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The Effect of Resistance Training on Bone Mineral Density in the Lumbar Spine and Femoral Neck in Postmenopausal Women - literature review.

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Abstract

Introduction:

Osteoporosis is a chronic disease of the skeletal system characterised by reduced bone strength and an increased risk of fractures. In postmenopausal women, estrogen deficiency accelerates bone loss. Resistance training provides mechanical stimuli that may help maintain or increase bone mineral density (BMD).

Materials and methods:

A narrative review of randomized controlled trials, intervention studies, systematic reviews, and meta-analyses was conducted. The analysis focused on changes in BMD measured by dual-energy X-ray absorptiometry (DXA), particularly at the lumbar spine and femoral neck, considering training intensity, frequency, duration, and progression.

Aim of the study:

To evaluate the effects of resistance training on BMD in postmenopausal women and assess the influence of training characteristics on its effectiveness.

Conclusions:

Resistance training may increase BMD or attenuate its decline in postmenopausal women. The most consistent effects were observed at the lumbar spine, while findings for the femoral neck were more heterogeneous. Higher intensity and progressive loading may provide a stronger osteogenic stimulus, although no single optimal protocol has been established. Further research is needed to determine optimal training parameters and their impact on fracture risk.

Keywords:

osteoporosis; postmenopausal women; resistance training; bone mineral density; lumbar spine; femoral neck; DXA

1. Introduction

1.1. Osteoporosis

Osteoporosis is a chronic disease of the skeletal system characterised by reduced bone strength and an increased risk of fractures. Its development is associated with decreased bone mass and changes in bone tissue structure, resulting, among other things, from an imbalance in bone remodelling processes. The clinical significance of osteoporosis stems primarily from the occurrence of fractures, which can lead to pain, reduced functional ability, a decline in quality of life, and loss of independence [1–3].

An important parameter used in the assessment of bone tissue is bone mineral density (BMD). A decrease in BMD is associated with an increased risk of fractures and is one of the most important parameters used in the diagnosis of osteoporosis and the assessment of fracture risk [1–3]. However, it is important to note that BMD primarily reflects the quantitative aspect of bone tissue and does not address all factors influencing its strength, such as microarchitecture or the material properties of bone [2,3].

In the densitometric diagnosis of osteoporosis in postmenopausal women, the T-score is used, among other measures; it indicates the difference between the subject's BMD and the average BMD of the healthy population, expressed in standard deviations. According to World Health Organisation (WHO) criteria, a T-score of ≤ -2.5 corresponds to a densitometric diagnosis of osteoporosis. The interpretation of the result should take into account the site of measurement, the technique used, and the appropriate reference population [1–3].

Bone is a dynamic tissue that undergoes remodeling throughout life. Under normal conditions, the resorption of old or damaged bone tissue by osteoclasts is coordinated with the formation of new bone tissue by osteoblasts. Maintaining a balance between these processes allows bone mass and structure to be preserved. If resorption exceeds bone formation, gradual bone mass loss occurs, leading to a deterioration in the mechanical properties of the skeleton [4,5].

1.2. Menopause and Loss of Bone Mineral Density

One of the most important factors affecting bone health in women is menopause. The accompanying decline in estrogen levels leads to increased bone turnover and accelerated loss of BMD. Estrogen is a key regulator of bone metabolism and acts on osteoclasts, osteoblasts, and osteocytes, and thus influences the balance of remodeling processes [6–8].

The effect of estrogen on bone tissue is associated, among other things, with the regulation of osteoclast activity. Through its receptors, estrogen influences the Receptor Activator of Nuclear Factor κ B/Receptor Activator of Nuclear Factor κ B Ligand/Osteoprotegerin (RANK/RANKL/OPG) system, limiting osteoclast differentiation and activity and helping to maintain remodeling balance. Under conditions of estrogen deficiency, RANKL expression increases and the protective effect of OPG decreases, which promotes enhanced osteoclastogenesis and bone resorption [7,8].

Estrogen deficiency also affects bone formation processes. Estrogen influences pathways associated with osteoblast activity, including the Wnt/ β -catenin pathway, and affects the production of factors such as IGF-1 and TGF- β . Consequently, its deficiency leads to an imbalance between bone resorption and formation [8].

Menopause-related BMD loss does not begin many years after menopause sets in. The highest rate of BMD loss is observed during the menopausal transition, particularly during the perimenopausal and early postmenopausal periods [6,7]. In analyses covering the period from approximately one year before to two years after the last menstrual period, the annual loss of BMD was approximately 2.46% in the lumbar spine and 1.76% in the femoral neck [6].

In the long term, the cumulative loss of BMD remains significant. Over a 10-year period, it was approximately 10.6% in the lumbar spine and 9.1% at the femoral neck [6]. The greater loss of BMD in the spine may be partly due to the higher proportion of trabecular bone in this area, which is particularly susceptible to metabolic changes [6].

The importance of estrogens for skeletal health is also reflected in the association between estradiol levels and fracture risk. Lower estradiol levels in postmenopausal women are associated with a higher risk of BMD loss and fractures, indicating the important role of sex hormones in maintaining normal bone homeostasis [6]. At the same time, the relationship between hormone levels, BMD, and fracture risk is complex and varies depending on the stage of the menopausal transition [6,7].

The rate of bone loss is also influenced by other factors, including age, body weight, physical activity, lifestyle, and the presence of diseases or the use of medications that increase the risk of osteoporosis [5,7]. Among the modifiable factors, physical activity is of particular importance, as it can affect both bone mass and the functioning of the musculoskeletal system [5].

1.3. Assessment of Bone Mineral Density Using the DXA Method

The primary method for the quantitative assessment of BMD is dual-energy X-ray absorptiometry (DXA). This method allows for the determination of bone mineral content in the examined area and the calculation of BMD by relating the amount of mineral to the surface area of the examined region. This means that DXA provides a measurement of areal bone mineral density rather than actual volumetric bone mineral density [2–4].

In the diagnosis of osteoporosis, a central DXA scan covering the lumbar spine and the proximal femur is of particular importance. BMD measurement in the hip region, particularly the femoral neck, has high prognostic value in assessing the risk of hip fracture, while measurement in the spine is used, among other things, to monitor changes in BMD over time [3,9,10].

Significant advantages of DXA include a short examination time, a low radiation dose, and high measurement precision. This method is widely used both in the diagnosis of osteoporosis and in the assessment of fracture risk and the monitoring of changes in BMD over time [3,4,9]. In studies examining the effects of physical activity on bone tissue, BMD measurement using the DXA method is therefore often used as an objective endpoint.

DXA results can be presented as an absolute BMD value or as a T-score or Z-score, depending on the subject's age and the purpose of the interpretation. In postmenopausal women, the T-score is used for the densitometric classification of osteoporosis. It is important to note, however, that T-scores obtained at different anatomical sites or using different techniques

should not be considered fully interchangeable, as their prognostic significance may vary [3,4,9].

For the lumbar spine, the standard measurement area consists of the L1–L4 vertebrae; however, in certain situations, individual vertebrae may need to be excluded from the analysis, for example, due to structural changes, fractures, or artifacts. Within the hip, the areas analyzed may include, among others, the entire hip and the femoral neck [9]. The appropriate selection of the measurement site is important both for diagnosis and for comparing changes in BMD across subsequent examinations.

1.4. Bone Tissue Physiology and Response to Mechanical Loading

Bone remodeling is a lifelong process that enables both the removal of damaged tissue and the adaptation of bone structure to changing mechanical conditions. This process primarily involves osteoclasts, osteoblasts, and osteocytes. Proper skeletal function requires adequate coordination of bone resorption and formation [4,5,11].

Osteocytes are believed to play a special role in regulating bone remodeling. These are cells derived from osteoblasts that, once embedded in the mineralized bone matrix, form an extensive communication network. Osteocytes function as mechanosensors, enabling them to detect changes in the mechanical load acting on bone tissue and transmit signals that influence the activity of other bone cells [11,12].

The process of converting a mechanical stimulus into a cellular response is referred to as mechanotransduction. This process involves, among other things, the osteocyte cytoskeleton, dendritic processes, integrins, intercellular junctions, primary cilia, ion channels, and components of the extracellular matrix [11]. Thanks to these mechanisms, osteocytes can respond to changes in stress and fluid flow within the canaliculo-lacunar system and trigger a response that regulates bone remodeling [11,12]. One of the most important signaling pathways involved in the bone tissue's response to mechanical loading is the Wnt/ β -catenin pathway. Osteocytes also participate in the regulation of the RANKL/OPG axis and produce sclerostin, which inhibits Wnt signaling and may limit bone formation processes. In this way, osteocytes serve as a crucial link between mechanical stimuli and the processes of bone formation and resorption [8,11,12].

The importance of mechanical loading for maintaining normal bone structure is confirmed by observations regarding reduced physical activity. The loss of mechanical stimuli, including as a result of prolonged immobilization, leads to increased resorption and decreased bone formation, and consequently to bone mass loss and skeletal weakness [4,5]. On the other hand, appropriately selected mechanical loading can stimulate adaptive processes in bone tissue [4,5].

Resistance training is a particularly interesting form of physical activity in the context of bone health, as it subjects the skeleton to both forces associated with muscle contraction and external loads. These stimuli can be detected by osteocytes and trigger mechanotransduction mechanisms associated with bone tissue adaptation [4,11,12].

Resistance training may be particularly important for postmenopausal women, in whom estrogen deficiency promotes increased remodeling and a predominance of resorptive

processes. Physical activity is one of the modifiable factors influencing bone health, and appropriately selected weight-bearing exercises can be part of a strategy to reduce bone mass loss [5,8].

Therefore, it is reasonable to determine the extent to which resistance training affects BMD in postmenopausal women and whether its effectiveness depends on the characteristics of the training stimulus used. Assessing changes in BMD, particularly in the lumbar spine and hip, allows for an objective evaluation of the impact of this type of activity on bone tissue. An analysis of the available studies thus allows us to assess whether resistance training can be an effective strategy for reducing bone loss in postmenopausal women.

2. Results

2.1. Characteristics of the analysed studies

The analyzed literature assessed the effect of resistance training on BMD in postmenopausal women, with particular emphasis on the lumbar spine and the femoral neck. The studies differed in terms of the participants' age, their baseline bone status, the duration of the intervention, training frequency, and the loads used. The training programs lasted from approximately 12 weeks to 2 years and most often consisted of 2–3 sessions per week. Both high-intensity training and protocols using light loads with a high number of repetitions were employed. In some studies, the participants had normal BMD, while in others, they had osteopenia or osteoporosis.

One of the earliest studies was a randomized trial by Pruitt et al., in which women in early postmenopause participated in a 9-month resistance training program performed three times a week. BMD of the spine and femoral neck was analyzed. Similarly, Nelson et al. evaluated the effects of intensive strength training performed twice a week over the course of a year in women aged 50–70 [13,14]. Subsequent studies analyzed, among other things, training performed three times a week for 24 weeks, squat-focused training, as well as long-term programs lasting one or two years [15–19].

It is worth noting that not all studies involved women with reduced BMD. Nicholson et al. included healthy, active women over the age of 55 in their study, while Eslamipour et al. studied postmenopausal women with osteopenia [15,16]. Differences in the participants' characteristics should be taken into account when interpreting the results, as the bone's response to mechanical loading may depend, among other factors, on baseline BMD and the degree of bone mass deficiency.

2.2. The Effect of Resistance Training on BMD of the Lumbar Spine

The results regarding the lumbar spine indicate a relatively consistent beneficial effect of resistance training, although the magnitude of this effect varied across studies. Pruitt et al. demonstrated that after 9 months of training, spinal BMD increased by $1.6 \pm 1.2\%$ in the training group, while it decreased by $3.6 \pm 1.5\%$ in the control group. The difference between the groups was statistically significant. At the same time, no significant effect of training on femoral neck BMD was observed [13].

Nelson et al. obtained similar results in a study involving 40 postmenopausal women. After one year of intensive strength training, lumbar spine BMD increased by an average of $0.009 \pm$

0.033 g/cm², corresponding to an increase of $1.0 \pm 3.6\%$. At the same time, the control group showed a decrease in BMD of 0.019 ± 0.035 g/cm², or $1.8 \pm 3.5\%$. The difference between the groups was statistically significant [14].

The beneficial effects of training were also indicated by the results of Bocalini et al. After 24 weeks of strength training in women not receiving hormone replacement therapy, no significant decrease in spinal BMD was observed. BMD changed from 0.881 ± 0.001 to 0.880 ± 0.001 g/cm². In contrast, the non-training group experienced a significant decrease from 0.882 ± 0.002 to 0.873 ± 0.002 g/cm². This corresponded to a change of $-0.13 \pm 0.09\%$ in the training group and $-0.98 \pm 0.11\%$ in the control group [15].

Maddalozzo et al. obtained interesting results by using only two free-weight exercises—squats and deadlifts—performed twice a week for one year. In women not receiving hormone replacement therapy, spinal BMD increased by $0.43 \pm 4.3\%$, while in women receiving hormone replacement therapy and simultaneously performing the training, it increased by $0.70 \pm 2.2\%$. By comparison, in the control group, BMD decreased by $3.60 \pm 3.70\%$. The authors noted that resistance training reduced BMD loss regardless of hormone replacement therapy use [17].

However, not all results were unequivocally positive. In the study by Nicholson et al., a 6-month training program with very low load and a very high number of repetitions (BodyPump) was used. A significant group $\times$ time interaction was observed for lumbar spine BMD. A small, non-significant increase in BMD was observed in the training group, whereas a significant decrease occurred in the control group. However, no beneficial effect of training on femoral neck BMD was demonstrated. The authors noted that the modest progression of loads and the relatively short duration of the intervention may have limited the osteogenic effect [18].

In contrast, no significant effect on spinal BMD was found in a study by Duff et al. involving 90 postmenopausal women. After 9 months of resistance training performed three times a week, no significant changes in lumbar spine BMD were observed. This result should be interpreted because the study was multifactorial and simultaneously assessed the effect of ibuprofen supplementation [19].

The results of individual studies are supported by meta-analyses. A meta-analysis by Kelley et al., which included controlled studies on resistance training in women, demonstrated a beneficial effect of exercise on BMD, although the effect size was rather small. A subsequent meta-analysis by Shojaa et al., encompassing 75 studies on various forms of exercise in postmenopausal women, also confirmed the beneficial effect of exercise on BMD. An analysis of dynamic resistance training demonstrated a significant increase in lumbar spine BMD compared to baseline values [20,21].

More recent findings reinforce this observation. In a 2025 meta-analysis by Zhao et al., encompassing 17 randomized trials and 690 postmenopausal women, resistance training significantly improved lumbar spine BMD (SMD = 0.88; 95% CI: 0.21–1.56; $p = 0.01$). However, it is important to note the considerable heterogeneity among the studies ($I^2 = 91\%$), indicating that the effect size was not consistent across the various training protocols [22].

Similar conclusions were presented by Wang et al. in a network meta-analysis of 19 studies involving 919 postmenopausal women. Moderate-intensity training was shown to be superior, particularly at a frequency of three sessions per week, in terms of improving lumbar spine BMD. The authors noted that a protocol involving approximately 65–80% of 1RM and three training sessions per week may be particularly beneficial [23].

2.3. The Effect of Resistance Training on Femoral Neck BMD

The effect of resistance training on femoral neck BMD was less clear-cut than in the case of the lumbar spine. In a study by Nelson et al., after one year of intensive training, femoral neck BMD increased by 0.005 ± 0.039 g/cm², or $0.9 \pm 4.5\%$, while in the control group it decreased by 0.022 ± 0.035 g/cm², or $2.5 \pm 3.8\%$. The difference between the groups was statistically significant [14].

Pruitt et al. obtained different results; they found no significant difference between the training and control groups in terms of femoral neck BMD after 9 months of training [13]. Similarly, Nicholson et al. found no significant group $\times$ time interaction for femoral neck BMD after 6 months of very low-load training [18].

As with the spine, Bocalini et al. primarily demonstrated a slowing of BMD loss. After 24 weeks of training, femoral neck BMD in the training group changed from 0.705 ± 0.001 to 0.704 ± 0.001 g/cm², and the change of $-0.09 \pm 0.05\%$ was not statistically significant. In the control group, BMD decreased by $1.58 \pm 0.20\%$ [15].

In the study by Maddalozzo et al., a decrease in femoral neck BMD was also observed in the groups performing resistance training; however, the decline was smaller than in the control group. In women not receiving hormone replacement therapy, the decrease was $-1.2 \pm 4.3\%$, and in the control group, $-3.9 \pm 3.8\%$; however, the differences were not statistically significant [17].

In contrast, a study by Eslamipour et al., conducted among 45 postmenopausal women with osteopenia, indicates a beneficial effect of training on the femoral neck. The women were randomly assigned to a high-intensity training group, a low-intensity training group, or a control group. The intervention lasted 24 weeks and was performed three times a week. The high-intensity protocol used 80% of 1RM and 8 repetitions, while the low-intensity protocol used 40% of 1RM and 16 repetitions. The authors demonstrated significant differences in BMD, BMC, T-score, and Z-score in both the lumbar spine and the femoral neck, with the overall results indicating greater improvement in bone parameters in the high-intensity group [16].

More recent meta-analyses also provide important information regarding training parameters. Zhao et al. demonstrated a significant overall effect of resistance training on femoral neck BMD (SMD = 0.89; 95% CI: 0.40–1.39; $p = 0.0004$); however, as with the spine, there was considerable heterogeneity in the results ($I^2 = 87\%$). A subgroup analysis indicated a particularly beneficial effect of high-intensity training, defined as $\geq 70\%$ of 1RM [22].

In contrast, Wang et al. indicated that, for the femoral neck, moderate-intensity training performed three times a week may be beneficial. In this analysis, a frequency of ≥ 3 sessions

per week was associated with better femoral neck BMD outcomes, and the moderate-intensity, high-frequency protocol was considered the most promising among the analyzed options [23].

Altogether, the analyzed studies indicate that resistance training may reduce postmenopausal BMD loss in both the lumbar spine and the femoral neck. This effect appears to be more consistent for the spine, while the results regarding the femoral neck are more varied. These differences may stem, among other factors, from the intensity and progression of the loads, training frequency, duration of the intervention, type of exercises used, and the participants' baseline bone condition. The use of an appropriate mechanical load and its progression appears to be particularly important, as studies using very low, non-progressive loads more often showed only a halt in BMD loss rather than a marked increase in BMD [18,22,23].

Discussion

The aim of this study was to evaluate the effect of resistance training on bone mineral density in postmenopausal women, with particular emphasis on the lumbar spine and the femoral neck. The analyzed studies indicate that resistance training can effectively reduce postmenopausal BMD loss and, in some cases, even lead to an increase in BMD. However, the effect was not consistent across all studies and likely depended on the characteristics of the mechanical stimulus used, the duration of the intervention, the baseline bone condition, and the type of bone site analyzed.

The most consistent results were obtained for the lumbar spine. In several randomized studies, an increase in BMD was observed following resistance training, whereas a decrease was more common in the control groups. This is particularly evident in the results of Nelson et al., Pruitt et al., and the more recent studies by Eslamipour and Holubiac [13,14,16,24]. These findings are consistent with the conclusions of meta-analyses in which physical training, including resistance training, demonstrated a positive effect on lumbar spine BMD. In a large meta-analysis by Mohebbi et al., encompassing 80 studies and 5,581 female participants, the effect on lumbar spine BMD was an SMD of 0.29 (95% CI 0.16–0.42), indicating a small but significant beneficial effect of exercise [25].

At the same time, the effect size observed in individual studies varied widely. For example, in the LIFTMOR study, an 8-month, high-intensity resistance-impact training program led to a 2.9% increase in lumbar spine BMD, while the control group experienced a 1.2% decrease [26]. This result is significantly greater than the effect observed in some older studies. It can be assumed that one of the reasons is the nature of the stimulus used. The LIFTMOR program included loads exceeding 85% of 1RM, performed twice a week under supervision, and thus provided relatively high mechanical forces with a low training volume.

The importance of training intensity is also confirmed by the analyses of Kistler-Fischbacher et al. The authors indicated that low exercise intensity is largely insufficient as an osteogenic stimulus, whereas higher intensity, particularly when combined with impact loading, can elicit a greater bone response [27,28]. However, this does not mean that a single optimal intensity level can be unequivocally identified. More recent meta-analyses reveal significant heterogeneity in the protocols used, and the findings regarding optimal frequency and intensity are not entirely consistent.

It is interesting to compare studies using high and low intensity. In a study by Eslamipour et al. involving postmenopausal women with osteopenia, training at 80% of 1RM yielded better results than training at 40% of 1RM, both in terms of spinal BMD and femoral neck BMD. A similar trend was observed in the LIFTMOR study [16,26]. This may suggest that, to achieve a pronounced osteogenic effect, it is not only muscle activity itself that is important, but also a sufficiently high force transmitted to the bone tissue.

On the other hand, the results do not support the claim that only very heavy training is effective. In the study by Holubiak et al., a relatively short strength training program was also associated with an improvement in spinal BMD, and in some studies, moderate loads led at least to a halt in bone mass loss [24]. Furthermore, Wang et al., in a network meta-analysis, pointed to beneficial outcomes from moderate-intensity programs performed three times a week [23]. This suggests that there is likely a range of effective training loads, although further research is needed to precisely determine the optimal protocol.

Load progression is also a key factor in interpreting these findings. A study by Nicholson et al., which used training with very low load and a very high number of repetitions, demonstrated a beneficial effect primarily in terms of maintaining spinal BMD, while no improvement in femoral neck BMD was observed [18]. This may indicate that simply performing resistance exercises is not sufficient. To achieve a strong osteogenic stimulus, the ability to gradually increase the load is likely important, thereby subjecting the bone to sufficiently high and varying mechanical stresses.

The results regarding the femoral neck are different. Although some studies have shown a beneficial effect of training, the effect was less consistent than for the lumbar spine. Nelson et al. demonstrated a significant improvement in femoral neck BMD, whereas Pruitt et al. and Nicholson et al. found no significant differences between the groups [13,14,18]. In the Bocalini study, exercise primarily reduced BMD loss, whereas greater demineralization was observed in the control group [15]. These differences are consistent with the results of meta-analyses, which indicate a positive—though not always large—effect of exercise on the femoral neck.

In the meta-analysis by Mohebbi et al., the effect of exercise on femoral neck BMD was an SMD of 0.27 (95% CI 0.16–0.39), which was similar to the effect on the lumbar spine but smaller than that for the total hip. The authors also emphasized the significant heterogeneity of the results across some of the included studies [25]. A more recent meta-analysis by Zhao et al., focusing exclusively on resistance training, also confirmed the beneficial effect of training on BMD in both the spine and the femoral neck; however, there was considerable heterogeneity among the studies [22].

One possible explanation for the differences between these sites is their varying responses to mechanical stimuli. The lumbar spine contains a significant amount of trabecular bone, which is characterized by high metabolic activity and may respond more quickly to changes in load. The femoral neck, on the other hand, contains both cortical and trabecular bone, and the response may depend on the direction and nature of the applied forces. For this reason, it cannot be automatically assumed that training designed to improve spinal BMD will have the same effect on the proximal end of the femur.

Menopausal status and baseline bone condition also influence the interpretation of results. The loss of estrogen after menopause leads to increased bone turnover and a predominance of resorption over bone formation; therefore, the application of an appropriate mechanical stimulus may be of particular importance during this stage of life. At the same time, the results of a large meta-analysis by Mohebbi et al. showed no significant differences in exercise response between women with osteopenia or osteoporosis and women with normal BMD, nor between women in the early and late postmenopausal periods [25].

It is worth noting the safety of higher-intensity training. For many years, there were concerns about using high loads in people with osteoporosis due to the potential risk of fractures. However, the results of the LIFTMOR study suggest that properly designed and supervised high-intensity training can be used in selected women with low bone mass. In this study, only one minor adverse event was reported—a brief spasm in the lower back muscles—while adherence to the program remained high [26]. This does not mean, however, that high-intensity training should be directly recommended for every woman with osteoporosis. The study included carefully selected participants and was conducted under strict supervision. Therefore, these results should not be directly extrapolated to individuals with severe osteoporosis, a history of vertebral fractures, multiple comorbidities, or contraindications to intense exercise.

Another important aspect is the distinction between an increase in BMD and an actual reduction in fracture risk. BMD is the most commonly used and best-standardized endpoint in studies on exercise and bone health; therefore, it forms the basis of most of the available evidence [22,25]. However, a small increase in BMD cannot be equated with a proportional reduction in fracture risk. Fracture risk is also influenced by bone geometry, microarchitecture, bone quality, muscle strength, balance, and the risk of falls. Meanwhile, direct studies on fracture incidence are much less common than DXA studies.

This is particularly important in the context of interpreting the results of this review. Based on the available data, it can be stated with relative certainty that resistance training has a beneficial effect on BMD or reduces its loss in postmenopausal women. However, it cannot be concluded on this basis that resistance training alone prevents osteoporosis or eliminates the risk of fractures. Such a conclusion would go beyond the endpoints of the analyzed studies.

The results should also be interpreted in light of the heterogeneity of the available studies. Individual programs differed in intensity, number of sets and repetitions, training frequency, duration, and choice of exercises. The populations of participants, their baseline BMD, the use of hormone replacement therapy, and other factors that may influence bone metabolism also varied. Significant heterogeneity has also been demonstrated in meta-analyses [22,25].

Another important limitation is the relatively short duration of many interventions. Changes in BMD occur more slowly than changes in muscle strength or physical fitness; therefore, a program lasting several months may be insufficient to reveal the full effect on bone health. At the same time, some older studies included small groups of participants, which reduced statistical power and increased the susceptibility of the results to the influence of individual observations.

Another limitation is that BMD is primarily an indirect marker of bone health. Although it is a clinically significant parameter and is widely used in the diagnosis of osteoporosis, it does not

describe all of the mechanical properties of bone. For this reason, future studies should also take greater account of bone geometry, microarchitecture, markers of bone remodeling, muscle strength, fall frequency, and—above all—the actual incidence of fractures. A gap regarding such hard endpoints is clearly evident in the current literature.

In summary, the available evidence indicates that resistance training is a valuable method for promoting bone health in postmenopausal women. The most compelling data pertain to the ability to increase or maintain lumbar spine BMD, whereas the effect on the femoral neck is somewhat more variable. It appears that the effectiveness of training depends not only on its presence but also on an appropriate load level, the potential for progression, and sufficient program duration. At the same time, the current evidence does not allow for the identification of a single universal training protocol or for the direct translation of changes in BMD into a reduction in fracture rates.

Conclusions

Resistance training has a beneficial effect on bone health in postmenopausal women, leading to an increase in BMD or a reduction in its physiological decline.

The most consistent results were obtained for the lumbar spine. In many studies, resistance training led to an increase in BMD or prevented its loss compared to the control group.

The effect of training on femoral neck BMD is also beneficial but more variable. Some studies showed a significant increase in BMD, while in others, training primarily slowed its decline or did not result in significant changes.

Higher intensity and a progressive increase in load may promote a stronger osteogenic response; however, the available data do not allow for a clear identification of a single optimal protocol in terms of intensity, frequency, and training volume.

High-intensity training may also be effective in women with osteopenia or osteoporosis if it is properly planned, preceded by appropriate screening, and conducted under supervision. However, this does not mean that every type of high-intensity training is suitable for every patient.

BMD remains the best-documented endpoint in studies on the effects of exercise on bone. Available data on the direct effects of exercise on fracture rates and the development of clinical osteoporosis are much more limited.

Due to the high heterogeneity of the studies, further randomized trials are needed to more accurately determine the optimal intensity, frequency, volume, and duration of resistance training and to assess its impact on long-term fracture risk.

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AI tools were used only to refine the language and improve text readability. The authors retain full accountability for the academic integrity of the work. The conceptual design, literature review, data analysis, and final drafting were executed solely by the authors.

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