

Weight-adjusted waist as an integrated index for fat, muscle and bone health in adults

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Abstract

Background Unhealthy body composition, including high fat mass, low muscle mass and low bone mass, is a critical health issue in adults. The weight-adjusted waist index (WWI) estimates fat and muscle mass and may have implications for bone health. We examined its association with body composition outcomes in a large Korean adult cohort.

Methods This study used data from the Korean National Health and Nutrition Examination Survey (2008–2011). WWI was calculated as waist circumference (cm) divided by the square root of body weight (kg). Dual-energy X-ray absorptiometry was used to measure bone mineral density (BMD), appendicular lean mass (ALM) and total body fat percentage. Unhealthy body composition was defined as combined presence of high fat mass, low bone mass and low muscle mass.

Results A total of 5983 individuals (3034 men [50.7%] and 2949 women [49.3%]; mean age: 63.5 ± 8.7 years) were included. WWI was positively correlated with total body fat percentage ($r = 0.478$, $P < 0.001$) and inversely with ALM/weight ($r = -0.485$, $P < 0.001$) and BMD at the lumbar spine ($r = -0.187$, $P < 0.001$), femoral neck ($r = -0.269$, $P < 0.001$) and total hip ($r = -0.255$, $P < 0.001$). Higher WWI quartiles correlated with lower BMD, T-scores and ALM/weight, along with increased total body fat, evident in both genders and more pronounced in women, even after adjusting for confounders. This trend remained statistically significant across WWI quartiles for all analyses ($P < 0.001$). Higher WWI quartiles were also significantly associated with higher odds of unhealthy body composition, with adjusted odds ratio in the highest WWI group of 18.08 (95% CI, 4.32–75.61) in men and 6.36 (95% CI, 3.65–11.07) in women. The optimal cutoff values of WWI for unhealthy body composition were $10.4 \text{ cm}/\sqrt{\text{kg}}$ in men and $10.5 \text{ cm}/\sqrt{\text{kg}}$ in women.

Conclusions In community-dwelling adults, high WWI values are associated with unfavourable body composition outcomes, indicating high fat mass, low muscle mass and low bone mass. WWI can potentially serve as an integrated index of body composition, underscoring the need for further research to validate its use in clinical settings.

Keywords Anthropometry; Body composition; Obesity; Osteoporosis; Sarcopenia

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Introduction

Decreased bone and muscle mass and increased fat mass are frequently observed in older adults and are associated with pathophysiological processes of aging.¹ The deterioration of

musculoskeletal health is affected by multiple factors, including genetic, mechanical and endocrine factors.² As society ages, an increasing number of people develop multiple age-related disorders such as osteoporosis, sarcopenia and obesity.³ The triad of bone, muscle and adipose tissue dys-

function has been associated with a worsening outcome and has led researchers to propose a new syndrome called 'osteosarcopenic obesity'.⁴ This body composition phenotype is associated with poor functional and clinical outcomes, resulting in a high risk of morbidity and mortality.⁵

The weight-adjusted waist index (WWI) is a recently introduced anthropometric index that is calculated by standardizing waist circumference (WC) to body weight.⁶ Kim et al. reported that WWI is positively associated with fat mass and negatively associated with muscle mass in older adults.⁷ A large-scale cohort study showed that WWI, but not body mass index (BMI), had a positive linear association with cardiometabolic morbidity and mortality.⁶ In older men, WWI has also been shown to be more strongly associated with sarcopenic obesity than other anthropometric indices, including BMI and WC.⁸ Considering that WWI is closely associated with age-related changes in body composition, it may also be associated with changes in bone mass. However, the association between WWI and comprehensive body composition measures, including bone mass, is largely unknown.

This study aimed to evaluate the associations between WWI and three components of osteosarcopenic obesity (fat, muscle and bone mass) in community-dwelling adults. We hypothesized that individuals with a higher WWI have a higher risk of osteosarcopenic obesity and lower bone mass than those with a lower WWI.

Methods

Data sources

Since 1998, the Korea Disease Control and Prevention Agency has periodically conducted the Korean National Health and Nutrition Examination Survey (KNHANES) to evaluate the health and nutritional status of the civilian non-institutionalized population of Korea.⁹ This nationwide survey uses a stratified, multistage, clustered probability sampling method, as previously described.⁹ The KNHANES database contains anonymized personal information, including overall lifestyle habits, anthropometric measurements, laboratory tests, responses to health-related questionnaires and nutritional survey results. Our study was based on data from the fourth and fifth editions of the KNHANES, conducted between 2008 and 2011. The database is publicly available in Korean and English at the KNHANES website (<http://knhanes.cdc.go.kr>).^{10,11}

Study population

The total number of participants in the KNHANES dataset for the 2008–2011 period was 37 753. From this population, we excluded participants aged <50 years, premenopausal

women and participants with no or inadequate whole-body dual-energy X-ray absorptiometry (DXA) data (Figure S1). We further excluded participants who were taking anti-osteoporotic agents, had a history of fractures, had conditions affecting bone metabolism (e.g. chronic renal failure, chronic hepatitis, liver cirrhosis, thyroid disease, rheumatoid arthritis or any type of malignancy), or had missing measurements for WWI calculation. Finally, a total of 5983 participants were included in the analysis.

Measurements of clinical and laboratory parameters

The study participants, comprising 3034 men and 2949 women, underwent a thorough physical examination. Height, weight and WC were measured while the participants were wearing disposable non-woven clothing without shoes or socks. BMI was calculated as weight (kg) divided by height squared (m²). WWI was calculated as WC (cm) divided by the square root of weight (√kg). The details of the development of WWI have been described in a previous study.⁶

Smoking status (none or current), alcohol consumption (never, mild or moderate) and physical activity were also recorded. Moderate alcohol consumption was defined as consuming ≥2 drinks/week. Regular exercise was defined as moderate-intensity exercise for >30 min more than five times per week or high-intensity exercise for >20 min more than three times per week. Systolic blood pressure (mmHg) was recorded twice after a 15-min rest using a mercury manometer with an appropriate cuff size, and the mean value was calculated. In the morning after 8 h of fasting, blood samples were drawn from the antecubital vein, immediately refrigerated, transported to the Central Testing Institute (Neodin Medical Inc., Seoul, Korea) and analysed within 24 h. Fasting plasma glucose, total cholesterol, high-density lipoprotein cholesterol, low-density lipoprotein cholesterol, triglyceride, aspartate aminotransferase, alanine aminotransferase, creatinine, parathyroid hormone and serum 25(OH)D (25-hydroxy vitamin D) levels were measured. Co-morbidities, including hypertension, diabetes, dyslipidaemia and osteoporosis, were defined as a history of relevant diagnoses or use of relevant medications.

Definition of high fat mass, low bone mass and low muscle mass

Body composition was measured using a DXA system (QDR 4800A; Hologic, Bedford, MA, USA), operated by trained and licensed technicians. Bone mineral density (BMD) measurements at the lumbar spine (L1–4), femoral neck and total hip were analysed using standard techniques. Appendicular lean mass (ALM [kg]) was defined as the sum of the lean soft

tissue mass of the four limbs. ALM adjusted for weight (ALM/weight) was analysed as the appendicular muscle mass index.

High fat mass was defined as a total body fat percentage of >25% in men and >35% in women.^{5,12} Low bone mass, ranging from osteopenic to osteoporotic levels, was defined as a T-score of ≤ -1.0 standard deviation (SD) for BMD at the lumbar spine, femoral neck, or proximal femur.² Low muscle mass was defined as ALM/weight <2 SDs below the mean for a young reference group (age 20–39 years), with a cutoff value of 28.8% in men and 22.8% in women.^{13,14}

Statistical analysis

Data are presented as numbers with percentages for categorical variables and means with SDs for continuous variables. Independent t-tests and chi-square analyses were used to compare the clinical characteristics of male and female participants. We used Spearman's partial correlation analysis to investigate the correlation between WWI (as an independent variable) and the body composition parameters (as dependent variables). Subsequent analyses were separately performed for men and women according to WWI quartiles. One-way analysis of variance was conducted to evaluate the association between WWI and metabolic variables. To further analyse the composite fat, muscle and bone outcomes according to WWI quartiles, multivariate logistic regression analysis was used to calculate odds ratios (ORs) and 95% confidence intervals (95% CIs) after adjustment for age, smoking, alcohol consumption, regular exercise, co-morbidities (hypertension, diabetes and dyslipidaemia) and serum 25(OH)D levels. Receiver operating characteristic curves were plotted, and the area under the curve was calculated to compare the relative diagnostic strengths of the analysed parameters in identifying composite body composition outcomes. Statistical significance was defined as a two-sided *P*-value of <0.05. All analyses were performed using the SAS software (version 9.4; SAS Institute Inc., Cary, NC, USA).

Results

Baseline characteristics of study participants

The characteristics of participants are shown in Table S1. The mean age of male and female participants was 63.2 ± 8.6 and 63.9 ± 8.8 years, respectively. The mean BMI and WC were 23.8 ± 3.0 kg/m² and 85.4 ± 8.53 cm in men and 24.2 ± 3.2 kg/m² and 82.4 ± 9.2 cm in women, respectively. The WWI values were normally distributed in a bell-shaped curve between 8.17 and 13.93 cm/vkg (Figure S2). The mean WWI value was higher in women than in men (11.0 ± 0.8 vs. 10.5 ± 0.6 cm/vkg). Table 1 shows the baseline characteristics of male and female participants according to the quartiles of

WWI. Participants in the higher quartile groups were older, had higher obesity levels, and had an unhealthier lifestyle, characterized by a higher prevalence of current smoking and moderate alcohol consumption, and lower prevalence of regular exercise, than those in the lower quartile groups. Participants in the higher quartile groups also had unhealthy metabolic characteristics, including high fasting plasma glucose and triglyceride levels and low high-density lipoprotein cholesterol levels. The prevalence of osteoporosis was higher in the higher WWI quartiles only in women.

Association between weight-adjusted waist index and fat, muscle and bone parameters

Table 2 shows the association between WWI and each body composition measurement (total body fat for fat mass, ALM/weight for muscle mass and BMD at all sites for bone mass). BMD at all sites and ALM/weight were negatively associated, whereas total body fat was positively associated, with WWI in all participants. When data were separately analysed for men and women, similar results were obtained; however, the negative association between WWI and BMD was clearer in women than in men.

Table 3 compares the mean values of body composition measurements according to WWI quartiles. Both male and female participants in the higher quartiles of WWI tended to have lower BMD values and T-scores than those in the lower quartiles. This linear association was clearer in women than in men. For example, when female participants were compared across all WWI quartiles, those in the highest quartile (Q4) showed the lowest BMD values and T-scores at all sites. Figure S3 shows that women in the higher WWI quartiles (Q3 and Q4) showed lower BMD values at all sites than those in the lowest quartile (Q1), even after adjustment for confounders such as age, smoking, alcohol consumption, regular exercise, co-morbidities and serum 25(OH)D levels (all $P < 0.01$). In addition, ALM/weight tended to decrease, whereas total body fat tended to increase, from the lowest to the highest quartile in both men and women ($P < 0.01$ for all analyses).

Odds of an unhealthy body composition according to weight-adjusted waist index quartiles

The prevalence of an unhealthy body composition (combination of high fat mass, low muscle mass and low bone mass) was the lowest in Q1 and the highest in Q4 of WWI (Table 4). The ORs for unhealthy body composition outcomes were significantly higher in Q3 and Q4 of WWI than in Q1 in both men and women (OR, 5.52 [95% CI, 1.24–24.62] in Q3 and 18.08 [95% CI, 4.32–75.61] in Q4 in men; OR, 2.80 [95% CI, 1.58–4.95] in Q3 and 6.36 [95% CI, 3.65–11.07] in Q4 in women).

Table 1 Baseline characteristics according to WWI quartiles

Variables	Men (n = 3034)					Women (n = 2949)				
	Q1 (WWI ≤ 10.1 cm/ √kg) (n = 758)	Q2 (WWI 10.1– 10.5 cm/√kg) (n = 759)	Q3 (WWI 10.5– 10.9 cm/√kg) (n = 759)	Q4 (WWI ≥ 10.9 cm/ √kg) (n = 758)	P- value	Q1 (WWI ≤ 10.4 cm/ √kg) (n = 736)	Q2 (WWI 10.4– 11.0 cm/√kg) (n = 738)	Q3 (WWI 11.0– 11.5 cm/√kg) (n = 738)	Q4 (WWI ≥ 11.5 cm/ √kg) (n = 737)	P- value
WWI (cm/√kg)	9.8 ± 0.3	10.3 ± 0.1	10.7 ± 0.1	11.3 ± 0.3	<0.01	10.0 ± 0.4	10.7 ± 0.2	11.2 ± 0.1	12.0 ± 0.4	<0.01
Age (years)	60.8 ± 8.7	61.8 ± 8.3	63.5 ± 8.3	66.5 ± 8.1	<0.01	59.7 ± 8.1	62.4 ± 8.4	64.4 ± 8.1	68.9 ± 7.9	<0.01
Waist circumference (cm)	77.5 ± 7.2	84.0 ± 6.0	87.4 ± 6.2	92.5 ± 6.7	<0.01	73.3 ± 6.3	80.2 ± 6.0	85.2 ± 6.3	91.0 ± 7.6	<0.01
Height (cm)	168.3 ± 5.8	167.5 ± 5.6	166.1 ± 5.5	164.2 ± 5.7	<0.01	155.5 ± 5.4	154.0 ± 5.6	152.7 ± 5.3	150.0 ± 5.6	<0.01
Weight (kg)	63.1 ± 10.4	66.4 ± 9.3	66.8 ± 9.3	67.6 ± 9.2	<0.01	54.3 ± 7.8	56.2 ± 8.0	57.9 ± 8.5	58.2 ± 9.1	<0.01
Body mass index (kg/m ²)	22.2 ± 3.0	23.6 ± 2.6	24.2 ± 2.7	25.0 ± 2.8	<0.01	22.4 ± 2.7	23.6 ± 2.7	24.7 ± 2.9	25.8 ± 3.3	<0.01
Systolic blood pressure (mmHg)	125.2 ± 17.9	126.5 ± 16.5	129.6 ± 17.7	129.3 ± 16.6	<0.01	122.6 ± 18.0	126.9 ± 18.1	129.4 ± 17.5	133.5 ± 17.9	<0.01
Current smoking, n (%)	589 (77.8)	634 (83.9)	615 (81.2)	616 (81.5)	0.03	46 (6.3)	49 (6.7)	55 (7.5)	83 (11.3)	<0.01
Moderate alcohol consumption, n (%)	294 (39.9)	314 (41.5)	333 (44.1)	322 (42.7)	0.11	43 (5.9)	43 (5.9)	42 (5.7)	45 (6.2)	<0.01
Regular exercise, n (%)	236 (31.2)	197 (26.1)	172 (22.7)	185 (24.5)	<0.01	192 (26.2)	170 (23.1)	151 (20.5)	137 (18.7)	<0.01
Fasting plasma glucose (mmol/L)	100.3 ± 26.1	104.3 ± 26.2	108.1 ± 32.3	108.7 ± 27.7	<0.01	94.6 ± 13.5	99.7 ± 21.6	105.4 ± 29.0	106.6 ± 27.8	<0.01
Total cholesterol (mg/dL)	184.7 ± 35.1	186.7 ± 36.1	189.7 ± 37.0	186.0 ± 38.1	0.07	201.1 ± 34.4	202.8 ± 36.0	203.6 ± 37.4	203.7 ± 39.0	0.51
HDL cholesterol (mg/dL)	48.5 ± 12.2	45.4 ± 10.9	43.5 ± 10.8	43.1 ± 10.5	<0.01	51.9 ± 12.1	48.2 ± 10.6	46.1 ± 10.1	45.5 ± 10.2	<0.01
LDL cholesterol (mg/dL)	111.0 ± 33.1	110.2 ± 34.7	110.9 ± 36.8	106.0 ± 40.0	0.03	125.1 ± 30.3	127.2 ± 33.9	127.8 ± 34.1	126.6 ± 36.3	0.48
Triglyceride (mg/dL)	126.1 ± 95.4	155.9 ± 109.8	176.4 ± 142.0	184.2 ± 173.1	<0.01	120.0 ± 73.0	137.0 ± 91.4	148.5 ± 92.2	157.8 ± 92.5	<0.01
Aspartate aminotransferase (IU/L)	25.1 ± 15.4	26.0 ± 17.0	26.3 ± 15.7	27.1 ± 17.9	0.15	22.5 ± 9.0	22.2 ± 7.3	22.9 ± 9.1	23.5 ± 9.2	0.04
Alanine aminotransferase (IU/L)	21.8 ± 13.4	24.2 ± 14.9	26.0 ± 20.0	26.3 ± 15.0	<0.01	19.1 ± 11.9	19.3 ± 10.4	21.1 ± 16.0	21.3 ± 13.1	<0.01
Creatinine (μmol/L)	0.95 ± 0.17	0.95 ± 0.17	0.95 ± 0.17	0.97 ± 0.21	0.06	0.71 ± 0.11	0.72 ± 0.12	0.72 ± 0.14	0.74 ± 0.22	<0.01
Parathyroid hormone (pg/mL)	64.6 ± 23.3	64.2 ± 23.7	65.8 ± 26.8	67.0 ± 28.1	0.15	64.5 ± 23.3	66.4 ± 35.8	66.3 ± 26.8	74.4 ± 39.9	<0.01
25(OH)D (ng/mL)	21.4 ± 7.6	21.7 ± 7.3	21.7 ± 7.1	21.4 ± 7.5	0.78	17.8 ± 6.5	19.0 ± 7.2	18.6 ± 6.8	19.2 ± 7.2	<0.01
Hypertension, n (%)	189 (24.9)	268 (35.3)	310 (40.8)	368 (48.6)	<0.01	179 (24.3)	263 (35.6)	320 (43.4)	414 (56.2)	<0.01
Diabetes mellitus, n (%)	65 (8.6)	88 (11.6)	147 (19.4)	161 (21.2)	<0.01	27 (3.7)	85 (11.5)	112 (15.2)	163 (22.1)	<0.01
Dyslipidaemia, n (%)	64 (8.4)	83 (10.9)	98 (12.9)	114 (15.0)	<0.01	117 (15.9)	131 (17.8)	123 (16.7)	113 (15.3)	0.62
Osteoporosis, n (%)	10 (1.3)	5 (0.7)	10 (1.4)	14 (1.9)	0.24	63 (8.8)	87 (11.9)	96 (13.1)	121 (16.6)	<0.01

Data are presented as mean ± standard deviation or number (percentage).
 25(OH)D, 25-hydroxy vitamin D; HDL, high-density lipoprotein; Q, quartile; WWI, weight-adjusted waist index.

Table 2 Spearman partial correlation analysis of WWI and each body composition parameter

	Total		Men		Women	
	<i>r</i>	<i>P</i> -value	<i>r</i>	<i>P</i> -value	<i>r</i>	<i>P</i> -value
Total body fat percentage	0.478	<0.001	0.475	<0.001	0.338	<0.001
ALM/weight	−0.485	<0.001	−0.498	<0.001	−0.361	<0.001
Lumbar spine BMD	−0.187	<0.001	0.030	0.097	−0.142	<0.001
Femoral neck BMD	−0.269	<0.001	−0.065	0.003	−0.219	<0.001
Total hip BMD	−0.255	<0.001	−0.036	0.005	−0.186	<0.001

The Spearman partial correlation analysis was done for WWI (independent variable) and body composition parameters (dependent variables).

ALM, appendicular lean mass; BMD, bone mineral density; WWI, weight-adjusted waist index.

Table 3 Mean values of musculoskeletal parameters according to WWI quartiles

Variables	Q1	Q2	Q3	Q4	<i>P</i> -value
WWI quartile (men)					
Lumbar spine BMD (g/cm ²)	0.927 ± 0.152	0.954 ± 0.158	0.949 ± 0.152	0.941 ± 0.156	0.005
Femoral neck BMD (g/cm ²)	0.748 ± 0.123	0.761 ± 0.121	0.750 ± 0.119	0.729 ± 0.116	<0.001
Total hip BMD (g/cm ²)	0.921 ± 0.133	0.940 ± 0.129	0.932 ± 0.125	0.909 ± 0.124	<0.001
Lumbar spine T-score	−0.8 ± 1.3	−0.6 ± 1.3	−0.6 ± 1.3	−0.7 ± 1.3	0.005
Femoral neck T-score	−0.8 ± 1.0	−0.7 ± 1.0	−0.8 ± 1.0	−0.9 ± 0.9	<0.001
Total hip T-score	−0.1 ± 1.0	0.0 ± 0.9	−0.1 ± 0.9	−0.2 ± 0.9	<0.001
Lowest T-score	−1.2 ± 1.0	−1.0 ± 1.0	−1.1 ± 1.0	−1.2 ± 1.0	0.002
ALM/weight (%)	35.1 ± 2.6	33.6 ± 2.4	32.9 ± 2.4	31.6 ± 2.5	<0.001
Total fat percentage (%)	19.0 ± 4.9	21.9 ± 4.5	23.4 ± 4.5	25.3 ± 4.5	<0.001
WWI quartile (women)					
Lumbar spine BMD (g/cm ²)	0.817 ± 0.152	0.816 ± 0.149	0.796 ± 0.134	0.765 ± 0.127	<0.001
Femoral neck BMD (g/cm ²)	0.643 ± 0.112	0.634 ± 0.110	0.621 ± 0.108	0.581 ± 0.104	<0.001
Total hip BMD (g/cm ²)	0.792 ± 0.125	0.787 ± 0.119	0.775 ± 0.118	0.733 ± 0.116	<0.001
Lumbar spine T-score	−1.6 ± 1.3	−1.7 ± 1.3	−1.8 ± 1.2	−2.1 ± 1.1	<0.001
Femoral neck T-score	−1.5 ± 1.1	−1.6 ± 1.0	−1.7 ± 1.0	−2.1 ± 1.0	<0.001
Total hip T-score	−0.5 ± 1.1	−0.6 ± 1.0	−0.7 ± 1.0	−1.0 ± 1.0	<0.001
Lowest T-score	−1.9 ± 1.1	−2.0 ± 1.1	−2.1 ± 1.0	−2.5 ± 0.9	<0.001
ALM/weight (%)	27.5 ± 2.8	26.6 ± 2.5	25.8 ± 2.4	25.0 ± 2.5	<0.001
Total fat percentage (%)	31.7 ± 5.7	33.6 ± 5.0	35.1 ± 5.0	36.4 ± 4.8	<0.001

Data are presented as mean ± standard deviation. The means of musculoskeletal parameters were compared by one-way analysis of covariance.

ALM, appendicular lean mass; BMD, bone mineral density; Q, quartile; WWI, weight-adjusted waist index.

Table 4 Prevalence and odds ratios of unhealthy body composition outcomes of high fat mass, low muscle mass and low bone mass according to WWI quartiles

	Prevalence (%)	OR (95% CI)	Adjusted OR* (95% CI)
Unhealthy body composition outcomes (high fat mass, ^a low bone mass ^b and low muscle mass ^c)			
Men			
WWI Q1	2 (2.4%)	Ref.	Ref.
WWI Q2	8 (9.8%)	4.03 (0.85–19.02)	3.63 (0.76–17.26)
WWI Q3	14 (17.1%)	7.10 (1.61–31.36)	5.52 (1.24–24.62)
WWI Q4	58 (70.7%)	31.32 (7.62–128.69)	18.08 (4.32–75.61)
<i>P</i> for trend		<0.001	<0.001
Women			
WWI Q1	17 (7.4%)	Ref.	Ref.
WWI Q2	30 (13%)	1.79 (0.98–3.28)	1.48 (0.79–2.77)
WWI Q3	56 (24.2%)	3.47 (2.00–6.04)	2.80 (1.58–4.95)
WWI Q4	128 (55.4%)	8.89 (5.30–14.91)	6.36 (3.65–11.07)
<i>P</i> for trend		<0.001	<0.001

CI, confidence interval; OR, odds ratio; Q, quartile; WWI, weight-adjusted waist index.

^aFat mass > 25% in men and >35% in women.

^bWeight-adjusted appendicular lean mass (appendicular lean mass/weight × 100) < 2 standard deviations below the sex-specific average for a young reference group.

^cLowest T-score ≤ −1.0 at the lumbar spine, femoral neck and total hip.

*Adjusted for age, smoking, alcohol consumption, exercise, co-morbidities (hypertension, diabetes and dyslipidaemia) and 25-hydroxy vitamin D levels.

According to receiver operating characteristic curve analysis, the optimal cutoff value of WWI for an unhealthy body composition was 10.4 cm/vkg (0.851 [95% CI, 0.811–0.890]; sensitivity, 0.803; specificity, 0.841) and 10.5 cm/vkg (0.749 [95% CI, 0.714–0.783]; sensitivity, 0.704; specificity, 0.701) in men and women, respectively (Figure 1).

Discussion

In this population-based cohort study of middle-aged and older adults, we found that WWI was differently associated with body composition measures: As WWI increased, fat mass increased and muscle and bone mass decreased. Participants with a higher WWI had higher odds of an unhealthy body composition (combination of high fat mass, low bone mass and low muscle mass) after adjustment for possible confounders. The optimal cutoff value for detecting an unhealthy body composition was 10.4 cm/vkg in men and 10.5 cm/vkg in women.

Aging leads to changes in body composition measurements, including fat, muscle and bone mass.¹ Increasing age is also associated with the redistribution of fat tissue into the visceral area as well as increased adipogenesis in bone and muscle tissues.¹⁵ Muscle mass or strength peaks between ages 30 and 40 years and decreases thereafter, resulting in sarcopenia.¹⁶ In addition, bone mass also de-

creases after peaking at approximately age 30 years.¹⁷ The rate of bone loss accelerates after menopause in women.¹⁷ Growing evidence suggests that crosstalk between fat, muscle and bone tissues during aging results in common body composition changes such as increased fat mass and decreased muscle and bone mass.^{18–20} This triad of body composition changes contributes to unhealthy body composition outcomes such as metabolic disorders, falls, fractures, impaired functional performance and mortality.⁴ Therefore, a comprehensive evaluation of body composition is required.

DXA is the gold standard method for analysing body composition; however, it is costly and time consuming.²¹ In addition, it does not provide a single body composition indicator that is associated with unhealthy outcomes. Multiple anthropometric indices have been evaluated for their role as potential indicators of body composition. In a prior study, traditional anthropometric indices, BMI and WC, were found to have a stronger association with high fat mass compared to the WWI, as evidenced by their age-adjusted ORs of 3.9 and 4.6 versus 2.3 respectively, per one standard deviation.⁸ BMI and WC are valuable in predicting obesity-related health risks owing to their significant associations with body fat mass.²² However, these indices are limited by their inability to distinguish fat and muscle mass, which often resulted in 'obesity paradox' phenomenon.^{6,23–26} Previous researches suggested that sarcopenic obesity, rather than simple obesity, posed a significantly elevated risk of morbidity and mortality.^{27,28} The coexistence of sarcopenia and obesity con-

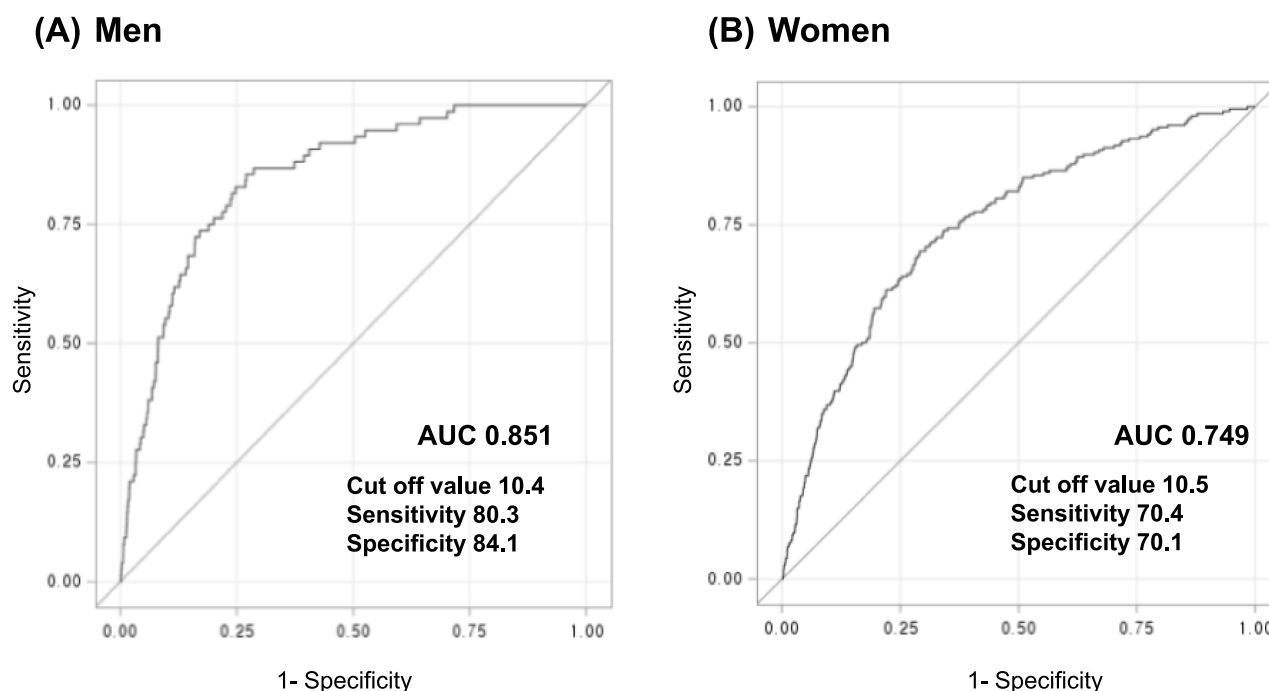


Figure 1 Area under the receiver operating characteristic curve of weight-adjusted waist index (WWI) for predicting the composite outcome (high fat mass, low muscle mass, and low bone mass) in (A) men and (B) women. The cutoff value of WWI was 10.4 cm/vkg in men (area under the curve, 0.851) and 10.5 cm/vkg in women (area under the curve, 0.749). AUC, area under the receiver operating characteristic curve.

stituted a substantial risk factor for all-cause mortality, independently of established risk elements such as cardiovascular disease, systemic inflammation and weight loss.²⁹ Of note, this elevated mortality risk was not associated with obesity in isolation, underscoring the consideration of body composition would be required for health risk calculation. In this regard, WWI, as an anthropometric metric to represent a complex condition of sarcopenic obesity, could potentially outperform traditional measures like BMI and WC regarding various health outcomes.

Unlike conventional anthropometric indices, WWI simultaneously reflects different age-related changes in body composition. A contradictory association between WWI and fat and muscle mass has been reported in several previous studies.^{7,8} Although the negative correlation of WWI with muscle mass is rather weak compared with its positive correlation with fat mass, WWI has been shown to be a potential single indicator that can reflect different body composition changes.⁷ This relationship was first demonstrated in older Asian adults and later confirmed in a multiethnic cohort study. WWI is an index that standardizes WC for body weight.³⁰ Therefore, a high WWI indicates that a person with a larger WC has a higher amount of fat mass and a proportionally lower amount of muscle mass than a person of the same weight with a smaller WC. Our study further revealed a negative correlation between WWI and bone mass based on the observation that WWI was negatively correlated with fat-free mass. However, because WWI is associated with sarcopenic obesity, decreased bone mass in individuals with a high WWI may reflect secondary changes related to sarcopenic obesity.³¹ Further studies investigating this issue in more detail are needed.

In our study, several sex-specific differences were observed in the association between WWI and body composition measures. Women had a higher mean WWI than men (11.0 vs. 10.5 cm/Vkg), suggesting that women have an unhealthier body composition than men. Similar results have been observed in previous studies.⁸ The inverse association between WWI and bone mass was more significant in women than in men. The exact reason for this result is unclear; however, the rapid decrease in bone mass that occurs after menopause in women, which leads to a wide range of bone mass distributions, may have resulted in statistical significance.

This study has several strengths and limitations. As this study has a cross-sectional design, it has the limitation of presenting only simple correlations. Nevertheless, this study has the strengths of being based on a large population-based cohort and using a precise tool to measure body composition. As this study targeted a specific population group (Korean men and women aged ≥ 50 years), additional studies including other races or younger populations are required for the generalizability of our findings. In addition, cultural differences, which can impact body composition and the as-

sociation between WWI and body composition outcomes, were not accounted for in our study.³² Lastly, despite adjusting for several potential confounders, there may be other unmeasured or unknown factors that could influence our findings. Future studies should consider these limitations and extend the investigation to more diverse populations, taking into account additional potential confounders and cultural variables, to improve the understanding and applicability of WWI as a measure for assessing body composition and health outcomes.

In conclusion, this study indicated that among middle-aged and older adults, WWI was inversely associated with bone and muscle mass, but positively correlated with fat mass. This implies that individuals with higher WWI values may exhibit an unhealthy body composition, marked by low muscle and bone mass. Accordingly, measurement of WWI would help to identify individuals at risk of sarcopenia or frailty. We proposed a cutoff value of 10.4 cm/Vkg in men and 10.5 cm/Vkg in women for unhealthy body composition. Currently, there are limited strategies to increase muscle mass and prevent aging-related body compositional changes. The identification of people at risk of unhealthy body composition would be the starting point to improve health outcomes in affected people. Clinical research related to anti-obesity, anti-aging and anti-sarcopenia in the future will be able to present changes in BMI as well as changes in WWI as an outcome.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Online supplementary material

Additional supporting information may be found online in the Supporting Information section at the end of the article.

References

1. Ilich JZ, Kelly OJ, Inglis JE, Panton LB, Duque G, Ormsbee MJ. Interrelationship among muscle, fat, and bone: connecting the dots on cellular, hormonal, and whole body levels. *Ageing Res Rev* 2014;**15**:51–60.
2. Kelly OJ, Gilman JC, Boschiero D, Ilich JZ. Osteosarcopenic obesity: current knowledge, revised identification criteria and treatment principles. *Nutrients* 2019;**11**: 747.
3. Ilich JZ, Kelly OJ, Inglis JE. Osteosarcopenic obesity syndrome: what is it and how can it be identified and diagnosed? *Curr Gerontol Geriatr Res* 2016;**2016**.
4. Ormsbee MJ, Prado CM, Ilich JZ, Purcell S, Siervo M, Folsom A, et al. Osteosarcopenic obesity: the role of bone, muscle, and fat on health. *J Cachexia Sarcopenia Muscle* 2014;**5**:183–192.
5. Lee K. Association of osteosarcopenic obesity and its components: osteoporosis, sarcopenia and obesity with insulin resistance. *J Bone Miner Metab* 2020;**38**: 695–701.
6. Park Y, Kim NH, Kwon TY, Kim SG. A novel adiposity index as an integrated predictor of cardiometabolic disease morbidity and mortality. *Sci Rep* 2018;**8**:16753.
7. Kim NH, Park Y, Kim NH, Kim SG. Weight-adjusted waist index reflects fat and muscle mass in the opposite direction in older adults. *Age Ageing* 2021;**50**:780–786.
8. Kim JE, Choi J, Kim M, Won CW. Assessment of existing anthropometric indices for screening sarcopenic obesity in older adults. *Br J Nutr* 2022;**129**:1, 875–13, 887.
9. Kweon S, Kim Y, Jang MJ, Kim Y, Kim K, Choi S, et al. Data resource profile: the Korea National Health and Nutrition Examination Survey (KNHANES). *Int J Epidemiol* 2014;**43**:69–77.
10. Kim SG, Ko K, Hwang IC, Suh HS, Kay S, Caterson I, et al. Relationship between indices of obesity obtained by anthropometry and dual-energy X-ray absorptiometry: the Fourth and Fifth Korea National Health and Nutrition Examination Survey (KNHANES IV and V, 2008–2011). *Obes Res Clin Pract* 2015;**9**:487–498.
11. Ahn SH, Lee SH, Kim H, Kim BJ, Koh JM. Different relationships between body compositions and bone mineral density according to gender and age in Korean populations (KNHANES 2008–2010). *J Clin Endocrinol Metab* 2014;**99**:3811–3820.
12. Li Y, Wang H, Wang K, Wang W, Dong F, Qian Y, et al. Optimal body fat percentage cut-off values for identifying cardiovascular risk factors in Mongolian and Han adults: a population-based cross-sectional study in Inner Mongolia. *China BMJ Open* 2017;**7**: e014675.
13. Janssen I, Heymsfield SB, Ross R. Low relative skeletal muscle mass (sarcopenia) in older persons is associated with functional impairment and physical disability. *J Am Geriatr Soc* 2002;**50**:889–896.
14. Kim JA, Hwang SY, Yu JH, Roh E, Hong SH, Lee YB, et al. Association of the triglyceride and glucose index with low muscle mass: KNHANES 2008–2011. *Sci Rep* 2021;**11**:450.
15. Migliaccio S, Greco EA, Wannenens F, Donini LM, Lenzi A. Adipose, bone and muscle tissues as new endocrine organs: role of reciprocal regulation for osteoporosis and obesity development. *Horm Mol Biol Clin Invest* 2014;**17**:39–51.
16. Cruz-Jentoft AJ, Baeyens JP, Bauer JM, Boirie Y, Cederholm T, Landi F, et al. Sarcopenia: European consensus on definition and diagnosis: report of the European Working Group on Sarcopenia in Older People. *Age Ageing* 2010;**39**:412–423.
17. Matkovic V, Jelic T, Wardlaw GM, Ilich JZ, Goel PK, Wright JK, et al. 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* 1994;**93**:799–808.
18. Hirschfeld H, Kinsella R, Duque G. Osteosarcopenia: where bone, muscle, and fat collide. *Osteoporos Int* 2017;**28**: 2781–2790.
19. Jung YW, Hong N, Na JC, Han WK, Rhee Y. Computed tomography-derived skeletal muscle radiodensity is an early, sensitive marker of age-related musculoskeletal changes in healthy adults. *Endocrinol Metab (Seoul)* 2021;**36**:1201–1210.
20. Kim KJ, Choi J, Kim JY, Bae JH, Kim KJ, Kim HY, et al. Statin therapy and the risk of osteoporotic fractures in patients with metabolic syndrome: a nested case-control study. *J Lipid Atheroscler* 2021;**10**:322–333.
21. Scafoglieri A, Clarys JP. Dual energy X-ray absorptiometry: gold standard for muscle mass? *J Cachexia Sarcopenia Muscle* 2018;**9**:786–787.
22. Ross R, Neeland IJ, Yamashita S, Shai I, Seidell J, Magni P, et al. Waist circumference as a vital sign in clinical practice: a Consensus Statement from the IAS and ICCR Working Group on Visceral Obesity. *Nat Rev Endocrinol* 2020;**16**:177–189.
23. Gurunathan U, Myles PS. Limitations of body mass index as an obesity measure of perioperative risk. *Br J Anaesth* 2016;**116**: 319–321.
24. Kim SH, Yi SW, Yi JJ, Kim YM, Won YJ. Association between body mass index and the risk of hip fracture by sex and age: a prospective cohort study. *J Bone Miner Res* 2018;**33**:1603–1611.
25. Lee G, Choi S, Park SM. Association of waist circumference with muscle and fat mass in adults with a normal body mass index. *Nutr Res Pract* 2021;**15**:604–612.
26. Yoo MC, Won CW, Soh Y. Association of high body mass index, waist circumference, and body fat percentage with sarcopenia in older women. *BMC Geriatr* 2022;**22**:937.
27. Atkins JL, Whincup PH, Morris RW, Lennon LT, Papacosta O, Wannamethee SG. Sarcopenic obesity and risk of cardiovascular disease and mortality: a population-based cohort study of older men. *J Am Geriatr Soc* 2014;**62**:253–260.
28. Sanada K, Chen R, Willcox B, Ohara T, Wen A, Takenaka C, et al. Association of sarcopenic obesity predicted by anthropometric measurements and 24-y all-cause mortality in elderly men: the Kuakini Honolulu Heart Program. *Nutrition* 2018;**46**:97–102.
29. Roh E, Choi KM. Health consequences of sarcopenic obesity: a narrative review. *Front Endocrinol (Lausanne)* 2020;**11**:332.
30. Kim JY, Choi J, Vella CA, Criqui MH, Allison MA, Kim NH. Associations between weight-adjusted waist index and abdominal fat and muscle mass: multi-ethnic study of atherosclerosis. *Diabetes Metab J* 2022;**46**:747–755.
31. Chung JH, Hwang HJ, Shin HY, Han CH. Association between sarcopenic obesity and bone mineral density in middle-aged and elderly Korean. *Ann Nutr Metab* 2016;**68**: 77–84.
32. Dressler WW, Oths KS, Balieiro MC, Ribeiro RP, Dos Santos JE. How culture shapes the body: cultural consonance and body mass in urban Brazil. *Am J Hum Biol* 2012;**24**: 325–331.