Effects of High-Impact Training and Detraining on Femoral Neck Structure in Premenopausal Women: A Hip Structural Analysis of an 18-Month Randomized Controlled Exercise Intervention with 3.5-Year Follow-Up

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ABSTRACT

Purpose: This study evaluated the training effects of an 18-month exercise intervention and subsequent 3.5-year follow-up on femoral neck structure in premenopausal women. **Methods:** Of 98 women who participated in this randomized controlled study, 84 (39 trainees and 45 controls) completed the 18-month intervention. At both 18 months and 3.5 years, dual-energy X-ray absorptiometry data on 22 trainees and 22 control participants (ages 35–45 y) were available for hip structural analysis. The section modulus (Z), cross-sectional area (CSA), and subperiosteal width at the femoral neck were analyzed. Lower-leg explosive power and estimated maximal oxygen uptake ($\text{VO}_{2\text{max}}$) were assessed by vertical countermovement jump and standardized 2 km walking test, respectively. Progressive supervised high-impact exercises were done three times per week for 18 months. **Results:** Significant between-group differences in favour of trainees were observed after the 18-month intervention in Z (3.2%, $p = 0.047$) and CSA (2.8%, $p = 0.043$). At the 3.5-year follow-up point, the exercise-induced benefits in Z and CSA had diminished and were statistically insignificant. A between-group difference in favour of trainees was observed in lower-limb power after intervention (4.2%, $p = 0.002$) and at 3.5-year follow-up (5.1%, $p = 0.003$). A similar difference was seen in estimated $\text{VO}_{2\text{max}}$ (5.6% after intervention, $p = 0.002$, and 4.6% at 3.5-y follow-up, $p = 0.005$). **Conclusion:** The 18-month high-impact exercise intervention strengthened the femoral neck in premenopausal women by enhancing its structural properties; however, this benefit was not maintained at 3.5-year follow-up. In contrast, the exercise benefits on physical performance continued to be maintained 3.5 years after intervention.

Key Words: bone and bones; bone mineral density; exercise; osteoporosis; women.

RÉSUMÉ

Objectif : L'objectif de cette étude était d'évaluer les effets de l'entraînement dans le cadre d'une intervention avec exercice de 18 mois, puis d'un suivi de 3,5 ans sur la structure du col du fémur chez la femme en préménopause. **Méthode :** Des 98 femmes qui ont participé à cette étude randomisée contrôlée, 84 (39 à l'entraînement et 45 du groupe de contrôle) ont complété l'intervention de 18 mois. À 18 mois et à 3,5 ans, des données DXA sur 22 participantes à l'entraînement et sur 22 participantes du groupe de contrôle (35–45 ans) étaient disponibles pour une analyse de la structure de la hanche (HSA). La section du module (Z), la section transversale (CSA) et la largeur sous-périostée (W) à la hauteur du col fémoral ont été analysées. La puissance explosive de la portion inférieure de la jambe et la consommation maximale d'oxygène ($\text{VO}_{2\text{max}}$) ont été évaluées à l'aide de sauts à la verticale vers l'arrière et d'un test normalisé de 2 km à la marche, respectivement. Des exercices progressifs supervisés ont été exécutés trois fois par semaine pendant 18 mois. **Résultats :** Des différences considérables ont été observées entre le groupe de femmes à l'entraînement dans le cadre de l'intervention de 18 mois pour Z (3,2 %, $p = 0,047$) et CSA (2,8 %, $p = 0,043$). Lors du suivi après 3,5 ans, les bienfaits apportés par l'exercice pour Z et CSA avaient diminué et étaient non significatifs sur le plan statistique. Une différence entre les groupes, à l'avantage des femmes à l'entraînement, a été observée dans la puissance des membres inférieurs à la suite de l'intervention (4,2 %, $p = 0,002$) et lors du suivi après 3,5 ans (5,1 %, $p = 0,003$). Une différence similaire a été constatée dans l'estimation du $\text{VO}_{2\text{max}}$ (5,6 %, $p = 0,002$ et 4,6 %, $p = 0,005$). **Conclusion :** L'intervention de 18 mois d'exercices avec sauts a renforcé le col du fémur chez les femmes en préménopause par l'amélioration de ses propriétés structurelles. Cet avantage ne s'était toutefois pas maintenu lors du suivi après 3,5 ans. À l'opposé, les avantages de l'exercice sur la performance physique se sont maintenus 3,5 ans après l'intervention.

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Prevention of osteoporosis and related fractures presents a considerable challenge to health care systems worldwide. Osteoporosis, falls, and related bone fractures cause individual suffering and impose an economic burden on society.^{1,2} Many factors such as age, fracture history, balance, falling mechanics, neuromuscular function, and bone strength are associated with the risk of fractures resulting from falls.³ Bone strength-related factors such as genetics, bone cell mechanisms, hormonal factors, exercise, and nutrition are all under investigation in terms of fracture resulting from falls. Because exercise and exercise-related mechanical loading are one of the most important external factors determining bone structure properties,^{4,5} exercise loading would seem to be a cost-effective and feasible option to improve bone strength.

Previous studies have clearly shown that regular training can increase areal bone mineral density (aBMD; g/cm²) in premenopausal women,^{6–11} and high-impact training has been shown to be most effective.^{4,5} According to randomized controlled exercise studies, reported mean gains in aBMD have varied between 1% and 3% at the loaded regions of the skeleton.^{12–20} Most previous exercise interventions have focused on measuring aBMD as the main outcome variable. However, we should note that aBMD is only one determining factor in whole bone strength, and the exercise response of other traits of bone structure, not obtainable from aBMD, should also be examined.^{21,22} Even a small change in bone mass distribution can lead to a larger increase in whole bone strength independent of change in aBMD.^{22,23} Moreover, whole bone strength is an important determinant of fracture risk and is therefore the most important bone trait in fracture prevention.^{23,24} In our recent meta-analysis of exercise effects on bone strength, we concluded that exercise can significantly enhance bone strength at loaded sites, especially in children but not in adults.⁴ Our literature search also found that only five randomized controlled trials have assessed exercise effects on bone structure.⁴ The purpose of this study, therefore, was to gain more information on this topic by evaluating the training effects of a previous 18-month high-impact exercise intervention and a subsequent 3.5-year follow-up on femoral neck structure in premenopausal women^{15,25} using hip structural analysis (HSA).^{26,27}

METHODS

Design and Participants

Measurements were performed at baseline, after the 18-month intervention, and at 3.5-year follow-up. Originally,¹⁵ 98 healthy, sedentary (exercising less than twice a week), normally menstruating premenopausal women age 35–45 years were recruited to the study through newspaper advertising. Of 242 volunteer responders, 140

were excluded from the study after telephone interviews on the basis of these exclusion criteria: cardiovascular, musculoskeletal, respiratory, or other chronic diseases that might limit training or testing; medication that could affect the skeleton; menstrual irregularities; specific diet; smoking; obesity (body mass index >31); and regular exercise (either weight-bearing or non-weight-bearing activities) more than twice a week. Four more were excluded after a medical examination because of concurrent breastfeeding, neck and shoulder complaints, and a previous ankle and knee injury, respectively. The remaining 98 women were assigned to either the exercise or the control group according to a computer-generated randomization list (see Figure 1). The study design and protocol have been described in detail in a previous article.¹⁵

Of the 98 women, 84 (39 trainees and 45 controls) completed the 18-month intervention.¹⁵ Five-year follow-up measurements (3.5 y after the end of the intervention) were done for 34 trainees and 31 control participants. At 18-month and 3.5-year follow-up, DXA data on 22 trainees and 22 controls were available for HSA. The clinical baseline characteristics of this sample did not differ from those of the original sample. The 5-year follow-up has been described in detail in a previous article.²⁵

The 18-month progressive high-impact exercise program included a supervised 1-hour training session three times per week. Each workout session consisted of 15 minutes of warm-up, 20 minutes of high-impact training (jumping and step aerobics), 15 minutes of nonimpact and stretching exercises, and 10 minutes of cooling down. The control group was instructed to maintain its normal level of activity.

The study was approved by the Ethics Committee of the UKK Institute. All participants gave their written informed consent before the study.

Bone Structure

The right proximal femur was scanned using a dual-energy X-ray absorptiometry (DXA) device (XR-26, Norland Corp., Fort Atkinson, WI) according to our standard procedures.²⁸ Specifically, section modulus (Z, mm³), an index of a bending resistance; cross-sectional area (CSA, mm²); and subperiosteal width (W, mm) were determined from three adjacent 1.5 mm-thick scan lines representing the narrowest section of the femoral neck and two sections above and below it. The mean of these three sections was used. In vivo precision (coefficient of variation) in our laboratory was 4.5% for Z, 2.7% for CSA, and 2.5% for W.²⁹

Physical Performance

Physical performance was assessed as flight time (index of lower-leg explosive power) in a vertical counter-movement jump test on a contact platform (Newtest Oy,

Figure 1 Trial profile.
HSA = hip structural analysis.

Oulu, Finland). The coefficient of variation (%) for the countermovement jump in our laboratory was 3.9%.³⁰ Cardiorespiratory fitness (estimated maximal oxygen uptake; VO_2max) was assessed by a standardized 2 km walk test.^{31,32}

Over the entire study period, the participants kept an exercise diary with consecutive 7-day forms for type and duration of all physical activities.

Statistical Analysis

Data were examined using SPSS 14.0 (SPSS Inc., Chicago, IL). Means and standard deviations are given as descriptive statistics. Analysis of covariance was used to estimate the between-group differences in bone structure and physical performance at 18 months and 5 years. Baseline values, including height, weight, and age, were

Table 1 Baseline Characteristics of the Exercise and Control Groups

Characteristics	Group; mean (SD)	
	Exercise; <i>n</i> = 22	Control; <i>n</i> = 22
Age, y	39 (2)	38 (2)
Weight, kg	62 (8)	61 (7)
Height, cm	164 (1)	165 (1)
Body mass index, kg/m ²	23 (3)	23 (2)
Calcium intake, mg/d	1,102 (330)	1,102 (300)

used as covariates. The level of statistical significance was set at $\alpha = 0.05$.

RESULTS

At baseline, there were no statistically significant differences between the groups in any of the background characteristics, including diet, other living habits, medication, injuries, diseases, or general physical activity at baseline or during the follow-up period.^{15,25} The amount and types of physical activity reported at post-intervention follow-ups were also similar for both groups, consisting mostly of walking, cycling, and other nonimpact aerobic and low-resistance exercise.

The baseline characteristics of the study groups are shown in Table 1. No major changes in body weight in either group were observed during the study. Mean weight gain in both groups was 0.6 kg at 18-month follow-up. At 5-year follow-up, mean weight gain relative to baseline was 0.4 kg in the training group and 0.2 kg in the control group. No between-group differences in

calcium intake were found during the 18-month intervention. The rate of compliance with training was 83%.

Femoral neck Z, CSA, and W values (means and SDs) at baseline and at 18-month and 3.5-year follow-up, as well as mean between-group differences (95% CIs) at 18-month and 3.5-year follow-up, are given in Table 2. The percentage changes in bone traits are shown in Figure 2. Training effects were seen in Z and CSA but not in W after the 18-month intervention; at 3.5-year follow-up, the exercise-related benefits in femoral neck structure were no longer significant. The adjusted mean between-group differences for femoral neck Z were 3.2% ($p = 0.047$) at 18-month and 2.2% ($p = 0.24$) at 5-year follow-up; for CSA, 2.8% ($p = 0.043$) and 2.6% ($p = 0.09$); and for W, 1.0% ($p = 0.23$) and 0.1% ($p = 0.88$) in favour of the trainees.

Baseline, post-intervention, and 3.5-year follow-up values for physical performance (means and SDs) and between-group differences (95% CIs) are given in Table 2. A significant ($p < 0.05$) group difference in favour of trainees was observed at both 18-month and 5-year follow-up. The percentage changes in physical performance are shown in Figure 3. The percentage differences between the groups in vertical jump flight time were 4.2% ($p = 0.002$) after the 18-month intervention and 5.1% ($p = 0.003$) at the 3.5-year follow-up. The respective differences in VO_2max were 5.6% ($p = 0.002$) and 4.6% ($p = 0.005$).

DISCUSSION

In this study, an 18-month high-impact exercise intervention increased femoral neck strength by improving its structural properties (CSA and Z) in premenopausal

Table 2 Between-Group Differences (Adjusted for Age, Weight and Height) in Bone and Neuromuscular Performance Variables at Baseline, 18-Month Follow-Up, and 5-Year Follow-Up

Variables	Mean (SD)									
	Baseline		Follow-up				Between-group difference at follow-up			
			18 mo		5 y		18 mo		5 y	
	Trainees	Controls	Trainees	Controls	Trainees	Controls	Δ (95% CI)	<i>p</i> -value	Δ (95% CI)	<i>p</i> -value
Bone variables										
Z, mm	1,386 (161)	1,373 (240)	1,443 (170)	1,414 (253)	1,425 (166)	1,398 (222)	47 (1–92)	0.047	30 (–21–82)	0.237
CSA, mm	285 (33)	281 (38)	295 (33)	287 (39)	290 (32)	281 (38)	8 (0–15)	0.043	7 (–1–16)	0.090
W, mm	30.9 (1.7)	30.8 (1.3)	31.0 (1.5)	31.0 (1.6)	31.0 (1.4)	31.0 (1.4)	0.3 (–0.2–0.8)	0.231	0.1 (–0.4–0.5)	0.877
Physical performance										
Vertical jump flight time, ms	447 (39)	449 (36)	484 (31)	469 (39)	465 (37)	448 (45)	20 (8–32)	0.002	23 (8–37)	0.003
VO_2max	36.5 (3.5)	37.9 (2.8)	38.3 (3.5)	37.7 (3.1)	38.3 (3.3)	37.8 (3.8)	2.1 (0.8–3.4)	0.002	1.7 (0.6–2.9)	0.005

Z = bending strength, CSA = cross-sectional area, W = periosteal width; VO_2max = maximal oxygen uptake.

Figure 2 Percentage changes in Z, CSA, and W at the femoral neck after the 18-month intervention and at 3.5-year follow-up. Bars indicate the 95% CIs. Z = section modulus; CSA = cross-section area; W = subperiosteal width.

women. However, these exercise-induced bone benefits seemed to disappear, at least statistically, at 3.5-year follow-up. With respect to physical performance, the training effects continued to be evident at 5-year follow-up, 3.5 years after the end of the exercise intervention.

The results of this study show that the CSA and Z of the femoral neck increased after training, reflecting enhanced structural strength against compressive and bending loading, respectively. As would be expected, the W of the femoral neck remained unchanged.³³ These observations may indicate corticalization of the subcortical

Figure 3 Percentage changes in neuromuscular performance after the 18-month intervention and at 3.5-year follow-up. Bars indicate the 95% CIs. VO₂max = maximal oxygen uptake.

trabecular bone, which shows as thickened cortical bone without any external expansion. Similar observations on the weight-bearing femoral neck were previously found in triple jumpers.³⁴ By contrast, in the non-weight-bearing upper-limb bones, skeletal loading has been shown to be associated with a larger outer diameter of the humerus and radius in tennis players.^{35,36} This finding is also in line with our previous observation of enlarged radii in weightlifters without significant differences in volumetric density compared with control participants; the weightlifters had higher volumetric density at the distal femur and only slightly greater bone size than control participants.³⁷ These site-specific observations clearly indicate that a mechanically reasonable bone structure evolves in relation to the prevailing magnitude and type of incident loading. Thus, it seems that the changes in cortical wall thickness are a major response to exercise loading and are primarily responsible for the increase in bone structural strength.

Notably, the percentage changes in CSA and Z in this study were greater than the changes in femoral neck aBMD (1.3%) reported in our previous study.¹⁵ The aBMD at the lumbar spine, distal femur, patella, proximal tibia, and calcaneus, as well as at the femoral neck, increased significantly more in the training group than in the control group. At the trochanter and distal radius, the aBMD difference was not significant. These results suggest that structural traits of the femoral neck have a

greater capacity to adapt to mechanical loading in adulthood than can be inferred from aBMD, which essentially lumps together all bone structural traits.³⁸ Similar findings have been observed in pre- and early pubertal girls by Petit and colleagues.³⁹ This limited ability of aBMD to reflect structural properties should be recognized when selecting or interpreting outcome variables for exercise intervention studies.

Research results related to the maintenance of exercise-induced benefits in bone structure are somewhat conflicting. It is known, however, that total immobilization or disuse can be deleterious to bone structure and bone mass.⁴⁰ Detraining is also associated with decreased bone mass.^{41–43} However, there is some evidence that previous training history can have at least some permanent benefits on bone in later life,⁴⁴ although some studies of athletes have indicated that positive training effects on bone are gradually lost after cessation of an active athletic career.^{43,45} According to retrospective studies, exercise-induced beneficial effects on bone seem to be maintained for many years and even several decades, at least in early adulthood.^{46–48} In the present HSA study, the statistically significant between-group differences in bone structure declined somewhat and lost their statistical significance 3.5 years after the intervention; however, in our earlier analyses of aBMD values for this group, we reported that the relatively small exercise-induced benefit in femoral neck aBMD continued to be statistically significant 3.5 years after the intervention.²⁵ Although between-group differences in structural traits in this study were not statistically significant at 3.5-year follow-up, there was a positive trend toward maintenance of the high-impact training effects on CSA in the trainee group. It would appear that the loss of statistical significance was attributable to the relatively poor precision in the measurement of structural traits.²⁸ A major future research question, therefore, is what minimum level and type of physical activity is needed for the maintenance of exercise-induced bone benefits.

Although neither the level of physical activity nor the specific exercise that is optimal for promoting bone strength has yet been established, it seems that the high-impact type of loading arising from jumping, or exercises that include high acceleration (high forces) in unusual and varying directions (e.g., playing squash and soccer), may be the most beneficial for increasing bone strength.^{29,49,50} In this study, the training included jumping and step aerobic exercises in which peak force varied from two to six times body weight.¹⁵ It has been suggested that quite a short period of jumping can be enough to strengthen bone, provided that the mechanical stimulus clearly exceeds the individual's normal level of loading;⁵¹ this principle very likely applied to the sedentary women who participated in this exercise intervention study.

Because falls are the strongest independent risk factor for hip fractures,² it is also reasonable to analyze the effects of exercise interventions on risk factors for falling. Disturbed balance and poor muscle strength and power in the legs play an essential role in the propensity to fall.³ In our original study, we showed that high-impact training was beneficial not only for bone but also for neuromuscular performance and aerobic fitness¹⁵ and that exercise-related benefits were maintained for several years after cessation of high-intensity supervised training.²⁵ Obviously, this was also true in this analysis of a subsample of the original study population. The maintenance of physical performance can be explained by the fact that some of the exercise-induced benefits in neuromuscular performance and aerobic fitness can also be maintained with a moderate level of physical activity.⁵²

A major limitation of this study was the rather small number of participants ($N = 44$) available for HSA, which represented only about half of the original study sample. However, the clinical baseline characteristics of this sample did not differ from those of the original sample. With a bigger sample size, the rather wide 95% CIs would have been narrower and the between-group differences in CSA and Z might have reached statistical significance at 3.5-year follow-up, assuming that the present changes were representative of those in the original sample of 98 participants. Another limitation of the study pertains to modelling the three-dimensional femoral neck structure on the basis of data extracted from two-dimensional DXA scans. The HSA, which is based on bone projection image, is sensitive to changes in scanning position of the bone (especially the amount of femoral anteversion), which can lead to misrepresentation of the real dimensions of the femoral neck.⁵³ Moreover, the spatial resolution of the proximal femur DXA scan (pixel size = 1 mm × 1 mm) complicates the correct detection of bone edges and respective dimensions, not only because of its coarseness but also because of the partial volume effect. The latter can affect the aBMD value of the bone-edge pixels and thus compromise the thresholding that is fundamental in detection of bone area. Furthermore, it is also possible that the training effects on bone structure may not occur in the imaged bone projection or in the narrowest section of the femoral neck, in which case the major effects on bone structure would not be captured. Obviously, DXA is not an ideal instrument for the measurement of bone structure; magnetic resonance imaging and quantitative computerized tomography imaging are more appropriate.⁴⁰

CONCLUSION

The most important and promising fall and fracture prevention strategy in physiotherapy is exercise training, and several physiotherapy components have been shown to be efficacious in this respect.³ Within a health care system, physiotherapy plays a crucial role in promoting

exercise and using exercise therapy to improve bone health and prevent fractures. Physiotherapists are therefore best situated to understand and implement exercise in populations from fitness centres to the clinical practice. It can thus be said that physiotherapists are on the front lines of the promotion of exercise advances in health care.

We found that high-impact exercise intervention strengthened the femoral neck in premenopausal women by enhancing its structural properties, but this benefit was no longer visible at 3.5-year follow-up. However, the exercise benefits for physical performance continued to be maintained 3.5 years after the intervention.

KEY MESSAGES

What Is Already Known on This Topic

Regular training has been shown to increase aBMD (g/cm^2) in adults. However, aBMD is only one factor in whole bone strength, and even a small change in the distribution of bone mass can lead to a larger increase in whole bone strength, independent of change in aBMD. To date, information on the effect of exercise on bone strength in adults remains scarce.

What This Study Adds

The results of this study show that high-impact exercise can increase femoral neck strength in premenopausal women by improving its structural properties (CSA and Z). Similar exercise also has a beneficial effect on the muscular power of the lower limbs and on aerobic fitness, and these effects can be maintained by regular physical activity. These findings may be of some value in fracture prevention by indicating how bone structure can be improved, leading in turn to a reduction in certain fall-related risk factors.

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