

Appendicular skeletal muscle index and bone mineral density in postmenopausal women: The moderating role of BMI and site-specific differences between lumbar spine and femoral neck

Qingqiang Huang

Capital University of Physical Education and Sports

Xiaohong Chen

chenxiaohong@cupes.edu.cn

Capital University of Physical Education and Sports

Research Article

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Abstract

Objective

This study aimed to explore the effects of the appendicular skeletal muscle index (ASMI) on T-scores of lumbar spine and femoral neck bone mineral density (BMD) in postmenopausal women with different body mass index (BMI) levels, analyze the interaction between ASMI and BMI grouping, and investigate the site-specific characteristics of BMD in response to body composition indicators.

Methods

A total of 249 community-dwelling postmenopausal women were enrolled and stratified into the non-overweight/obese group (n = 96) and the overweight/obese group (n = 153) based on a BMI cutoff value of 24 kg/m². Dual-energy X-ray absorptiometry was applied to detect BMD, body composition, ASMI, grip strength and other physical indicators. Independent sample t-test, chi-square test, Pearson correlation analysis and age-adjusted partial correlation analysis were performed for statistical evaluation. BMD residuals excluding the influence of age were extracted, and BMI-stratified regression analysis as well as interaction analysis between ASMI and BMI grouping were further conducted.

Results

Baseline characteristics and BMD indicators differed significantly between the two groups (all $P < 0.05$). The prevalence of osteoporosis was 28.13% in the non-overweight/obese group, which was significantly higher than 6.54% in the overweight/obese group ($\chi^2=20.06$, $P < 0.001$). The correlation coefficients of age with lumbar spine and femoral neck BMD were -0.221 and -0.297 , while those of BMI were 0.338 and 0.372 . The original correlation coefficients of ASMI for lumbar spine and femoral neck BMD were 0.263 and 0.237 , and the age-adjusted partial correlation coefficients were 0.242 and 0.209 , respectively (all $P < 0.001$). Stratified regression analysis showed that ASMI positively predicted BMD residuals of the lumbar spine ($\beta = 0.580$) and femoral neck ($\beta = 0.541$) in the non-overweight/obese group (all $P < 0.05$). In the overweight/obese group, only body fat percentage significantly affected lumbar spine BMD ($\beta = 6.843$, $P < 0.05$). A significant interaction between ASMI and BMI grouping was identified for femoral neck BMD ($\beta = 0.679$, $P < 0.05$). Additionally, age and BMI exhibited stronger correlations with femoral neck BMD, whereas ASMI was more closely correlated with lumbar spine BMD.

Conclusion

The protective effect of ASMI on BMD is exclusively observed in non-overweight/obese postmenopausal women, and high BMI can attenuate this protective effect, indicating a significant regulatory role of BMI. The influences of body composition on BMD present distinct site-specific differences between the

lumbar spine and femoral neck. Clinical attention should be paid to the evaluation of skeletal muscle mass in low-BMI postmenopausal women, and individualized osteoporosis intervention strategies should be formulated based on the structural and functional characteristics of different skeletal sites.

1. Introduction

Osteoporosis is a prevalent systemic skeletal disorder characterized by reduced bone mass, deteriorated bone microarchitecture, increased bone fragility, and elevated fracture risk. As a global public health burden affecting hundreds of millions of individuals worldwide, osteoporosis disproportionately impacts postmenopausal women. The sharp decline in estrogen levels after menopause accelerates bone resorption and exacerbates bone loss, rendering postmenopausal women highly susceptible to osteoporosis [1]. This disease imposes substantial socioeconomic burdens globally, including increased disability, mortality, and excessive medical expenditure [2].

Body mass index (BMI) has long been recognized as a critical determinant of bone mineral density (BMD). Conventional perspectives suggest that elevated mechanical load induced by higher BMI exerts a protective effect on bone tissue. A 2024 cross-sectional analysis based on the National Health and Nutrition Examination Survey (NHANES) demonstrated that high BMI was positively correlated with BMD in postmenopausal women, with obese individuals presenting significantly higher BMD than normal-weight counterparts, confirming the mechanical protective effect of high BMI on bone health [3].

Nevertheless, a considerable number of non-overweight/obese postmenopausal women maintain normal BMD in clinical practice, implying that factors beyond BMI, particularly body composition, play indispensable roles in bone homeostasis. Therefore, it is essential to explore the potential protective factors for BMD in postmenopausal women with low BMI.

With the advancement of body composition detection technology, the relationships between muscle mass, fat mass and BMD can be quantitatively evaluated. Although numerous studies have verified the correlations of muscle and fat mass with BMD, consistent conclusions have not been reached. Several studies have confirmed that the appendicular skeletal muscle index (ASMI) is positively correlated with BMD, suggesting that skeletal muscle protects bone tissue via mechanical loading stimulation and myokine secretion. However, some studies failed to identify an independent association between ASMI and BMD after adjusting for confounding factors such as BMI [4, 5]. Such inconsistent findings may be attributed to the complex interactions among different body composition components under varying adiposity statuses.

Adipose tissue exerts dual regulatory effects on bone metabolism. Moderate fat mass protects BMD through mechanical loading and endogenous estrogen synthesis, whereas excessive fat accumulation, especially visceral fat, impairs bone metabolism by triggering chronic low-grade inflammation and endocrine dysregulation [6, 7]. Accordingly, the association between muscle mass and BMD may vary significantly under different BMI and adiposity conditions.

Currently, limited studies have focused on the heterogeneous relationships between ASMI and BMD across different BMI strata in postmenopausal women, especially the protective factors of BMD in non-overweight/obese populations. This study aimed to investigate the correlations between body composition and BMD under different BMI conditions, further clarify the stratified differences in the ASMI-BMD association, and explore the potential role of skeletal muscle mass in maintaining bone health among postmenopausal women.

2. Materials and Methods

2.1 Study Participants

Participants were postmenopausal women recruited from multiple communities in Haidian District, Beijing, covering old residential communities, commercial apartment complexes and urban residential buildings. The inclusion criteria were as follows: (1) natural menopause for at least one year; (2) absence of severe chronic or acute systemic diseases; (3) voluntary participation with signed informed consent. The exclusion criteria included: (1) premature menopause (menopause before 40 years of age); (2) history of medication use affecting bone metabolism or hormone replacement therapy; (3) diagnosis of bone metabolic diseases.

The sample size was calculated based on multivariate linear regression using the pwr package in R software. Referring to previous studies and adopting conservative parameter settings [8], the significance level α was set at 0.05 (two-tailed), statistical power ($1-\beta$) at 0.80, and expected effect size f^2 at 0.10 (moderate effect). The regression model included five independent variables: age, BMI grouping, ASMI, menopausal years, and interaction term. A minimum sample size of 166 was required to achieve sufficient statistical power. Considering potential missing data, a total of 249 participants were finally enrolled. Participants were stratified into two groups according to the Chinese BMI classification standard: non-overweight/obese group ($BMI < 24 \text{ kg/m}^2$, $n = 96$) and overweight/obese group ($BMI \geq 24 \text{ kg/m}^2$, $n = 153$), which met the statistical power requirement. This study was approved by the Biomedical Ethics Committee of Capital University of Physical Education and Sports (Approval No. 2021A33), and all participants provided written informed consent.

2.2 Measurement Methods

2.2.1 Skeletal Muscle Mass and Grip Strength Measurement

Whole-body body composition and BMD were measured using a Lunar Prodigy dual-energy X-ray absorptiometry (GE Healthcare, USA) with enCORE2006 software (Version 10.50.086) [9]. Scanning covered the whole body, trunk, limbs and hip regions to automatically calculate whole-body fat mass and regional body composition parameters. ASMI was calculated as appendicular skeletal muscle mass (kg) divided by the square of height (m^2). BMD T-scores were measured at the lumbar spine and bilateral

femoral neck. All measurements were performed by a single trained professional, and daily instrument calibration was conducted before detection to ensure data accuracy.

Hand grip strength was tested using a WCS-99.9 digital grip dynamometer. Two repeated measurements were performed, and the maximum value was recorded for subsequent analysis.

2.2.2 BMI Measurement and Grouping Criteria

Height and weight were measured using a DS-102 body analyzer (JINEX, Korea). BMI was calculated as body weight (kg) divided by the square of body height (m²).

2.2.3 Baseline Information Collection

A self-developed Health and Physical Activity Questionnaire was used to collect general demographic and lifestyle information, including age, menopausal years, physical activity habits (exercise type, duration, and frequency), chronic disease history (hypertension, diabetes, heart disease, etc.), and long-term medication history. The full English version of this questionnaire is available as Supplementary File S1.

2.2.4 Statistical Analysis

All statistical analyses and data visualization were performed using R software. Measurement data were presented as mean $\pm$ standard deviation with minimum and maximum values, while enumeration data were described as case number and constituent ratio. Participants were stratified by the BMI cutoff of 24 kg/m². Independent sample t-test was used for inter-group comparison of measurement data, and chi-square test was adopted for comparison of osteoporosis prevalence.

Pearson correlation analysis was used to explore the correlations between all indicators and BMD T-scores of the lumbar spine and femoral neck. Given the significant multicollinearity between age and menopausal years, only age was selected as the confounding factor for age-adjusted partial correlation analysis.

To eliminate the baseline interference of age on BMD, a linear regression model with age as the independent variable was constructed, and BMD residuals excluding age effects were extracted using the broom package. Multivariate linear regression models were established separately in the two BMI groups to analyze the independent effects of ASMI, body fat percentage and grip strength on age-adjusted BMD residuals.

Furthermore, a regression model with interaction terms was constructed to explore the interactive effect of ASMI and BMI grouping on BMD. The ggplot2 package was used to generate scatter plots with fitted lines to visualize the correlation trends. All statistical tests were two-tailed, and $P < 0.05$ was considered statistically significant.

3. Results

3.1 Baseline Characteristics of Participants

A total of 249 postmenopausal women were enrolled in this study, including 96 cases in the non-overweight/obese group and 153 cases in the overweight/obese group. Significant inter-group differences were observed in age, menopausal years, body weight, BMI, body fat percentage, ASMI and grip strength (all $P < 0.05$). Osteoporosis was diagnosed when the BMD T-score of the lumbar spine or femoral neck was ≤ -2.5 . The prevalence of osteoporosis was 28.13% in the non-overweight/obese group, which was significantly higher than 6.54% in the overweight/obese group ($\chi^2=20.06$, $P < 0.001$). Detailed baseline characteristics, extreme value ranges and inter-group comparison results are shown in Table 1.

Table 1
Basic characteristic information

Variables	Non-overweight/obese group (n = 96)	Overweight/obese group (n = 153)	P value
Lumbar spine BMD T-score	-1.46 ± 1.25 (– 3.90, 1.20)	-0.68 ± 1.34 (– 3.80, 4.70)	< 0.05
Femoral neck BMD T-score	-1.34 ± 0.96 (– 3.30, 1.10)	-0.65 ± 0.92 (– 3.20, 1.50)	< 0.05
Age (years)	66.48 ± 6.40 (55.1, 85.8)	64.81 ± 5.36 (50, 84.9)	< 0.001
Height (m)	1.57 ± 0.06 (1.40, 1.67)	1.56 ± 0.05 (1.42, 1.68)	< 0.001
Body weight (kg)	53.76 ± 6.03 (39.00, 64.40)	65.48 ± 6.68 (53.00, 86.20)	< 0.001
BMI (kg/m ²)	21.65 ± 1.66 (16.30, 23.87)	26.96 ± 2.42 (24.03, 36.30)	< 0.001
Body fat percentage	0.32 ± 0.05 (0.21, 0.42)	0.38 ± 0.05 (0.27, 0.51)	< 0.001
ASMI (kg/m ²)	5.70 ± 0.61 (4.21, 7.32)	6.32 ± 0.68 (4.89, 8.12)	< 0.001
Grip strength (kg)	22.62 ± 3.15 (16.00, 30.00)	23.83 ± 3.26 (17.00, 32.00)	< 0.05
Osteoporosis prevalence (%)	28.13	6.54	< 0.001

3.2 Correlation Analysis Between Study Indicators and BMD

Pearson correlation analysis was performed to evaluate the basic associations between each indicator and BMD T-scores of the lumbar spine and femoral neck. The results showed that age was significantly negatively correlated with BMD T-scores (lumbar spine: $r=-0.221$; femoral neck: $r=-0.297$; all $P < 0.01$).

BMI, ASMI, body fat percentage and grip strength were all significantly positively correlated with BMD T-scores of both skeletal sites (all $P < 0.01$).

Considering the confounding effect of age on the muscle-bone association, age-adjusted partial correlation analysis was further conducted for the core indicator ASMI. After eliminating age interference, the partial correlation coefficients of ASMI with lumbar spine and femoral neck BMD T-scores were 0.242 and 0.209, respectively (all $P < 0.01$), indicating a stable positive correlation between ASMI and BMD independent of age. The confounding effects of age on other indicators were further explored in subsequent multivariate regression analysis. Detailed correlation results are presented in Table 2.

Table 2
Correlation between various indicators and bone mineral density

Variables	Lumbar spine BMD T-score		Femoral neck BMD T-score	
	Original r	Age-adjusted r	Original r	Age-adjusted r
Age	-0.221**	-	-0.297**	-
BMI	0.338**	-	0.372**	-
ASMI	0.263**	0.242**	0.237**	0.209**
Body fat percentage	0.247**	-	0.255**	-
Grip strength	0.227**	-	0.233**	-
Note: ** $P < 0.001$, * $P < 0.05$				

3.3 BMD Residual Regression Analysis

A linear regression model with age as the independent variable was established to extract age-adjusted BMD residuals. After controlling for age confounding effects, significant stratified differences were observed in the effects of body composition indicators on BMD residuals across different BMI groups. In the non-overweight/obese group, ASMI was significantly positively correlated with femoral neck BMD residuals ($\beta = 0.541$, $P < 0.05$), while body fat percentage and grip strength showed no significant effects. No indicators exerted significant influences on femoral neck BMD residuals in the overweight/obese group ($P > 0.05$).

For lumbar spine BMD, ASMI was an independent positive predictor of BMD residuals in the non-overweight/obese group ($\beta = 0.580$, $P < 0.05$). In the overweight/obese group, only body fat percentage significantly and positively affected lumbar spine BMD residuals ($\beta = 6.843$, $P < 0.05$), with no significant effects observed for other indicators. Detailed results are shown in Table 3 and Table 4.

Table 3
Residual regression analysis of femoral neck BMD T-score

Variables	Non-overweight/obese group		Overweight/obese group	
	β	P value	β	P value
ASMI	0.541	< 0.05	-0.055	> 0.05
Body fat percentage	1.172	> 0.05	2.625	> 0.05
Grip strength	0.015	> 0.05	0.021	> 0.05

Table 4
Residual regression analysis of lumbar spine BMD T-score

Variables	Non-overweight/obese group		Overweight/obese group	
	β	P value	β	P value
ASMI	0.580	< 0.05	0.279	> 0.05
Body fat percentage	1.227	> 0.05	6.843	< 0.05
Grip strength	0.035	> 0.05	0.029	> 0.05

3.4 Interaction Analysis Between ASMI and BMI Grouping

A regression model with interaction terms was constructed to analyze the interactive effect of ASMI and BMI grouping on BMD T-scores. With the overweight/obese group set as the reference group, a significant interaction between ASMI and BMI grouping was observed for femoral neck BMD ($\beta = 0.679$, $P < 0.05$), indicating that the positive protective effect of ASMI on femoral neck BMD was significantly stronger in the non-overweight/obese group. The interaction effect for lumbar spine BMD was not statistically significant ($P > 0.05$). Age was an independent risk factor for reduced BMD ($P < 0.05$), and non-overweight/obese status was negatively correlated with BMD ($P < 0.05$). Detailed results are presented in Table 5.

Table 5
Interaction analysis of ASMI and BMI grouping on BMD

Variables	Femoral neck BMD	Lumbar spine BMD
Age	-0.041**	-0.040*
BMI grouping (reference: overweight/obese group)	-4.548**	-3.737*
ASMI	-0.099	0.147
Menopausal years	0.001	0.001
BMI grouping × ASMI	0.679*	0.547
Model fit	R ² =0.215, P < 0.001	R ² =0.142, P < 0.001
Note: **P<0.001, *P<0.05		

4. Discussion

The present study demonstrated that ASMI was significantly positively correlated with BMD T-scores in postmenopausal women, with distinct stratified differences across BMI groups. The protective association between ASMI and BMD was only significant in non-overweight/obese individuals, while no notable effect was observed in the overweight/obese population. Interaction analysis confirmed that BMI status modulates the magnitude of the ASMI-BMD association, indicating divergent effects of skeletal muscle on bone health under different body mass conditions.

4.1 Protective Effect of ASMI on Bone Mineral Density

Accumulating evidence has verified the close correlation between skeletal muscle mass and BMD. As a standardized indicator for evaluating skeletal muscle mass, ASMI is widely applied in research on sarcopenia and bone homeostasis [10, 11]. Consistent with our findings, previous studies have confirmed a positive correlation between ASMI and BMD in postmenopausal women [12]. Additional research has further indicated that muscle mass and muscle function are positively associated with hip BMD and bone geometric structure, highlighting the comprehensive regulatory effect of skeletal muscle on bone quality [13].

Traditionally, the protective effect of skeletal muscle on bone is attributed to mechanical loading stimulation. Tensile stress generated by skeletal muscle contraction acts on bone tissue, thereby promoting bone formation and maintaining bone mass stability. Mechanical stimuli from skeletal muscle are critical for bone remodeling and metabolic balance, and altered muscle loading directly affects bone turnover [14, 15].

In recent years, the "muscle-bone crosstalk" mechanism has been extensively explored, revealing that skeletal muscle serves as an endocrine organ that regulates bone metabolism via myokine secretion,

inflammatory modulation and metabolic pathway regulation [16–18]. A 2023 study illustrated that muscle-derived endocrine signals mediate muscle-bone interaction, regulating bone metabolism and facilitating fracture repair [19]. A 2025 study further confirmed that myokines including irisin and myostatin modulate osteoblast and osteoclast activity, thus maintaining bone homeostasis under physiological and diabetic conditions [20]. These findings indicate that the muscle-bone association is mediated by both mechanical loading and complex endocrine interactions. Accordingly, the positive effect of ASMI on BMD observed in this study may be explained by the dual mechanical and endocrine protective mechanisms of skeletal muscle.

4.2 Heterogeneous ASMI-BMD Associations Across Different BMI Statuses

Notably, the protective association between ASMI and BMD was only significant in non-overweight/obese postmenopausal women and disappeared in the overweight/obese group. This discrepancy may be attributed to obesity-induced chronic low-grade inflammation, abnormal adipokine secretion, and impaired muscle quality. Adipose tissue participates in bone metabolism regulation via inflammatory and metabolic pathways, in addition to providing mechanical loading [21]. Excessive fat accumulation in high-BMI individuals may counteract the protective effects of skeletal muscle on bone tissue.

Obesity alters body composition profiles and disrupts the physiological muscle-bone crosstalk. Adipose tissue secretes pro-inflammatory cytokines (TNF- α , IL-6) and adipokines (leptin, adiponectin), which interfere with bone remodeling and bone mineralization [22, 23]. A 2025 study on sarcopenic obesity and bone health confirmed that the combination of high body fat and low muscle mass impairs BMD, demonstrating that fat-derived adverse factors can offset muscle-mediated bone protection under high-BMI conditions [24], which is consistent with our results. In high-BMI populations, the negative metabolic effects of adipose tissue dominate over the protective mechanical and endocrine effects of skeletal muscle, leading to the attenuation of the ASMI-BMD association.

Moreover, even obese individuals with relatively higher BMD may have deteriorated bone microarchitecture due to fat infiltration and metabolic disorders, implying hidden bone damage despite preserved bone mass [25, 26]. It is noteworthy that high BMI still provides mechanical protection for bone tissue to a certain extent [27]. However, our study indicated that the metabolic adverse effects of excessive fat could abolish muscle-derived bone protection. Therefore, BMI alone is insufficient for bone health assessment in postmenopausal women, and body composition and muscle mass status should be comprehensively evaluated.

4.3 Site-Specific Responses of Lumbar Spine and Femoral Neck BMD to Body Composition

Our results revealed distinct site-specific characteristics in the association between body composition and BMD. Age and BMI exhibited stronger correlations with femoral neck BMD, while ASMI was more

closely associated with lumbar spine BMD. Stratified regression and interaction analyses further confirmed that the magnitude and significance of the effects of ASMI and body fat on BMD differed substantially between the two skeletal sites, indicating heterogeneous regulatory mechanisms of body composition on different bones.

Such site specificity is closely related to anatomical structure, mechanical loading patterns and metabolic microenvironment differences. The lumbar spine is predominantly composed of trabecular bone with high metabolic activity, which is highly sensitive to local mechanical traction and muscle-bone regulatory signals. Paravertebral muscles generate local mechanical stress during contraction, activating canonical Wnt/ β -catenin signaling pathways to promote bone formation and regulate lumbar spine BMD [28]. In contrast, the femoral neck is a major weight-bearing site with a mixed structure of cortical and trabecular bone. Its BMD is primarily regulated by systemic mechanical loading (ground reaction force induced by body weight/BMI) and global metabolic status, rather than local muscle mass alone [29].

Body fat percentage also exerts site-specific effects on bone metabolism. For the metabolically active lumbar trabecular bone, moderate adipose tissue protects bone by promoting peripheral estrogen synthesis via aromatase. However, excessive body fat induces chronic low-grade inflammation with increased secretion of IL-6 and TNF- α , disrupting the balance between bone formation and bone resorption and causing greater damage to lumbar spine bone. For the femoral neck, the mechanical protective effect of high BMI can partially offset the metabolic adverse effects of adipose tissue, resulting in a relatively stable fat-bone association [30, 31]. Furthermore, muscle-bone endocrine crosstalk contributes to this site specificity. Myokine-mediated osteogenic effects are more direct on the spine due to anatomical proximity, primarily via the Wnt/ β -catenin signaling pathway [28].

In conclusion, the associations between body composition and BMD in postmenopausal women exhibit significant site specificity, which is determined by differences in mechanical loading modes, bone tissue structure, and the sensitivity of muscle-fat-bone metabolic regulation. These findings suggest that individualized intervention strategies should be developed based on skeletal site characteristics. Resistance training to improve skeletal muscle mass is recommended to prevent lumbar spine bone loss, while scientific weight management is essential to maintain femoral neck bone strength.

4.4 Limitations and Prospects

This study has several limitations. First, the cross-sectional design cannot establish causal relationships between ASMI and BMD changes. Longitudinal cohort studies are required to track dynamic changes in ASMI and BMD over time to clarify causal effects. Second, this study failed to comprehensively collect and adjust for potential confounding factors, including genetic background and detailed lifestyle parameters. Third, all participants were recruited from urban communities, which limits the generalizability of the findings to rural populations. Furthermore, this study only analyzed macroscopic body composition indicators; future research can incorporate molecular biology and metabolomics approaches, such as detecting circulating myokines (irisin, IGF-1), to further elucidate the underlying endocrine mechanisms of muscle-bone crosstalk.

5. Conclusions

ASMI exerts a significant protective effect on BMD in non-overweight/obese postmenopausal women, whereas high BMI substantially attenuates this protective effect, confirming the regulatory role of BMI in the muscle-bone association. The effects of body composition on BMD present distinct site-specific differences: femoral neck BMD is more susceptible to age and body weight changes, while lumbar spine BMD is more sensitive to variations in skeletal muscle mass. A balanced body composition with adequate muscle reserve is beneficial for maintaining bone homeostasis in postmenopausal women. Clinically, targeted attention should be paid to skeletal muscle assessment and intervention in low-BMI postmenopausal women, and individualized osteoporosis prevention strategies should be implemented based on the site-specific characteristics of different skeletal regions.

Declarations

Ethical Approval and Informed Consent

This study was formally reviewed and authorized by the Biomedical Ethics Committee of Capital University of Physical Education and Sports (Approval No.: 2021A33). The study protocol strictly complies with the Declaration of Helsinki and relevant medical ethical guidelines. All postmenopausal women participating in this study voluntarily provided written informed consent after fully understanding the study's purpose, procedures, potential risks, and benefits. During the research process, the personal information and test data of participants were treated with strict confidentiality and used exclusively for academic research purposes, so as to safeguard the legitimate rights, interests, and privacy of all participants. Consent for Publication☐Not applicable.

Consent for Publication

Not applicable.

Data Availability

The dataset(s) supporting the conclusions of this article are included within the article (and its additional file(s)). The English version of the self-developed Health and Physical Activity Questionnaire is provided as Supplementary File S1. The datasets generated and/or analysed during the current study, including participants' basic information, body composition results, bone mineral density measurements, grip strength data, and the statistical analysis codes, are not publicly available due to ethical and confidentiality restrictions. However, these raw data are archived and can be made available from the corresponding author upon reasonable request. Requests for access should be made by email to the first author (3466934416@qq.com) and must include verification of the requester's identity and research objectives. Data will be provided in accordance with ethical guidelines to support reproducibility of the research findings.

Competing Interests

All authors declare that there are no competing interests that could compromise the objectivity of the research or the fairness of the results. This includes, but is not limited to, financial interests related to the research (such as commercial funding, patent holdings, consulting fees, or equity ownership) and non-financial conflicts of interest at the personal, professional, or institutional levels. This declaration applies to all authors and encompasses the entire process of study design, data collection, analysis, and manuscript preparation.

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Author Contributions

All authors made substantial contributions to this study, with specific responsibilities as follows:

Qingqiang Huang: Responsible for data processing and manuscript drafting;

Xiaohong Chen: Responsible for participant experiments and manuscript revision;

All authors participated in the discussion and interpretation of the study findings, and reviewed and approved the final submitted manuscript.

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