



OPEN Myostatin as a plausible biomarker for early stage of sarcopenic obesity

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Since sarcopenic obesity (SO) impacts negatively on our health, early detection of SO is essential. However, prevalence of SO in an apparently healthy population has not been well examined. This study aimed to elucidate the prevalence and related factors of SO in middle-aged women, and to investigate useful diagnostic criteria for SO. Body component analyses were conducted on 432 female Osaka University employees aged 30–59 during their health checkups. Healthy (H) and SO groups were defined using cutoff values of 5.7 kg/m² for skeletal muscle mass index and 30% for percent body fat. Serum myostatin and insulin levels were additionally measured. Among 432 participants, the prevalence of SO was 6.3%. Grip strength ($P < 0.0001$) was lower and triglyceride ($P = 0.0004$) and low-density lipoprotein cholesterol ($P = 0.0105$) levels, and Homeostatic Model Assessment of Insulin Resistance ($P = 0.0262$) were higher in the SO group than in the H group. Serum myostatin levels in the SO group were lower than in the H group (3,107 pg/mL vs. 3,957 pg/mL, $P = 0.0003$). Myostatin levels may be suppressed in individuals with SO without any pre-existing conditions. Our diagnostic criteria for SO could reveal the risks for metabolic-related diseases and may be useful for the early detection of SO.

Keywords Myostatin, Sarcopenia, Obesity, Metabolic diseases

Sarcopenic obesity (SO) is characterized by a concomitant reduction in skeletal muscle mass and increase in body fat. Since previous studies have shown that patients with SO are more likely to have hypertension¹, dyslipidemia², metabolic syndrome^{3,4}, and vascular events⁵ than those with sarcopenia or obesity alone, SO has been gaining attention in recent years. While often reported in older adults and even young to middle-aged women, those with SO have higher complication rates of metabolic syndrome⁶, type 2 diabetes⁷, and hypertension⁷ than those without SO. Moreover, SO is associated with reduced physical function in middle-aged women⁸. Thus, early detection and management of SO in the early stages is important. However, because SO is typically unaccompanied by obesity or thinness, distinguishing individuals with SO from healthy individuals is challenging. In general, SO is defined using body composition analyses. However, because body composition analyses are not usually performed during periodic health checkups at workplaces, the prevalence of SO and its related factors in relatively young populations remain unknown.

Our study also focused on myostatin, cytokine within the TGF- β family in 1997⁹. Myostatin is predominantly produced and secreted in the skeletal muscle, so serum myostatin levels are positively correlated with skeletal muscle mass^{10–12}, grip strength^{10,13}, lower limb muscle strength¹⁴, and gait speed¹⁵. Myostatin suppresses skeletal muscle proliferation by binding to receptors on the surface of skeletal muscle cells. Circulating myostatin levels have also been reported to be inappropriately elevated in older adults^{16,17} and patients with liver cirrhosis^{18–20}, renal failure^{21–23}, heart failure^{24–26} and diabetes mellitus²⁷. In addition, myostatin has been implicated in visceral fat augmentation. Myostatin-knockout mice display reduced visceral fat accumulation, improved glucose tolerance²⁸, and increased insulin sensitivity²⁹. Myostatin signaling regulates muscle differentiation and induces insulin resistance by suppressing downstream insulin signaling^{30,31}. Serum myostatin increases in obesity, positively correlates with insulin resistance indices^{32,33}, and serves as a significant predictor of fat accumulation in non-obese patients with non-alcoholic fatty liver disease³⁴. Myostatin is associated with skeletal muscle homeostasis in men and sarcopenia in women¹⁷. These findings suggest that serum myostatin may serve as a

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biomarker of SO, particularly in women. However, no previous studies have examined the association among myostatin, skeletal muscle reduction, and obesity in an apparently healthy population.

This study aimed to explore the prevalence of SO and its associated factors, including serum myostatin levels, in a middle-aged female population.

Methods

Study participants

University employees who participated in annual health examinations at Osaka University Health and Counseling Center between May 2022 and October 2022 were enrolled in this study. The inclusion and exclusion criteria for this study were as follows: (1) female individuals, (2) age between 30 and 59 years old, and (3) individuals without an acute disease on the day of their health checkups. Written informed consent was obtained from all 432 individuals. We classified the participants into four distinct groups: healthy (H), sarcopenia-only (S), obesity-only (O), and sarcopenic obesity (SO), as described in a subsequent section. Serum myostatin and insulin levels were measured in 80 participants: 53 randomly selected participants from the H group and 27 participants from the SO group.

Clinical parameters

Clinical parameters, including age, height, body weight, body mass index (BMI), waist circumference (WC), systolic blood pressure (SBP), diastolic blood pressure (DBP), white blood cell count (WBC), hemoglobin (Hb), platelet count (Plt), aspartate aminotransferase (AST), alanine aminotransferase (ALT), γ -glutamyl transpeptidase (γ GTP), blood urea nitrogen (BUN), creatinine (Cr), uric acid (UA), total cholesterol (T-Cho), triglycerides (TG), high-density lipoprotein cholesterol (HDL-C), low-density lipoprotein cholesterol (LDL-C), glucose (Glu), hemoglobin A1c (HbA1c), and exercise-related behaviors were extracted from health checkup records. Exercise-related behaviors included the frequency of engaging in sweat-inducing exercise in excess of 30 min per week, daily duration of physical activity equivalent to walking, walking speed compared with other females of approximately the same age, and daily TV/video viewing time on weekdays.

Percent body fat (PBF) and skeletal muscle mass index (SMI) were determined using the InBody 270 Body Composition Analyzer (InBody Japan, Tokyo). Grip strength was measured using a Smedley hand dynamometer (TKK5401; Takei Scientific Instruments Co., Ltd., Niigata, Japan). The finger ring test was performed by instructing participants to make a ring with the thumb and index finger of both hands around the thickest part of calf of non-dominant leg, and checking whether the calf circumference is “bigger,” “just fits” or “smaller” compared with the finger-ring circumference³⁵.

Serum concentrations of myostatin and insulin were quantified using Enzyme-linked Immunosorbent Assay (GDF-8/Myostatin Quantikine ELISA Kit, R&D Systems, Minneapolis, MN, USA) and chemiluminescent enzyme immunoassay (Lumipulse Presto insulin, Fujirebio, Tokyo, Japan), respectively, using excess serum from health checkups. The serum myostatin levels were measured in duplicate and the coefficient of variation between measurements was 4.6 (2.7–6.6) %. The waist-to-height ratio (WHtR) was calculated as WC/height, and body shape index (ABSI) as $WC / (BMI^{2/3} \times height^{1/2}) [m^{11/6} kg^{(-2/3)}]$ ³⁶. The Homeostatic Model Assessment of Insulin Resistance (HOMA-R) score was calculated as $Glu (mmol/L) \times insulin (\mu U/mL) / 22.5$ ³⁷.

Definition of SO

We defined sarcopenia as skeletal muscle mass loss indicated with $SMI < 5.7 \text{ kg/m}^2$, as described by the Asian Working Group for Sarcopenia in 2019³⁸. Obesity was defined as having a percentage of body fat (PBF) $\geq 0\%$, according to the previous studies^{39,40}. Subsequently, participants were classified into four groups: those with $SMI \geq 5.7 \text{ kg/m}^2$ and $PBF < 30\%$ were classified into the H group, those with $SMI < 5.7 \text{ kg/m}^2$ and $PBF < 30\%$ into the S group, those with $SMI \geq 5.7 \text{ kg/m}^2$ and $PBF \geq 30\%$ into the O group, and those with $SMI < 5.7 \text{ kg/m}^2$ and $PBF \geq 30\%$ into the SO group.

Statistical analyses

All statistical analyses were carried out using JMP® Pro 17 software (SAS Institute Inc., Cary, NC, USA). Continuous variables are expressed as median (interquartile range). The distribution of continuous variables was tested by Shapiro–Wilk test and most variables were non-normally distributed. Therefore, the Wilcoxon test was used to compare differences of continuous variables between the two groups, and the Kruskal–Wallis test followed by the post hoc Steel–Dwass test was used for multi-group comparison. The chi-square test was used to compare the proportions of categorical values. For the comparison of myostatin level between the groups, the analysis of covariance (ANCOVA) was used and adjusted for relevant factors. Relationships among clinical parameters was assessed using the Pearson's correlation coefficient analysis. The multiple regression analysis was performed to identify independent factors for myostatin level. Explanatory variables were determined using the stepwise method. In the Pearson's correlation coefficient analysis, the multiple regression analysis, and the ANCOVA, non-normally distributed variables were log-transformed. Statistical significance was set at $P < 0.05$.

Study approval

The research protocol was approved by the Ethics Committee of the Health and Counseling Center of Osaka University and adhered to the principles outlined in the Declaration of Helsinki. All patients provided written informed consent before participation.

Results

Clinical characteristics of SO

Of the 432 participants, 193 were classified into the healthy (H) group, 73 into the sarcopenia-only (S) group, 139 into the obesity-only (O) group, and 27 into the SO group. Supplementary Table S1 provides the detailed clinical background information for each group. The overall prevalence of SO in the study population was 6.3% (27 out of 432). The proportions of groups in each generation are shown in Fig. 1. No significant differences were observed among each generation ($P=0.0891$). The prevalence rates of SO were 6.4% for individuals in their 30s ($n=47$), 5.1% for those in their 40s ($n=235$), and 8.0% for those in their 50s ($n=150$). While the prevalence rates of S were significantly different ($P=0.0131$), a significant difference was not observed regarding the prevalence rates of SO among each generation ($P=0.5195$).

Relationship between SO and exercise-related behaviors

Exercise-related behaviors were compared between the H ($n=193$) and SO ($n=27$) groups (Fig. 2). The proportion of individuals who answered that their daily TV/video viewing time was greater than 120 min was higher in the SO group than in the H group (26% vs. 11%, $P=0.0366$). Furthermore, there was a higher proportion of individuals who answered that their “walking speed is slow” in the SO group compared to the H group (19% vs. 8%, $P=0.0689$).

Body component analyses and correlation of clinical parameters with myostatin levels

Myostatin and insulin levels were evaluated in 80 participants. Table 1 presents the clinical background of the participants. No significant differences in age, BMI, WC, finger-ring test results, Glu, and HbA1c levels were observed between the H and SO groups. However, the grip strength ($P<0.0001$) was lower and the WHtR ($P=0.0046$), ABSI ($P=0.0233$), T-Cho ($P=0.0423$), TG ($P=0.0004$), LDL-C ($P=0.0105$), insulin ($P=0.0236$), and HOMA-R scores ($P=0.0262$) were higher in the SO group than in the H group. Serum myostatin levels (3,107 pg/mL vs. 3,957 pg/mL, $P=0.0003$; Fig. 3) were significantly lower in the SO group than in the H group. As the indices of skeletal muscle mass^{10–12}, grip strength^{10,13}, obesity^{32,33}, and insulin sensitivity^{32,33} are reportedly related to circulating myostatin levels, we further assessed the differences in myostatin levels after adjusting for these factors. We found that the myostatin levels remained lower in the SO group than in the H group even after adjustment (Supplementary Table S2). Correlation analysis showed that myostatin levels

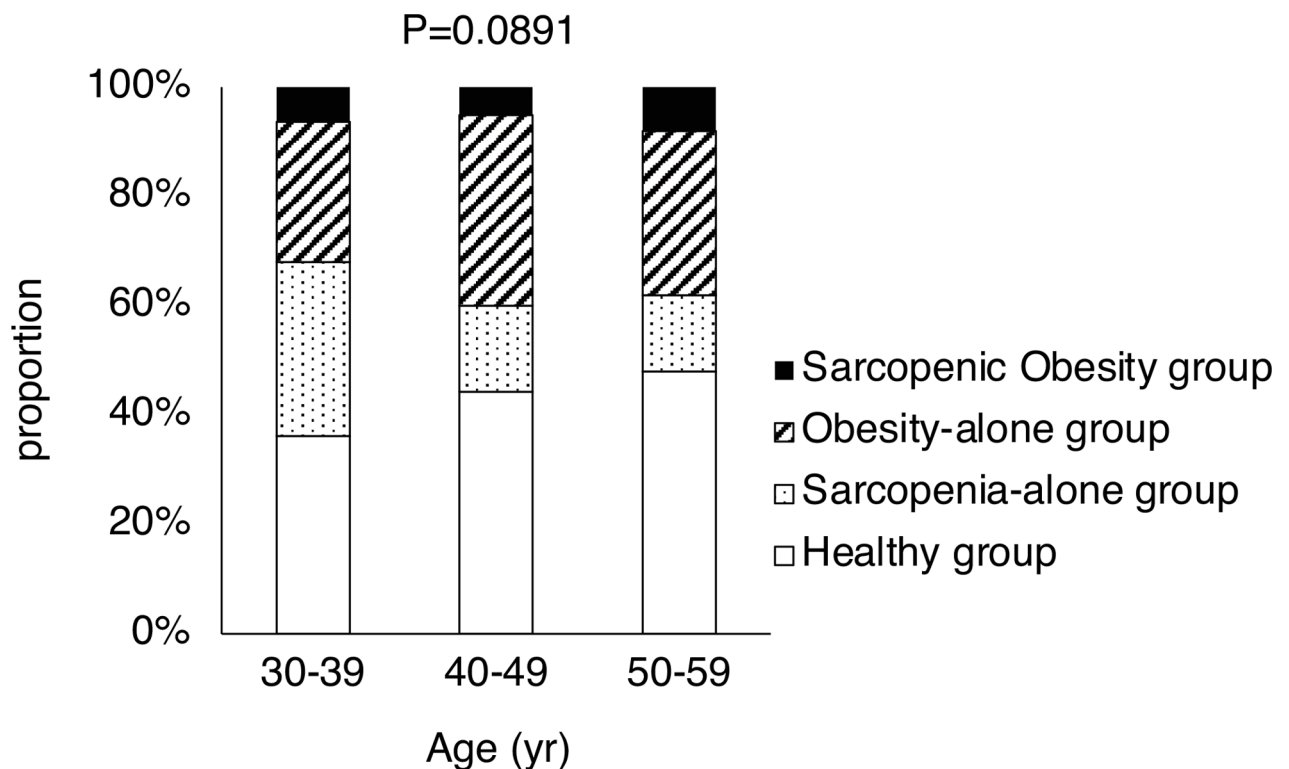


Fig. 1. Proportion of participants classified into the healthy, sarcopenia-only, obesity-only, and sarcopenic obesity groups. Data are presented as the proportion of participants in each group according to age bracket. The chi-square test was used to compare proportions among the age groups. Age 30–39: $n=47$, age 40–49: $n=235$, age 50–59: $n=150$.

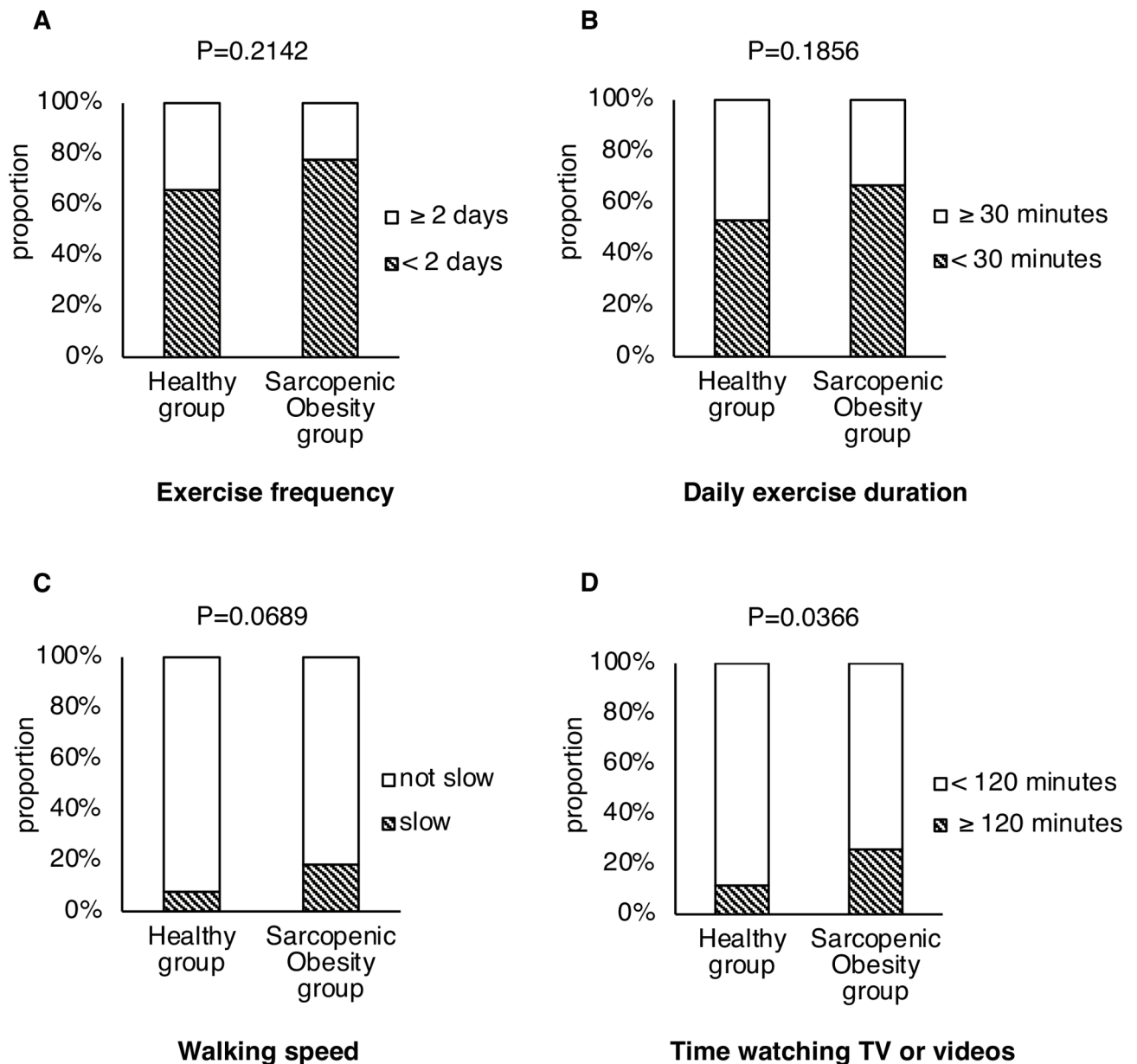


Fig. 2. Differences in exercise-related behaviors between the healthy and sarcopenic obesity groups. Comparison of (a) exercise frequency, (b) daily exercise duration, (c) walking speed, and (d) time spent watching TV or videos between the healthy and sarcopenic obesity groups. Data are shown for participants who answered questions on exercise-related behaviors. The chi-square test was used to compare the proportions between the healthy and sarcopenic obesity groups. Healthy group: $n = 193$, sarcopenic obesity group: $n = 27$.

significantly correlated with PBF, SMI, AST, ALT, TG, and HbA1c levels, and tended to correlate with age, Plt and Cr levels (Table 2). Among these factors, stepwise regression analysis identified SMI, HbA1c, and Plt as influencing factors of myostatin (Table 3).

Discussion

Here, we report a prevalence of 6.3% for SO in a middle-aged Japanese female population using our specified cut-off values. As Asians exhibit a higher body fat percentage at equivalent BMI levels than Caucasians^{41,42} and African Americans⁴¹, numerous studies on SO have emerged, especially in Asia. However, most studies have focused on older adults and only a few reports have focused on the prevalence of SO in the middle-aged population. As SO causes metabolic disorders and vascular events^{1–5}, it is important to detect SO in the relatively young population. A survey based on a Korean population reported a prevalence of 4.8% of SO in women aged 40–49 years⁴³, with SO defined as $\text{SMI} < 5.38 \text{ kg/m}^2$ (assessed using dual-energy x-ray absorptiometry: DXA) and $\text{WC} \geq 85 \text{ cm}$. Another study conducted in Singapore⁴⁴ reported that the proportion of community-dwelling

	Healthy group (<i>n</i> = 53)	Sarcopenic obesity group (<i>n</i> = 27)	<i>P</i>
Age, years	48 (45–52)	48 (44–54)	0.7869
BMI, kg/m ²	20.6 (19.6–21.7)	20.8 (19.9–21.5)	0.9756
WC, cm	72.0 (66.8–77.8)	72.5 (70.0–76.5)	0.5278
WHtR	0.45 (0.42–0.48)	0.47 (0.45–0.50)	0.0046
ABSI, *10 ⁻³ m ^{11/6} kg ^{-2/3}	75 (73–79)	78 (75–82)	0.0233
PBF, %	23.6 (20.7–26.6)	32.8 (31.4–34.6)	<0.0001
SMI, kg/m ²	6.3 (6.1–6.6)	5.3 (5.2–5.5)	<0.0001
Finger-ring test n, (%) bigger/just fits/smaller	14/29/10 (26/55/19)	4/15/7 (<i>n</i> = 26) (15/58/27)	0.4759
Grip strength, kg	26.0 (23.5–28.8)	20.5 (18.0–22.5) (<i>n</i> = 26)	<0.0001
SBP, mmHg	113 (106–123)	115 (107–124)	0.9553
DBP, mmHg	69 (64–77)	73 (67–75)	0.2963
WBC, *10 ³ /μL	5.1 (4.7–6.0)	4.8 (4.3–5.8)	0.3462
Hb, g/dL	13.0 (12.2–13.4)	13.8 (12.7–14.4)	0.0006
Plt *10 ⁴ , /μL	23.2 (19.3–27.2)	22.6 (20.8–26.9)	0.8787
AST, IU/L	20 (17–23)	19 (17–22)	0.2446
ALT, IU/L	13 (11–18)	12 (11–16)	0.2785
γGTP, IU/L	17 (14–24)	16 (13–22)	0.2576
BUN, mg/dL	10.9 (9.4–12.9)	11.3 (9.6–13.0)	0.7408
Cr, mg/dL	0.67 (0.62–0.74)	0.61 (0.55–0.67)	0.0016
UA, mg/dL	4.3 (3.8–4.9)	4.4 (3.8–5.3)	0.7097
T-Chol, mg/dL	193 (171–211)	215 (180–229)	0.0423
TG, mg/dL	51 (39–73)	76 (59–97)	0.0004
HDL-C, mg/dL	72 (60–86)	74 (55–82)	0.5756
LDL-C, mg/dL	105 (85–123)	119 (104–145)	0.0105
Glu, mg/dL	85 (81–90)	87 (82–90)	0.3252
HbA1c, %	5.2 (5.1–5.5)	5.2 (5.1–5.4)	0.9183
insulin, μU/mL	3.1 (2.2–4.2)	4.0 (2.9–4.6)	0.0236
HOMA-R	0.65 (0.45–0.87)	0.84 (0.64–1.0)	0.0262

Table 1. Clinical characteristics of study participants. Data are expressed as median (interquartile range). BMI body mass index, WC waist circumference, WHtR waist-to-height ratio, ABSI a body shape index, PBF percent body fat, SMI skeletal muscle mass index, SBP systolic blood pressure, DBP diastolic blood pressure, WBC white blood cell count, Hb hemoglobin, Plt platelet, AST aspartate aminotransferase, ALT alanine aminotransferase, γGTP γ-glutamyl transpeptidase, BUN blood urea nitrogen, Cr creatinine, UA uric acid, T-Chol total cholesterol, TG triglyceride, HDL-C high-density lipoprotein cholesterol, LDL-C low-density lipoprotein cholesterol, Glu glucose, HbA1c hemoglobin A1c, HOMA-R homeostatic Model Assessment of Insulin Resistance. The Wilcoxon test was used to compare continuous variables between the groups, and the chi-square test was used to compare the proportions of categorical values. Bold font indicates statistical significance.

women aged 21–59 years meeting criteria for both sarcopenia (SMI < 5.4 kg/m² assessed by DXA and hand grip strength < 18 and/or gait speed < 1.0 m/s) and obesity (WC ≥ 80 cm or PBF > upper two quintiles, 41.4%) was 1.7% (using WC cutoff) and 1.3% (using PBF cutoff). The variability in the prevalence of SO may be due to the lack of standard criteria for SO diagnosis^{40,44,45}. Therefore, to provide effective measures against SO, it is necessary to establish unified and useful diagnostic criteria. SO is often defined according to the criteria for sarcopenia and obesity determined in each study. In general, SMI using DXA or bioelectrical impedance analysis (BIA) is used to define sarcopenia, whereas BMI, abdominal circumference, and body fat percentage are used to define obesity. In this study, sarcopenia was defined according to the Asian Working Group for Sarcopenia criterion for low skeletal muscle mass, which is the most commonly used criterion in Asian populations. As our study participants were relatively young, the low physical performance criterion was omitted. Obesity was defined as PBF exceeding 30%^{39,40}. Using these criteria, our study revealed that the SO group exhibited diminished grip strength and significantly elevated levels of TG, LDL-C, and HOMA-R compared with the H group. This suggests that individuals in the SO group are at risk of developing various metabolic diseases in the future, verifying the clinical validity of our SO criteria. We propose that our criteria of SMI < 5.7 kg/m² and PBF ≥ 30%, measured by BIA, would be useful for diagnosing SO in the Asian female population.

While the BMI and WC in the SO group did not differ significantly from those in the H group, the WHtR and ABSI showed notable differences between the groups. This implies that these indices may serve as useful tools for identifying SO in situations where body composition analyses are not available. In addition, grip strength test results showed a significant difference between the SO and H groups in this study, which is consistent

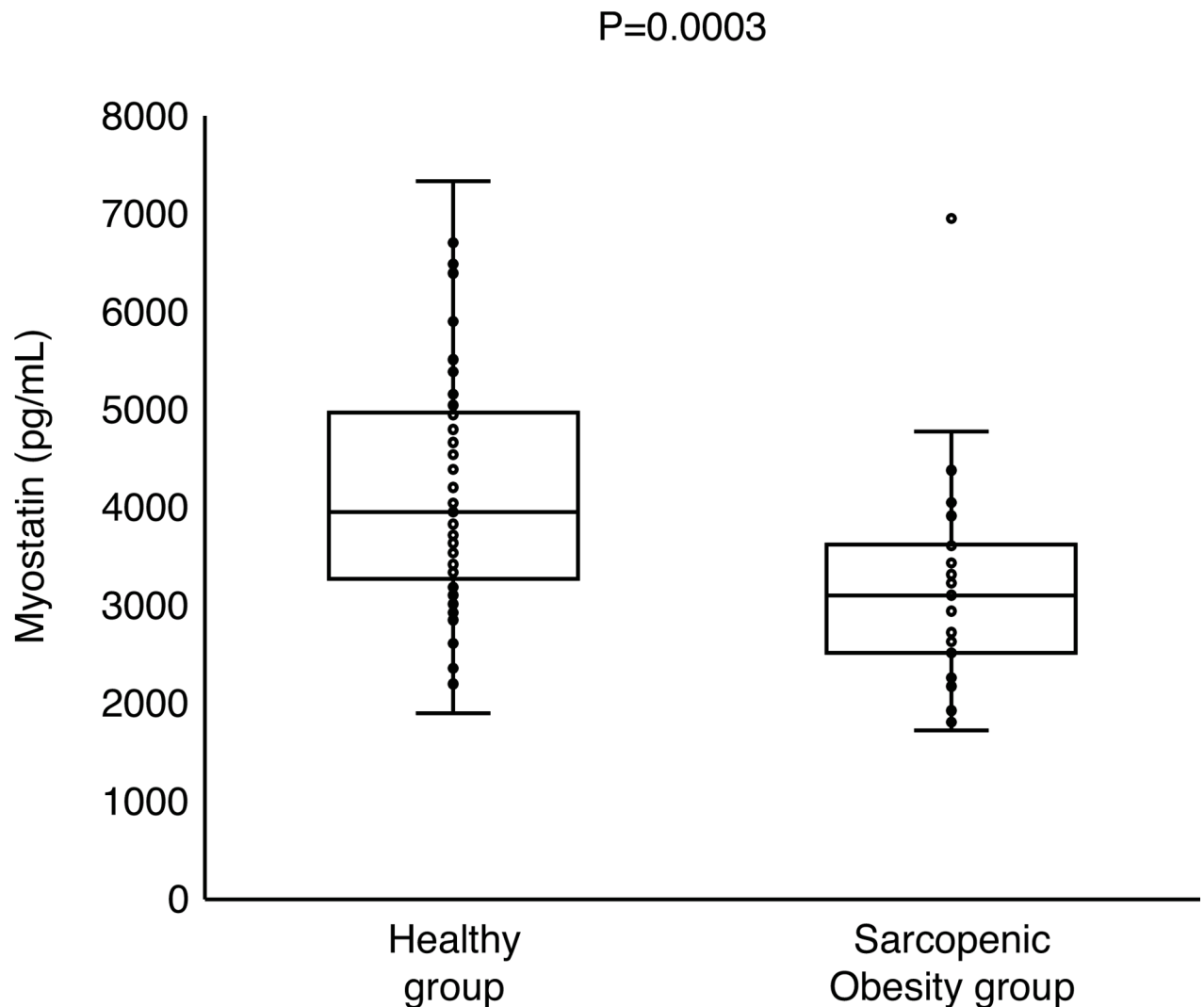


Fig. 3. Serum myostatin levels in the healthy and sarcopenic obesity groups. Box plots show the minimum, lower quartile, median, upper quartile, and maximum myostatin levels. The Wilcoxon test was used to compare serum myostatin levels between the two groups. Healthy group: $n = 53$, sarcopenic obesity group: $n = 27$.

with previous reports^{10,13}. As grip strength tests are simple and easy to perform, they should be incorporated into routine health checkups. Regarding exercise-related behaviors, the SO group had a higher proportion of individuals whose daily TV/video clip viewing time was greater than 120 min than the H group. Lower levels of physical activity are associated with an increased risk of SO in older adults^{46,47}. Providing health guidance to encourage people to engage in physical activities might be beneficial in preventing SO.

To the best of our knowledge, no previous study has evaluated myostatin levels in apparently healthy middle-aged women. Myostatin inhibits the growth of skeletal muscles by binding to the activin type IIB myostatin receptor, activating the small mothers against decapentaplegic (Smad)-mediated pathway, and inhibiting the Akt/mammalian target of rapamycin (mTOR)/p70S6 protein synthesis pathway, which mediates differentiation in myoblasts and hypertrophy in myotubes^{48,49}. Myostatin is also known to promote obesity by inhibiting fatty acid oxidation⁵⁰ and the formation of brown adipose tissue^{50,51} which exert anti-obesity effects by increasing energy expenditure. Circulating myostatin levels are increased in individuals with sarcopenia^{16–26} and obesity^{32,33}. In this context, myostatin is considered a biomarker of SO, a combination of sarcopenia and obesity. We hypothesized that serum myostatin levels might be higher in the SO group than in the H group. However, contrary to our expectations, myostatin levels were lower in the SO group than in the H group. As serum myostatin levels have been reported to be associated with skeletal muscle mass^{10–12} and obesity^{32,33}, we further evaluated myostatin levels after adjusting for the relevant factors (Supplementary Table S2). Even after adjusting for these factors, myostatin levels remained lower in the SO group than in the H group. This discrepancy may

<i>n</i> = 80	ln myostatin	
	<i>R</i>	<i>P</i>
Age	0.21	0.0617
BMI	0.079	0.4880
WC	0.021	0.8552
WHtR	0.0056	0.9605
ABSI	−0.037	0.7419
PBF	−0.28	0.0108
SMI	0.29	0.0083
Grip strength (<i>n</i> = 79)	0.058	0.6123
ln AST	0.33	0.0032
ln ALT	0.30	0.0068
ln Plt	−0.20	0.0765
ln γGTP	0.17	0.1288
ln BUN	0.13	0.2461
ln Cr	0.20	0.0823
UA	0.072	0.5270
ln T-Cho	−0.092	0.4156
ln TG	−0.24	0.0298
ln HDL-C	0.041	0.7203
LDL-C	−0.032	0.7807
ln Glu	0.024	0.8343
ln HbA1c	0.28	0.0127
ln Insulin	−0.13	0.2358
ln HOMA-R	−0.12	0.2764

Table 2. Correlation between serum myostatin levels and clinical characteristics. *BMI* body mass index, *WC* waist circumference, *WHtR* waist-to-height ratio, *ABSI* a body shape index, *PBF* percent body fat, *SMI* skeletal muscle mass index, *AST* aspartate aminotransferase, *ALT* alanine aminotransferase, *Plt* platelet, *γGTP* γ-glutamyl transpeptidase, *BUN* blood urea nitrogen, *Cr* creatinine, *UA* uric acid, *T-Cho* total cholesterol, *TG* triglyceride, *HDL-C* high-density lipoprotein cholesterol, *LDL-C* low-density lipoprotein cholesterol, *Glu* glucose, *HbA1c* hemoglobin A1c, *HOMA-R* homeostatic Model Assessment of Insulin Resistance. Log-transformed values were expressed with *ln* at the beginning. The Pearson’s correlation coefficient analysis was used for the assessment of relationship between serum myostatin levels and clinical characteristics. Bold font indicates statistical significance.

be attributed to differences in the characteristics of the study participants. Previous studies have focused on the elderly and patients presenting with dysfunction of vital organs such as the liver, heart, and kidney, whereas our study focused on apparently healthy individuals with abnormalities in body composition measurements. It has been hypothesized that myostatin is appropriately suppressed in individuals with mild SO, as observed in this study; however, this feedback mechanism may be disrupted during SO progression.

Myostatin levels have been reported to positively correlate with HOMA-R, an index of insulin resistance, in obese individuals³³. While a correlation between myostatin and HOMA-R was not observed in this study, HbA1c showed a positive correlation with serum myostatin levels. Generally, elevated HbA1c levels are caused by increased insulin resistance or decreased insulin secretion capacity. Increased serum myostatin levels are associated with type 1 diabetes and insulin secretion deficiency^{52,53}. These results suggest that HbA1c might be more influenced by insulin secretory capacity than by insulin resistance in the study participants, and the positive correlation between serum myostatin and HbA1c might be explained by reduced insulin secretion capacity.

This study has some limitations. First, the small number of participants, especially those with SO, limited the statistical robustness of our findings, and may not allow them to be applied to other populations. To validate our findings, multicenter studies with larger samples are required in the future. Second, as this was a cross-sectional study, it cannot be ascertained whether the observed SO group was prone to developing metabolic disorders or cardiovascular events. Finally, the analysis did not examine factors beyond myostatin. For instance, myostatin competes with follistatin^{54,55}, and other myokines, adipokines, or hepatokines^{56–58} implicated in the pathogenesis of SO were not considered in this study.

In conclusion, we revealed the prevalence of SO in middle-aged female, as defined by the criteria of $SMI < 5.7 \text{ kg/m}^2$ and $PBF \geq 30\%$ measured by BIA, and found low serum myostatin levels in individuals with SO. It is important to detect SO in an early stage for prevention of metabolic disorders and cardiovascular diseases that may occur in the future. For the early detection and management of SO, body composition analyses, which are essential for the diagnosis of SO, should be widely performed, and clinically meaningful and uniform

	ln myostatin	
	β	P
SMI	0.2792	0.0067
ln HbA1c	0.2362	0.0318
ln Plt	-0.2291	0.0257
ln AST	0.2024	0.0643

Table 3. The multivariate regression analysis for myostatin. *SMI* skeletal muscle mass index, *HbA1c* hemoglobin A1c, *Plt* platelet, *AST* aspartate aminotransferase. Log-transformed values were expressed with *ln* at the beginning. The multiple regression analysis was performed to identify independent factors for myostatin level. Explanatory variables were determined using the stepwise method. Bold font indicates statistical significance.

diagnostic criteria should be established. We believe that the diagnostic criteria used in this study will be useful in diagnosing SO in the general Asian female population.

Data availability

The authors confirm that the data supporting the findings of this study are available in the article.

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References

1. Han, K. et al. Sarcopenia as a determinant of blood pressure in older Koreans: Findings from the Korea National Health and Nutrition Examination Surveys (KNHANES) 2008–2010. *PLOS ONE*. **9**, e86902 (2014).
2. Baek, S. J. et al. Sarcopenia and sarcopenic obesity and their association with dyslipidemia in Korean elderly men: The 2008–2010 Korea National Health and Nutrition Examination Survey. *J. Endocrinol. Invest.* **37**, 247–260 (2014).
3. Lim, S. et al. Sarcopenic obesity: Prevalence and association with metabolic syndrome in the Korean Longitudinal Study on Health and Aging (KLoSHA). *Diabetes Care*. **33**, 1652–1654 (2010).
4. Lu, C. W. et al. Sarcopenic obesity is closely associated with metabolic syndrome. *Obes. Res. Clin. Pract.* **7**, e301–e307 (2013).
5. Stephen, W. C. & Janssen, I. Sarcopenic-obesity and cardiovascular disease risk in the elderly. *J. Nutr. Health Aging*. **13**, 460–466 (2009).
6. Poggiogalle, E. et al. Sarcopenic obesity and metabolic syndrome in adult caucasian subjects. *J. Nutr. Health Aging*. **20**, 958–963 (2016).
7. Kreidieh, D. et al. Association between sarcopenic obesity, type 2 diabetes, and hypertension in overweight and obese treatment-seeking adult women. *J. Cardiovasc. Dev. Dis.* **5**, 51 (2018).
8. Moreira, M. A. et al. Sarcopenic obesity and physical performance in middle aged women: A cross-sectional study in Northeast Brazil. *BMC Public Health*. **16**, 43 (2016).
9. McPherron, A. C., Lawler, A. M. & Lee, S. J. Regulation of skeletal muscle mass in mice by a new TGF-beta superfamily member. *Nature*. **387**, 83–90 (1997).
10. Loumaye, A. et al. Role of activin A and myostatin in human cancer cachexia. *J. Clin. Endocrinol. Metab.* **100**, 2030–2038 (2015).
11. Yamada, S. et al. Factors associated with the serum myostatin level in patients undergoing peritoneal dialysis: Potential effects of skeletal muscle mass and vitamin D receptor activator use. *Calcif Tissue Int.* **99**, 13–22 (2016).
12. Kurose, S. et al. Association of serum adiponectin and myostatin levels with skeletal muscle in patients with obesity: A cross-sectional study. *PLOS ONE*. **16**, e0245678 (2021).
13. Delanaye, P. et al. Myostatin and insulin-like growth factor 1 are biomarkers of muscle strength, muscle mass, and mortality in patients on hemodialysis. *J. Ren. Nutr.* **29**, 511–520 (2019).
14. Furihata, T. et al. Serum myostatin levels are independently associated with skeletal muscle wasting in patients with heart failure. *Int. J. Cardiol.* **220**, 483–487 (2016).
15. Planella-Farrugia, C. et al. Circulating irisin and myostatin as markers of muscle strength and physical condition in elderly subjects. *Front. Physiol.* **10**, 871 (2019).
16. Yarasheski, K. E., Bhasin, S., Sinha-Hikim, I. & Pak-Loduca, J. Gonzalez-Cadavid, N. F. Serum myostatin-immunoreactive protein is increased in 60–92 year old women and men with muscle wasting. *J. Nutr. Health Aging*. **6**, 343–348 (2002).
17. Bergen, H. R. et al. Myostatin as a mediator of Sarcopenia versus homeostatic regulator of muscle mass: Insights using a new mass spectrometry-based assay. *Skelet. Muscle*. **5**, 21 (2015).
18. Qiu, J. et al. Hyperammonemia in cirrhosis induces transcriptional regulation of myostatin by an NF-κB-mediated mechanism. *Proc. Natl. Acad. Sci. U S A*. **110**, 18162–18167 (2013).
19. Nishikawa, H. et al. Elevated serum myostatin level is associated with worse survival in patients with liver cirrhosis. *J. Cachexia Sarcopenia Muscle*. **8**, 915–925 (2017).
20. Alexopoulos, T. et al. Myostatin in combination with creatine phosphokinase or albumin may differentiate patients with cirrhosis and sarcopenia. *Am. J. Physiol. Gastrointest. Liver Physiol.* **321**, G543–G551 (2021).
21. Yano, S. et al. Relationship between blood myostatin levels and kidney function: Shimane CoHRE Study. *PLoS One*. **10**, e0141035. <https://doi.org/10.1371/journal.pone.0141035> (2015).
22. Raptis, V. et al. Serum Fas ligand, serum myostatin and urine TGF-β1 are elevated in autosomal dominant polycystic kidney disease patients with impaired and preserved renal function. *Kidney Blood Press. Res.* **43**, 744–754 (2018).
23. Bataille, S. et al. Mechanisms of myostatin and activin A accumulation in chronic kidney disease. *Nephrol. Dial Transpl.* **37**, 1249–1260 (2022).
24. Heineke, J. et al. Genetic deletion of myostatin from the heart prevents skeletal muscle atrophy in heart failure. *Circulation*. **121**, 419–425 (2010).
25. Breitbart, A., Auger-Messier, M., Molkentin, J. D. & Heineke, J. Myostatin from the heart: Local and systemic actions in cardiac failure and muscle wasting. *Am. J. Physiol. Heart Circ. Physiol.* **300**, H1973–H1982 (2011).
26. Gruson, D., Ahn, S. A., Ketelslegers, J. M. & Rousseau, M. F. Increased plasma myostatin in heart failure. *Eur. J. Heart Fail.* **13**, 734–736 (2011).

27. Assyov, Y. S., Velikova, T. V. & Kamenov, Z. A. Myostatin and carbohydrate disturbances. *Endocr. Res.* **42**, 102–109 (2017).
28. McPherron, A. C. & Lee, S. J. Suppression of body fat accumulation in myostatin-deficient mice. *J. Clin. Invest.* **109**, 595–601 (2002).
29. Guo, T. et al. Myostatin inhibition in muscle, but not adipose tissue, decreases fat mass and improves insulin sensitivity. *PLOS ONE*. **4**, e4937 (2009).
30. Consitt, L. A. & Clark, B. C. The vicious cycle of myostatin signaling in sarcopenic obesity: Myostatin role in skeletal muscle growth, insulin signaling and implications for clinical trials. *J. Frailty Aging*. **7**, 21–27 (2018).
31. Lee, S. J. Targeting the myostatin signaling pathway to treat muscle loss and metabolic dysfunction. *J. Clin. Invest.* **131**, e148372 (2021).
32. Amor, M. et al. Serum myostatin is upregulated in obesity and correlates with insulin resistance in humans. *Exp. Clin. Endocrinol. Diabetes*. **127**, 550–556 (2019).
33. Tanaka, M. et al. Role of serum myostatin in the association between hyperinsulinemia and muscle atrophy in Japanese obese patients. *Diabetes Res. Clin. Pract.* **142**, 195–202 (2018).
34. Shida, T. et al. Clinical and anthropometric characteristics of non-obese non-alcoholic fatty liver disease subjects in Japan. *Hepatol. Res.* **50**, 1032–1046 (2020).
35. Tanaka, T., Takahashi, K., Akishita, M., Tsuji, T. & Iijima, K. Yubi-Wakka (finger-ring) test: a practical self-screening method for Sarcopenia, and a predictor of disability and mortality among Japanese community-dwelling older adults. *Geriatr. Gerontol. Int.* **18**, 224–232 (2018).
36. Krakauer, N. Y. & Krakauer, J. C. A new body shape index predicts mortality hazard independently of body mass index. *PLOS ONE*. **7**, e39504 (2012).
37. Bonora, E. et al. Homeostasis model assessment closely mirrors the glucose clamp technique in the assessment of insulin sensitivity: studies in subjects with various degrees of glucose tolerance and insulin sensitivity. *Diabetes Care*. **23**, 57–63 (2000).
38. Chen, L. K. et al. Asian working group for sarcopenia. *J. Am. Med. Dir. Assoc.* **21**, 300–307 (2019) Consensus Update on Sarcopenia Diagnosis and Treatment. (2020).
39. Yin, T. et al. The association between sarcopenic obesity and hypertension, diabetes, and abnormal lipid metabolism in Chinese adults. *Diabetes Metab. Syndr. Obes.* **14**, 1963–1973 (2021).
40. Peng, T. C. et al. Associations between different measurements of sarcopenic obesity and health outcomes among non-frail community-dwelling older adults in Taiwan. *Br. J. Nutr.* **126**, 1749–1757 (2021).
41. Gallagher, D. et al. Healthy percentage body fat ranges: An approach for developing guidelines based on body mass index. *Am. J. Clin. Nutr.* **72**, 694–701 (2000).
42. Ko, G. T. et al. Lower BMI cut-off value to define obesity in Hong Kong Chinese: An analysis based on body fat assessment by bioelectrical impedance. *Br. J. Nutr.* **85**, 239–242 (2001).
43. Kim, Y. S. et al. Prevalence of Sarcopenia and sarcopenic obesity in the Korean population based on the Fourth Korean National Health and Nutritional examination surveys. *J. Gerontol. Biol. Sci. Med. Sci.* **67**, 1107–1113 (2012).
44. Pang, B. W. J. et al. Obesity measures and definitions of sarcopenic obesity in Singaporean adults—The Yishun study. *J. Frailty Aging*. **10**, 202–210 (2021).
45. Khor, E. Q. et al. Obesity definitions in sarcopenic obesity: Differences in prevalence, agreement and association with muscle function. *J. Frailty Aging*. **9**, 37–43 (2020).
46. Lee, D. C., Shook, R. P., Drenowatz, C. & Blair, S. N. Physical activity and sarcopenic obesity: Definition, assessment, prevalence and mechanism. *Future Sci. OA*. **2**, FSO127 (2016).
47. Schoufour, J. D. et al. The relevance of diet, physical activity, exercise, and persuasive technology in the prevention and treatment of sarcopenic obesity in older adults. *Front. Nutr.* **8**, 661449 (2021).
48. Goodman, C. A., McNally, R. M., Hoffmann, F. M. & Hornberger, T. A. Smad3 induces atrogen-1, inhibits mTOR and protein synthesis, and promotes muscle atrophy in vivo. *Mol. Endocrinol.* **27**, 1946–1957 (2013).
49. Trendelenburg, A. U. et al. Myostatin reduces Akt/TORC1/p70S6K signaling, inhibiting myoblast differentiation and myotube size. *Am. J. Physiol. Cell. Physiol.* **296**, C1258–C1270 (2009).
50. Zhang, C. et al. Inhibition of myostatin protects against diet-induced obesity by enhancing fatty acid oxidation and promoting a brown adipose phenotype in mice. *Diabetologia*. **55**, 183–193 (2012).
51. Shan, T., Liang, X., Bi, P. & Kuang, S. Myostatin knockout drives browning of white adipose tissue through activating the AMPK-PGC1 α -Fndc5 pathway in muscle. *FASEB J.* **27**, 1981–1989 (2013).
52. Dial, A. G. et al. Muscle and serum myostatin expression in type 1 diabetes. *Physiol. Rep.* **8**, e14500 (2020).
53. Efthymiadou, A., Vasilakis, I. A., Giannakopoulos, A. & Chrysos, D. Myostatin serum levels in children with type 1 diabetes mellitus. *Horm. (Athens)*. **20**, 777–782 (2021).
54. Amthor, H. et al. Follistatin complexes myostatin and antagonises myostatin-mediated inhibition of myogenesis. *Dev. Biol.* **270**, 19–30 (2004).
55. Cash, J. N., Rejon, C. A., McPherron, A. C., Bernard, D. J. & Thompson, T. B. The structure of myostatin:follistatin 288: Insights into receptor utilization and heparin binding. *EMBO J.* **28**, 2662–2676 (2009).
56. Gonzalez-Gil, A. M. & Elizondo-Montemayor, L. The role of exercise in the interplay between myokines, hepatokines, osteokines, adipokines, and modulation of inflammation for energy substrate redistribution and fat mass loss: A review. *Nutrients*. **12**, 1899 (2020).
57. Batsis, J. A. & Villareal, D. T. Sarcopenic obesity in older adults: Aetiology, epidemiology and treatment strategies. *Nat. Rev. Endocrinol.* **14**, 513–537 (2018).
58. de Santos, O. D. Adipokines, myokines, and hepatokines: Crosstalk and metabolic repercussions. *Int. J. Mol. Sci.* **22**, 2639 (2021).

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Author contributions

C.I., K.N., I.N. and K.Y.-T. designed the study. C.I. collected and analyzed the data and wrote the manuscript. K.N. supervised the study, interpreted data, and edited the manuscript. I.N. and K.Y.-T. provided suggestions for the development of the study and reviewed the manuscript. D.K. and T.K. contributed to preparation of the serum samples. M.N., H.S., M.S., and R.Y. contributed to discussion. All the authors approved the final version of the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

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