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Effect of different types of exercise on bone mineral density in postmenopausal women: a systematic review and network meta-analysis

Li Xiaoya, Zhu Junpeng, Xu Li, Zhang Haoyang, Fu Xueying & Wang Yu✉

Postmenopausal women (PMW) experience the decline of ovarian function; estrogen reduction will accelerate bone mass loss. Exercise is an effective means of mitigating bone mineral density (BMD) loss in PMW, but the relative effectiveness of different exercise types remains under investigation. Our study encompassed a thorough assessment and network meta-analysis, following the principles specified in the Preferred Reporting Items for Systematic Reviews and Network Meta-analysis (PRISMA) statement. Data sources and searches Literature search databases include PubMed, Embase, Cochrane, Google Scholar, Web of Science (WOS), and Scopus. The data search combined keywords like bone mineral density (BMD), postmenopausal women, and various exercise types. Data synthesis and analysis Perform a network meta-analysis by integrating both direct and indirect comparisons using the R environment. This network meta-analysis aimed to evaluate and compare various exercise types with bone mineral density in PMW to identify the most effective types. The literature comprised a collective of 49 papers, encompassing 3360 people across eight interventions. The Network Meta-analysis ranked the effects of exercise interventions on lumbar spine BMD in descending order, based on the p-scores assigned to them in the forest plot. The exercise modalities that showed significant efficacy were AE + RT(Aerobic Mixed Resistance Exercise, MD = 32.35, 95% CrI [8.08;56.62], *p* = 0.87), AE(Aerobic Exercise, MD = 22.33, 95% CrI [6.67;37.99], *p* = 0.74), and RT(Resistance Training, MD = 16.98, 95% CrI [8.98;24.99], *p* = 0.60). Similarly, the femoral neck sites were ranked in descending order based on their p-scores in the forest plot, and the exercise patterns with significant effects on lumbar spine bone mineral density were AE + RT(MD = 140, 95% CrI [40.89;239.11], *p* = 0.99), WBV(Whole Body Vibration, MD = 26.07, 95% CrI [2.97;49.16], *p* = 0.80), and RT(MD = 16.98, 95% CrI [8.98;24.99], *p* = 0.72). Exercise intervention significantly and effectively alleviated BMD in postmenopausal women, with AE + RT having the best effect.

Keywords Exercise, Network metaanalysis, Osteoporosis, Bone mineral density, Postmenopausal women

Ovarian dysfunction in PMW (postmenopausal women) leads to decreased estrogen synthesis, resulting in bone metabolism disorders, increased osteoclast activity, accelerated bone loss, insufficient bone formation, and decreased bone density, resulting in osteoporosis[1–3]. In China, the incidence of postmenopausal osteoporosis is approximately 25% among perimenopausal women, 29.1% among women over 50, and 51.6% among those over 65[4]. Osteoporotic fractures, resulting from diminished bone density, are one of the leading causes of disability and death in older adults patients. Within a span of one year following a hip fracture, around 20% of patients will succumb to a range of complications, and roughly 50% of patients will have disability and a notable decline in their quality of life[5,6]. Moreover, the medical and nursing care of osteoporosis and fractures requires a large amount of human, material, and financial resources, placing a heavy burden on families and society[7]. Projections indicate that the global number of hip fractures will rise to 2.6 million annually by 2025 and 4.5 million by 2050. It is expected that China will experience a comparable pattern, with the annual incidence of hip fractures projected to rise from 690,000 in 2006 to 1.64 million in 2020 and further to 5.91 million by 2050. In 2006, the

School of Physical Education, Henan University, Kaifeng City 475000, Henan Province, China. ✉email: 10180111@vip.henu.edu.cn

anticipated yearly cost of fractures of the hip in China was around $2.05 billion (in 2013 dollars). This figure is projected to increase to $27.48 billion and $581.97 billion by 2020 and 2050, respectively[8]. Hence, it is imperative to promptly identify, intervene, and treat osteoporosis.

Physical activity is widely acknowledged as a highly effective approach for mitigating the process of bone loss. At present, there are also many head-to-head randomized controlled trials and meta-analyses comparing the differences in the effects of different exercise methods on BMD (Bone Mineral Density) in PMW. For example, the results of Li et al.[9] showed that 6 months of *Yi Jin Jing(易筋经)* plus elastic resistance exercise had significant effects on BMD of spine, thigh, lumbar vertebra and whole body of PMW; Riaz et al.[10] showed that 8 months of high-intensity mixed training significantly improved lumbar spine BMD in PMW; Dutto et al.[11] demonstrated that a 6-month period of high-intensity aerobic exercise yielded superior results compared to moderate-intensity resistance training in enhancing BMD in the lumbar vertebrae of PMW; The results of de Oliveira et al.[12] showed that aerobic exercise and WBV training for 6 months were equally effective in improving BMD in PMW; in a meta-analysis of a cohort of PMW by Rahimi et al.[13], resistance exercise, weight-bearing aerobic exercise, and combined exercise had no effect on lumbar vertebra bone mineral density in PMW, while WBV was an effective method for improving lumbar vertebra BMD in PMW. However, in a subsequent meta-analysis by Hejazi et al.[14], aerobic exercise and combined training significantly improved lumbar BMD in PMW, while WBV training had no significant benefit. Concurrently, other studies have systematically evaluated the impact of physical activity on BMD in PMW. However, these studies focused on the impact of single intervention measures, such as resistance exercise[15–18]、aerobic exercise[19–22]、tai chi exercise[23–26], and some compare the impact of intervention measures[9,27–31]. Conventional meta-analyses restrict their scope to direct comparisons between two exercise interventions, thereby offering a limited amount of information. The lack of head-to-head testing between certain interventions further complicates the determination of the most effective exercise modality. As a result, there is a need for more comprehensive evidence on the effects of various exercise treatments on BMD in PMW to guide optimal intervention strategies. Network meta-analysis is a method that allows for the simultaneous comparison of many intervention methods in a single study. It achieves this by incorporating both direct and indirect data from a network of randomized controlled trials. This study enables the classification of various therapies according to the efficacy of their outcomes[32]. The major objective of the research was to comprehensively analyze and evaluate the effects of different exercise modalities on BMD in PMW. Additionally, we sought to elucidate the strengths and limitations of these effects, aiming to furnish clinical healthcare professionals with a scientifically grounded foundation for discerning and selecting optimal exercise interventions.

Methods

Our study encompassed a thorough assessment and network meta-analysis, following the principles specified in the Preferred Reporting Items for Systematic Reviews and Network Meta-analysis (PRISMA) statement[33]. PROSPERO has officially recorded the protocol and assigned it the registration number CRD42023472051.

Data sources and searches

Literature search databases include PubMed, Embase, Cochrane, Google Scholar, WOS, and Scopus. The search period spans from its start date to April 1, 2023. We perform the search by utilizing a blend of specific subject terms and unrestricted keywords. The data search combined keywords like bone mineral density (BMD), postmenopausal women, and various exercise types. The search approach employed was as follows (using PubMed to serve as an exemplar): Bone Mineral Density (BMD) AND (exercise OR Aerobic exercise OR Resistance exercise OR Mixed exercise OR Aerobic exercise combined with resistance exercise OR Vibrating plate exercise OR Tai Chi OR walking OR impact exercise) AND (post-menopausal OR postmenopausal), the literature for inclusion was manually searched and included as comprehensively as possible. Also, searching the references listed in published systematic evaluation articles is a primary way to access the articles (Supplementary2).

Study selection

The inclusion requirements were determined using the PICOS (Participants, Interventions, Comparators, Outcomes, and Study Design) methodology[33]. (1) The participants in the study were postmenopausal women who had experienced menopause for more than one year at the beginning of the study; (2) exercises were categorized into eight types based on content; the types of sports training are clearly defined in Supplementary 3; (3) the control group (CON) consisted of either non-intervention, regular daily activities, waiting list, health instruction, or usual care. Additionally, for head-to-head studies, the control group can be any of the eight exercises that are different from the experimental group; (4) studies should include the outcome metrics of interest: BMD at the lumbar vertebra along with femoral neck sites; and (5) in terms of study design, we included published RCTs (individual designs, cluster designs, or the first half of cross-sectional studies). We excluded studies in which (1) a single treatment session had an acute effect on participants' BMD; (2) studies in which the type of exercise was not explicitly described; (3) no outcome assessment of BMD status was made based on change scores between baseline and follow-up.

Data abstraction and quality assessment

After all pertinent articles were retrieved in the aforementioned databases, they were archived in the EndNote X9 Reference Manager. The researchers conducted independent evaluation of the search results, obtained the complete text, and collected pertinent information from the studies that were included. Studies were assessed and rated according to Cochrane Risk Bias 2.0 criteria (Supplementary 4)[34]. All inconsistencies were addressed by consensus and arbitration among the researchers in the review team. Furthermore, we assessed the certainty of the evidence by utilizing the Confidence in Network Meta-Analyses (CINeMA) online program. This application classifies the confidence level of the findings into four categories: high, medium, low, and extremely low (Supplementary 5)[35].

Data synthesis and analysis

Perform a network meta-analysis by integrating both direct and indirect comparisons using the R environment. Measured data were mean difference (MD) and their 95% confidence interval (95%CI) were used as effect indicators. The statistical analysis evaluated discrepancies in the treatment design tests, distinguishing between indirect and direct evidence using the SIDE tests in the R netmeta software package. For further details, refer to Supplementary 6. The transferability hypothesis was evaluated through contrasting the distribution of underlying effect modifiers (year of publication, mean age, sample size, and exercise period) in grouped studies (Supplementary 7). The variables and literature quality with significant transitivity were subjected to sensitivity analysis, with detailed methodologies outlined in Supplementary 8. Simultaneously, the network relationship chart and the ranking diagram of various interventions were created, and each intervention was rated based on the p-score assigned to it in the forest plot. The larger the p-score, the better the effect. The detection of publication bias was achieved by employing funnel plots (Supplementary9).

Results

Study characteristics and quality assessment

An overall of 5,983 studies were retrieved from the initial database search, and 3834 studies were obtained after deduplication. Of these, 2,049 items were excluded by reading the title and abstract. After obtaining the complete text of 96 research, literature with inconsistent themes, non-observational studies, no full text, and missing data were excluded, and finally, 49 studies were finally included, seeas described in the process described in Supplementary 10. Supplementary 10 for specific procedures. Figure 1 presents a comprehensive flow chart that illustrates the process of study selection.

The 49 research, published from 1993 to 2023, were included , with a combined sample size of 3,360. The Supplementary 11 contains the research and demographic characteristics that have been incorporated. All study participants were postmenopausal women. The average age was 60.83 years with a standard deviation of 5.87, Tand the 49 studies were categorized into eight types according to the content of the exercises, with an average age of 60.83 years and a standard deviation of 5.87. The duration of exercise varied between 2 and 72 months, with an average duration of 11.81 months and a standard deviation of 9.87. The frequency of exercise fluctuated between 1 and 7 times per week, with an average of 3.10 and a standard deviation of 1.43, and the overall duration of a single exercise session spanned from 5 to 75 min, with an average of 47.24 min and a standard deviation of 19.10.

The risk of bias (Fig. 2) for randomized sequence generation was low in 29 studies (59.2%), of which no study had a high risk, and the risk of bias was some concern in 20 studies (40.8%). The method of allocation concealment was appropriately described in 20 studies (40.8%) with a low risk of bias, and the risk of bias for allocation concealment was unclear in 29 studies (59.2%). Of all 49 studies, the majority of included randomized controlled trials (63.3%, n = 31) exhibited a low risk of bias in relation to incomplete outcomes, and 49 studies (100%) shown a low risk of bias in relation to selective outcome reporting. Comprehensive details regarding the potential biases associated with the research included in the analysis can be found in Supplementary 4.

Network meta-analysis

Evidence network

The evidence network for eight distinct exercise modalities aimed at intervening in osteoporosis outcome indicators is depicted in Fig. 3. The network relationships are centered on the control group, with the area of the circle representing the sample size for which the measure was used and the thickness of the line segment representing the amount of included literature comparing the interventions.

Bone density of lumbar vertebra

A total of 46 of 49 articles were included, and a total of 2,963 PMW were measured before and after lumbar vertebrae BMD. The Network Meta-analysis (Table 1, 2) revealed that exercise types AE + RT (MD = 32.35, 95% CrI [8.08;56.62]), AE (MD = 22.33, 95% CrI [6.67;37.99]), and RT (MD = 16.38, 95% CrI [5.03;27.73]) were significantly effective in enhancing BMD at the lumbar level in PMW, when compared to the control group. Based on the P-score ranking of the forest plot (Fig. 4), it can be shown that the exercise therapy effect of the AE + RT group exhibited the highest value (P-score = 0.87), followed by the AE exercise group (P-score = 0.74) and the RT exercise group (P-score = 0.60). The findings from the league table indicate that there were no statistically significant differences seen across the various types of exercise.

Bone density of femoral neck

37 out of 49 literature items were included, and an aggregate of 2,679 PMW were assessed for BMD before and after the femur neck position. Significant effects on BMD improvement at the femur neck position were seen in PMW when comparing exercise types of AE + RT (MD = 140, 95% CrI [40.89;239.11]), WBV (MD = 26.07, 95% CrI [2.97;49.16]), and RT (MD = 16.98, 95% CrI [8.98;24.99]) to the control group. According to the forest plot (Fig. 4) ranking of P-score, the exercise therapy effect of the AE + RT group was the best (P-score = 0.99), followed by the WBV exercise group (P-score = 0.80), RT exercise group (P-score = 0.72). The outcomes of the two-by-two comparison indicated that there were no statistically significant disparities observed across the various forms of exercise.

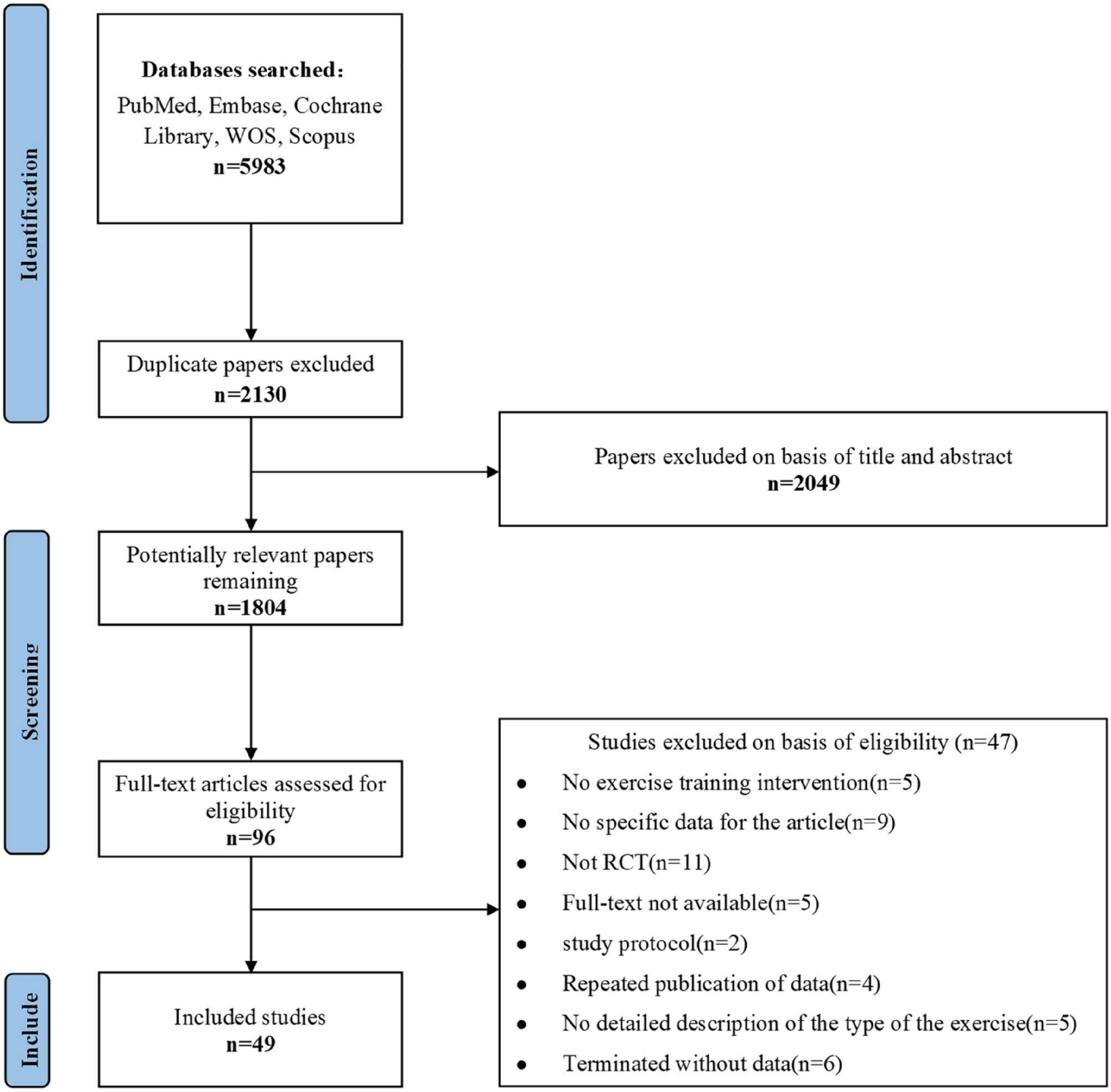

Fig. 1. PRISMA flow diagram of the selection process of the included studies.

Discussion

This study aimed to determine the best efficacious exercise programs for enhancing bone density in PMW by a network meta-analysis. The analysis includes data from 49 randomized controlled studies, which involved a total of 3,360 participants. The results of the study indicated that the intervention of exercise had a significant effect on improving BMD in both the lumbar vertebra and femur neck. However, the benefits of various exercise modalities varied. The combination of AE + RT and RT had a notable and favorable impact on bone mineral density in the lumbar vertebra and femur neck of PMW, surpassing the advantages of alternative treatments. The AE + RT and RT was determined to be the most efficacious exercise modality for enhancing BMD in both areas. Certain exercises outperformed the control group on specific outcome measures. For instance, AE significantly enhanced lumbar spine BMD, whereas WBV effectively improved BMD at the femoral neck region. It is worth noting that no significant improvement was found for any other exercise types than those mentioned above.

Effects of exercise on the lumbar spine

Our results indicate that AE + RT was identified as the optimal exercise type for enhancing lumbar BMD. This finding aligns with previous studies indicating that AE + RT significantly decreases the pace at which bone is lost[36]. Research has consistently demonstrated that multi-component exercise interventions, like AE + RT, have

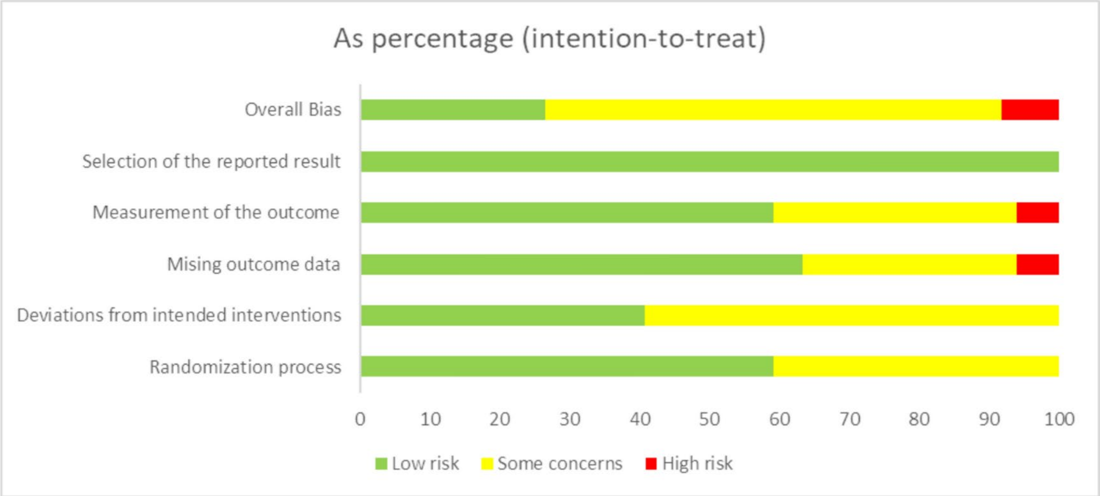

Fig. 2. Bias risk of the included studies.

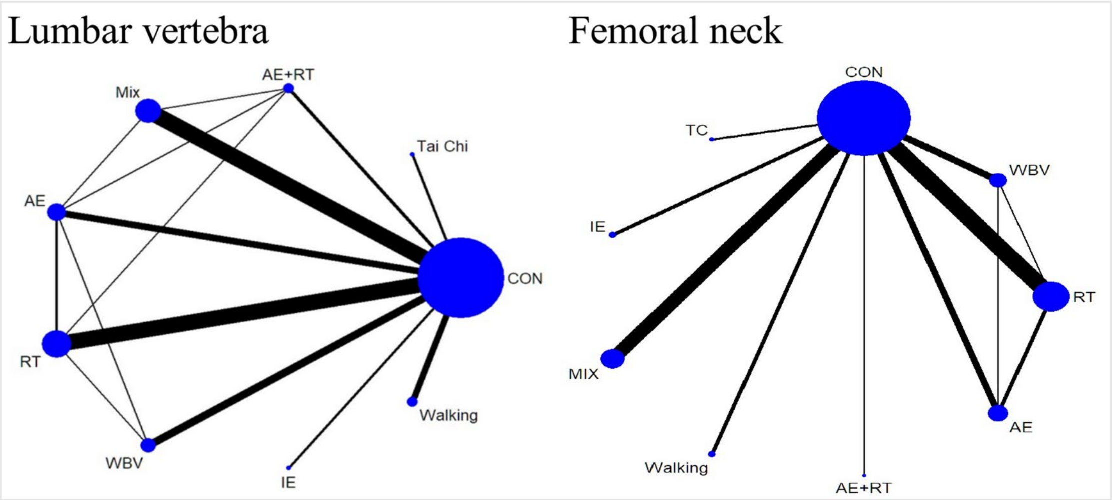

Fig. 3. Network plot of clinical symptoms. The magnitude of the nodes is directly proportional to the quantity of participants assigned randomly to each type of Exercise. A line is used to connect exercise kinds that involve direct comparisons, with the thickness of the line corresponding to the number of trials conducted to evaluate the comparison. *AE + RT* Aerobic Mixed Resistance Exercise, *WBV* Whole Body Vibration, *RT* Resistance Training, *TC* Tai Chi, *AE* Aerobic Exercise, *MIX* Mixed Exercise, *IE* Impact Exercise, *Walking* Walking Exercise.

a more pronounced positive effect on lumbar BMD compared to single-exercise programs[37–39]. AE + RT, on the other hand, increased muscle strength and bone turnover markers, with significant correlations[40]. Aerobic exercise and resistance exercise have distinct impacts on lumbar BMD. However, the combination of resistance exercise and aerobic exercise is found to be effective in preserving lumbar BMD in PMW[41]. Other studies explain that, at a more microscopic level, the osteogenic index of the multicomponent exercise pattern is about twice that of the single exercise pattern[42]. Moderate-intensity aerobic exercise has the potential to safeguard bone and cartilage through the management of body trace elements that play a role in the production of bone matrix structures. Additionally, it may prevent the process of bone resorption by exerting an anti-free radical mechanism[43]. High biomechanical loads such as resistance exercise can stimulate osteoblasts to form new bone by activating ion channels in osteoblasts and osteocytes[44]. The adaptation of bones to the mechanical pressures induced by resistance exercise has been shown to have a substantial positive impact on geometric indicators of bone strength, hence facilitating an augmentation in bone density[45,46]. The integration of aerobic and resistance exercise in AE + RT training to maximize the advantageous impact of exercise on bone density in PMW. Mixed-load exercise programs that combine jogging with other low-impact activities and resistance training programs that mix impact activities with high-intensity exercise seem to be useful in decreasing postmenopausal bone loss in the hip and spine[47]. Nevertheless, it is imperative to conduct sufficient controlled investigations in order to

AE + RT	**-1.00 (-140.59; 138.59)**	**NA**	**43.00 (-11.49; 97.49)**	**7.00 (-146.83; 160.83)**	**NA**	**NA**	**NA**	**25.99 (-1.55; 53.53)**
10.02 (-18.42; 38.47))	AE	-10.00 (-116.10; 96.10)	0.56 (-24.39; 25.51)	8.00 (-119.35; 135.35)	NA	NA	NA	21.93 (4.55; 39.31)
15.18 (-18.06; 48.42)	5.16 (-22.21; 32.53)	WBV	-4.00 (-88.88; 80.88)	NA	NA	NA	NA	16.60 (-6.57; 39.77)
15.97 (-9.83; 41.77)	5.95 (-11.35; 23.25)	0.79 (-24.37; 25.95)	RT	NA	NA	NA	NA	15.12 (3.13; 27.11)
21.74 (-4.70; 48.17)	11.71 (-7.14; 30.56)	6.56 (-18.57; 31.68)	5.77 (-9.76; 21.29)	MIX	NA	NA	NA	10.56 (-0.11; 21.22)
32.29 (-70.35; 134.94)	22.27 (-78.69; 123.22)	17.11 (-85.19; 119.41)	16.32 (-84.06; 116.70)	10.55 (-89.74; 110.85)	IE	NA	NA	0.06 (-99.68; 99.79)
28.07 (-17.13; 73.27)	18.05 (-23.18; 59.27)	12.89 (-31.53; 57.31)	12.10 (-27.69; 51.88)	6.33 (-33.25; 45.92)	-4.22 (-111.00; 102.55)	TC	NA	4.28 (-33.85; 42.41)
26.24 (-2.88; 55.35)	16.22 (-6.23; 38.66)	11.06 (-16.82; 38.94)	10.27 (-9.41; 29.95)	4.50 (-14.77; 23.77)	-6.05 (-107.07; 94.97)	-1.83 (-43.21; 39.56)	Walking	6.11 (-9.97; 22.19)
32.35 (8.08; 56.62)	**22.33 (6.67; 37.99)**	17.17 (-5.61; 39.94)	**16.38 (5.03; 27.73)**	10.61 (-0.01; 21.23)	0.06 (-99.68; 99.79)	4.28 (-33.85; 42.41)	6.11 (-9.97; 22.19)	CON

Table 1. League table of lumbar vertebra. *MD* Mean Difference, *CI* Credible Interval, *AE + RT* Aerobic Mixed Resistance Exercise, *WBV* Whole Body Vibration, *RT* Resistance Training, *TC* Tai Chi, *AE* Aerobic Exercise, *MIX* Mixed Exercise, *IE* Impact Exercise, *Walking* Walking Exercise. All results are presented in the form of MD (95% CI). The network meta-analysis findings are displayed in the lower left section, while the upper right half displays the results from pairwise comparisons, if they are available. Significant results are indicated by cells displayed in bold.

AE + RT	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**140.00 (40.89; 239.11)**
113.93 (12.16; 215.70)	WBV	13.00 (-55.13; 81.13)	NA	0.00 (-79.08; 79.08)	NA	NA	NA	**25.59 (1.97; 49.21)**
123.02 (23.58; 222.45)	9.08 (-15.09; 33.26)	RT	NA	7.86 (-4.32; 20.04)	NA	NA	NA	**17.37 (9.01; 25.73)**
130.86 (28.63; 233.08)	16.92 (-17.13; 50.97)	7.84 (-18.43; 34.11)	TC	NA	NA	NA	NA	9.14 (-15.88; 34.16)
132.47 (32.67; 232.27)	18.53 (-6.99; 44.06)	9.45 (-1.38; 20.28)	1.61 (-25.99; 29.21)	AE	NA	NA	NA	3.16 (-12.68; 18.99)
134.76 (35.34; 234.18)	20.83 (-3.54; 45.20)	11.75 (0.58; 22.92)	3.91 (-22.30; 30.11)	2.30 (-11.72; 16.31)	MIX	NA	NA	5.24 (-2.55; 13.02)
136.99 (35.72; 238.27)	23.06 (-8.02; 54.14)	13.98 (-8.31; 36.26)	6.14 (-26.40; 38.67)	4.53 (-19.31; 28.36)	2.23 (-19.97; 24.43)	IE	NA	3.01 (-17.79; 23.80)
140.19 (39.76; 240.63)	26.26 (-1.98; 54.50)	17.18 (-0.94; 35.29)	9.34 (-20.50; 39.17)	7.72 (-12.27; 27.72)	5.43 (-12.59; 23.45)	3.20 (-23.19; 29.59)	Walking	-0.19 (-16.44; 16.06)
140.00 (40.89; 239.11)	**26.07 (2.97; 49.16)**	**16.98 (8.98; 24.99)**	9.14 (-15.88; 34.16)	7.53 (-4.12; 19.19)	5.24 (-2.55; 13.02)	3.01 (-17.79; 23.80)	-0.19 (-16.44; 16.06)	CON

Table 2. League table of femoral neck. *MD* Mean Difference, *CI* Credible Interval, *AE + RT* Aerobic Mixed Resistance Exercise, *WBV* Whole Body Vibration, *RT* Resistance Training, *TC* Tai Chi, *AE* Aerobic Exercise, *MIX* Mixed Exercise, *IE* Impact Exercise, *Walking* Walking Exercise. All results are presented in the form of MD (95% CI). The network meta-analysis findings are displayed in the lower left section, while the upper right half displays the results from pairwise comparisons, if they are available. Significant results are indicated by cells displayed in bold.

establish direct evidence. Future research should prioritize conducting rigorous randomized controlled trials of high quality.

Our results indicate that three exercise types significantly improved lumbar BMD in PMW compared with controls, with AE + RT being the best, followed by AE training and RT training, significantly higher than the rest of the exercise types. First, aerobic exercise improves bone density by regulating hormone levels. This is consistent with previous research showing[48] that 18 weeks of moderate-intensity aerobic exercise can significantly increase estrogen levels in older women, which in turn reduces bone loss. Ettinger et al.[49] also showed that aerobic exercise increases resting estrogen levels in women inhibits osteoclasts, and promotes calcitonin production, thereby reducing bone loss. The mechanism of aerobic exercise promoting lumbar BMD was explained microscopically. In addition, aerobic exercise improves BMD by modulating markers of bone turnover. A study comparing aerobic exercise, tai chi, and walking found that bone health indicators in the aerobic exercise group improved significantly after four months of exercise intervention[50]. Previous meta-analyses have also reported that aerobic exercise improves lumbar BMD better than other exercise types in PMW[51]. Weycker D[52] et al. demonstrated that an exercise program that included walking, jogging, and stair climbing significantly increased BMD throughout the body, lumbar vertebra, femoral neck, and Ward's triangle. Notably, high-intensity strength training is more effective at increasing bone mass in the spine and hips than low-intensity or moderate-intensity strength training[53]. Some studies have explained from a microscopic perspective that moderate-intensity aerobic exercise can effectively inhibit bone resorption and reduce the incidence of bone loss by regulating bone

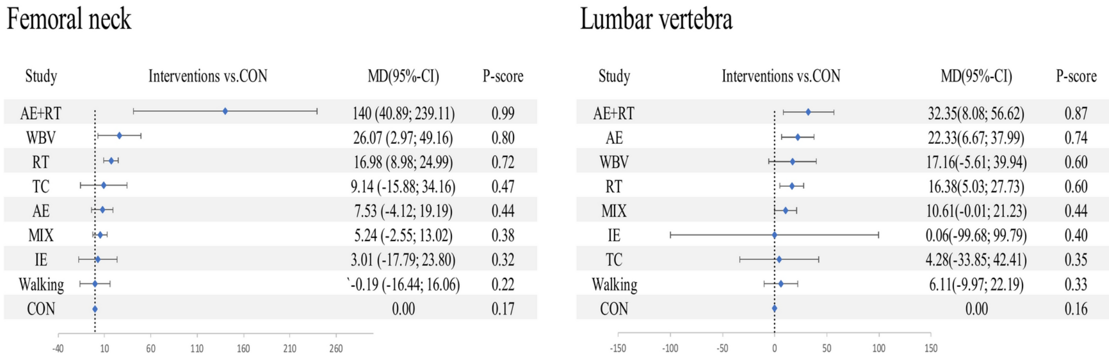

Fig.4. Forest plot change in efficacy of 8 interventions. The ranking of exercise types is determined based on the probability of P-score ranking. No substantial disparity is evident between treatments that intersect the y-axis and the control group. The variable "n" denotes the quantity of research that were directlyplaced in comparison to the control group. *MD* Mean Difference, *CI* Credible Interval, *AE + RT* Aerobic Mixed Resistance Exercise, *WBV* Whole Body Vibration, *RT* Resistance Training, *TC* Tai Chi, *AE* Aerobic Exercise, *MIX* Mixed Exercise, *IE* Impact Exercise, *Walking* Walking Exercise.

resorption and formation in the body[43,54]. It is well known that resistance exercise, strength training, etc., are forms of exercise that have a significant impact on BMD[29,55–57]. Previous studies have shown the same results as this study: resistance training has obvious advantages over other exercise methods in reducing bone loss and increasing BMD, but there has yet to be a consensus on the optimal intensity and frequency of training[58,59]. In other ways, resistance exercise maintains bone mass indirectly by strengthening muscles and improving balance ability[10,60–62]. From the mechanical stimulation point of view, during resistance exercise, a large mechanical load is applied to the bone, stimulating and promoting the osteogenic response of the bone[63]. Studies have also shown that high-speed resistance training twice or more per week produces the greatest skeletal benefits, but that benefits may be lost if training is stopped for more than six months[64]. Further investigation is required to ascertain the most effective level and regularity of resistance training.

Our results indicate that three exercise types significantly improved femoral neck BMD in PMW, with AE + RT being the best, followed by WBV and RT, significantly higher than the other exercise types. Prior research[65] investigating the impact of WBV and other exercise interventions on bone mineral density in PMW has demonstrated notable enhancements in BMD specifically in the femur neck and lumbar vertebra areas among the WBV group. However, no significant effect was observed on the lumbar vertebra and femoral neck in the impact training group. In addition, some animal experiments[66] also showed that bone structure was significantly improved after receiving WBV, mainly manifested by increased bone density and increased bone hardness, this is explained in terms of how motion affects the physical properties of bones. This is consistent with the conclusions of this study. Meta-analyses of muscle strength studies have shown that WBV significantly improves PMW's lower limb strength, improves balance, and somewhat reduces the probability and risk of falls[67]. In addition, randomized controlled trials analyzing bone metabolism have shown that 6 months of WBV training can reduce bone loss in PMW[65]. However, WBV exercise regimens are highly controversial[68,69], with questions focusing on duration, frequency, and intensity of intervention. Compared to other interventions, WBV exercise does not require a large exercise load to achieve improvement. However, specific exercise parameters need to be continuously explored to maintain its effectiveness and safety.

AE, RT, AE + RT, and WBV had significant effects on the lumbar vertebra or femur neck in PMW, while TC, Walking, IE, and MIX had no significant effects. The impact of Taijiquan training on human BMD is a subject of dispute. Woo et al.[31] conducted the Taiji exercise for 48 weeks (3 times/week) in PMW and compared it with the resistance group and control group. The Taiji group and the resistance group exhibited lumbar vertebra and hip BMD alterations, although these changes were not statistically significant when compared to the control group. Chan et al.[70] believe that 48 weeks of Tai Chi exercise (5 times/week) has a significant effect on the maintenance of trabecular bone and cortical bone density in PMW, and the Tai Chi group (compared with the control group) has slower bone loss. Gába et al.[71] demonstrated that a 10-week walking intervention, conducted 5 times per week, did not have a significant impact on bone mineral density of the upper limbs and heels in PMW aged 50 and above. Kelley et al.[72], however, concluded that 16 weeks of brisk walking plus muscle strength exercise significantly increased Ward's triangle BMD in PMW but had no significant effect on BMD at the lumbar vertebra and other proximal femur sites. The implications of a mixture of impact activity, high-intensity exercise, and resistance training on bone programs vary. A blend of these types of exercise has been shown to effectively reduce bone loss in the hip and spine during the postmenopausal era. Alternative types of impact exercise seemed to have a lower efficacy in preserving BMD in this particular group[47].

Research limitations

Exercise program, exercise time, exercise frequency, and exercise intensity are the four factors in formulating an exercise prescription. However, the randomized controlled trials designed in the included literature failed to describe the exercise intensity and exercise frequency in detail, and the number of literature needed to be more comprehensive to support subgroup analysis of exercise intensity and frequency. This study included all women who could participate in sports. Few studies have been conducted on older adults and women with mobility difficulties. The design of future experiments on exercise mode, time, intensity, frequency, and age should be scientific and standardized, and large-scale, multi-sample, double-blind, randomized controlled trials should be adopted for further verification.

Although the network meta-analysis provides a high level of evidence, its methodological limitations need further discussion. First, indirect comparisons rely on the transitivity assumption, but unmeasured confounding factors may affect the reliability of the results. Second, heterogeneity in the included studies (such as exercise intensity, frequency, and duration) may contribute to instability in the results, and although we adjusted for it through random effects models and subgroup analyses, some heterogeneity could not be completely eliminated. In addition, imbalances in network structure (e.g., fewer direct comparisons of WBV and TC) may affect the accuracy of indirect comparisons. Data and methodological heterogeneity in exercise parameters limited the depth of dose–response analysis. Although sensitivity analyses showed high robustness to the primary conclusions, these limitations may have led to underestimation or overestimation of the effects of certain interventions.

Future studies should report motion parameters in more detail and supplement high-quality RCTs to enhance the robustness of the network structure. In addition, the exploration of individualized intervention strategies will help optimize the application of exercise intervention in clinical practice.

Conclusion
In summary, it can be concluded that engaging in scientific and rational physical activity has a beneficial impact on enhancing the BMD of PMW. Moreover, interventions such as AE, RT, AE + RT, and WBV have been found to yield more substantial changes in BMD among older adults.

Data availability
Data provided in manuscript or supplementary information file.

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Author contributions

Li X.Y. carried out experimental work and data analysis and wrote the manuscript. Xu L. and Zhu J.P. provided domain expertise. Zhang H.Y. and Fu X.Y. performed data analysis and detailed corrections. Wang Y. designed and supervised the study. All authors approved the final submitted version.

Declarations

Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Additional information

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Correspondence and requests for materials should be addressed to W.Y.