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The association between the healthy lifestyle index and MRI-derived body composition measurements in the UK Biobank study

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A high healthy lifestyle index (HLI) score, which reflects an adequate amount of sleep, no alcohol consumption, no smoking, a moderate to high physical activity level, a high quality diet, and a normal body mass index (BMI), has been associated with reduced risk of morbidity and mortality. We examined the relationship between the HLI and measurements of adipose and lean tissue volumes measured using magnetic resonance imaging (MRI). We studied 33,002 participants in the UK Biobank study, aged 40–69 years at enrolment. Information on lifestyle components was obtained at the baseline examination (2006–2010), while MRI was performed at a later exam (2014–2020). A multilevel HLI score, constructed by assigning individual scores to each HLI component, was categorized into quartiles in multivariable linear regression analyses. Higher HLI levels were associated with lower levels of body composition parameters (visceral and subcutaneous adipose tissue, total adipose tissue, total lean tissue, muscle fat infiltration, abdominal fat ratio, weight to muscle ratio) in a dose-dependent manner (tests-for-trend p-value < 0.001 for all parameters). When BMI was excluded from the HLI score and included separately in the model, a direct association between HLI score and total lean tissue volume was observed. Higher HLI scores were associated with a better body composition profile.

Body composition is described according to the percentage of adipose, bone, and muscle tissue in the body, and variations in body composition have been associated with altered risk of morbidity and mortality[1,2]. In particular, there is evidence to suggest that an elevated amount of adipose tissue, and especially visceral adiposity, is associated with increased risk of insulin resistance, type 2 diabetes, cardiovascular disease, dyslipidemia, hypertension, cardiovascular disease, certain types of cancer, and overall mortality[3]. Abdominal subcutaneous fat appears to have less of an impact on cardiometabolic risk, although some studies suggest a potential association with elevated levels of markers of chronic inflammation[4]. Muscle mass and strength are also essential for a healthy life; indeed, relatively low total lean mass is associated with lower quality of life, increased disability and risk of fracture, and with mortality[5–7], while myosteatosis, defined as adipose tissue infiltration into muscle, is associated with reduced muscle quality and function, with increased risk of type 2 diabetes and body frailty, and decreased mobility and balance[3,8].

In the clinical setting, body mass index and waist circumference have been used as proxies for adipose tissue accumulation. However, these measurements have limitations when used to estimate visceral adipose tissue (VAT). Techniques such as densitometry, bioelectrical impedance, and dual-energy X-ray absorptiometry (DXA) have been used to quantify various parameters of body composition, but these methodologies are limited in their measurement accuracy, while the use of computed tomography (CT) scans for clinical purposes is often limited to specific populations due to concerns about radiation exposure[9]. Magnetic resonance imaging (MRI) enables quantification of adipose and lean tissues and their distribution in the body, and of fat infiltration into organs and muscles[10–12], while avoiding radiation exposure, thereby reducing the health risk of the procedure[9,13].

Body composition at various stages of life, and in particular adipose tissue deposition, has a multifactorial etiology determined by a combination of genetic and environmental factors, as well as disease status[14]. Several studies have shown that the genetic factors account for 30–50% of fat volume and distribution in the body[15], suggesting that there is a significant lifestyle contribution to this complex trait. A multilevel healthy lifestyle

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index (HLI), constructed from scores assigned to several parameters including duration of sleep, alcohol consumption, smoking history, physical activity level, diet quality, and body mass index, has been used to study the relationship between lifestyle factors and several obesity-related health outcomes including cancers, cardiovascular disease, and multimorbidity[16–20], based on the idea that a combination of these risk factors may have a stronger association with the outcome studied than individual lifestyles evaluated separately. Therefore, in the study reported here, we examined the association of the HLI with future MRI measurements of body composition among participants in the UK Biobank imaging study.

Methods

Study population

The UK Biobank is a large prospective cohort study designed to investigate the determinants of major diseases of middle and old age[21]. A detailed study protocol is available online (https://www.ukbiobank.ac.uk/media/gnkeyh2q/study-rationale.pdf). Briefly, between 2006 and 2010, individuals registered with the United Kingdom's National Health Service (NHS), aged 40–69 years, were invited to participate in the study and were recruited at 22 assessment centres across the UK. Approximately 500,000 individuals from the general population (5.5% response rate) were ultimately enrolled and participated in the baseline visit. Informed written consent was obtained from the participants at the time of enrollment. The UK Biobank was approved by the North West Multi-Centre Research Ethics Committee, the National Information Governance Board for Health and Social Care in England and Wales, and the Community Health Index Advisory Group in Scotland. The study was conducted in accordance with the Declaration of Helsinki and an independent Ethics and Governance Council continuously monitors UK Biobank adherence to the Ethics and Governance framework.

UK Biobank MRI study

The UK Biobank imaging substudy extension was established in 2014 to obtain body scans from 100,000 participants in four imaging centres located in Newcastle, Manchester, Reading, and Bristol[22]. Details regarding the imaging acquisition and analytical processing methods were published previously[11,23]. Participants were scanned using a Siemens MEGNETOM Aera 1.5-T MRI scanner (Siemens Healthineers, Erlangen, Germany) with the dual-echo Dixon Vibe protocol, while body composition analysis was performed using AMRA Profiler™ (AMRA AB, Linköping, Sweden)[13,24]. Body composition parameters used in the present study included volumetric (in liters, L) measurements of abdominal visceral adipose tissue (VAT), abdominal subcutaneous adipose tissue (ASAT), total trunk adipose tissue (TTAT), which combined VAT and ASAT, total adipose tissue (measured between the bottom of the thigh muscles and the top of the vertebrae T9) (TAT) , total lean tissue (measured between the bottom of the thigh muscles and the top of the vertebrae T9) (TLT), and total thigh fat-free muscle (TTFM); plus muscle fat infiltration (%) (MFI), abdominal fat ratio (defined as total abdominal fat volume/total abdominal fat volume plus thigh muscle volume) (%) (AFR), and weight to muscle ratio (defined as body weight/total thigh fat-free muscle volume) (WMR). The MRI data used in the present analysis were obtained between April 2014 and March 2020.

Healthy lifestyle index

During the baseline visit, socio-demographic, lifestyle, and health-related characteristics of the study participants were collected via questionnaires and/or measured directly (http://www.ukbiobank.ac.uk/resources/). Lifestyle factors included in the HLI were selected according to the recommendations of the American Heart Association, and included sleep duration, alcohol intake, smoking status, diet quality information, physical activity, and body mass index ((BMI)[25]. Self-reported sleep duration was based on the answer to the question: "About how many hours of sleep do you get in every 24 h (h)? (Please include naps)". Individuals who indicated < 3 h, or > 12 h were asked to confirm their response. Sleep duration was categorized into 3 groups (*< 7*, *7- < 9*, and *≥ 9 h*). Validated questionnaires were used to acquire information on the average frequency of consumption (per week) of food groups (meat, fruit, vegetable, and grain) over the past year. For bread type and cereal, portion sizes were also obtained. Reported alcohol frequency (drinks/day) was categorized as: *never or on special occasion, ≥ once/month—≤ four times/week,* and *daily or almost daily*, while smoking history was categorized as *current, former,* and *never*. Total physical activity during the last 4 weeks was computed by multiplying the minutes/week (min/wk) of each type of physical activity by the metabolic equivalent (MET) of that activity, and summing these values across all activities; the obtained variable was categorized as *< 600*, *600- < 3000*, and *≥ 3000 MET min/wk*[26]. Anthropometric parameters were measured by trained personnel following standardized procedures[27]. BMI was calculated by dividing weight (kg) by the square of height (m^2), and was categorized as *≥ 30.0, 25.0– < 30.0*, and *18.0- < 25.0 kg/m²*. Waist circumference (cm) was measured at the narrowest part of the torso and categorized into 3 groups (*≥ 102, 94- < 102*, and *< 94 cm* in men, and *≥ 88, 80- < 88*, and *< 80 cm* in women). The individual lifestyle components were scored separately with the highest scores assigned to the healthiest categories and then summed to create a combined HLI score (Supplementary table 1).

Statistical analysis

By July 2023, MRI-derived body composition measurements were available for 40,178 individuals (51.8% women), except for TAT and TLT, for which data were only available for 8,522 individuals. Of this group, 33,002 (50.1% women) had information on all HLI components and constituted the analytical cohort for this study (6,939 of these individuals had data on TAT and TLT) (Supplementary Fig. 1). We compared the baseline characteristics of the analytical cohort with those of the rest of the UK Biobank cohort using the ANOVA test to compare means and standard deviations for continuous variables, and Chi-squared test to compare percentages for categorical variables. Baseline characteristics of the analytical cohort were summarized by HLI quartiles and compared with similar statistical tests. Furthermore, we examined correlations between the body composition measurements by calculating Pearson's correlation coefficients.

The ranges of the body composition measurements differed by sex, and therefore all analyses were conducted separately for men and women. Multivariable linear regression was used to compare mean levels or standard deviations of body composition measurements between HLI quartiles, using the lowest quartile as the referent category. Tests for trend in the associations across quartiles were performed by assigning the HLI median values to each quartile and modeling them as continuous variables. Selection of the variables included in the final model as potential confounders was based on their association with the exposure and the outcome and included age at baseline, time between recruitment and MRI exam, race/ethnicity (*White, Black, Asian, mixed*, and *others*), education *(<*/≥ *college*), employment status (*employed, retired, caregiver, disabled, unemployed, volunteer, student,* and *not reported*), height (*cm*), socioeconomic status (Townsend deprivation coefficient), and (for women) menopausal status. Women were considered to be post-menopausal if they had had a natural menopause, were aged at least 53 years and did not report their menopausal status, or had had a bilateral oophorectomy before this age[28]. Amongst women, separate analyses were conducted by menopausal status. Since BMI is strongly associated with body composition measurements, we tested the association between HLI, calculated without BMI, and the various outcomes, and we included BMI separately in the model. In addition, we evaluated whether the relationship between HLI and body composition was modified by BMI level. To this end, we created a different HLI index using waist circumference categories instead of BMI (HLI_{wst}), and carried out the analyses stratified by BMI categories. Finally, we evaluated the association of the individual HLI components with the body composition parameters. For this purpose, we used the categories of each lifestyle factor as reported in Supplementary table 1, except for diet (9-point score) for which we created 4 categories *(< 0.75, 0.75–1.25. > 1.25–1.50,* and *> 1.50*).

All statistical analyses were performed using Stata version 18 (StataCorp LLC, College Station, TX). All *p* values were 2-sided and considered statistically significant for *p* values < 0.05.

Results

The average time between the HLI assessment and the MRI measurements was 8.8 yrs (standard deviation ± 1.7yrs). Comparing the analytical cohort to the rest of the UK Biobank study, we observed that the former group was younger, included more men, had higher percentages of individuals who were college graduates, actively employed, and with a higher socioeconomic status, and had a lower percentage of postmenopausal women (Supplementary table 2). The analytical cohort had, on average, a different lifestyle profile than the rest of the UK Biobank cohort, with lower BMI and waist circumference, a lower level of physical activity, more daily sleeping hours, a higher percentage of daily alcohol intake, and a higher percentage of never-smokers.

Baseline characteristics of the study sample by HLI quartiles are summarized in Table 1. Compared to participants with lower HLI scores, those with higher scores were more likely to be slightly younger, to be women, to have a college degree and to be retired, and were less likely to include postmenopausal women. A low correlation was observed between VAT and other MRI parameters including ASAT, AFR, MFI and WMR, while strong correlations were observed among several measurements of adipose tissue volume (TAAT, ASAT and VAT; TAT and ASAT; TTAT and TAT), and between WMR and AFR (Supplementary table 3). Total lean tissue volume was not correlated with other body composition components except for TTFM volume. Examination of sex-specific levels of the body composition components showed that compared to men, women had lower volumes of VAT, TTAT, TLT, and TTFM, while having a higher volume of the other body composition measurements (Supplementary table 4).

In both men and women, higher HLI levels were associated with lower levels of all body composition parameters in a dose-dependent manner (test for trend *p*-values all *< 0.001)* (Table 2). The association of HLI quartiles with VAT was stronger in men than in women (in men: $HLI_{4th\text{-}quartile}$ β-coefficient (β): -1.71, 95% confidence interval (CI) -1.80– -1.62; in women: $HLI_{4th\text{-}quartile}$ β: -1.09, 95%CI -1.15– -1.03; *p*-trend < 0.001 in both groups; interaction term HLI*sex *p*-value *< 0.001*), while the opposite was observed for ASAT (in men: $HLI_{4th\text{-}quartile}$ β: -1.62, 95%CI -1.72– -1.52; in women: $HLI_{4th\text{-}quartile}$ β: -2.42, 95%CI -2.55– -2.28; *p*-trend *< 0.001* in both groups, interaction term HLI*sex *p*-value *< 0.001*), MFI (in men: $HLI_{4th\text{-}quartile}$ β: -0.88, 95%CI -0.95– -0.81; in women: $HLI_{4th\text{-}quartile}$ β: -1.10, 95%CI -1.17– -1.03; *p*-trend *< 0.001* in both groups, interaction term HLI*sex *p*-value *< 0.001*) and WMR (in men: $HLI_{4th\text{-}quartile}$ β: -0.56, 95%CI -0.60– -0.53; in women: $HLI_{4th\text{-}quartile}$ β: -0.82, 95%CI -0.86– -0.77; *p*-trend *< 0.001* in both groups, interaction term HLI*sex *p*-value *< 0.001*). The associations of HLI level with TTAT, TAT, TLT, and AFR were similar in men and women. The results were similar when the differences between quartiles were expressed in terms of standard deviations (Supplementary table 5).

After exclusion of BMI from the HLI score, the results were similar except for the associations of HLI with TLT and TTFM, in which direct associations were observed after adjusting for BMI (TLT in men: $HLI_{4th\text{-}quartile}$: β: 0.67, 95%CI 0.46–0.85, and in women: $HLI_{4th\text{-}quartile}$ β: 0.24, 95%CI 0.09–0.39; and TTFM in men: $HLI_{4th\text{-}quartile}$ β: 0.35, 95%CI 0.30–0.40, and in women $HLI_{4th\text{-}quartile}$ β: 0.17, 95%CI 0.14–0.21) (Supplementary table 6 and 7). In women, when the analyses were stratified by menopausal status, there were similar relationships of HLI with most of the body composition components in the premenopausal and postmenopausal strata; however, higher HLI was associated with lower VAT in premenopausal women compared to postmenopausal women (premenopause: $HLI_{4th\text{-}quartile}$ β: -1.25, 95%CI -1.35– -1.14; postmenopause: $HLI_{4th\text{-}quartile}$ β: -0.99, 95%CI -1.06– -0.91; *p-value* for interaction *< 0.001*), while higher HLI was associated with lower ASAT and WMR in postmenopausal women compared to premenopausal women (ASAT: premenopause $HLI_{4th\text{-}quartile}$ β: -2.98, 95%CI -3.23– -2.73; postmenopause $HLI_{4th\text{-}quartile}$ β: -2.09, 95%CI -2.25– -1.93; *p-value* for interaction *< 0.001*; and WMR: premenopause $HLI_{4th\text{-}quartile}$ β: -0.96, 95%CI -1.06– -0.88; postmenopause: $HLI_{4th\text{-}quartile}$ β: -0.74, 95%CI -0.80– -0.68; *p-value* for interaction < 0.001) (Supplementary table 9).

Healthy lifestyle index quartiles	Healthy lifestyle index									
	1	2	3	4	*P*	1	2	3	4	*P*
	Men					Women				
N	**4,300**	**3,546**	**3,893**	**4,725**		**3,945**	**3,580**	**4,204**	**4,809**	
Characteristics										
Age, [a] yrs	55.8 (7.4)	56.0 (7.5)	55.5 (7.6)	55.2 (7.8)	< 0.001	54.4 (7.1)	54.1 (7.2)	53.9 (7.3)	53.9 (7.5)	< 0.001
Interval time, yrs	8.8 (1.7)	8.8 (1.7)	8.8 (1.7)	8.8 (1.7)	0.736	8.8 (1.7)	8.8 (1.7)	8.8 (1.7)	8.8 (1.7)	0.445
Race, n (%)										
White	4,178 (97.2)	3,435 (96.9)	3,792 (97.4)	4,547 (96.2)		3,840 (97.4)	3,484 (97.3)	4,084 (97.2)	4,649 (96.7)	
Black	37 (0.9)	26 (0.7)	25 (0.6)	17 (0.4)		35 (0.9)	25 (0.7)	28 (0.7)	26 (0.5)	
Asian	24 (0.6)	39 (1.1)	37 (1.0)	103 (2.2)		12 (0.3)	18 (0.5)	2y (0.6)	58 (1.2)	
Mixed	20 (0.5)	10 (0.3)	10 (0.3)	11 (0.2)		6 (02)	11 (0.3)	15 (0.4)	15 (0.5)	
Other	36 (0.8)	25 (0.7)	22 (0.6)	34 (0.7)	< 0.001	25 (0.6)	18 (0.5)	22 (0.5)	25 (0.5)	0.001
Education, n (%)										
< college	2,318 (53.9)	1,846 (52.1)	1,923 (49.4)	2,176 (46.1)		2,226 (56.4)	1,905 (53.2)	2,217 (52.7)	2,467 (51.3)	
≥ college	1,982 (46.1)	1,700 (47.9)	1,970 (50.6)	2,549 (54.0)	< 0.001	1,719 (43.6)	1,675 (46.8)	1,987 (47.3)	2,342 (48.7)	< 0.001
SES	-1.2 (2.5)	-1.3 (2.2)	-1.3 (2.7)	-1.3 (3.0)	0.089	-1.2 (2.2)	-1.3 (2.2)	-1.3 (2.7)	-1.3 (3.1)	0.092
Occupation, n (%)										
Employed	3,093 (72.0)	2,458 (69.3)	2,723 (70.0)	3,278 (69.4)		2,755 (69.8)	2,462 (68.8)	2,891 (68.8)	3,235 (67.3)	
Retired	994 (23.1)	973 (27.4)	1,032 (26.5)	1,266 (26.8)		895 (22.7)	855 (23.9)	992 (23.6)	1,174 (24.4)	
Caregiver	23 (0.5)	8 (0.2)	17 (0.4)	25 (0.5)		133 (3.4)	159 (4.4)	188 (4.5)	248 (5.2)	
Disabled	72 (1.7)	39 (1.1)	27 (0.7)	23 (0.5)		77 (2.0)	31 (0.9)	31 (0.7)	28 (0.6)	
Unemployed	73 (1.7)	48 (1.4)	60 (1.5)	67 (1.4)		30 (0.8)	25 (0.7)	28 (0.7)	40 (0.8)	
Volunteer	15 (0.4)	5 (0.1)	8 (0.2)	19 (0.4)		23 (0.6)	14 (0.4)	32 (0.8)	38 (0.8)	
Student	9 (0.2)	5 (0.1)	8 (0.2)	9 (0.2)		14 (0.4)	19 (0.5)	18 (0.4)	19 (0.4)	
Unknown	19 (0.4)	10 (0.3)	18 (0.5)	38 (0.8)	< 0.001	18 (0.5)	15 (0.4)	24 (0.6)	27 (0.6)	< 0.001
Height, cm	176.5 (6.6)	176.6 (6.6)	176.8 (6.5)	176.7 (6.6)	< 0.001	163.1 (6.2)	163.3 (6.2)	163.5 (6.2)	163.7 (6.1)	< 0.001
Menopause, n %)	-	-	-	-		2,642 (67.0)	2,270 (63.4)	2,644 (62.9)	2,975 (61.9)	< 0.001
Sleeping hours	6.7 (1.2)	7.1 (1.0)	7.3 (0.8)	7.4 (0.6)	< 0.001	6.7 (1.3)	7.2 (1.0)	7.4 (0.8)	7.5 (0.6)	< 0.001
Alcohol, daily, n %)	2,085 (48.5)	1,213 (34.2)	876 (22.5)	369 (7.8)	< 0.001	1,466 (37.2)	790 (22.1)	560 (13.3)	215 (4.5)	< 0.001
Smoking, never, n (%)	1,277 (29.7)	1,739 (49.0)	2,479 (63.5)	3,927 (83.1)	< 0.001	1,412 (35.8)	2,007 (56.1)	2,962 (70.5)	4,177 (86.9)	< 0.001
Physical activity [a], MET (min/wk)	1,790.2 (2,366.7)	2,509.6 (2,718.1)	2,894.8 (2,764.8)	4,115.0 (2,056.4)	< 0.001	1,590.3 (1,904.2)	2,198.0 (2,246.3)	2,613.5 (2,338.7)	3,967.2 (2,706.9)	< 0.001
BMI[a], (kg/m^2)	28.6 (4.0)	27.5 (3.7)	26.9 (3.5)	25.6 (3.1)	< 0.001	28.0 (5.1)	26.6 (4.6)	25.7 (4.2)	24.2 (3.3)	< 0.001
WC [a], (cm)	99.0 (10.7)	95.8 (9.8)	94.0 (9.4)	90.4 (9.0)	< 0.001	86.3 (12.1)	83.1 (11.3)	80.9 (10.5)	77.4 (8.8)	< 0.001

Table 1. Baseline characteristics of the study population by healthy lifestyle index quartiles. p-values were obtained from ANOVA test for continuous variables and from Chi-squared test for categorical variables. Age, age at enrollment, Interval time, Time between enrollment and MRI exam SES, socio-economic status (Townsend index); MET < BMI, body mass index; WC, waist circumference. [a] data represent means (standard deviations), unless otherwise specified.

Subgroup analyses by BMI groups, using quartiles of HLI*wst* (Table 3), showed that the associations of HLI*wst* with the outcomes were similar across BMI categories for all of the body composition parameters except for ASAT in men, for which the dose–response relationship was stronger in those with BMI ≥ *30 kg/m²* than in those in the other BMI categories.

When we examined the relationship of each HLI component with the body composition measurements, we observed strong positive association of BMI with all measurements in both sexes (Supplementary Fig. 2 & 3). Compared to the referent category, among men, sleep duration of 7- < 9 h was associated with lower VAT, ASAT, TAT, AFR, MFI, and WMR, no alcohol consumption was associated with higher levels of ASAT, AFR, and WMR and lower levels of TTFM, TLT, and MFI, while the highest categories of smoking history (*never smokers*) and physical activity levels were associated with lower levels of all measurements of body composition. Higher diet quality was associated with lower levels of VAT and WMR. Amongst women, higher categories of sleep and physical activity were associated with lower levels of VAT, ASAT, TTAT, AFR, MFI and WMR, and higher levels of TLT and TTFM , no alcohol consumption was associated with higher levels of ASAT and WMR, and lower levels of TLT and TTFM, and higher diet quality was associated with lower VAT levels.

Quartiles	Healthy lifestyle index							
	Men				Women[a]			
	1	2	3	4	1	2	3	4
N	4,307	3,733	4,110	4,314	3,945	3,580	4,204	4,809
		β (95%CI)	β (95%CI)	β (95%CI)		β (95%CI)	β (95%CI)	β (95%CI)
VAT	Ref	-0.67 (-0.76–0.57)	-0.98 (-1.07–0.88)	-1.71 (-1.80 – -1.62)	Ref	-0.39 (-0.45 – -0.32)	-0.66 (-0.72 – -0.60)	-1.09 (-1.15 – -1.03)
ASAT	Ref	-0.63 (-0.73 – -0.52)	-0.93 (-1.04–0.83)	-1.62 (-1.72 – -1.52)	Ref	-0.74 (-0.89 – -0.60)	-1.34 (-1.48 – -1.20)	-2.42 (-2.55 – -2.28)
TTAT	Ref	-1.28 (-1.47 – -1.10)	-1.91 (-2.09 – -1.73)	-3.33 (-3.50 – -3.16)	Ref	-1.13 (-1.33 – -0.93)	-2.00 (-2.20 – -1.81)	-3.51 (-3.69 – -3.32)
TAT[b]	Ref	-1.59 (-2.19 – -0.98)	-2.54 (-3.13 – -1.94)	-4.41 (-4.98 – -3.85)	Ref	-1.96 (-2.62– -1.29)	-3.31 (-3.96 – -2.67)	-6.02 (-6.66 – -5.40)
TLT[b]	Ref	-0.27 (-0.54 – 0.01)	-0.60 (-0.87 – -0.34)	-0.57 (-0.82 – -0.32)	Ref	-0.35 (-0.55 – 0.15)	-0.51 (-0.70 – -0.32)	-0.83 (-1.02 – -0.65)
AFR	Ref	-0.026 (-0.030– -0.021)	-0.039 (-0.043 – -0.035)	-0.074 (-0.077 – -0.070)	Ref	-0.022 (-0.027 – -0.018)	-0.039 (-0.043 – -0.034)	-0.075 (-0.079 – -0.070)
MFI	Ref	-0.39 (-0.46 – -0.32)	-0.59 (-0.66 – -0.52)	-0.88 (-0.95 – -0.81)	Ref	-0.41 (-0.48 – -0.33)	-0.67 (-0.75 – -0.60)	-1.10 (1.17 – -1.03)
TTFM	Ref	-0.10 (-0.16 – 0.04)	-0.15 (-0.21 – -0.09)	-0.24 (-0.30– -0.18)	Ref	-0.08 (-0.12 – 0.04)	-0.16 (-0.20 – -0.12)	-0.25 (-0.29– -0.21)
WMR	Ref	-0.22 (-0.26 – -0.19)	-0.34 (-0.37 – -0.31)	-0.56 (-0.60 – -0.53)	Ref	-0.27 (-0.33 – -0.22)	-0.45 (-0.50 – -0.40)	-0.82 (-0.86 – -0.77)

Table 2. Association between quartiles of the healthy lifestyle index and body composition measurements obtained by MRI. Results represent beta coefficients and 95% confidence intervals estimated by multivariable linear regression. All analyses are adjusted for age, time between recruitment and MRI exam, race/ethnicity, education, employment status, socioeconomic status, and height. [a] Analysis adjusted for menopausal status. [b] Number of participants (HLI quartiles n = 802, 643, 660, and 606 in men; and n = 833, 745, 817, and 638 in women). Tests for trend p-value < 0.001. Ref., referent group; VAT, visceral adipose tissue volume; ASAT, Abdominal subcutaneous adipose tissue volume; TTAT, total trunk fat volume; TAT, total adipose tissue volume; TLT, total lean tissue volume; AFR, abdominal fat ratio; MFI, muscle fat infiltration; TTFM, total thigh fat-free muscle volume; and WMR, weight to muscle ratio.

Discussion

In the present study, we investigated the association between the Healthy Lifestyle Index, a composite score consisting of several lifestyle factors that have been associated with risk of chronic disease, and body composition measurements obtained an average of 8.8 years after the assessment of the lifestyle characteristics among participants in the UK Biobank imaging study. The results of the study indicated that in both men and women, higher levels of HLI were associated with lower adipose tissue volumes, and in particular, lower volumes of VAT, ASAT, and TAT. Higher HLI scores were also associated with lower muscle mass as represented by TLT and TTFM, but also with a lower level of adipose tissue infiltration into muscle, and an overall lower fat to muscle ratio in the body, as represented by AFR and WMR measurements. Some sex differences were observed in the magnitude of the relationship between the lifestyle index and the type and distribution of adipose tissue, which reflect differences in body fat distribution, fat percentage, and muscle mass content between men and women, and are likely regulated by circulating sex-hormone levels[29]. Previous studies on the effect of lifestyle interventions have shown greater reduction of visceral fat in men than in women following physical activity with and without a caloric restricted diet[30,31], although both sexes have been shown to benefit from such interventions[32] The strong relationship observed between the HLI and these outcomes did not change when BMI was excluded from the lifestyle index but included in the model as a confounding factor, with the exception of TLT, for which there was a change in the direction of the association. The higher the BMI, the higher the levels of adipose and muscle tissue[33] but the lower the muscle quality[34], as indicated in the present study by the higher level of MFI among those with higher BMI, subjects who are more likely to be included in lower HLI quartiles. As expected, our results indicate that BMI plays a major role in the association between HLI and all measurements of body composition. Nevertheless, our results suggest an association between a healthy lifestyle and body composition that is independent of BMI levels.

This is the first study that has examined the relationship of a multilevel lifestyle score with body composition measurements. Given the cost related to the use of MRI in large-scale population-based studies, data on the association of lifestyle factors with MRI-derived measures of body composition are limited, have mainly come from clinical trials and small observational studies conducted over a short period of follow-up, and have focused only on one or a few lifestyle characteristics[35–37].

Regarding the individual components of the HLI, we observed that a relatively high diet quality score (with low intake of red and processed meat, and high intake of fruit, vegetables and whole grain) was associated with lower levels of VAT, AFR and WMR, but was not associated with other body composition parameters. In contrast, higher levels of physical activity appeared to be associated with lower levels of MRI measurements of adipose tissue. These results are in agreement with several intervention studies conducted in adults that have shown that

	Healthy lifestyle index$_{WST}$							
	Men				Women[a]			
	1	2	3	4	1	2	3	4
		β (95%CI)	β (95%CI)	β (95%CI)		β (95%CI)	β (95%CI)	β (95%CI)
VAT	Ref.[b]	-0.78 (-0.86- -0.69)	-1.30 (-1.41- -1.20)	-1.94 (-2.04- -1.82)	Ref.[b]	-0.40 (-0.47- -0.34)	-0.70 (-0.76- -0.64)	-1.15 (-1.21- -1.09)
	Ref.[c]	-0.35 (-0.49—-0.22)	-0.54 (-0.68—-0.40)	-0.86 (-0.99- -0.72)	Ref.[c]	-0.17 (-0.22-—0.10)	-0.25 (-0.31- -0.19)	-0.43 (-0.49- -0.38)
	Ref.[d]	-0.35 (-0.45—-0.25)	-0.57 (-0.68—-0.46)	-0.95 (-1.07—-0.84)	Ref.[d]	-0.20 (-0.28- -0.11)	-0.37 (-0.46- -0. 29)	-0.58 (-0.67- -0.49)
	Ref.[e]	-0.32 (-0.49—-0.14)	-0.47 (-0.71—-0.23)	-0.74 (-1.06- -0.42)	Ref.[e]	-0.15 (-0.30- 0.01)	-0.35 (-0.51- -0.19)	-0.39 (-0.60- -0.17)
ASAT	Ref.[b]	-0.73 (-0.83- -0.64)	-1.22 (-1.33- -1.12)	-1.85 (-1.96- -1.75)	Ref.[b]	-0.72 (-0.86- -0.57)	-1.32 (-1.46- -1.19)	-2.41 (-2.54- -2.27)
	Ref.[c]	-0.26 (-0.37- -0.15)	-0.30 (-0.41—-0.18)	-0.51 (-0.62—-0.40)	Ref.[c]	-0.21 (-0.36- -0.07)	-0.23 (-0.36- -0.10)	-0.59 (-0.72- -0.47)
	Ref.[d]	-0.13 (-0.22—0.04)	-0.26 (-0.35—-0.16)	-0.59 (-0.69—-0.49)	Ref.[d]	-0.06 (-0.21- 0.09)	-0.38 (-0.53- -0.23)	-0.57 (-0.73- -0.42)
	Ref.[e]	-0.22 (-0.46—0.01)	-0.33 (-0.64—-0.02)	-0.89 (-1.30- -0.48)	Ref.[e]	0.07 (-0.22- 0.37)	-0.28 (-0.58- 0.03)	-0.52 (-0.94- -0.10)
TTAT	Ref.[b]	-1.49 (-1.66—-1.33)	-2.52 (-2.71—-2.34)	-3.79 (-3.98- -3.60)	Ref.[b]	-1.12 (-1.31—-0.92)	-2.02 (-2.21—-1.83)	-3.56 (-3.74- -3.37)
	Ref.[c]	-0.61 (-0.83—-0.38)	-0.84 (-1.08—-0.61)	-1.36 (-1.59- -1.14)	Ref.[c]	-0.38 (-0.57- -0.18)	-0.48 (-0.66- -0.30)	-1.01 (-1.18- -0.85)
	Ref.[d]	-0.47 (-0.63—-0.31)	-0.83 (-1.01—-0.66)	-1.54 (-1.73- -1.35)	Ref.[d]	-0.26 (-0.47- -0.05)	-0.75 (0.96- -0.54)	-1.15 (-1.36- -0.93)
	Ref.[e]	-0.52 (-0.86—-0.18)	-0.82 (-1.29—-0.36)	-1.63 (-2.24- -1.02)	Ref.[e]	-0.107 (-0.46- 0.33)	-0.63 (-1.04- -0.22)	-0.90 (-1.54- -0.37)
TAT	Ref.[a]	-2.01 (-2.56—-1.46)	-3.40 (-4.01—-2.79)	-4.97 (-5.59- -4.35)	Ref.[b]	-1.85 (-2.52– -1.19)	-3.10 (-3.74– -2.46)	-5.80 (-6.42– -5.18)
	Ref.[b]	-1.05 (-1.77– 0.33)	-0.96 (-1.70– -0.22)	-1.99 (-2.70– -1.28)	Ref.[c]	-0.66 (-1.30– 0.02)	-0.81 (-1.40– -0.22)	-1.38 (-1.94– -0.83)
	Ref.[c]	-0.58 (-1.11– 0.06)	-1.29 (-1.86– -0.72)	-1.82 (-2.43– -1.20)	Ref.[d]	-0.67 (-1.33– -0.02)	-1.06 (-1.72– -0.40)	-1.81 (-2.46– -1.15)
	Ref.[d]	-0.54 (-1.64– 0.56)	-0.05 (-1.62– 1.53)	-1.98 (-3.76– -0.20)	Ref.[e]	-0.14 (-1.42– 1.14)	-0.68 (-2.00– 0.63)	-2.31 (-4.31– 0.31)
TLT	Ref.[b]	-0.37 (-0.62– -0.13)	-0.57 (-0.85– -0.30)	-0.44 (-0.72– -0.16)	Ref.[b]	-0.36 (-0.56– -0.17)	-0.54 (-0.73– -0.35)	-0.76 (-0.94– -0.57)
	Ref.[c]	0.07 (-0.37– 0.52)	0.62 (-0.16– 1.08)	0.57 (-0.13– 1.01)	Ref.[c]	-0.21 (-0.48– 0.06)	-0.18 (-0.43– 0.07)	0.10 (-0.13– 0.34)
	Ref.[d]	0.19 (-0.08– 0.46)	0.18 (-0.12– 0.48)	0.82 (0.51– 1.14)	Ref.[d]	0.11 (-0.14– 0.36)	0.13 (-0.12– 0.39)	0.21 (-0.04– 0.46)
	Ref.[e]	0.0 (-0.53– 0.72)	-0.13 (-0.81—0.55)	1.02 (0.25– 1.79)	Ref.[e]	-0.19 (-0.16– 0.23)	-0.34 (-0.77– 0.09)	-0.38 (-1.04– 0.27)
AFR	Ref.[b]	-0.031 (-0.035– -0.027)	-0.053 (-0.057– -0.049)	-0.085 (-0.090– -0.081)	Ref.[b]	-0.013 (-0.020 – -0.057)	-0.016 (-0.022 – -0.010)	-0.038 (-0.044– -0.031)
	Ref.[c]	-0.023 (-0.031– -0.002)	-0.033 (-0.042– -0.025)	-0.053 (-0.062– -0.046)	Ref.[c]	-0.013 (-0.020– -0.006)	-0.016 (-0.022 – -0.009)	-0.038 (-0.0442 -0.031)
	Ref.[d]	-0.013 (-0.017– -0.008	-0.024 (-0.028– -0.019)	-0.043 (-0.047– -0.038)	Ref.[d]	-0.007 (-0.012– -0.002)	-0.016 (-0.021 – -0.011)	-0.029 (-0.034– -0.024)
	Ref.[e]	-0.011 (-0.016– -0.005	-0.017 (-0.024– -0.009)	-0.036 (-0.046– -0.026)	Ref.[e]	-0.001 (-0.007– 0.005)	-0.008 (-0.014 – -0.002)	-0.013 (-0.021– -0.005)
MFI	Ref.[b]	-0.47 (-0.54 – -0.41)	-0.73 (-0.80 – -0.66)	-1.00 (-1.07– -0.93)	Ref.[b]	-0.39 (-0.47– -0.32)	-0.66 (-0.73– -0.59)	-1.11 (-1.18– -1.04)
	Ref.[c]	-0.38 (-0.49 – -0.27)	-0.46 (-0.58 – -0.35)	-0.64 (-0.75– -0.53)	Ref.[c]	-0.19 (-0.29 – -0.09)	-0.36 (-0.45 – -0.27)	-0.60 (-0.69– -0.52)
	Ref.[d]	-0.24 (-0.32 – -0.16)	-0.38 (-0.47 – -0.29)	-0.51 (-0.60– -0.42)	Ref.[d]	-0.26 (-0.37 – -0.15)	-0.37 (-0.48 – -0.26)	-0.56 (-0.67– -0.45)
	Ref.[e]	-0.27 (-0.43 – -0.11)	-0.38 (-0.59 – -0.16)	-0.54 (-0.83– -0.26)	Ref.[e]	-0.19 (-0.38 – -0.01)	-0.30 (-0.50 – -0.10)	-0.46 (-0.74– -0.18)
TTFM	Ref.[b]	-0.11 (-0.16 – -0.05)	-0.14 (-0.20 – -0.10)	-0.16 (-0.22– -0.10)	Ref.[b]	-0.08 (-0.12 – -0.04)	-0.16 (-0.20 – -0.12)	-0.23 (-0.27– -0.20)
	Ref.[c]	0.15 (0.05- 0.25)	0.29 (0.18 – 0.40)	0.40 (0.30 – 0.50)	Ref.[c]	0.01 (-0.05 – 0.07)	0.03 (-0.03 – 0.08)	0.11 (0.06– 0.17)
	Ref.[d]	0.07 (0.01 – 0.13)	0.18 (0.10 – 0.25)	0.31 (0.23– 0.38)	Ref.[d]	-0.07 (0.01– 0.12)	0.05 (-0.01 – 0.12)	0.12 (0.06– 0.18)
	Ref.[e]	0.14 (0.03 – 0.25)	0.23 (0.08 – 0.38)	0.53 (0.34– 0.73)	Ref.[e]	0.02 (-0.07 – 0.11)	0.02 (-0.07– 0.12)	-0.01 (-0.13– 0.12)

Continued

	Healthy lifestyle index$_{WST}$							
	Men				Women[a]			
	1	2	3	4	1	2	3	4
		β (95%CI)	β (95%CI)	β (95%CI)		β (95%CI)	β (95%CI)	β (95%CI)
WMR	Ref.[b]	-0.27 (-0.30 – -0.24)	-0.45 (-0.48 – -0.41)	-0.66 (-0.70– -0.62)	Ref.[b]	-0.25 (-0.30– -0.20)	-0.43 (-0.48 – -0.38)	-0.80 (-0.85– -0.75)
	Ref.[c]	-0.19 (-0.24 – -0.13)	-0.26 (-0.33 – -0.20)	-0.39 (-0.44– -0.33)	Ref.[c]	-0.10 (-0.16– -0.03)	-0.14 (-0.21 – -0.07)	-0.30 (-0.36– -0.23)
	Ref.[d]	-0.12 (-0.15 – -0.08)	-0.22 (-0.26 – -0.18)	-0.35 (-0.39– -0.31)	Ref.[d]	-0.08 (-0.15– -0.02)	-0.15 (-0.21 – -0.09)	-0.31 (-0.37– -0.26)
	Ref.[e]	-0.16 (-0.24 – -0.09)	-0.25 (-0.35 – -0.15)	-0.49 (-0.63– -0.36)	Ref.[e]	-0.04 (-0.16– 0.09)	-0.16 (-0.29 – -0.04)	-0.21 (-0.38– 0.03)

Table 3. Association between quartiles of health lifestyle index$_{WST}$ and body composition measurements obtained by MRI by body mass index categories. Healthy lifestyle index$_{WST}$ includes: sleep, alcohol, smoking, physical activity, diet, and waist circumference. Results represent beta coefficients and 95% confidence intervals estimated by multivariable linear regression. All analyses are adjusted for age, time between recruitment and MRI exam, race/ethnicity, education, employment status, socioeconomic status, and height. [a] Analysis adjusted for menopausal status. [b] Analysis performed in the whole cohort. [c] Analysis performed in individuals with BMI < 25.0 kg/m^2. [d] Analysis performed in individuals with BMI 25.0 – < 30.0 kg/m^2. [e] Analysis performed in individuals with BMI ≥ 30.0 kg/m^2. Ref., referent group; VAT, visceral adipose tissue volume; ASAT, Abdominal subcutaneous adipose tissue volume; TTAT, total trunk fat volume; TAT, total adipose tissue volume; TLT, total lean tissue volume; AFR, abdominal fat ratio; MFI, muscle fat infiltration; TTFM, total thigh fat-free muscle volume; and WMR, weight to muscle ratio.

diet alone or in combination with physical activity reduced both VAT and ASAT over a period of 12 weeks to 12 months[38]. We also found that a sleep duration of 7- < 9 h was associated with a lower level of adipose tissue and adipose muscle infiltration compared to a shorter sleep duration, but it was not associated with total lean mass. Previous large-scale studies have evaluated the cross-sectional association of sleep duration with body composition [39]. A study conducted in ~ 16.900 Korean men and women measured body composition using DXA and reported that short sleep duration (≤ 5 h/day) was associated with higher adipose tissue volume, while long sleep duration (≥ 9 h/day) was associated with lower lean tissue volume[39,40]. A Swedish study, measured body composition using bio-impedance in ~ 20,000 adults aged 47–75 years, and reported that short (≤ 5 h/day) and long (≥ 8 h/day) sleep durations were associated with higher adipose tissue mass and lower fat-free mass [40]. Our study showed that individuals who did not consume alcohol, particularly men, had a better body composition profile compared to those reporting daily alcohol intake. Previous studies on the association between alcohol intake and body composition measured by DXA have produced contrasting results[41–43]. With regard to cigarette smoking at baseline, we observed that never-smokers had lower VAT, MFI and WMR compared to current smokers. On average, cigarette smokers tend to have a lower BMI compared to never-smokers; however, they also appear to have lower muscle mass and endurance[44]. In addition, the number of cigarettes smoked per day has been found to be directly associated with the level of central adiposity as measured by bio-impedance[45,46]. Some smoking-related effects on muscle are reversible, and while most previous studies have analyzed such relationships cross-sectionally, our prospective study suggested that never-smokers were more likely to have a better subsequent body composition (characterized by lower VAT, ASAT, WMR, MFI and, in men, higher TTFM) compared to current smokers. Taken together, these observations suggest that it is the combination of lifestyle components rather than a specific component that is associated with better body composition.

The analysis by menopausal status showed some differences in the relationship between HLI and the major components of abdominal fat, indicating that while in both menopausal groups higher HLI was associated with lower VAT and ASAT, in premenopausal women the differences in means between the upper HLI quartiles and the referent group were greater for VAT, ASAT, and WMR than in postmenopausal women. Menopause is accompanied by hormonal changes and usually with an increase of adipose tissue and loss of bone and muscle mass, which may not be captured by significant changes in body mass index[47,48]. Our results, based on MRI measures of body composition, indicate that a favorable combination of lifestyle factors is associated with better body composition parameters later in life, even among postmenopausal women.

To the best of our knowledge this is the first study that has combined lifestyle factors into a multilevel index and evaluated its association with several subsequent measurements of body composition. The use of MRI-derived data allowed us to evaluate volumetric components of adipose and muscle tissues, their compartmentalization, their percentage in the body, and the amount of muscle fat infiltration, and to assess their relationship with the HLI. The results of this study showed a dose–response association between the exposure (HLI) and the outcomes, and suggest that a healthy lifestyle may be related to a lower level of adipose tissue and a better muscle profile, but also indicate that having only a few healthy lifestyle characteristics (intermediate levels of HLI), reflecting a less than optimal lifestyle, is associated with a more favorable body composition compared to those with the least healthy lifestyle. The study was conducted on a very large sample, which allowed us to perform the analysis separately in men and women, and in the latter group, by menopausal status. The prospective design suggests a potential long-term impact of healthy habits on body composition. We focused on MRI measurements representing adipose tissue distribution and percentage of body fat content; however, a relationship may also occur between lifestyle index and other indicators of body composition. Lifestyle exposure was either self-reported or directly measured during the baseline visit, rendering the measurements potentially susceptible to misclassification. Self-reported and direct measurements of lifestyle factors were based on data collected at a single point in time and changes may have occurred over time. The analyses were performed in a subgroup of the UK Biobank population; however, despite the relatively younger age of the analytical group compared to the rest of the cohort, this group appeared to be fairly representative of the general cohort. This study included almost only White individuals, and no analysis by race/ethnic group could be performed. Therefore, the results of this study may not be generalizable to other racial/ethnic groups.

In conclusion, the present study showed that there is an inverse association between HLI and the subsequent volume, distribution, and overall percentage of adipose tissue, as well as with muscle mass and muscle adipose infiltration in adult men and women. The aging process is characterized by changes in body composition that are associated with morbidity and mortality and represents an important public health challenge. The adoption of multiple lifestyle habits related to a better body composition profile may be an important approach to reducing the risk of multiple health problems later in life.

Data availability

This work has been conducted using the UK Biobank Resource. The UK Biobank is an open access resource and bona fide researchers canapply to use the UK Biobank dataset by registering and applying at http://ukbiobank.ac.uk/register-apply/ . Further information is avail-able from the corresponding author upon request.

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Author contributions

TER was responsible to the conception and design. RP contributed to the study design, performed statistical analyses and wrote the first draft of the manuscript. Both authors contributed to the interpretation of results, edited the manuscript and approved the final version. RP wrote the first draft of the manuscript. All authors reviewed the manuscript and approved the final version of it.

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Declarations

Competing interests

The authors declare no competing interests.

Ethics statement

The UK Biobank follows the line with the principles of the Declaration of Helsinki. The UK Biobank Study received approval from the National Information Governance Board for Health and Social Care and the National Health Service North West Multicentre Research Ethics Committee. Written informed consent was obtained from all study participants at recruitment.

Additional information

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