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Relationship between Muscle Mass and Muscle Strength with Bone Density in Older Adults: A Systematic Review

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Background: Understanding the relationship between muscle mass, muscle strength, and bone density in older adults is crucial for addressing age-related conditions like osteoporosis and sarcopenia. This review aims to evaluate the relationship between muscle mass and muscle strength with bone density in older adults. **Methods:** This systematic review, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, involved a comprehensive search across seven databases from 2014 to April 2024. Included were observational studies in English and Indonesian on adults aged 60 and older. The Appraisal Tool for Cross-Sectional Studies (AXIS) tool assessed the risk of bias, and the GRADE (Grading of Recommendations Assessment, Development, and Evaluation) framework evaluated the evidence quality. Study selection was independently reviewed, and consensus was reached through discussion. **Results:** Ten studies were included. For muscle mass and bone density, five studies showed a significant association, while four did not. For muscle strength and bone density, four of seven studies reported a significant association. However, the evidence quality was low due to inconsistency. **Conclusion:** The relationship between muscle mass, muscle strength, and bone density in older adults shows variability and inconsistent evidence.

Key Words: Muscle mass, Muscle strength, Bone density, Older adults, Systematic review

INTRODUCTION

Aging is a complex process that involves various physiological changes, including the gradual decline in both bone mass and muscle mass, which can lead to conditions such as osteoporosis and sarcopenia.[1)] Research has consistently demonstrated significant age-related losses in bone and muscle tissues during adulthood.[2)] Understanding the relationship between muscle mass, muscle strength, and bone density is essential for comprehending the impact of aging on musculoskeletal health. Previous studies have shown that muscle strength is correlated with bone mineral density (BMD), especially in populations such as postmenopausal women with osteoporosis.[3)] Handgrip strength, for instance, has been identified as an independent predictor of distal radius BMD in postmenopausal women, highlighting the importance of muscle strength in assessing osteoporosis risk factors.[4)] Moreover, a simultaneous decline in muscle strength and BMD has been observed in older age, indicating a close association between these factors.[5)] The reduction in physical activity throughout life may not fully explain the age-related loss of bone mass, pointing to the need for further research to establish the direct link between muscle mass and bone density.[6)] Evaluating muscle-bone interactions is crucial, as muscle loading affects bone structure and strength, underscoring the interconnected nature of these musculoskeletal components.[7)]

Osteoporosis and sarcopenia are common conditions in older adults that significantly impact their health and well-being. These two musculoskeletal disorders are closely related and often coexist, leading to an increased risk of adverse health outcomes.[8)] Research has shown that the decline in muscle performance is linked to the

deterioration of bone microarchitecture, with individuals developing sarcopenia facing a higher risk of also developing osteoporosis.[9] The dynamic relationship between impaired muscle and bone health highlights the need to address both conditions simultaneously to mitigate their combined effects on older adults. The coexistence of osteoporosis and sarcopenia in older individuals is associated with increased frailty, morbidity, and mortality.[10] Older adults, particularly those with frailty, are more likely to have concurrent osteoporosis and sarcopenia, further increasing their risk of disease-related complications.[11] This combination can lead to a higher susceptibility to falls, fractures, and disability, significantly affecting the quality of life and independence of older adults.[12] The concept of "osteosarcopenia" has emerged to emphasize the strong correlation between sarcopenia and osteoporosis, suggesting the need to consider both conditions collectively in clinical assessments and interventions.[13,14] The shared risk factors, such as aging, physical inactivity, and hormonal changes, highlight the interconnected nature of osteoporosis and sarcopenia. Addressing these shared risk factors through targeted interventions can help slow the progression of these conditions and improve outcomes in older adults.

Muscle mass and muscle strength are crucial for maintaining mobility and reducing the risk of osteoporosis and fractures in older adults. With aging, there is a natural decline in muscle mass and strength, leading to impaired physical function, mobility disability, falls, and fractures.[15] Sarcopenia, characterized by the loss of muscle mass and strength, significantly contributes to mobility limitations, increased risk of falls, and hospitalizations in older adults.[16] Research indicates that age-related decreases in muscle mass and strength are linked to reduced physical performance, mobility, diminished quality of life, and an elevated risk of cardiovascular events.[17,18] Preserving muscle strength is particularly vital for older adults as it is longitudinally associated with mobility and physical function.[19] Studies have shown that higher muscle mass and strength are correlated with improved bone microarchitecture and a reduced risk of fractures.[20] Additionally, low muscle strength is independently associated with a higher risk of all-cause mortality in older adults, underscoring the significance of muscle strength in predicting aging-related health outcomes.[21]

Low bone density is a critical factor that significantly increases the risk of fractures and other bone-related injuries in older adults. Osteoporosis, characterized by low BMD and microarchitectural deterioration, leads to decreased bone strength and an elevated risk of fractures.[22] Fractures associated with osteoporosis, such as hip and vertebral fractures, are a major concern in older adults, contributing to disability, loss of independence, and increased mortality.[23] The occurrence of fragility fractures, caused by low-energy trauma, often indicates underlying osteoporosis and poses a significant risk for subsequent fractures.[24] Studies have shown that individuals with low BMD are at a higher risk of fractures, particularly in the hip, spine, and wrist.[25] Wrist fractures, for example, are common symptomatic fractures related to osteoporosis and are considered strong predictors of future osteoporosis-related fractures in the spine or hip.[25] Despite the strong association between low bone mass and fractures, many older adults with fractures are not adequately screened or treated for osteoporosis, highlighting gaps in post-fracture care and secondary prevention efforts.[26] The burden of osteoporosis-related fractures is substantial, leading to increased healthcare costs, extended treatment, and specialized medical care.[27] Fractures resulting from osteoporosis not only impact physical health but also have significant psychological and social implications, affecting the quality of life and functional independence of older adults.[28] Addressing osteoporosis and low bone density through screening, diagnosis, and appropriate treatment is crucial for preventing fractures and reducing the overall burden of bone-related injuries in the aging population.[29]

Muscle mass and strength are key determinants of BMD. Studies have consistently shown a positive correlation between muscle mass and BMD, indicating that higher muscle mass is linked to greater bone density.[30] The mechanical forces generated by muscle contractions during physical activity are vital for maintaining bone health, especially in weight-bearing bones.[31,32] Lack of mechanical loading, as seen in cases of immobility, can lead to muscle atrophy and osteoporosis.[32] Additionally, muscle strength is an independent predictor of BMD, with evidence showing that increased muscle strength, including grip strength, correlates with higher BMD.[33,34] The relationship between muscle mass and BMD is not solely mechanical; metabolic and hormonal factors also play significant roles in modulating this interaction.[35] Muscle mass and strength influence bone density through the release of myokines, such as insulin-like growth factor 1 (IGF-1) and myostatin, which play crucial roles in bone metabolism. IGF-1 promotes osteoblast proliferation, enhancing bone formation, while myostatin can inhibit muscle growth and stimulate osteoclast activity, negatively impacting bone density.[36] Additionally, myokines like irisin can have protective effects on bone, further highlighting the complex biochemical crosstalk between muscle and bone tissues.[37,38]

Despite the growing body of research exploring the relationship between muscle mass, muscle strength, and bone density in older adults, there remains significant variability and inconsistency in the findings across different studies. These inconsistencies pose challenges for clinicians in making informed decisions regarding the prevention and management of conditions like osteoporosis

and sarcopenia. This systematic review addresses a critical gap in the literature by synthesizing recent evidence to provide a clearer understanding of these relationships. The insights gained from exploring these relationships can help guide early diagnosis, risk assessment, and intervention strategies. By identifying how muscle mass and muscle strength relate to bone density, healthcare providers can more effectively tailor treatments to prevent fractures, improve mobility, and enhance the overall quality of life for older adults. This knowledge allows clinicians to prioritize interventions that strengthen muscles, support bone health, and reduce the risk of falls, thereby decreasing hospitalization rates and healthcare costs associated with injury-related complications. Moreover, as the global population continues to age, there is an urgent need for up-to-date, evidence-based guidelines that can guide clinical practice and public health initiatives aimed at improving musculoskeletal health in older adults. Furthermore, this systematic review may support the development of preventative programs and personalized treatment plans. For example, recognizing that low muscle mass and low muscle strength are potential risk factors for decreased bone density can inform routine screening practices. Such practices would enable clinicians to identify at-risk individuals early and implement suitable exercise regimens, nutritional support, or pharmacological interventions to mitigate muscle and bone loss. By bridging the gap between research and clinical practice, this review aims to evaluate the relationship between muscle mass, muscle strength, and bone density in the aging population.

MATERIALS AND METHODS

A comprehensive and systematic search was conducted according to the guidelines set by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020.[39] From the selected studies, we extracted data on muscle mass, muscle strength, and physical bone density. Our quantitative analysis examined the relationships between these variables, focusing on correlation coefficients and significance measures such as p-values to evaluate the strength of associations. These quantitative results were then synthesized qualitatively to discern common patterns and trends across the studies, providing a cohesive understanding of the relationship between muscle mass, muscle strength, and bone density in older adults.

Search Strategy

A comprehensive systematic search was conducted across seven electronic databases from 2014 to April 2024, namely PubMed, ScienceDirect, Sage journal, Tripdatabase, Cochrane Library, Embase, and CINAHL. The search included a range of keywords such as "muscle mass," "appendicular skeletal muscle index," "skeletal muscle index," "sarcopenia," "muscle strength," "handgrip strength," "knee extension strength," "bone density," "bone mass," and terms related to older adults and geriatrics to ensure thorough coverage. An example search in PubMed used the following terms: ("Muscle mass" OR "appendicular skeletal muscle index" OR "skeletal muscle index" OR "SMI" OR "ASMI" OR "sarcopenia") AND ("muscle strength" OR "muscle weakness" OR "handgrip strength" OR "knee extension strength") AND ("Bone density" OR "Bone Mass" OR "Osteoporosis" OR "Osteopenia") AND ("elderly" OR "older adults" OR "geriatric").

Eligibility Criteria

Inclusion criteria

Observational studies, specifically cross-sectional, cohort, and case-control studies, that investigated the relationship between muscle mass, muscle strength, and bone density in older adults were included. Quantitative methods for measuring muscle mass, muscle strength, and bone density were required for studies to be considered. The target population was comprised of older adults aged 60 years and above (aligning with the Indonesian Minister of Health Regulation No. 67 of 2015 which defines older adults as those aged 60 or above), including both community-dwelling individuals and those in clinical or institutional settings. The review was limited to studies published in English or Indonesian to ensure consistency in interpretation. Additionally, studies published between January 2014 and April 2024 were included to maintain the relevance and applicability of the findings to current clinical practice.

Exclusion criteria

Studies that did not meet stringent methodological standards were excluded. Specifically, interventional studies (e.g., randomized controlled trials), reviews, meta-analyses, case series, case reports, and editorials were not considered. Studies relying on non-quantitative or subjective measures of muscle mass, strength, or bone density were excluded. Studies focusing on populations younger than 60 years, or those including younger participants without providing segregated data for the older adult subgroup, were also excluded to maintain the focus on the aging population. Furthermore, studies that did not directly measure bone density or failed to report sufficient data on the association between muscle mass or muscle strength and bone density were excluded. To ensure accuracy in findings, studies published in languages other than English or Indonesian were excluded. Lastly, studies published before January 2014 were excluded to align the review with the most recent diagnostic criteria and clinical practices.

Study Selection and Data Extraction

Two reviewers independently screened the titles and abstracts from each database to select appropriate studies. The chosen studies were imported into Mendeley Reference Manager version 2.91 for organization and management (https://www.mendeley.com/release-notes-reference-manager/). If discrepancies arose, a third reviewer was consulted to reach a consensus. The data extracted included information on the first author, study title, demographic data (age, gender, study location), methodological details, and results. Contact was made with the first author of each study for any required additional data. Articles that did not measure or report on the relationships between muscle mass, muscle strength, and bone density in older adults were excluded from the review.

Risk of Bias Assessment

To evaluate the risk of bias, we utilized the Appraisal Tool for Cross-Sectional Studies (AXIS), as nearly all included studies were cross-sectional (with one cohort study). Each author conducted an independent assessment, and the results were then discussed collectively to reach an agreement. The AXIS tool consists of 20 items that cover various aspects of study design, conduct, and reporting. The AXIS evaluates the objective, design, sampling method, measurement method, bias control, data analysis, results, funding, and conflict of interest aspects of the studies.

Quality Assessment

The quality of evidence for each outcome was assessed using the GRADE (Grading of Recommendations Assessment, Development, and Evaluation) framework.[40] Each author conducted a separate evaluation, and the results were subsequently merged to form a unified consensus. The quality of evidence and its interpretation are detailed in Table 1.

RESULTS

Study Selection and Characteristics

Following the initial search, a substantial number of articles were retrieved from various electronic databases. In the case of PubMed, the initial search identified a total of 972 articles. To narrow down the scope of our review to observational studies published after 2014, we applied a filter based on the publication year, resulting in a reduction to 186 articles. To further refine the results, we used an additional filter for observational study types, labeled "Observational Study" under the publication type. This filtration process yielded a total of 48 articles that met the observational study criteria. These 48 articles were carefully reviewed to assess their relevance to our research topic and evaluated against the predefined inclusion and exclusion criteria. This screening process culminated in the final selection of studies included in the systematic review (Fig. 1).

A total of 24 articles from the electronic databases met our eligibility criteria based on their titles. After removing duplicates and conducting a detailed review of full-text articles, we excluded studies with a mean age of < 60 years.[41-46] After all, 13 articles remained that fulfilled our criteria for inclusion in this review. Articles that lacked the measurement of relationships between muscle mass, muscle strength, and bone density were excluded.[47-49] Nine of the final 10 articles included used a cross-sectional design, while one was a cohort study with baseline data. The studies were geographically diverse, with a significant concentration in Asian countries, three conducted in Korea,[50-52] two in Brazil,[53,54] and one in Germany,[55] Australia,[56] China,[57] Japan,[58] and Malaysia.[59] The total sample size for the included studies was 4,596 subjects (2,194 men and 2,402 women), with the mean age ranging from 63 to 74.2 years. In Asian countries, total studies collectively involved 4,308 older adults, with ages ranging from 63 to 75.5 years. In contrast, only 288 older adults were studied in research conducted on other continents, specifically in Germany and Australia, where participants' ages ranged from 63.3 to 70 years.

The studies employed various measurement methods to evaluate muscle mass, muscle strength, and bone density in older adults. Dual energy X-ray absorptiometry (DXA) was the most used tool to measure bone density, with nine out of 10 studies utilizing this method.[50-56,58,59] The remaining study used quantitative ultrasound to measure bone density.[57] Muscle strength was predominantly measured using hand grip strength, which was used in four out of the seven studies that assessed muscle strength in this review.[56-59] Additionally, knee extension and one-repetition maximum (1RM) tests were employed as measures of muscle strength.[52,58] Muscle mass assessments varied across the studies, but DXA emerged as the most frequently used method, applied in six studies.[50-54,56] These results indicate a diverse set of methodologies and geographic locations among the included studies, providing a comprehensive view of the relationship between muscle mass, muscle strength, and bone density in older adults.

Risk of Bias Assessment

The risk of bias in the included studies was evaluated using the AXIS tools. During the assessment, it was found that two studies exhibited selection bias, while another two did not provide sufficient information about their sample selection process. In terms of study limitations, only one study failed to mention any limitations. Based on our evaluation, two studies were categorized as having a high risk of bias,[53,54] one study a moderate risk of bias,[55] and the

Table 1. Risk of bias assessment using Appraisal Tool for Cross-Sectional Studies (AXIS)

	Question	Study index number									
		1	2	3	4	5	6	7	8	9	10
Introduction	1. Were the aims/objectives of the study clear?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Materials and Methods	2. Was the study design appropriate for the stated aim(s)?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	3. Was the sample size justified?	Unclear	Unclear	Unclear	Unclear	Yes	Unclear	Unclear	Unclear	Unclear	Yes
	4. Was the target/reference population clearly defined? (Is it clear who the research was about?)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes
	5. Was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation?	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Unclear	Yes
	6. Was the selection process likely to select subjects/participants that were representative of the target/reference population under investigation?	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Unclear	Yes
	7. Were measures undertaken to address and categorize non-responders?	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear
	8. Were the risk factors and outcome variables measured appropriate to the aims of the study?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	9. Were the risk factor and outcome variables measured correctly using instruments/measurements that had been trialed, piloted, or published previously?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	10. Is it clear what was used to determine statistical significance and/or precision estimates? (e.g., p-values, confidence intervals)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	11. Were the methods (including statistical methods) sufficiently described to enable them to be repeated?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Results	12. Were the basic data adequately described?	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes
	13. Does the response rate raise concerns about non-response bias?	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear
	14. If appropriate, was information about non-responders described?	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear
	15. Were the results internally consistent?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	16. Were the results presented for all the analyses described in the methods?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Discussion	17. Were the authors' discussions and conclusions justified by the results?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	18. Were the limitations of the study discussed?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Others	19. Were there any funding sources or conflicts of interest that may affect the authors' interpretation of the results?	No	No	No	No	No	No	No	No	Yes	Unclear
	20. Was ethical approval or consent of participants attained?	Yes	Yes	Yes	Yes	Yes	Unclear	Yes	Unclear	Yes	Yes
Overall results	-	Low	Low	Low	High	Low	Low	Low	High	Moderate	Low

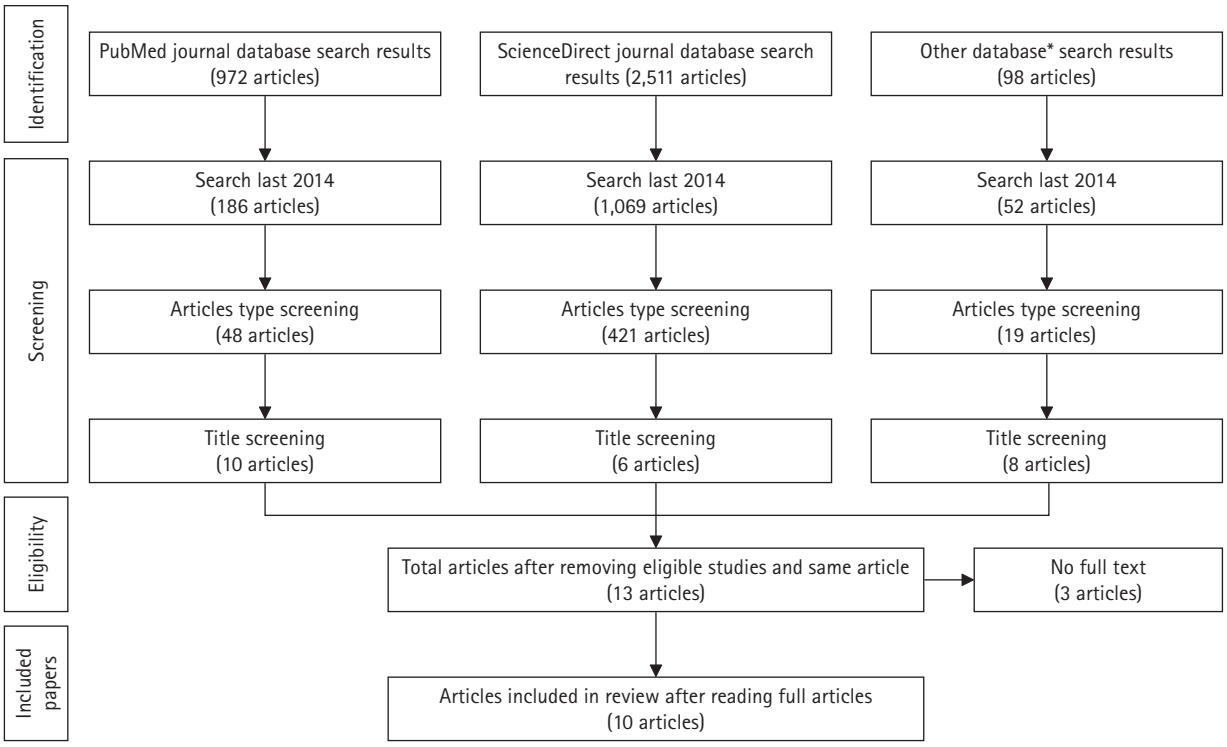

Fig. 1. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses flowchart.

remaining studies had a low risk of bias. For the detail, most studies had clear and relevant objectives, although some lacked specificity regarding how their objectives related to bone density. The majority of studies employed appropriate cross-sectional designs, but variations in sample sizes and methodologies were noted. Many studies had well-defined sampling methods, though some had limitations in sample representativeness or size. A range of measurement tools were used across the studies, with varying degrees of validation and reliability reported. Several studies implemented strategies to minimize bias, but not all provided detailed descriptions of these measures. Statistical analyses were generally appropriate, although some studies lacked detailed descriptions of their analytical methods. The results were reported with varying levels of clarity and detail, affecting the interpretability of the findings. Disclosure of funding sources and potential conflicts of interest varied among studies, with some lacking adequate transparency. These findings are summarized in Table 2, which provides an overview of the risk of bias assessment across all included studies.

Overall Outcomes

A summary of the study's findings is presented in Table 2. Concerning the relationship between muscle mass and bone density in older adults, four studies found no significant association between these variables. However, five studies identified a significant relationship, with two exhibiting a high risk of bias and one showing a moderate risk of bias. Of these, one study reported a strong correlation, two indicated a moderate correlation, and the remaining two studies did not provide correlation coefficients. Overall, the quality of evidence for this relationship was rated as low, reflecting inconsistency in the data supporting these associations.

On the other hand, for the relationship between muscle strength and bone density in older adults, four out of seven studies demonstrated a significant association. Of these four studies, one study indicated a strong correlation, two studies showed a weak correlation, and the last one did not report a correlation measurement. One of these studies had a high risk of bias. Additionally, three studies revealed no significant relationship between muscle strength and bone density. Given these varied findings, the quality of evidence for the relationship between muscle strength and bone density was also rated as low, due to inconsistent results and the risk of bias in some studies (Table 3).

DISCUSSION

Our systematic review finds four studies showed a significant relationship between muscle strength and bone density in older adults. Muscle strength influences bone density through various interconnected mechanisms. Mechanical loading, resulting from muscle

Table 2. Summary of included studies

Study	Country/Type	Subject characteristics	Measurement tools	Result
Gandham et al.[56]	Australia/Cross-sectional	n = 74 older adults with body fat percentage (assessed by DXA) ≥ 30% (men) or ≥ 40% (women). Mean age: 67.7 years (men 28, women 46) Exclusion: Inability to walk 400 m unassisted (without the use of walking aids); inability to speak English, diagnosis of any progressive neurological disorders, severe knee or hip osteoarthritis (awaiting joint replacement), lung diseases requiring the use of oxygen, renal kidney disease requiring dialysis or any other disorder of severity that life expectancy was < 12 months.	Bone density: aBMD by DXA Muscle strength: HGS with a hydraulic dynamometer (Jamar Plus dynamometer; Patterson Medical, Bolingbrook, IL, USA) Muscle mass: DXA	HGS was not significantly associated with total hip aBMD, femoral neck aBMD, and lumbar spine aBMD. ASMI was not correlated with BMD (r = 0.12, p = 0.32).
Nonaka et al.[58]	Japan/Cross-sectional	n = 214 older women (> 60 years) with no cognitive impairment (MMSE score ≥ 24), and the ability to complete all measurements. Exclusion: Male sex; implanted with a cardiac pacemaker; and receiving treatment for osteoporosis. Mean age: 72.6–75.5 years	Bone density: DXA Muscle strength: HGS with hand grip dynamometer (T.K.K.58401; Takei Scientific Instruments Co. Ltd., Niigata, Japan) and KES with hand-held dynamometer (μTas F-1; Anima Corp., Tokyo, Japan) Muscle mass: BIA (InBody 470; InBody Japan Inc., Tokyo, Japan).	Arm SMI, leg SMI, and appendicular SMI were significantly lower in the very low bone mass group compared to those of the low bone mass group (p = 0.034, p = 0.011, and p = 0.009, respectively). HGS and KES were not significantly different between the three groups (normal bone mass, low bone mass, and very low bone mass).
Kim et al.[52]	Korea/Cohort	n = 337 community-based older adults (> 65 years) Mean age: 70.5–71.3 years (men 172, women 165)	Bone density: DXA Muscle strength: KES with the isokinetic device at an angular velocity of 60°/s (Biodex Medical Systems, Shirley, NY, USA). Muscle mass: ALM with DXA	Men -Baseline BMDs for the lumbar spine, femur neck, and total hip did not show any significant relationships with baseline values of trunk muscle mass, ALM, leg lean mass, and leg strength. -The annual percentage change in total hip BMD was significantly correlated with the baseline ALM and leg lean mass (r = 0.195, p = 0.013 with ALM, and r = 0.205, p = 0.009 with leg lean mass). -The rate of loss in total hip BMD was positively associated with the rate of loss in leg muscle strength (r = 0.170, p = 0.033). Women -Baseline BMD values at the lumbar spine, femur neck, and total hip showed significant positive associations with the baseline values of trunk lean mass, ALM, and leg lean mass. -In associations with annual percentage changes in BMD, the rates of decline in ALM and leg lean mass showed significant positive relationships with annual percentage changes in total hip BMD (r = 0.196, p = 0.011 for ALM, and r = 0.169, p = 0.033 for leg lean mass). -The loss rate in total hip BMD was positively associated with the rate of decline in leg muscle strength (r = 0.24, p < 0.001).

(Continued to the next page)

Table 2. Continued

Study	Country/Type	Subject characteristics	Measurement tools	Result
da Cruz Siqueira et al.[53]	Brazil/Cross-sectional	n = 10 older men Mean age: 63.3 years Exclusion: Absence of comorbidity associated with metabolic and cardiac disturbances, and practicing resisted exercise regularly for at least 2 months	Bone density: DXA (Hologic model, QDR Discovery Wi) Muscle strength: One Maximum RSEEtition Test Muscle mass: Lean mass by DXA	45º leg-press exercise strength is associated to left leg BMC (r = 0.677; p = 0.032; 95% CI 0.23–0.93) and right leg (r = 0.714; p = 0.020; 95% CI 0.38–0.92) 45º leg-press strength is associated with torso BMC (r = 0.810; p < 0.01; 95% CI 0.56–0.96). No significant correlations were observed between BMC (whole-body or regional) and knee extensor exercise strength. Bench-press strength is related to left arm BMC (r = 0.764; p = 0.010; 95% CI 0.05–0.96) and right arm BMC (r = 0.748; p = 0.013; 95% CI -0.03–0.091) Arm curl exercise strength is related to right arm BMC (r = 0.688; p = 0.028; 95% CI -0.21–0.95) and right arm BMC (r = 0.856; p = 0.002; 95% CI -0.50–0.98) and whole-body BMC (r = 0.673; p = 0.033; 95% CI 0.36–0.90). There is a significant association between arm and leg lean mass with BMC (all r > 0.7).
Singh et al.[51]	Korea/Cross-sectional	n = 60 community-dwelling older adults Mean age: 63 years (men 27, women 33) Exclusion: Thyroid disorders; uncontrolled hypertension; metal in the body; any recent surgery within the previous 6 months; known prior fragility fracture within the previous 12 months; any tobacco use within the prior 10 years; body weight greater than 136 kg, which is the limit of the DXA; and on hormone replacement therapy or corticosteroids.	Bone density: DXA (GE Lunar Prodigy, enCORE 2010 Software Version 13.31.016; GE Medical Systems, Madison, WI, USA) Muscle strength: One-repetition maximum (1RM) tests Muscle mass: ASM with DXA	Total hip and femoral neck BMD (r = 0.34, p < 0.01), and (r = 0.32, p < 0.05) were positively correlated with leg press strength. No relationships between measures of bone density and hip abduction strength. Muscle mass was not related to any of the bone density.
Ma et al.[57]	China/Cross-sectional	n = 1,168 older adults Mean age: 66.9 years (men 516, women 652) Exclusion: Whose medical recording or histories showed diseases that may affect bone or calcium metabolism; who had a foot injury making the bone density test not feasible; and who were taking a drug that may interfere with bone or calcium metabolism (e.g., estrogen, calcitonin, diphosphonate).	Bone density: Quantitative ultrasound (OsteoPro UBD2002A; BMTech Worldwide Co. Ltd., Seoul, Korea) Muscle strength: HGS with a handheld dynamometer (DRIP-D; Takei Ltd., Niigata, Japan) Muscle mass: BIA (InBody 720; Biospace Co. Ltd., Seoul, Korea)	Lower grip strength was significantly more likely to suffer from osteoporosis (p = 0.007). This result still holds after adjusting all covariates (p = 0.023). There was no association between ASMI and osteoporosis in the unadjusted group (p = 0.843) and after adjustments of all covariates (p = 0.205).
Kim et al.[50]	Korea/Cross-sectional	n = 2,479 older adults Mean age: 71.9–74.2 years (men 1,308, women 1,171)	Bone density: DXA (DISCOVERYW fan-beam densitometer; Hologic Inc., Marlborough, MA, USA) Muscle mass: DXA	ASMI was positively correlated with BMD in both men and women and adjusting for age and body fat still resulted in a positive correlation.

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Table 2. Continued

Study	Country/Type	Subject characteristics	Measurement tools	Result
Alonso et al.[54]	Brazil/Cross-sectional	n = 87 older men in the Geriatrics Group at the Instituto de Ortopedia e Traumatologia at the Faculdade de Medicina da Universidade de São Paulo Mean age: 68.5 years	Bone density: DXA (Lunar-DPX device; Lunar Corp., Madison, WI, USA) Muscle mass: DXA	Arm lean mass ($r = 0.58$, $p < 0.001$), leg lean mass ($r = 0.47$, $p < 0.001$), trunk lean mass ($r = 0.48$, $p < 0.001$), and total body lean mass ($r = 0.53$, $p < 0.001$) are significantly associated with BMD.
Walowski et al.[55]	Germany/Cross-sectional	n = 117 older adults Mean age: 70 years (men 46, women 71) Exclusion: Edema, chronic diseases, heart failure, renal failure, paralysis (e.g. after a stroke), neurodegenerative diseases, tumors in treatment, amputation of limbs, electrical and metallic implants, current alcohol abuse, not removable piercings and large tattoos on the arms or legs (because of possible interference with MRI examinations) as well as medication which could influence body composition.	Bone density: DXA (Hologic Discovery A (S/N 82686) Inc., Bedford, MA, USA) Muscle mass: whole-body MRI with a 1.5 T scanner (MAGNETOM Avanto; Siemens Medical Systems, Erlangen, Germany)	Overall muscle mass and SMI were positively associated with bone parameters (for muscle mass in kg: BMC $r = 0.82$, BMD $r = 0.63$, T-score $r = 0.49$, all $p < 0.001$; and for SMI in kg/m2: BMC $r = 0.67$, BMD $r = 0.55$, T-score $r = 0.41$, all $p < 0.001$). In women, muscle mass was only positively correlated with BMC ($r = 0.49$, $p < 0.001$) In men, muscle mass was associated with higher BMC, BMD, and T-score (BMC $r = 0.53$, BMD $r = 0.37$, T-score $r = 0.37$, $p < 0.01$ to $p < 0.001$).
Chua et al.[59]	Malaysia/Cross-sectional	n = 50 older women Mean age: 64 years Exclusion: Chronic back pain with a numerical rating pain score of more than 4, had prior spine surgery, history of fractures and dislocations of the spine, had any known underlying pathologies such as tumor, spinal infections, tuberculosis, and had any inflammatory joint disease which may affect walking speed and grip strength tests.	Bone density: DXA Muscle strength: HGS with a handheld dynamometer (Jamar, White Plains, NY, USA), Back extensor muscle strength with a load cell (LC501- 200/N sensor, Load cell, 200lb, 3MV/V; Newport Electronic Inc., Santa Ana, CA, US)	HGS and back extensor muscle strength have a significant association with lumbar bone density ($r = 0.22$ and $r = 0.39$).

DXA, dual energy X-ray absorptiometry; HGS, handgrip strength; BMD, bone mineral densitometry; aBMD, areal bone mineral density; ASMI, appendicular skeletal mass index; MMSE, Mini-Mental state Examination; SMI, skeletal mass index; KES, knee extension strength; BIA, bioelectrical impedance analysis; ALM, appendicular lean mass; BMC, bone mineral content; MRI, magnetic resonance imaging; CI, confidence interval.

Table 3. Assessment of quality of the evidence

Assessed parameter	Results	Number of studies	Quality of the evidence (GRADE)
Association between muscle mass and bone density in older adults	Five studies show a significant association between muscle mass and bone density (two studies show a moderate correlation and one study shows a strong correlation with two studies having a high risk of bias and one showing a moderate risk of bias).	9 (observational)	Low
	Three studies show there's no significant association between muscle mass and bone density (all studies have low risk of bias).		
Association between muscle strength and bone density in older adults	Four studies show a significant association between muscle strength and bone density with one study showing a strong correlation, two studies showing a weak correlation, and one study does not provide correlation analysis (one study has a high risk of bias).	7 (observational)	Low
	Four studies show there is no significant association between muscle strength and bone density (one study has a high risk of bias).		

GRADE, Grading of Recommendations Assessment, Development, and Evaluation.

contractions during weight-bearing activities or resistance exercises, stimulates bone cells to adapt and remodel, enhancing bone density and strength over time.[60,61] This process is crucial for maintaining bone health and preventing age-related bone loss.[7] Some studies included in our review indicate that individuals with higher muscle strength generally exhibit better BMD, particularly in weight-bearing bones like the hip and spine.[62] This positive correlation underscores the importance of muscle health in maintaining bone integrity and preventing conditions like osteoporosis. For instance, strong muscles provide structural support to the skeletal system, improving stability and reducing the risk of falls and fractures.[63] This is particularly important in older adults at increased risk for such injuries. Our findings align with research showing that muscle contractions exert mechanical forces on bones and trigger the release of growth factors and hormones that influence bone metabolism and remodeling processes.[61] These signaling pathways are vital for maintaining bone homeostasis and structural integrity. Studies have independently and positively linked muscle strength to BMD, emphasizing the significant impact of muscle health on bone health.[3,4] The decline in muscle strength associated with aging can lead to reduced physical activity, further exacerbating bone density loss. Therefore, interventions aimed at preserving or enhancing muscle strength through regular exercise, such as resistance training, are critical not only for muscle function but also have the potential for maintaining bone density and overall musculoskeletal health.[64]

The significant relationship between muscle mass and bone density in older adults was found in five of nine studies. Muscle mass plays a crucial role in influencing bone density through several interconnected mechanisms, one of which is the functional muscle-bone unit. Studies indicate that muscle mass exerts mechanical loading on bones, stimulating bone cells to adapt and remodel in response to these mechanical stresses.[9] This mechanical stimulation is critical for triggering bone formation and remodeling, leading to increased bone density and strength over time. Thus, maintaining optimal muscle mass through regular physical activity and strength training can positively impact bone health by promoting bone adaptation and growth.[6] Some evidence from our review shows that individuals with higher muscle mass generally exhibit better BMD, particularly in weight-bearing bones such as the hip and spine. This positive correlation highlights the importance of muscle mass in maintaining bone health and preventing conditions like osteoporosis.[65] Strong muscles provide essential structural support to the skeletal system, which is crucial for maintaining bone integrity and reducing the risk of fractures. By stabilizing the bones and joints, muscle mass enhances overall stability and reduces the likelihood of falls and fractures.[66] In addition to mechanical loading, muscle mass influences bone density through hormonal and metabolic pathways. Muscle contractions during physical activity trigger the release of growth factors and hormones that affect bone metabolism and remodeling processes.[67] These signaling pathways are vital for maintaining bone homeostasis and structural integrity. The studies included in our review demonstrate a direct and positive relationship between muscle mass and BMD, emphasizing the significant impact of muscle health on bone health. Furthermore, our review suggests that the relationship between muscle mass and bone density is not solely dependent on mechanical factors but also involves complex biochemical interactions. Optimizing muscle mass through regular exercise and proper nutrition is essential not only for muscle function but also for maintaining bone density and overall musculoskeletal health.[68,69]

Regarding the inconsistent results about relationship between muscle mass and muscle strength with bone density, this can be in-

fluence by several factors. Differences in study design, sample size, and participant characteristics could contribute to the variability in findings. For instance, the studies varied in their assessment methods for muscle mass, muscle strength, and bone density, which may have led to discrepancies in results. Additionally, factors such as adiposity and inflammation, which were not uniformly accounted for across studies, can influence bone density. Visceral adiposity is negatively associated with bone density, highlighting the impact of body composition on bone health.[70] Chronic low-grade inflammation and hormonal imbalances can predispose individuals to poor bone health, emphasizing the importance of addressing underlying health conditions to maintain bone density. For instance, conditions such as glucocorticoid therapy and growth disorders can significantly impact bone density in specific populations.[65] Furthermore, lifestyle factors such as physical activity, nutrition, and weight status play a substantial role in bone density. Exercise, particularly weight-bearing activities and strength training, is crucial for maintaining bone density and reducing the risk of osteoporosis.[71] Dietary protein intake is also linked to bone health, with muscle mass acting as a mediating factor.[72] Addressing these lifestyle factors through targeted interventions can help mitigate the risk of osteoporosis and fractures in older adults. In summary, the relationship between muscle mass, muscle strength, and bone density is complex and influenced by a variety of factors. By addressing these determinants through a comprehensive approach, we can improve bone health and reduce the risk of osteoporosis in older adults.

The quality of the included studies varied, as revealed by the AXIS tool's risk of bias assessment. While some studies demonstrated strong methodological rigor, others exhibited potential biases, particularly in selection bias and measurement methods. Two studies indicated a high risk of bias, mainly due to inadequate sample selection processes and lack of control for confounding variables. The overall quality of evidence revealed that the evidence supporting the relationship between muscle mass, muscle strength, and bone density is of low quality, primarily due to inconsistencies in the results and the presence of bias in some studies. These limitations highlight the need for future research with more rigorous designs, larger sample sizes, and standardized measurement methods to clarify these relationships.

This review has certain limitations due to the inclusion of only observational studies, which inherently carry a higher risk of bias compared to randomized controlled trials. Potential biases include selection bias, information bias, and confounding, all of which could influence the observed associations. Despite these limitations, we used the AXIS tool and the GRADE framework to systematically evaluate the quality and risk of bias in the included studies. Additionally, significant heterogeneity was observed among the studies, including differences in participant characteristics, measurement methods, and statistical approaches. This variability precluded the possibility of conducting a meta-analysis, and as a result, the review relied on qualitative synthesis. This approach limits our ability to provide precise quantitative summaries of the relationships between muscle mass, muscle strength, and bone density in older adults. These limitations underscore the need for caution when interpreting the findings and highlight the necessity for future research that employs more rigorous designs, larger sample sizes, and standardized measurement methods. Despite these constraints, this review contributes valuable insights into the complex relationship between muscle mass, muscle strength, and bone density in older adults. The findings provide new scientific evidence that can inform clinical practice, particularly in evaluating low muscle strength or low muscle mass as potential risk factors for osteoporosis.

In conclusion, this systematic review explored the relationship between muscle mass, muscle strength, and bone density in older adults. The findings suggest a complex and inconsistent relationship across studies. In terms of muscle mass and bone density, several studies reported significant associations, while others found no significant correlation, leading to a low-quality grade due to inconsistency and varying risk of bias. Similarly, when examining muscle strength and bone density, the results were mixed, with some studies demonstrating significant correlations while others did not. The inconsistency and low-quality grade of evidence underscore the need for caution in drawing definitive conclusions. These discrepancies highlight the importance of further research, particularly longitudinal studies with standardized methodologies, to better understand the impact of muscle mass and muscle strength on bone density in older adults.

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CONFLICT OF INTEREST

The researchers claim no conflicts of interest.

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AUTHOR CONTRIBUTIONS

Conceptualization, NR, SD, MR; Data curation, BI; Funding acquisition, NR; Investigation, NR, SD, MR; Methodology, NR, SD, MR; Project administration, BI; Supervision, SD, MR; Formal analysis, NR, BI; Writing-original draft, NR, BI; Writing-review & editing, NR, BI.

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