25, 26]. One study in 933 Puerto Rican subjects (aged 47–79 years) found that each 5 of 110 unit increase of the AHA-DLS was associated with a 5–8 mg/cm^2 (or 5.5–8.8 per 5% unit) increased BMD as well as a lower prevalence of osteoporosis/osteopenia (OR, 0.83–0.91) at the hip sites and lumbar spine (all *P* values < 0.05) [25]. Another study showed a significant increase in BMD (4.20–6.07 mg/cm^2) in the whole body, lumbar spine and hip sites with each 5% increase in the BMI-excluded AHA-DLS in 3143 Chinese women and men aged 40–75 years (all *P* values < 0.01) [26].

Since several other important lifestyle-related factors, such as smoking, sleeping habits and mental stress, were not

Table 2 Comparisons of bone mineral density by healthy lifestyle score (HLS)

	HLS					*P*-trend	%Difference [a]	*P*-Difference	β(SE) [b]
	0–2	3	4	5	6–7				
N(3,051)	244	728	1004	764	311				
BMD (mean ± SE), g/cm²									
Whole body									
Model I[c]	1.082 ± 0.006	1.088 ± 0.004	1.096 ± 0.003	*1.102 ± 0.004**	*1.113 ± 0.006**	*< 0.001*	*2.87*	*0.002*	*7.55 (1.62)*¶
Model II[d]	1.077 ± 0.005	1.091 ± 0.003	1.101 ± 0.003	1.101 ± 0.004	*1.106 ± 0.006**	*< 0.001*	*2.69*	*< 0.001*	*7.63 (1.73)*¶
Lumbar spine $_{1–4}$									
Model I	0.870 ± 0.009	0.876 ± 0.005	0.877 ± 0.004	0.883 ± 0.005	0.893 ± 0.008	0.267	2.64	0.566	*4.91 (2.30)*¶
Model II	0.854 ± 0.007	0.868 ± 0.005	*0.887 ± 0.004**	*0.894 ± 0.006**	*0.894 ± 0.011**	*0.002*	*5.62*	*0.019*	*12.2 (2.45)*¶
Total hip									
Model I	0.813 ± 0.007	0.823 ± 0.004	0.828 ± 0.003	0.832 ± 0.004	*0.847 ± 0.006**	*0.002*	*4.18*	*0.002*	*6.96 (1.78)*¶
Model II	0.800 ± 0.006	0.819 ± 0.004	*0.833 ± 0.003**	*0.846 ± 0.004**	*0.849 ± 0.008**	*< 0.001*	*6.13*	*0.023*	*13.4 (1.88)*¶
Femur neck									
Model I	0.670 ± 0.006	0.681 ± 0.004	0.684 ± 0.003	*0.691 ± 0.003**	*0.713 ± 0.006**	*< 0.001*	*6.42*	*< 0.001*	*8.58 (1.66)*¶
Model II	0.666 ± 0.005	0.676 ± 0.003	*0.690 ± 0.003**	*0.704 ± 0.004**	*0.704 ± 0.008**	*< 0.001*	*5.71*	*0.001*	*11.6 (1.75)*¶

[a] %Difference: percentage difference = (HLS $_{6–7}$ – HLS $_{0–2}$)/HLS $_{0–2}$ × 100

[b] β(SE): regression coefficient ± standard error, in mg/cm² per 1 of 7 unit increase of HLS

[c] Model I: adjusted for age and gender

[d] Model II: further adjusted for marital status, education status, household income, calcium supplements use, multivitamin use and daily energy intake

**P* < 0.05, compared with HLS 0–2

¶ *P* < 0.05, based on regression result

included in the AHA-DLS, we calculated a more comprehensive HLS by including 7 items (non-smoking, physically active, normal BMI, healthy diet, moderate alcohol intake, good sleep and low anxiety neurosis), as has been done in many other studies of chronic diseases [19, 23, 27]. Each 1 of 7 unit increase in HLS was associated with an increase of 7.6–13.4 mg/cm² BMD at the studied sites in this analysis. The differences in BMDs between the groups of HLS 6–7 and 0–2

Table 3 Comparisons of bone mineral density by healthy lifestyle score (HLS) stratified by sex

	HLS					*P*-trend	%Difference [a]	*P*-Difference	β(SE) [b]
	0–2	3	4	5	6–7				
Men									
N (986)	38	241	352	240	115				
BMD (mean ± SE), g/cm²									
Whole body	1.155 ± 0.007	1.179 ± 0.005	*1.178 ± 0.006**	*1.189 ± 0.008**	*1.248 ± 0.033**	*0.002*	*8.05*	*0.042*	*10.8 (3.17)* ¶
Spine, $L_{1–4}$	0.928 ± 0.010	0.958 ± 0.008	0.960 ± 0.009	0.969 ± 0.013	*1.034 ± 0.050**	*0.028*	*11.4*	*0.046*	*13.6 (4.79)* ¶
Total hip	0.869 ± 0.008	0.902 ± 0.006	0.904 ± 0.007	0.914 ± 0.010	*0.944 ± 0.037**	*0.001*	*8.63*	*0.014*	*13.9 (3.62)* ¶
Femur neck	0.720 ± 0.007	0.740 ± 0.006	0.745 ± 0.006	*0.764 ± 0.009**	*0.830 ± 0.036**	*< 0.001*	*15.4*	*0.026*	*14.6 (3.47)* ¶
Women									
N (2,065)	206	487	652	524	196				
BMD (mean ± SE), g/cm²									
Whole body	1.040 ± 0.008	1.042 ± 0.004	1.058 ± 0.004	*1.055 ± 0.004**	1.053 ± 0.008	*0.037*	1.35	1.000	*4.67 (2.07)* ¶
Spine, $L_{1–4}$	0.815 ± 0.011	0.816 ± 0.006	0.843 ± 0.005	*0.845 ± 0.006**	0.848 ± 0.010	*0.001*	4.05	0.270	*10.8 (2.83)* ¶
Total hip	0.772 ± 0.008	0.772 ± 0.005	0.792 ± 0.004	*0.801 ± 0.005**	*0.809 ± 0.008**	*< 0.001*	*4.79*	*0.017*	*11.5 (2.21)* ¶
Femur neck	0.643 ± 0.008	0.640 ± 0.004	0.657 ± 0.004	*0.666 ± 0.004**	0.668 ± 0.007	*< 0.001*	3.89	0.206	*9.05 (2.04)* ¶

All analyses were adjusted for age, marital status, education status, household income, calcium supplement use, multivitamin use and daily energy intake and menopause age and oral oestrogen use (women)

[a] %Difference: percentage difference = (HLS $_{6–7}$ – HLS $_{0–2}$)/HLS $_{0–2}$ × 100

[b] β (SE): regression coefficient ± standard error, in mg/cm² per 1 of 7 unit increase of HLS

P-interaction, 0.058 (whole body); 0.099 (spine $L_{1–4}$); 0.075 (total hip) and 0.043 (femur neck)

**P* < 0.05, compared with HLS 0–2

¶ *P* < 0.05, based on regression result

Table 4 Percentage mean (95% CI) differences in BMD by each component of HLS

Healthy vs. unhealthy	Whole body	Lumbar spine $_{1-4}$	Total hip	Femur neck
Non-smoking	*0.64 (0.10, 1.38)* *	0.00 (− 1.30, 1.20)	*0.85 (0.22, 1.85)* *	*0.88 (0.27, 2.05)* *
BMI	0.00 (−0.74, 0.73)	*2.76 (1.40, 4.02)* *	*2.68 (1.58, 3.71)* *	*1.61 (0.47, 2.87)* *
Physical activity	*1.19 (0.56, 1.85)* *	*2.18 (1.08, 3.38)* *	*2.20 (1.34, 3.08)* *	*2.36 (1.36, 3.47)* *
Modified aMed score	*0.92 (0.22, 1.61)* *	*1.49 (0.25, 2.70)* *	*1.82 (0.82, 2.81)* *	*1.91 (0.83, 3.08)* *
Alcohol intake	1.19 (−0.91, 3.33)	1.48 (−2.25, 5.21)	1.93 (−1.12, 4.97)	*3.79 (0.40, 7.27)* *
Insomnia	0.09 (− 1.28, 1.44)	0.69 (− 1.78, 3.05)	1.72 (− 0.23, 3.75)	0.88 (− 1.32, 3.12)
Anxiety	0.00 (− 1.50, 1.94)	−0.45 (− 2.35, 1.37)	0.48 (− 1.08, 1.97)	0.15 (− 1.50, 1.94)

All analyses were adjusted for age, gender, marital status, education status, household income, calcium supplement use, multivitamin use, daily energy intake and the other factors in HLS except the one analysed

*$P < 0.05$

in this study represent risk increases of fractures by 24.9% (lumber spine) and 34.2% (FN) [34]. The corresponding changes of T score of HLS 0–2 were − 0.29 (L_{1-4}) and − 0.30 (FN) [3, 35], and changes of PMOF were 1.09% (L_{1-4}) and 1.04% (FN), respectively [36]. This 7-item HLS had a significant association with BMD even adjusted for the AHA-DLS, suggesting that this 7-item HLS had extra contribution in the prediction of BMD in this population (Supplementary Table 3).

Given that lifestyle behaviours may show different impacts on BMD, simply adding equally weighted scores of the 7-item lifestyle factor may lead to misclassification. To address this issue, we weighted each item according to their sβs. The results showed the β, R^2 and R^2 change of HLS and wHLS were similar (Supplementary Table 3). Considering the complicated nature of calculating the weighted HLS, the HLS with equal weights for each item would be more applicable for public use.

HLS components and bone health

Among the 7 components of the HLS, physical activity played a leading role in the favourable association between HLS and BMD. The BMDs in subjects with higher (vs. lower) physical activity were 1.19 (WB)–2.36% (FN) higher at the studied sites (all P values < 0.001). A meta-analysis of 22 cohort studies with 1,235,768 participants and 14,843 fractures showed that the pooled relative risk (RR, 95% CI) for the highest versus lowest category of physical activity was 0.71 (0.63–0.80) for total fractures, 0.61(0.54–0.69) for hip fracture and 0.72 (0.49–0.96) for wrist fracture [37]. Physical exercise creates mechanical strain on the bones, which deforms bone tissue and promotes bone formation and bone remodelling to maintain bone mass and increase bone density [38].

The other favourable determinants among the HLS components in this study were non-smoking, normal BMI and a higher aMed diet quality score. Consistent with previous results that were reviewed in a meta-analysis [4], our findings showed that smoking was a strong risk factor for decreased BMD at most sites (except L_{1-4}). We also observed that subjects with normal BMI (18.5–23.9 kg/m^2) had 1.61% (FN) and 2.76% (L_{1-4}) higher BMDs than those with low (< 18.5 kg/m^2) or high (≥ 24.0 kg/m^2) BMI. Possibly due to the biphasic effect of high BMI caused by higher weight load and more fat, U-shaped (for women) and reverse J-shaped (for men) associations were also observed between BMI and hip fracture in a Korean cohort study of 288,068 individuals [39]. A meta-analysis showed that subjects with the highest (vs. lowest) Mediterranean Diet score had a higher BMD of 0.12 g/cm^2, 0.10 g/cm^2 and 0.11 g/cm^2 at the lumber spine, femoral neck and total hip [40]. The above-mentioned studies and our findings support an association between a good lifestyle, in terms of physical activity, non-smoking, moderate BMI and better diet quality, and better bone health.

Interestingly, our group found a significant synergistic association of HLS combined alcohol intake, sleep and anxiety with BMD (Supplementary Table 3), although the associations observed between each individual factor and total hip BMD were not significant (Table 4). It was possible that there was a synergistic action between the various components of the HLS such that the effect of the sum, on BMD, was greater than its parts. Our results reinforced the importance of a pattern of healthy lifestyle behaviours rather than any single lifestyle choice in protecting BMD.

Strengths and limitations

There are several strengths in our study. First, to the best of our knowledge, this is the first study to examine the association of the 7-item HLS with BMD based on a relatively large sample. Improving patterns seemed to be more effective than changing each single item [41]. Our findings provide a potential clue for the improvement of bone health via the HLS approach. Second, the sensitivity analyses generally showed a consistent favourable association, suggesting good internal consistency for the HLS evaluated.

Our study has several limitations. First, the HLS items and the cut-offs for each item were chosen for general health or major chronic diseases and not specifically for bone health. Second, the sleep conditions were obtained by simply asking whether subjects had insomnia for over half a year instead of using a systematic index, such as the Pittsburgh Sleep Quality Index. Third, the cross-sectional study design limits the ability to infer causality between the HLS and BMD. Typically, the studied association might be attenuated but not overestimated because healthier lifestyles would be advised to the participants with poor BMD. Fourthly, we did not compare the frequency data used in our study and the diary for physical activity questionnaire, although the questionnaire had good long-term reliability (r 0.646, $P < 0.001$) between baseline and the next survey after 3 years apart.

In conclusion, there was a favourable association between the 7-item HLS and BMD in this middle-aged and elderly Chinese population. Our findings suggested that a healthier lifestyle pattern suggested for general health might also be helpful for bone health in this population. HLS-based interventional studies are needed to address the causality between the HLS and BMD.

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