

Original Article

Age-Dependent Differences in the Association Between Skeletal Muscle Mass Index and QUS-Derived Calcaneal Bone Status Among Participants in A Community-Based Osteoporosis Screening Program: A Cross-Sectional Study

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Abstract

Objectives: To examine the association between skeletal muscle mass index (SMI) and calcaneal quantitative ultrasonography (QUS)-derived YAM% and whether this association varied by age. **Methods:** This cross-sectional study included 325 participants (mean age 71.0 ± 8.9 years) from a community-based osteoporosis screening program. Multivariable linear regression assessed the SMI–YAM% association and exploratory effect modification by age group (<70 vs. ≥ 70 years), adjusting for age, sex, and body mass index. Sensitivity analyses used continuous age, alternative age cutoffs, additional lifestyle and clinical covariates, and exclusion of potentially influential observations. **Results:** Mean calcaneal QUS-derived YAM% was similar between age groups. The SMI $\times$ age-group interaction was significant in the full sample (B 4.76, 95% CI 1.66–7.87, $p=0.003$). The adjusted SMI slope was not significant among participants aged <70 years (B -0.85, 95% CI -3.93 to 2.23, $p=0.586$), but was positive among those aged ≥ 70 years (B 3.91, 95% CI 1.60–6.22, $p<0.001$). The interaction persisted after additional covariate adjustment (B 4.74, 95% CI 1.53–7.96, $p=0.004$), but was attenuated and no longer significant after potentially influential observations were excluded. **Conclusions:** The SMI–YAM% association may vary by age, but the interaction was sensitive to influential observations. These exploratory findings require confirmation in larger longitudinal studies.

Keywords: Aging, Bone Status, Muscle–Bone Interaction, Quantitative Ultrasonography, Skeletal Muscle Mass Index

Introduction

Osteoporosis is a major public health concern in aging societies, as well as a leading cause of fragility-related fractures, disability, and loss of independence among older adults^{1,2}. The early identification of individuals at an increased risk of osteoporosis is therefore essential to ensure the prevention of fractures and maintenance of

functional independence. Community-based osteoporosis screening programs are implemented in several countries, including Japan, to identify individuals who may require further assessment and preventive care^{3,4}.

Although dual-energy X-ray absorptiometry (DXA) is considered the reference standard for assessing bone mineral density, its use in large-scale screening settings is limited by cost, accessibility, and the potential risks associated with exposure to radiation⁴. As an alternative, quantitative ultrasonography (QUS) of the calcaneus has been widely adopted as a screening tool. Calcaneal QUS-derived parameters are influenced by bone quantity and certain structural and mechanical properties of bone and have been shown to predict fracture risk independently of DXA-derived bone mineral density^{5–8}. However, QUS-derived bone status is a screening measure and is not equivalent to DXA-derived bone mineral density. In Japan, QUS-assessed bone status is commonly expressed as

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the percentage of the young adult mean (YAM%), which is routinely used when screening for osteoporosis and communicating risk in clinical and public health settings⁹.

As bone loss increases over time, age-related declines in skeletal muscle mass and strength are becoming increasingly recognized as key contributors to limited mobility, falls, and fractures in older adults, and the concept of the muscle–bone unit emphasizes the close functional and biological interdependence between skeletal muscle and bone¹¹. Multiple studies have reported positive associations between skeletal muscle mass and bone mineral density, largely based on DXA-derived measurements in clinical or research-based cohorts^{12–14}, thereby highlighting the importance of muscle mass for skeletal health throughout an individual's full lifespan.

However, several notable gaps remain in this field. Firstly, most previous studies in this context have been based on DXA assessments of bone mineral density, and thus evidence based on QUS-assessed bone status in community-based osteoporosis screening settings remains limited. Secondly, research to date has focused primarily on average differences or overall associations between muscle mass and bone density, with less attention being paid to whether age modifies the association between skeletal muscle mass and QUS-derived bone status. Thus, given age-related differences in mechanical loading, hormonal milieu, patterns of physical activity, and comorbid conditions, the contribution of skeletal muscle mass to bone status may differ according to age^{15,16}, which may not be apparent when analyses are limited to mean bone status alone.

Given these limitations, this study aimed to investigate the association between skeletal muscle mass index (SMI) derived from body composition measurements and calcaneal bone status assessed using QUS and expressed as YAM% in community-dwelling adults. We further examined whether this muscle–bone relationship differed between participants aged <70 years and participants aged ≥70 years. Clarifying these age-related differences may contribute to a better understanding of muscle–bone interactions in aging populations.

The extent to which age modifies the association between skeletal muscle mass and QUS-derived calcaneal bone status in community-based screening populations remains insufficiently understood.

Materials and Methods

Study design and participants

This cross-sectional study was conducted using data obtained from a municipality-operated osteoporosis screening program in City A, Saitama Prefecture, Japan during the 2023 and 2024 fiscal years. During the study period, 724 individuals attended the screening program. Participants were recruited at the screening sites, and 338 individuals provided written informed consent to participate in the study. Information regarding the reasons

why screening attendees did not provide consent was not available.

The inclusion criteria were attendance at the municipality-operated osteoporosis screening program during the study period and provision of written informed consent. Participants were excluded if data required for the analyses, including bone status, body composition, or relevant covariates, were missing. Individuals who attended the screening program more than once during the study period were included only once. Of the 338 participants who provided written informed consent, 13 were excluded because one or more variables required for the analyses were missing. A total of 325 participants (mean age 71.0 ± 8.9 years) with complete analytical data were included in the final analysis.

This study was reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement. The study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Ethics Committee of Saitama Medical University (approval number: U2022-024).

Assessment of bone status

Calcaneal bone status was assessed via QUS, using an AOS-100SA instrument (FUJIFILM Healthcare Corporation, Tokyo, Japan). The right calcaneus was assessed. The device was calibrated according to the manufacturer's instructions. Measurements were performed following the standardized procedures recommended by the manufacturer, and the values obtained were expressed as YAM%, which is widely used in Japan for osteoporosis screening and risk stratification. Calcaneal QUS-derived parameters are influenced by bone quantity and certain structural and mechanical properties of bone and have been shown to predict fracture risk independently of DXA-derived bone mineral density^{5,8}. Only QUS-derived YAM% was available in the analytical dataset; SOS values were not available for analysis.

Assessment of skeletal muscle mass

Skeletal muscle mass was assessed using a body composition analyzer based on bioelectrical impedance analysis (TANITA MC-780A-N; Tanita Corp., Tokyo, Japan) according to the manufacturer's instructions. Measurements were performed with participants barefoot in a standing position on the device electrodes while holding the handgrips. SMI was calculated as appendicular skeletal muscle mass divided by height squared (kg/m^2), in accordance with established definitions¹⁷, and treated as a continuous variable in all analyses.

Covariates

Information regarding the age, sex, and body mass index (BMI) of participants was obtained at the time of

Table 1. Characteristics of the study population.

Variable	Total (n = 325)	Men (n = 70)	Women (n = 255)	Age <70 years (n = 112)	Age ≥70 years (n = 213)
Age, years	71.0 ± 8.9	75.8 ± 6.0	69.7 ± 9.1	61.7 ± 7.7	75.9 ± 4.4
BMI, kg/m ²	22.0 ± 2.9	22.9 ± 3.1	21.8 ± 2.8	21.8 ± 3.1	22.2 ± 2.8
SMI, kg/m ²	6.78 ± 0.75	7.74 ± 0.79	6.52 ± 0.48	6.77 ± 0.61	6.79 ± 0.82
YAM%	89.7 ± 9.7	94.7 ± 11.6	88.3 ± 8.7	90.2 ± 9.1	89.5 ± 10.0
Screening-defined low bone status (YAM% <80%), n (%)	41 (12.6)	6 (8.6)	35 (13.7)	12 (10.7)	29 (13.6)
Body fat, %	27.4 ± 7.3	21.1 ± 6.1	29.2 ± 6.7	28.2 ± 7.3	27.0 ± 7.3

Continuous variables are presented as means ± standard deviations (SD), and categorical variables as numbers (percentages). Screening-defined low bone status was defined as QUS-derived YAM% <80%. BMI, body mass index; QUS, quantitative ultrasonography; SMI, skeletal muscle mass index; YAM%, percentage of the young adult mean.

screening. Height and body weight were directly measured by trained staff, and BMI was calculated as body weight divided by height squared (kg/m²). These variables were selected *a priori*, based on their known associations with both muscle mass and bone status^{12–14}.

Information on lifestyle and clinical factors was obtained using a self-administered questionnaire completed at the screening examination. Smoking history was categorized as never or ever smoking, with current and former smokers combined into the ever-smoking category. Alcohol consumption was coded as yes when participants reported drinking alcoholic beverages almost every day. Regular exercise was coded as yes when participants reported engaging in regular exercise during the previous year. History of fracture was coded as yes when participants reported having experienced a fracture at any time in the past. Daily use of five or more medications was coded as yes when participants reported taking five or more types of medication every day. Responses regarding steroid hormone use were categorized as yes, no, or unknown; a yes response indicated a history of steroid hormone treatment lasting for at least one month.

Statistical Analysis

Descriptive statistics were calculated for both the total population and sub-groups stratified by sex and age (<70 vs. ≥70 years). Associations between SMI and YAM% were assessed by performing multivariable linear regression analyses, with adjustments made for age, sex, and BMI. To examine whether age modified the association between SMI and YAM%, an interaction term between mean-centered SMI and age group (<70 vs. ≥70 years) was included in the multivariable linear regression model. Because the 70-year cutoff was not prespecified, this interaction analysis was considered exploratory. To assess the robustness of the findings, sensitivity analyses

were performed by modeling age as a continuous effect modifier and by repeating the interaction analyses using alternative age-group cutoffs of 65 and 75 years. For the continuous-age interaction model, both SMI and age were mean-centered before constructing the interaction term. Models using age-group cutoffs were adjusted for continuous age, sex, and BMI.

Secondary analyses were performed using multivariable logistic regression to examine the factors associated with screening-defined low bone status, defined as QUS-derived YAM% <80%, based on Japanese osteoporosis screening guidance and previous Japanese calcaneal QUS research^{9,10}. Regression coefficients (B) from linear regression analyses and odds ratios (ORs) from logistic regression analyses are presented with 95% confidence intervals (CIs).

To further assess potential residual confounding, an additional complete-case sensitivity analysis was performed by adding available lifestyle and clinical factors to the main interaction model. These factors included smoking history (never vs. ever smoking), alcohol consumption, regular exercise, history of fracture, daily use of five or more medications, and steroid hormone use. Participants with unknown information regarding steroid hormone use were excluded from this sensitivity analysis.

Model fit for the main age-group interaction model was evaluated using the coefficient of determination (R²) and adjusted R². Multicollinearity was assessed using variance inflation factors (VIFs), and residual independence was assessed using the Durbin-Watson statistic. The assumptions of residual normality, linearity, and homoscedasticity were evaluated by visual inspection of the residual histogram, normal P–P plot, and scatterplot of standardized residuals against standardized predicted values. Potentially influential observations were assessed using studentized deleted residuals, centered leverage values, and Cook's distance. Observations with Cook's

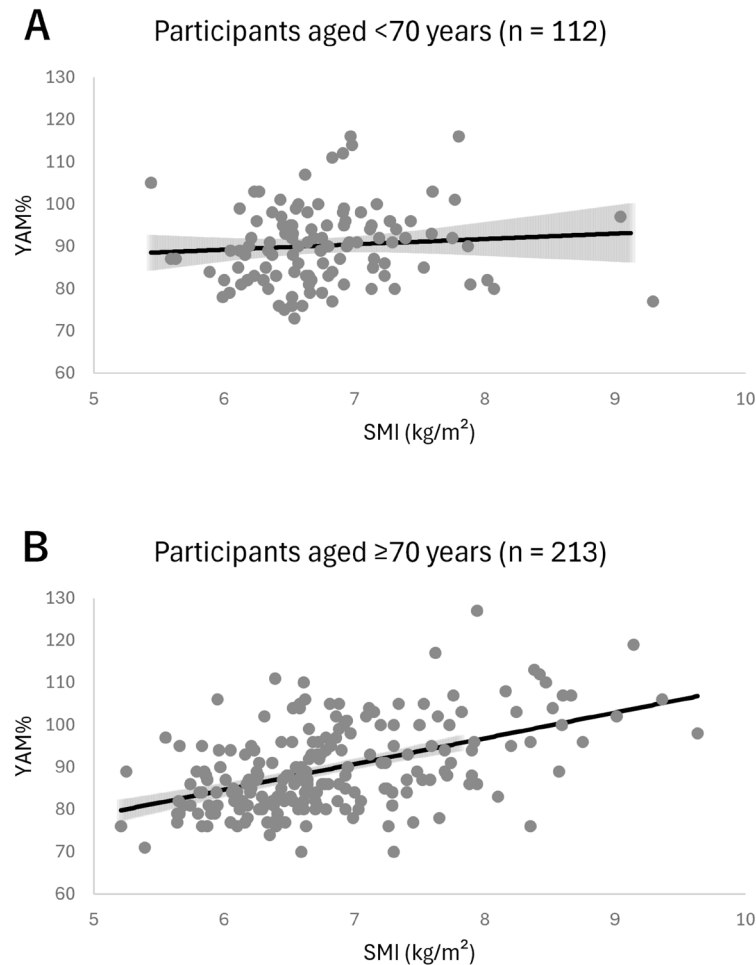


Figure 1. Association between skeletal muscle mass index and QUS-derived YAM% according to age group. Panel A shows participants aged <70 years (n = 112), and Panel B shows participants aged ≥70 years (n = 213). Points represent individual observed values. Solid lines and gray bands represent unadjusted group-specific linear regression lines and their 95% confidence intervals. Adjusted simple slopes were estimated from the multivariable linear interaction model adjusted for continuous age, sex, and BMI. The adjusted simple slope was -0.854 (95% CI -3.934–2.227, $p = 0.586$) among participants aged <70 years and 3.910 (95% CI 1.599–6.222, $p < 0.001$) among participants aged ≥70 years. The adjusted SMI $\times$ age-group interaction was statistically significant in the full-sample analysis ($p = 0.003$). Mean YAM% was similar between the two age groups. BMI, body mass index; CI, confidence interval; QUS, quantitative ultrasonography; SMI, skeletal muscle mass index; YAM%, percentage of the young adult mean.

distance values greater than $4/n$ were identified using a conservative screening threshold, and the interaction analyses were repeated after excluding these observations.

For the logistic regression model, model fit was assessed using the -2 log likelihood and Cox–Snell and Nagelkerke R^2 values, and calibration was evaluated using the Hosmer–Lemeshow goodness-of-fit test. The number of outcome events per predictor parameter was calculated, and event counts were summarized according to sex and age group.

P-values were derived from the respective regression models, with a two-sided p -value < 0.05 being considered

statistically significant. All analyses were performed using SPSS version 29.0 (IBM Corp., Armonk, NY, USA).

Results

The study population comprised 325 participants (mean age 71.0 ± 8.9 years, range 20–93 years), the characteristics of whom are shown in Table 1. Mean YAM% was similar between participants aged <70 years and those aged ≥70 years.

The results of multivariable linear regression (Table 2)

Table 2. Multivariable linear regression analysis examining the factors associated with YAM%.

Variable	Model 1 B (95% CI)	p-value	Model 2 B (95% CI)	p-value	Model 3 B (95% CI)	p-value
SMI (centered)	4.16 (2.32–6.00)	<0.001	-0.85 (-3.93–2.23)	0.586	0.92 (-1.93–3.78)	0.525
Age, years	-0.14 (-0.26– -0.02)	0.025	-0.21 (-0.38– -0.04)	0.018	-0.18 (-0.36– -0.01)	0.038
Sex	-2.18 (-5.68–1.32)	0.220	-2.71 (-6.35–0.93)	0.144	-1.17 (-4.69–2.35)	0.514
BMI, kg/m ²	—	—	0.58 (0.18–0.97)	0.005	—	—
Age ≥70 years	—	—	1.37 (-1.75–4.48)	0.388	1.56 (-1.59–4.70)	0.331
SMI × Age ≥70 years	—	—	4.76 (1.66–7.87)	0.003	4.61 (1.47–7.74)	0.004

SMI was mean-centered before construction of the interaction term. Model 1 was adjusted for age and sex. Model 2 was additionally adjusted for BMI and included the SMI × age-group interaction term. Model 3 excluded BMI as a sensitivity analysis. Sex was coded as 1 for men and 2 for women, with men serving as the reference category. In Model 2, the coefficient for SMI represents the adjusted simple slope among participants aged <70 years, whereas the SMI × age-group coefficient represents the difference in slopes between participants aged <70 and ≥70 years. The adjusted simple slope among participants aged ≥70 years was 3.910 (95% CI 1.599–6.222, $p < 0.001$). B, regression coefficient; CI, confidence interval; BMI, body mass index; SMI, skeletal muscle mass index; YAM%, percentage of the young adult mean.

revealed a significant positive association between SMI and YAM% in Model 1, which was adjusted for age and sex (B 4.16, 95% CI 2.32–6.00, $p < 0.001$). In Model 2, which included BMI and the SMI × age-group interaction, the coefficient for SMI, representing the simple slope among participants aged <70 years, was not statistically significant (B -0.854, 95% CI -3.934–2.227, $p = 0.586$). BMI was positively associated with YAM% (B 0.576, 95% CI 0.179–0.973, $p = 0.005$), and a significant interaction was observed between SMI and age group (<70 vs. ≥70 years; B 4.764, 95% CI 1.662–7.866, $p = 0.003$), indicating that the association between SMI and YAM% differed according to age. Age-specific simple slope analyses showed that SMI was positively associated with YAM% among participants aged ≥70 years (B 3.910, 95% CI 1.599–6.222, $p < 0.001$), whereas no significant association was observed among participants aged <70 years (B -0.854, 95% CI -3.934 to 2.227, $p = 0.586$; Figure 1). The interaction remained statistically significant in Model 3, in which BMI was excluded (B 4.605, 95% CI 1.470–7.740, $p = 0.004$).

In sensitivity analyses, the interaction between SMI and age was statistically significant when age was modeled as a continuous variable (B 0.179, 95% CI 0.004–0.354, $p = 0.044$). Significant interactions were also observed when alternative age-group cutoffs of 65 years (B 5.379, 95% CI 1.404–9.354, $p = 0.008$) and 75 years (B 2.641, 95% CI 0.086–5.196, $p = 0.043$) were applied in models adjusted for continuous age, sex, and BMI. In the full sample, these findings suggest that the observed effect modification was not limited to the 70-year cutoff.

In an additional complete-case sensitivity analysis including 306 participants, the model was further

adjusted for smoking history, alcohol consumption, regular exercise, history of fracture, daily use of five or more medications, and steroid hormone use. The SMI × age-group interaction remained statistically significant and was nearly unchanged in magnitude (B 4.744, 95% CI 1.525–7.963, $p = 0.004$). The model explained 22.1% of the variance in YAM% (adjusted $R^2 = 0.189$), and the maximum VIF was 6.011.

The main age-group interaction model explained 20.8% of the variance in YAM% ($R^2 = 0.208$; adjusted $R^2 = 0.193$). VIFs ranged from 1.450 to 5.882, and no VIF exceeded 10. The Durbin–Watson statistic was 2.021. Visual inspection of the residual histogram, normal P–P plot, and standardized residual-versus-predicted-value plot did not indicate marked departures from residual normality, linearity, or homoscedasticity. The maximum Cook's distance was 0.116, and no observation had a Cook's distance greater than 1. One observation had an absolute studentized deleted residual greater than 3, and 23 observations exceeded the leverage screening threshold. The BMI-excluded sensitivity model also showed no evidence of severe multicollinearity, with a maximum VIF of 4.950.

Using the conservative threshold of Cook's distance $>4/n$, 24 observations were identified as potentially influential. After excluding these observations, the interaction estimate for the 70-year age-group model remained positive but was attenuated and was no longer statistically significant (B 2.844, 95% CI -0.838 to 6.526, $p = 0.130$). The interaction estimates also remained positive but were not statistically significant when age was modeled as a continuous variable (B 0.100, 95% CI -0.076 to 0.277, $p = 0.265$) or using alternative age-group cutoffs of 65

Table 3. Multivariable logistic regression analysis for low bone status (YAM% <80%).

Variable	Model 1 OR (95% CI)	p-value	Model 2 OR (95% CI)	p-value
SMI, per kg/m ²	0.42 (0.21–0.83)	0.012	0.99 (0.44–2.25)	0.980
Age, years	1.02 (0.98–1.07)	0.367	1.05 (1.00–1.10)	0.069
Sex	0.75 (0.22–2.53)	0.647	1.66 (0.45–6.09)	0.442
BMI, kg/m ²	—	—	0.68 (0.57–0.82)	<0.001

Screening-defined low bone status was defined as QUS-derived YAM% <80%. Model 1 was adjusted for age and sex. Model 2 was additionally adjusted for BMI. Sex was coded as 1 for men and 2 for women, with men serving as the reference category; therefore, the OR for sex represents women compared with men. Odds ratios (ORs) were estimated using logistic regression analysis. —: not included in the model. CI, confidence interval; OR, odds ratio; BMI, body mass index; SMI, skeletal muscle mass index; YAM%, percentage of the young adult mean.

Table 4. Age-stratified multiple regression analyses for YAM%.

Variables	B (95% CI)	p value
Age group: <70 years		
SMI	2.160 (-1.780–6.100)	0.279
Age	-0.349 (-0.565–-0.133)	0.002
Sex	2.172 (-0.697–5.041)	0.135
BMI	0.240 (-0.342–0.822)	0.416
Age group: ≥70 years		
SMI	3.467 (0.859–6.075)	0.009
Age	0.041 (-0.192–0.274)	0.727
Sex	2.786 (-0.498–6.070)	0.094
BMI	0.727 (0.226–1.228)	0.005

B, unstandardized regression coefficient; CI, confidence interval; SMI, skeletal muscle mass index; BMI, body mass index. Separate multiple regression models were constructed for participants aged <70 years and ≥70 years. Sex was coded as 1 for men and 2 for women, with men serving as the reference category.

years (B 3.112, 95% CI -1.564 to 7.787, $p = 0.191$) and 75 years (B 1.750, 95% CI -0.679 to 4.179, $p = 0.157$). These findings indicate that the magnitude and statistical significance of the interaction estimates were sensitive to potentially influential observations.

Separate age-stratified multivariable regression analyses yielded a generally similar pattern. Among participants aged <70 years, SMI was not significantly associated with YAM% after adjustment for age, sex, and BMI (B = 2.160, $p = 0.279$), whereas age was independently and negatively associated with YAM% (B = -0.349, $p = 0.002$). In contrast, among participants aged ≥70 years, SMI was independently and positively associated with YAM% (B = 3.467, $p = 0.009$), and BMI was also positively associated with YAM% (B = 0.727, $p = 0.005$), whereas age was not significantly associated with YAM% (Table 4).

Multivariable logistic regression analyses for screening-

defined low bone status (YAM% <80%) revealed that SMI was significantly associated with screening-defined low bone status in Model 1 adjusted for age and sex (OR = 0.42, 95% CI 0.21–0.83, $p = 0.012$; Table 3). However, after additional adjustment for BMI, this association was attenuated and no longer statistically significant (Model 2: OR = 0.99, 95% CI 0.44–2.25, $p = 0.980$). BMI was significantly associated with lower odds of screening-defined low bone status (OR = 0.68, 95% CI 0.57–0.82, $p < 0.001$), whereas neither age nor sex was significantly associated with screening-defined low bone status in these models.

Screening-defined low bone status was observed in 41 of the 325 participants (12.6%). The event counts were 6 of 70 men (8.6%) and 35 of 255 women (13.7%), and 12 of 112 participants aged <70 years (10.7%) and 29 of 213 participants aged ≥70 years (13.6%). Model 2 included

four predictor parameters, corresponding to 10.25 events per parameter. The Hosmer–Lemeshow test did not indicate lack of fit ($\chi^2 = 5.018$, $df = 8$, $p = 0.756$). The -2 log likelihood was 214.404, and the Cox–Snell and Nagelkerke R² values were 0.094 and 0.176, respectively.

Discussion

The principal finding of this study was that the association between skeletal muscle mass and QUS-derived calcaneal bone status differed according to age in the full-sample analysis. Although mean YAM% was similar between participants aged <70 and ≥70 years, the adjusted SMI slope was not statistically significant among participants aged <70 years, whereas a 1 kg/m² higher SMI was associated with an approximately 3.91-percentage-point higher YAM% among participants aged ≥70 years. Statistically, the significant interaction indicates that the adjusted SMI slopes differed between the two age groups. However, this finding does not demonstrate that higher SMI causes better bone status, and its magnitude and statistical significance were sensitive to potentially influential observations.

Previous studies have consistently reported positive associations between skeletal muscle mass and bone mineral density, largely based on DXA-derived measurements^{12–14}. Previous Japanese calcaneal QUS studies have examined associations of bone status with physical function and fitness, whereas international muscle–bone research has more commonly assessed skeletal muscle mass in relation to DXA-derived bone mineral density. The present study extends this literature by examining whether age modifies the association between SMI and QUS-derived calcaneal bone status in a community-based osteoporosis screening sample. Moreover, the observed association is consistent with the “muscle–bone unit” concept, which emphasizes the close functional and biological coupling between muscle and bone through mechanical loading, endocrine signaling, and shared developmental pathways^{11,18,19}. However, previous studies have primarily focused on average associations across broad age ranges, with less attention to whether the strength of the muscle–bone relationship differs according to age. Our findings add to previous studies by examining whether the association between skeletal muscle mass and bone status varies according to age when bone status is assessed using QUS rather than DXA. These findings suggest that age may be relevant when interpreting the association between skeletal muscle mass and bone status; however, the interaction should be regarded as exploratory because it was sensitive to potentially influential observations.

The observed age-related pattern may be consistent with differences in mechanical loading and other biological or functional factors across age groups. Age-related changes in hormonal regulation, inflammation, physical

activity, and neuromuscular function may influence both muscle mass and bone status^{18,20–22}. However, these mechanisms were not directly assessed in the present study and should be regarded only as possible explanations for the observed association. Among participants aged <70 years, peak bone mass, genetic factors, and long-term lifestyle exposures may also contribute to variation in bone status, and may attenuate the observable association with current muscle mass.

One important aspect of this study was the use of calcaneal QUS. QUS-derived parameters may be influenced not only by bone quantity but also by aspects of bone microarchitecture and mechanical properties^{5,23}. However, QUS-derived YAM% should be interpreted as a screening measure of calcaneal bone status rather than as a direct measurement of bone mineral density or bone quality. The association between SMI and low bone status was attenuated after adjustment for BMI, and SMI was no longer a significant predictor, whereas BMI remained independently associated with low bone status. This finding suggests that overall body size and mechanical loading may partly account for the association between skeletal muscle mass and bone status^{18,24}. Because SMI and BMI are related components of body composition, adjustment for BMI may attenuate the apparent contribution of skeletal muscle mass. Therefore, the logistic regression findings do not support an independent association between SMI and screening-defined low bone status after adjustment for BMI. Nevertheless, in the full-sample linear regression analysis, the SMI × age-group interaction suggested that the association between skeletal muscle mass and bone status may differ according to age. However, because this interaction was attenuated after potentially influential observations were excluded, the finding should be interpreted cautiously. Muscle mass and overall body composition may provide complementary information when interpreting bone status, although their independent contributions could not be clearly distinguished in the present study.

The age-stratified analyses suggested that the association between SMI and YAM% was evident mainly in participants aged ≥70 years. In contrast, among participants aged <70 years, age showed a significant negative association with YAM%, whereas SMI was not independently associated with the outcome. Because the 70-year cutoff was not prespecified, the age-group interaction findings should be interpreted as exploratory. Statistically significant interactions were also observed in the full sample when age was modeled as a continuous variable and when alternative cutoffs of 65 and 75 years were applied, suggesting that the finding was not solely attributable to the selected cutoff. However, after observations identified using a conservative Cook’s distance threshold were excluded, the interaction estimates were attenuated and were no longer statistically significant, although their direction remained positive across the different age specifications. Thus, the magnitude

and statistical significance of the age-related interaction were sensitive to potentially influential observations. These findings should therefore be interpreted cautiously and require confirmation in larger independent cohorts.

This study was subject to certain limitations. Because of the cross-sectional design, the direction of the observed associations cannot be determined. Higher SMI may be associated with higher YAM%, whereas better overall health, greater physical activity, or other shared factors may be associated with both higher SMI and higher YAM%. Therefore, the present findings should not be interpreted as evidence that maintaining or increasing SMI preserves bone status. Longitudinal studies are needed to clarify the temporal relationship between skeletal muscle mass and bone status. In addition, participants were volunteers attending a municipality-operated osteoporosis screening program, and the analysis was restricted to participants with complete data. This may have introduced selection bias and may limit the generalizability of the findings to the broader community-dwelling population. Women comprised the majority of the sample, and the relatively small number of men limited sex-specific interpretation. Although the age-group interaction remained statistically significant after additional adjustment for available lifestyle and clinical factors, residual confounding cannot be excluded. Detailed information regarding osteoporosis-specific medications, calcium or vitamin D supplementation, diabetes, renal disease, menopausal hormone therapy, and other comorbidities was not available for analysis. Menopausal information was collected, but almost all women with available information were postmenopausal, which precluded stable adjustment for menopausal status. In addition, skeletal muscle mass was estimated using BIA, which is an indirect method of assessing muscle mass. We also did not assess muscle strength or physical performance, which could provide additional insights into the functional aspects of the muscle–bone unit. Furthermore, although QUS is well-suited for screening, QUS-derived YAM% is not equivalent to DXA-derived bone mineral density. SOS values were not available in the analytical dataset; therefore, we could not examine whether the association with SMI differed when SOS was used as the outcome. Accordingly, the screening-defined low bone status used in this study should not be interpreted as a clinical diagnosis of osteoporosis. Moreover, BMI includes both fat and lean components, which can complicate interpretations regarding its independent association with bone status. Despite these limitations, the standardized assessment of muscle mass and calcaneal bone status in a community-based screening setting, the inclusion of participants across a broad age range, and the examination of age-related effect modification using interaction and sensitivity analyses represent notable strengths of this study.

Our exploratory findings suggest that the association between SMI and QUS-derived calcaneal bone status may vary with age among community-dwelling adults

participating in an osteoporosis screening program. Although the association appeared stronger among participants aged ≥ 70 years in the full-sample analyses, the interaction estimates were attenuated and were no longer statistically significant after potentially influential observations were excluded. Therefore, the observed age-dependent association should be interpreted cautiously and regarded as hypothesis-generating. Larger longitudinal studies are needed to confirm these findings and clarify the temporal relationship between skeletal muscle mass and bone status.

Ethics approval

The study protocol was approved by the Ethics Committee of Saitama Medical University (approval number: U2022-024). This study was conducted in accordance with the principles of the Declaration of Helsinki.

Consent to participate

Written informed consent was obtained from all participants prior to enrollment in the study.

Authors' contributions

Yasuhiro Morita conceived and designed the study, performed the statistical analyses, interpreted the data, and drafted the manuscript. Kayo Miura contributed to data collection, interpretation of the results, and critical revision of the manuscript. Tomoyuki Arai contributed to study supervision, interpretation of the data, and critical revision of the manuscript. All authors read and approved the final version of the manuscript.

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References

1. Jordan KM, Cooper C. Epidemiology of osteoporosis. *Best Pract Res Clin Rheumatol* 2002;16(5):795–806.
2. Kanis JA, McCloskey EV, Johansson H, et al. European guidance for the diagnosis and management of osteoporosis in postmenopausal women. *Osteoporos Int* 2012;24(1):23–57.
3. Reginster JY, Beaudart C, Buckinx F, Bruyère O. Osteoporosis and sarcopenia: two diseases or one? *Curr Opin Clin Nutr Metab Care* 2016;19(1):31–36.
4. Oei L, Koromani F, Rivadeneira F, et al. Quantitative imaging methods in osteoporosis. *Quant Imaging Med Surg* 2016;6(6):680–698.
5. Krieg MA, Barkmann R, Gonnelli S, et al. Quantitative ultrasound in the management of osteoporosis: the 2007 ISCD Official Positions. *Osteoporos Int* 2008;19(1):1–12.
6. Hans D, Dargent-Molina P, Schott AM, et al. Ultrasonographic heel measurements to predict hip fracture in elderly women: the EPIDOS prospective

- study. *Lancet* 1996;348:511–514.
7. Moayyeri A, Adams JE, Adler RA, et al. Quantitative ultrasound of the heel and fracture risk assessment: an updated meta-analysis. *Osteoporos Int* 2012;23(1):143–153.
8. Bauer DC, Glüer CC, Cauley JA, et al. Broadband ultrasound attenuation predicts fractures strongly and independently of densitometry. *Arch Intern Med* 1997;157:629–634.
9. Orimo H, Nakamura T, Hosoi T, et al. Japanese 2011 guidelines for prevention and treatment of osteoporosis—executive summary. *Arch Osteoporos*. 2012;7:3–20.
10. Ohta T, Nagashima J, Fukuda W, Sasai H, Ishii N. Association of knee extensor muscle strength and cardiorespiratory fitness with bone stiffness in Japanese adults: a cross-sectional study. *J Epidemiol*. 2022;32(12):543–550.
11. Daly RM, Saxon L, Turner CH, Robling AG, Bass SL. The relationship between muscle size and bone geometry during growth and in response to exercise. *Bone* 2004;34(2):281–287.
12. Scott D, Seibel MJ, Cumming RG, et al. Sarcopenic obesity and its temporal associations with changes in bone mineral density, incident falls, and fractures in older men: the Concord Health and Ageing in Men Project. *J Bone Miner Res* 2017;32(3):575–583.
13. Novotny SA, Warren GL, Hamrick MW. Aging and the muscle–bone relationship. *Physiology* 2015;30(1):8–16.
14. Lang T, Streeper T, Cawthon P, Baldwin K, Taaffe DR, Harris TB. Sarcopenia, obesity, and osteoporosis: age-associated changes in body composition and bone mineral density in the Health ABC Study. *J Bone Miner Res* 2010;25(6):1356–1365.
15. Métrailler A, Hans D, Lamy O, Gonzalez Rodriguez E, Shevroja E. Heel quantitative ultrasound (QUS) predicts incident fractures independently of trabecular bone score (TBS), bone mineral density (BMD), and FRAX: the OsteoLaus Study. *Osteoporos Int* 2023;34(8):1401–1409.
16. Cruz-Jentoft AJ, Bahat G, Bauer J, et al. Sarcopenia: revised European consensus on definition and diagnosis. *Age Ageing* 2019;48(1):16–31.
17. Chen LK, Hsiao FY, Akishita M, et al. A focus shift from sarcopenia to muscle health in the Asian Working Group for Sarcopenia 2025 consensus update. *Nat Aging* 2025;5(11):2164–2175.
18. Hamrick MW. The skeletal muscle secretome: an emerging player in muscle–bone crosstalk. *BoneKey Rep* 2012;1:60.
19. Burr DB. Muscle strength, bone mass, and age-related bone loss. *J Bone Miner Res* 1997;12(10):1547–1551.
20. Kaji H. Interaction between muscle and bone. *J Bone Metab* 2014;21(1):29–40.
21. Beaudart C, Dawson A, Shaw SC, et al. Nutrition and physical activity in the prevention and treatment of sarcopenia: systematic review. *Osteoporos Int* 2017;28(6):1817–1833.
22. Yu C, Du Y, Peng Z, et al. Research advances in crosstalk between muscle and bone in osteosarcopenia. *Exp Ther Med* 2023;25(4):189.
23. Njeh CF, Boivin CM, Langton CM. The role of ultrasound in the assessment of osteoporosis: a review. *Osteoporos Int* 1997;7(1):7–22.
24. De Laet C, Kanis JA, Odén A, et al. Body mass index as a predictor of fracture risk: a meta-analysis. *Osteoporos Int* 2005;16(11):1330–1338.