Journal of Exercise Science & Fitness 23 (2025) 83–89

Contents lists available at ScienceDirect

Journal of Exercise Science & Fitness

journal homepage: www.elsevier.com/locate/jesf

Comparison of trabecular bone microarchitecture between older males with and without a running habit: A cross-sectional study

Chuan Zhang [a,*], Shubo Wang [b], Fanjing Meng [c,d], Dingbo Shu [e], Haizhen Huang [a], Yanjing Zhang [d], Siyu Dai [c,f,**]

[a] School of Physical Education and Sport, Central China Normal University, Wuhan, China
[b] Globus Medical Inc., Audubon, PA, USA
[c] School of Clinical Medicine, Hangzhou Normal University, Hangzhou, China
[d] The Affiliated Hospital of Hangzhou Normal University, Hangzhou, China
[e] Zhejiang University Shaoxing Hospital, Shaoxing, China
[f] Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China

ARTICLE INFO

Keywords:
Running
Trabecular bone morphology
Mechanical loading
Magnetic resonance imaging
Dual-energy X-ray absorptiometry

ABSTRACT

Objectives: Despite its prevalence among seniors, the impact of running on trabecular bone microarchitecture, especially in weight-bearing sites, remains relatively unexplored. This cross-sectional study aimed to investigate the impact of habitual running on bone health, specifically bone mineral density (BMD) and trabecular bone microarchitecture, in male older adults.

Methods: Twenty-five male recreational runners aged between 50 and 75 years old were recruited in this study (RUN; average running experience 7.5 ± 6.0 years, average monthly running volume 217 ± 120 km), and 25 age matched sedentary older males served as controls (CON). Dual-energy X-ray absorptiometry was used to obtain bone mineral density (BMD) measures at whole-body, bilateral proximal femur as well as lumbar spine for all participants. Magnetic resonance imaging was used to obtain trabecular bone microarchitectural parameters at distal femur and distal tibia for all participants.

Results: Findings revealed no significant difference in BMD between groups for all measured sites (all $p > 0.05$; d range 0.013–0.540). However, runners displayed higher bone volume fraction and trabecular thickness at the distal tibia ($p = 0.012$ and 0.001; 95 % CI of MD [-0.030, −0.004] and [-0.013, −0.004]; $d = 0.739$ and 1.034, respectively) and higher trabecular thickness at the distal femur ($p = 0.002$; 95 % CI of MD [-0.010, −0.002]; $d = 0.907$).

Conclusions: This study provides critical insights into the relationship between running and bone health in older adults, suggesting regular recreational running may positively influence trabecular bone microarchitecture, potentially enhancing bone strength and reducing fracture risk. These findings pave the way for future research to develop evidence-based exercise recommendations for an aging population.

1. Introduction

Bone is a dynamic tissue that performs essential physiological functions beyond its structural role. It is a complex and vital tissue that provides structural support, protects vital organs, and enables human movement. Trabecular bone, which is also known as cancellous or spongy bone, is a crucial component of the skeletal network. Trabecular bone is characterized by a network of interlinked trabeculae and is primarily found at the proximal and distal ends of long bones. It plays a pivotal role in regulating mineral homeostasis, blood forming, and withstanding mechanical loads.[1]

As the global demographic shifts towards an aging population, changes in bone health associated with advancing age have gained increased clinical attention in individuals past the fifth decade of life.[2] With advancing age, bone mass and quality naturally decline. This deterioration renders individuals more susceptible to osteoporosis, a condition marked by fragile bones and an increased risk of fractures, particularly in the aging population.[3,4] Importantly, osteoporosis is

* Corresponding author. School of Physical Education and Sport, Central China Normal University, Wuhan, Hubei, China.
** Corresponding author. School of Clinical Medicine, Hangzhou Normal University, Hangzhou, Zhejiang, China.
E-mail addresses: chuanzhang@ccnu.edu.cn (C. Zhang), daisiyu@hznu.edu.cn (S. Dai).

https://doi.org/10.1016/j.jesf.2025.01.002
Received 29 October 2024; Received in revised form 1 January 2025; Accepted 9 January 2025
Available online 10 January 2025

characterized by degenerative changes that occur in both the cortical and trabecular structures of bone.[5,6] Such alterations in bone have been linked to important clinical ramifications, including reduced mobility, increased fracture risks which ultimately translates into diminished quality of life.[7] Given the potential severity of these outcomes, it's crucial to identify and understand the factors influencing bone quality in the aging population, as it may facilitate strategies aiming at enhancing bone and reducing the incidence of fractures in this cohort.

The interplay between mechanical loading and bone properties, including density, strength, and microstructure, has been extensively studied.[8,9] Numerous studies have pointed out the pivotal role of mechanical stimuli in bone adaptation, and suggest that bone exhibit enhanced strength and density when subject to mechanical stress.[9–12] Therefore, weight-bearing exercises, which generate mechanical loading on the bone, have been identified as an important strategy for maintaining and improving bone health.[13] Specific exercises that involve substantial weight-bearing, like resistance training, have consistently demonstrate a favorable impact on bone mass, especially among the aging population. A seminar review by Guadalupe-Grau et al. discussed the significance of exercise in bone health, and suggested resistance exercises can lead to significant improvements in bone. The study also points out that the osteogenic effects of exercise are likely site-specific, with the greatest benefits observed in the loaded bones.[14] These findings are corroborated by another recent review, which indicate that progressive resistance training can concurrently improve muscle strength and bone density in older adults.[15]

However, controversy arises when examining aerobic weight-bearing activities, like running, which impose moderate, recurrent mechanical loads on bone. Some research suggests that running has a beneficial impact on bone health. For example, there is evidence pointing to runners exhibiting a higher bone mineral density (BMD) at specific bone sites relative to their non-running counterparts.[16,17] In contrast, other studies suggest that running does not offer equivalent bone-strengthening advantages as resistance training.[18,19] Furthermore, there are concerns that running may increase the risk of bone stress injury through repetitive loading which leads to bone fatigue.[20] Such concerns is likely more evident for trabecular bone, where the level of connectivity might influence susceptibility to stress injuries.[21]

It has been shown that aging leads to substantial trabecular bone deterioration characterized by prominent trabecular thinning and loss of connectivity, which often precedes cortical bone loss.[22] Additionally, it was pointed out that aging is associated with increased trabecular spacing and a transition from plate-like to rod-like trabeculae, a microarchitectural alteration that weakens the bone's structural integrity.[23] These changes weaken the bone's ability to resist mechanical stress, leading to a significant reduction in bone strength and an increased susceptibility to fractures. However, whether habitual running exercise affects trabecular bone in older adults remains poorly understood, despite its importance. Most existing relevant studies have predominantly examined the impact of running exercise on BMD. Nevertheless, BMD is a measure that might not comprehensively reflect the nuanced changes occurring at the microarchitectural level, which contributes significantly to bone strength and resistance to fracture.[24] This gap in understanding limits our ability to provide comprehensive guidelines for maintaining bone health during aging, especially in the context of the growing population of older adults who regularly engage in running. Therefore, our study aims to compare bone mineral density and analyze trabecular bone microarchitecture in male recreational runners aged over 50. The measurement sites were distal tibia and distal femur, which are weight-bearing sites where osteoporotic fractures are challenge to manage and results in high complication rates.[25,26] We hypothesized that recreational runners will have higher BMD and better trabecular bone microarchitecture compared to their sedentary counterparts.

2. Methods

2.1. Participants

This is a cross-sectional design. A convenient sample of twenty-five male recreational runners (RUN) between 50 and 75 years old were recruited from the Zhejiang University outdoor association. The inclusion criteria were 1) generally in good health, devoid of recognized cardiovascular or musculoskeletal disorders, and without any lower extremity injuries over the past year, 2) regularly participate in long distance running exercise for at least 3 years, 3) actively engage in running exercise twice a week for at least 8 months every year, 4) monthly running volume >100 km, and 5) BMI <30 kg/m^2. Those with professional running experience were excluded. Twenty-five males within the same age range who do not regularly perform physical exercise were also recruited via flyers and word of mouth to serve as control group (CON). The inclusion criteria were 1) generally healthy without known cardiovascular or musculoskeletal diseases, no lower extremity injury for the past year, 2) not having participated in any structured sports or exercise training program in their entire life, and 3) BMI <30 kg/m^2. This study was approved by the Ethics Review Board at Hangzhou Normal University (approval NO. 2021(E2)-KS-085). All participants gave written informed consent. The study was conducted in accordance with the Declaration of Helsinki.

2.2. Dual-energy X-ray absorptiometry (DXA)

A GE DXA scanner (Lunar DPX Prodigy, GE-Lunar Corp., Madison, WI, USA) was used to obtain BMD measures at whole-body (minus the head) as well as spine (L1-L4) in all participants with minimal clothing on and all metallic objects removed. Bilateral proximal femur scans, including femoral neck, Ward's triangle, femoral shaft, and total hip BMD measures were also collected. All scans were performed following daily calibration scan. Scan analysis was carried out according to manufacturer's instructions. The utility and reliability of DXA measured BMD has been extensively demonstrated in literature.[27–29]

2.3. Magnetic resonance imaging (MRI)

MRI scans were carried out using a 1.5 T MR scanner (Magnetom Aera, Siemens Healthcare, Germany), along with a 15-channel knee joint coil. During the scanning procedure, the subjects were positioned supine, entering the bore feet first. For distal femur and distal tibia scans, the scanning area encompassed the distal metaphysis of the bone on the dominant side, situated immediately above the fused growth plate, with the direction of the scan aligned along the bone's axis. The space within the coil was packed with sponge padding to minimize any motion-related artifacts, and the coil was strapped on the scanning bed. A transverse T1 VIBE sequence was implemented (with TR = 20 ms, TE = 4.77 ms, flip angle of 30°, bandwidth = 140 Hz), utilizing a field of view of 12 cm, a slice thickness of 0.5 mm, and a reconstructed image matrix of 512 × 512 (resolution 0.234 mm). A total of 40 slices above the growth plate were collected, and the middle 20 images were processed to obtain trabecular bone microarchitectural parameters.

2.4. Image processing

The acquired MR images were processed to obtain trabecular bone microarchitectural parameters. The region of interest (ROI) of trabecular bone area was first manually contoured using the ImageJ software.[30] Thereafter, a local threshold method proposed by Vasilic et al.[31] was adopted to identify trabecular bone from the segmented MR images. The method calculates bone marrow intensity value for each voxel based on nearest-neighbor statistics. In brief, a Laplacian kernel was first applied to the image. For each voxel (i,j) that has an intensity value of $I_{i,j}$ and Laplacian value of $L_{i,j}$, its neighbors are voxels within a disc (D)

defined by its diameter ($d = 15$ voxels). The conditional probability $p_D(L|I)$ was then determined within the neighborhood and average Laplacian values $\overline{L}_D(I)$ were calculated for each pixel intensity. The pixel intensity of bone marrow I_m was then determined using the condition $\overline{L}_D(I_m) = 0$. Trabecular bone segmentation was obtained using the local thresholds of each pixel ($I_{bone} < I_m$) and used to calculate bone volume fraction (BV/TV). Trabecular thickness (Tb.Th) was then calculated using local thickness algorithm (PoreSpy[32]). Trabecular separation (Tb. Sp) was quantified similarly using bone marrow segmentation. Trabecular number (Tb.N) was calculated as Tb.N = BV/TV/Tb.Th. The utility and reliability of using MRI to measure trabecular bone microarchitecture has been demonstrated in literature.[33,34] In our lab, the reproducibility (coefficient of variation) of BV/TV, Tb.N, Tb.Th, and Tb. Sp assessment in the distal femur and distal tibia using MRI, obtained 2–7 days apart, is 1–4%. A visual example of imaging processing is presented in Fig. 1.

2.5. Statistical analyses

Sample size estimation was carried out using G*power 3.1.9 software.[35] Using independent *t*-test and an estimated large effect size of 0.8, given an alpha level of 0.05 and power (1 – β) of 0.8, it was estimated that 21 participants are required for each group. Data were analyzed using SPSS 27.0 software (IBM Corp., Armonk, NY, USA). The distribution of data was determined using the Shapiro-Wilk method. For data that followed normal distribution, independent *t*-test was used to determine whether between groups difference exists. For data that do not follow normal distribution, Mann-Whitney nonparametric test was used to compare group differences. Significance level was set at $p < 0.05$. Cohen's d was calculated to determine effect size when applicable, with 0.2, 0.5 and 0.8 representing small, medium and large effects.

3. Results

Physical characteristics for all participants are summarized in Table 1. The RUN group and CON group had similar age, height, weight, and BMI (all $p > 0.05$). On average, the RUN group had 7.5 years of running experience, and average running volume was 217 km per month. Despite the similar basic physical characteristics, CON group had higher body fat percentage (23.3 ± 5.7 vs. 19.4 ± 6.1, p = 0.022; 95 % CI of MD [0.598, 7.331]; d = 0.661), as well as higher Android (36.0 ± 7.8 vs. 30.0 ± 9.5, p = 0.016; 95 % CI of MD [1.023, 10.900]; d = 0.690) and Gynoid fat percentage (24.4 ± 5.0 vs. 21.8 ± 8.3, p = 0.034; 95 % CI of MD [−1.292, 6.462]; d = 0.379).

The results of the Shapiro-Wilk tests suggest that all DXA measured BMD measures followed normal distribution (all $p > 0.05$). RUN and CON groups had similar whole-body BMD (p = 0.062; 95 % CI of MD [−0.107, 0.003]; d = 0.540) as well as lumbar spine BMD (p = 0.696; 95 % CI of MD [−0.122, 0.082]; d = 0.111). No between groups differences were found for the femoral neck, Ward's triangle, Trochanter, femoral shaft, and total BMD for the proximal femur at both dominant leg (p range 0.098–0.539; d range 0.013–0.491) as well as the non-dominant leg (p range 0.097–0.915; d range 0.003–0.479). Specific information regarding between groups comparisons can be found on Table 2.

Table 1
Physical characteristics for all participants. RUN, runner group; CON, control group. Abs t, absolute t value for the independent *t*-test. 95 % CI of MD, 95 % confidence interval for the mean difference.

	RUN (n = 25)	CON (n = 25)	p	d	Abs t	95 % CI of MD
Age (y)	56.5 ± 7.4	58.2 ± 6.2	0.390	0.245	0.868	[-2.214, 5.574]
Height (cm)	171.8 ± 4.6	169.9 ± 4.6	0.146	0.418	1.476	[-4.535, 0.695]
Body mass (kg)	69.0 ± 9.1	70.9 ± 8.4	0.441	0.220	0.776	[-3.054, 6.894]
BMI (kg/m^2)	23.3 ± 2.4	24.5 ± 2.4	0.085	0.498	1.760	[-0.172, 2.588]
Running experience (y)	7.5 ± 6.0	/				
Monthly running volume (km)	217 ± 120	/				

For trabecular bone microarchitectural assessments, BV/TV, Tb.Sp, Tb.N for the distal femur, and Tb.Th for the distal tibia didn't follow normal distribution (all $p < 0.05$), and the results for Mann-Whitney U tests are presented. RUN group had higher BV/TV as well as Tb.Th at the distal tibia (p = 0.012 and 0.001; 95 % CI of MD [−0.030, −0.004] and [−0.013, −0.004]; d = 0.739 and 1.034, respectively, Fig. 2). Tb.Sp and Th.N were similar between groups at this site (p = 0.208 and 0.187; 95 % CI of MD [−0.010, 0.044] and [−0.065, 0.013]; d = 0.361 and 0.378, respectively; Table 3). RUN group also had higher Tb.Th at the distal femur (p = 0.002; 95 % CI of MD [−0.010, −0.002]; d = 0.907, Fig. 3). No between groups difference was detected for other trabecular bone parameters at the distal femur (p range 0.304–0.938; d range 0.174–0.242). The results for comparisons, including 95 % CI of the mean differences, are presented in Table 3.

4. Discussion

The implications of chronic running exercise on bone health remain poorly understood, partly due to the lack of relevant studies on this topic. In the current investigation, we compared BMD and trabecular bone microarchitecture among recreational runners and individuals not engaged in running, all exceeding the age of 50 years. Notably, the data showed no significant differences in whole-body or site-specific BMD between the groups. However, the runners demonstrated higher BV/TV and Tb.Th at the distal tibia, suggesting enhanced structural integrity and potentially better mechanical resistance. Similarly, an elevated Tb. Th was identified in the distal femur of the runners, further supporting the notion of an improved bone microarchitecture.

The results from our study indicated no differences in BMD between runners and non-runners. This finding appears counterintuitive, given the well-established correlation between regular physical activity and enhanced BMD.[36] This is also in contradiction with previous research.[16]

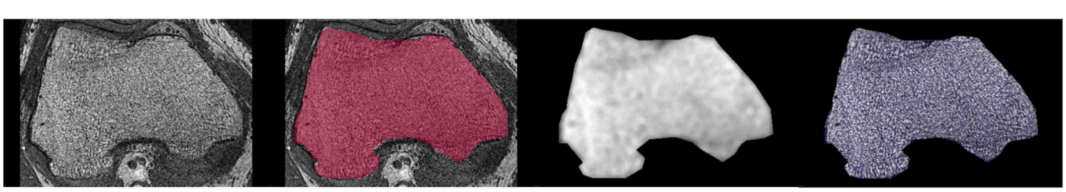

Fig. 1. Visual example of the MR images for trabecular bone assessment. A) raw MR image for trabecular bone assessment; B) manually traced region of interest (in red); C) local threshold effects; D) binarized image with trabecular bone painted blue.

Table 2
Bone mineral density (g/cm^2) measurements for all participants at the whole-body, lumbar spine and bilateral hips. RUN, runner group; CON, control group. Abs t, absolute t value for the independent *t*-test. 95 % CI of MD, 95 % confidence interval for the mean difference.

	RUN (n = 25)	CON (n = 25)	p	d	Abs t	95 % CI of MD
Whole-body	1.21 ± 0.10	1.16 ± 0.09	0.062	0.540	1.908	[-0.107, 0.003]
Lumbar spine	1.17 ± 0.21	1.15 ± 0.15	0.696	0.111	0.393	[-0.122, 0.082]
Dominant hip						
Femoral neck	0.99 ± 0.13	0.93 ± 0.12	0.089	0.491	1.735	[-0.132, 0.010]
Ward's triangle	0.72 ± 0.19	0.72 ± 0.11	0.920	0.029	0.101	[-0.093, 0.084]
Trochanter	0.83 ± 0.14	0.82 ± 0.12	0.819	0.065	0.230	[-0.081, 0.065]
Femoral shaft	1.21 ± 0.16	1.17 ± 0.15	0.319	0.245	0.866	[-0.125, 0.050]
Total hip	1.03 ± 0.14	1.00 ± 0.12	0.396	0.242	0.856	[-0.106, 0.043]
Non-dominant hip						
Femoral neck	0.98 ± 0.13	0.93 ± 0.11	0.097	0.479	1.695	[-0.126, 0.011]
Ward's triangle	0.73 ± 0.15	0.70 ± 0.11	0.452	0.214	0.758	[-0.102, 0.046]
Trochanter	0.81 ± 0.13	0.82 ± 0.11	0.915	0.030	0.107	[-0.064, 0.071]
Femoral shaft	1.21 ± 0.17	1.16 ± 0.13	0.303	0.295	1.041	[-0.132, 0.042]
Total hip	1.02 ± 0.14	0.99 ± 0.11	0.447	0.217	0.766	[-0.100, 0.045]

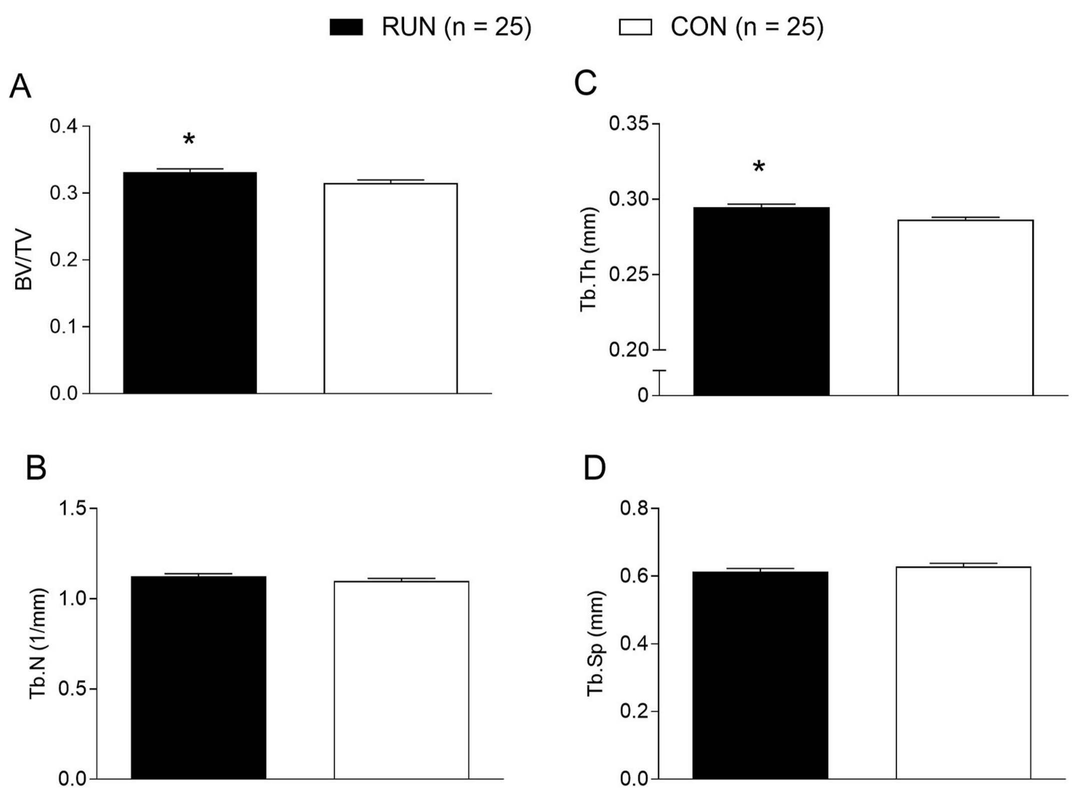

Fig. 2. Trabecular bone microarchitectural parameters comparison at the distal tibia for runner group (RUN) compared to control group (CON). BV/TV, bone volume fraction (A); Tb.N trabecular bone number (B); Tb,Th, trabecular bone thickness (C); Tb.Sp, trabecular bone separation (D). *Significant between groups difference.

A plausible explanation for our findings may lie in the nature of bone's adaptive response to mechanical loading. The process of osteogenesis is predominantly activated by dynamic rather than consistent static loads.[37] Optimal bone adaptation to mechanical stress requires variability in loading, rather than repetitive uniform stress.[38] Thus, it can be inferred that even though running exerts substantial mechanical impact, the consistent nature of the loading might not precipitate significant augmentations in BMD within the assessed regions. Additionally, it should be acknowledged that the lack of enhanced enhancement of BMD in runners may be partly attributed to the frequency and intensity of running. Previous studies suggest that high-impact exercise performed with greater frequency and intensities yielded the more pronounced improvement in BMD.[39–41] Given that the participants included in the current study were recreational runners, it's possible that they generally engage in moderate running frequencies and intensities, which may not be sufficient to stimulate significant osteogenic responses in the regions assessed by DXA.[10,38] These findings suggest that both frequency and intensity are critical factors, which could contribute to the absence of notable variations in BMD. Moreover, the influence of running on BMD could be modulated by other determinants, including dietary practices, hormonal equilibrium, and genetic predispositions.[38,42] For instance, in aged males, a progressive decline in testosterone levels might adversely influence BMD, possibly counteracting the osteogenic advantages conferred by running.[43] On the other hand, the characteristics of the control participants may also influence the results. We excluded those who had exercise training experience; however, the specific nature of the participants' jobs daily routine (e.g. time on the screen, daily working time, sitting or standing at work) could also impact bone status

Table 3
Trabecular bone microarchitecture measures for all participants at the distal femur and distal tibia. CON, control group. Statistics, t value for independent *t*-test, or z value for Mann-Whitney *U* test. 95 % CI of MD, 95 % confidence interval for the mean difference. BV/TV, bone volume fraction; Tb.N trabecular bone number; Tb,Th, trabecular bone thickness; Tb.Sp, trabecular bone separation.

	RUN (n = 25)	CON (n = 25)	p	d	Statistics	95 % CI of MD
Distal tibia						
BV/TV	0.332 ± 0.024	0.315 ± 0.022	0.012*	0.739	2.613	[-0.030, −0.004]
Tb.Th (mm)	0.295 ± 0.009	0.287 ± 0.007	0.001*	1.034	3.308	[-0.013, −0.004]
Tb.Sp (mm)	0.611 ± 0.043	0.063 ± 0.051	0.208	0.361	1.276	[-0.010, 0.044]
Th.N (1/mm)	1.126 ± 0.069	1.100 ± 0.068	0.187	0.378	1.337	[-0.065, 0.013]
Distal femur						
BV/TV	0.327 ± 0.023	0.323 ± 0.020	0.304	0.196	1.028	[-0.016, 0.008]
Tb.Th (mm)	0.293 ± 0.007	0.287 ± 0.007	0.002*	0.907	3.207	[-0.010, −0.002]
Tb.Sp (mm)	0.587 ± 0.045	0.577 ± 0.037	0.614	0.242	0.504	[-0.034, 0.014]
Th.N (1/mm)	1.114 ± 0.061	1.124 ± 0.053	0.938	0.174	0.078	[-0.023, 0.042]

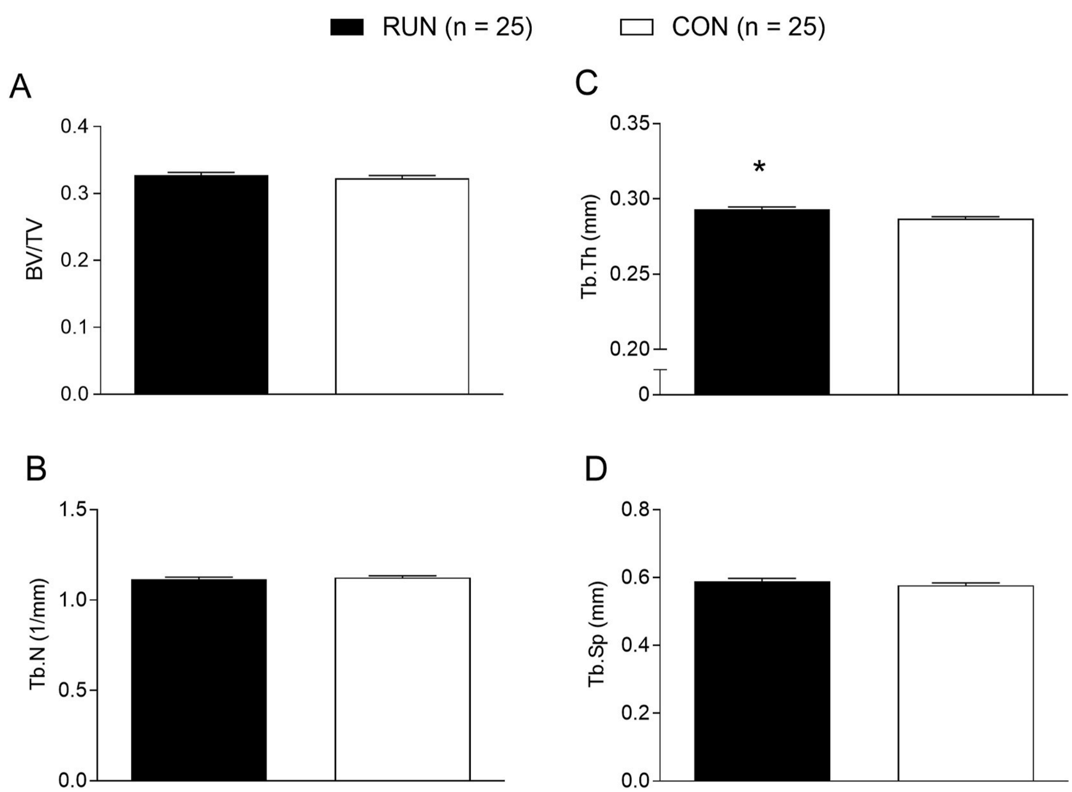

Fig. 3. Trabecular bone microarchitectural parameters comparison at the distal femur for runner group (RUN) compared to control group (CON). BV/TV, bone volume fraction (A); Tb.N trabecular bone number (B); Tb,Th, trabecular bone thickness (C); Tb.Sp, trabecular bone separation (D). *Significant between groups difference.

of the participants in the control group, thus contribute to the observed lack of differences in BMD. Future studies should consider these variables in greater detail to provide a more comprehensive understanding of the relationship between running and BMD.

A key finding of this study was the observed differences in trabecular bone microarchitecture at the distal tibia and femur. Despite no changes in global BMD, the higher BV/TV and Tb.Th in runners indicate a more robust trabecular structure, which suggests increased resistance to fracture that is not reflected by BMD. It is believed that trabecular bone, due to its larger surface area to volume ratio compared to cortical bone,[44] may be more sensitive to mechanical loading.[45,46] Consequently, the repeated loading imposed by running could have triggered an adaptive response, leading to denser and thicker trabeculae in these specific sites. These localized changes highlight the regional specificity of bone's response to low level repetitive loading, an aspect which is often overlooked when only BMD is considered. Our findings underscore the potential of running as a means of improving bone microarchitecture in aging males, even in the absence of significant BMD changes. Enhanced trabecular bone microarchitecture can confer increased resistance against bone fractures, which is especially crucial in this demographic due to the increased risk of osteoporosis and related fractures. However, it should also be noted that the cross-sectional nature of the current study prevents the inference of causality, and more carefully designed longitudinal studies are needed to determine the long-term effects of running on trabecular bone microarchitecture and its potential for preventing osteoporosis and fractures.

Our findings suggest that running, a repetitive weight-bearing exercise, may provide advantages beyond BMD detectable by DXA, which is traditionally used to assess bone health. Although running did not confer a measurable advantage in terms of BMD, it does appear to influence the bone's microstructure in locations subjected to the repetitive impact nature of the sport, a finding of particular importance for this demographic. This suggests that a singular focus on BMD might limit our understanding and management of bone health, particularly when interventions like running seem to influence other important aspects of bone health.

There are practical implications of our study. Our results add additional understanding to the current knowledge regarding the impact of exercise on bone health, and they also highlighted the complex relationship between repetitive aerobic exercise such as running and bone health in older adults. It should be noted that although running appears to be beneficial for the trabecular bone microarchitecture, this does not imply that running is a comprehensive solution for preventing osteoporosis and related fractures in aging males, as it does not lead to noticeable BMD changes. Furthermore, excessive running can lead to overuse injuries and potentially have a negative impact on bone health.[47] Those who wish to practice running exercise as a strategy to combat osteoporosis should weigh in the benefits and risks associated with this particular sport. On the other hand, when comparing the effects of aerobic exercise to resistance training, the general consensus is that resistance training has more significant and consistent effects on BMD.[48] This necessitates the need for a diversified and balanced exercise regimen for optimizing bone health in older adults. An exercise plan that incorporates both resistance and aerobic exercises could potentially yield an optimal benefit for bone health, which requires further examination. Additionally, our study also demonstrated the importance of incorporating advanced imaging techniques like MRI to provide a more comprehensive assessment of bone quality beyond the traditional BMD measures, which could help guide personalized exercise prescription targeting bone health in older adults in the future.

The present study has certain limitations that warrant discussion. First and foremost, the analysis of the current study was based on a cross-sectional comparison and hence not able to establish causality. Future longitudinal investigations should explicitly elucidate the implications of sustained running exercises on bone health in the elderly. The second limitation is the small sample size included in the current study, which may inflate type 2 error. As such, this study should be viewed as a pilot study for future larger scale, well-designed intervention or longitudinal observation studies aiming at examining the impact of running exercise on bone health in older adults. Third, the participants in this research were males aged above 50 years. Consequently, the results may not be generalized to other demographic groups, especially females, younger cohorts, or those with varied physical activity patterns. The absence of female participants hampers our grasp on gender-specific differences in the effects of running on bone health, given the distinct running biomechanics they exhibit in comparison to their male counterparts.[49] This area warrants further investigation. Fourth, it is important to note that other potential determinants, such as nutritional intake, pre-existing health conditions, or genetic predispositions,[38,42] were not integrated into this study but could significantly influence bone health. It is recommended that ensuing studies incorporate these variables for an enriched comprehension of bone health dynamics in aging groups.

5. Conclusions

In conclusion, our study revealed that while recreational long-distance running does not influence traditional BMD measurements in males aged over 50, it appears to beneficially impact the microarchitecture of trabecular bone in this population. Our findings suggest that habitual running exercise is beneficial in the maintenance of bone microarchitecture health in aging populations.

Author contributions

CZ: Conceptualization, Methodology, supervision, investigation, funding acquisition, Writing- Original draft preparation. SW: software, validation, data curation, formal analysis. FM: investigation, data curation, methodology. DS: investigation, methodology. HH: data curation, formal analysis. YZ: methodology, formal analysis. SD: Conceptualization, Methodology, supervision, funding acquisition, writing - review & editing.

Ethical statement

This study was approved by the Ethics Review Board at Hangzhou Normal University (approval NO. 2021(E2)-KS-085). All participants gave written informed consent. The study was conducted in accordance with the Declaration of Helsinki.

Funding statement

This study was supported by the National Natural Science Foundation of China (NO.82301791), the Self-determined Research Funds of CCNU from the colleges' basic research and operation of MOE (Grant CCNU24JC040), the Hangzhou Normal University faculty startup grant (NO. 8015C50221204117), and the Central China Normal University (Grant NO. 31101222041).

Declaration of interest statement

The authors declare no conflict of interest.

References

1. Park Y, Cheong E, Kwak JG, Carpenter R, Shim JH, Lee J. Trabecular bone organoid model for studying the regulation of localized bone remodeling. *Sci Adv*. 2021;7(4).
2. Looker AC, Sarafrazi Isfahani N, Fan B, Shepherd JA. Trends in osteoporosis and low bone mass in older US adults, 2005–2006 through 2013–2014. *Osteoporos Int*. 2017;28:1979–1988.
3. Chan GK, Duque G. Age-related bone loss: old bone, new facts. *Gerontology*. 2002;48(2):62–71.
4. Sfeir JG, Drake MT, Khosla S, Farr JN. Skeletal aging. *Mayo Clin Proc*. 2022;97(6):1194–1208.
5. Faibish D, Ott SM, Boskey AL. Mineral changes in osteoporosis: a review. *Clin Orthop Relat Res*. 2006;443:28.
6. Frank M, Reisinger AG, Pahr DH, Thurner PJ. Effects of osteoporosis on bone morphometry and material properties of individual human trabeculae in the femoral head. *JBMR Plus*. 2021;5(6).
7. Kirk B, Phu S, Brennan-Olsen SL, Bani Hassan E, Duque G. Associations between osteoporosis, the severity of sarcopenia and fragility fractures in community-dwelling older adults. *Eur Geriatr Med*. 2020;11(3):443–450.
8. Mellon SJ, Tanner KE. Bone and its adaptation to mechanical loading: a review. *Int Mater Rev*. 2012;57(5):235–255.
9. Wang LJ, You XL, Zhang LL, Zhang CQ, Zou WG. Mechanical regulation of bone remodeling. *Bone Res*. 2022;10(1).
10. Frost HM. Bone's mechanostat: a 2003 update. *Anat Rec A Discov Mol Cell Evol Biol*. 2003;275(2):1081–1101.
11. Turner CH, Pavalko FM. Mechanotransduction and functional response of the skeleton to physical stress: the mechanisms and mechanics of bone adaptation. *J Orthop Sci*. 1998;3(6):346–355.
12. Carina V, Della Bella E, Costa V, et al. Bone's response to mechanical loading in aging and osteoporosis: molecular mechanisms. *Calcif Tissue Int*. 2020;107(4):301–318.
13. Beck BR, Daly RM, Singh MA, Taaffe DR. Exercise and Sports Science Australia (ESSA) position statement on exercise prescription for the prevention and management of osteoporosis. *J Sci Med Sport*. 2017;20(5):438–445.
14. Guadalupe-Grau A, Fuentes T, Guerra B, Calbet JA. Exercise and bone mass in adults. *Sports Med*. 2009;39(6):439–468.
15. O'Bryan SJ, Giuliano C, Woessner MN, et al. Progressive resistance training for concomitant increases in muscle strength and bone mineral density in older adults: a systematic review and meta-analysis. *Sports Med*. 2022;52(8):1939–1960.
16. MacKelvie KJ, Taunton JE, McKay HA, Khan KM. Bone mineral density and serum testosterone in chronically trained, high mileage 40-55 year old male runners. *Br J Sports Med*. 2000;34(4):273–278.
17. Infantino NA, McCormack WP, Almstedt HC. Bone mineral density and hip structure changes over one-year in collegiate distance runners and non-athlete controls. *BoneKEy Rep*. 2021;14.
18. Hetland ML, Haarbo J, Christiansen C. Low bone mass and high bone turnover in male long distance runners. *J Clin Endocrinol Metab*. 1993;77(3):770–775.
19. Lee JH. The effect of long-distance running on bone strength and bone biochemical markers. *Journal of Exercise Rehabilitation*. 2019;15(1):26–30.

20. Boudenot A, Achiou Z, Portier H. Does running strengthen bone? *Appl Physiol Nutr Metabol*. 2015;40(12):1309–1312.
21. Kiuru MJ, Pihlajamaki HK, Ahovuo JA. Bone stress injuries. *Acta Radiol*. 2004;45(3): 317–326.
22. Chen H, Zhou X, Fujita H, Onozuka M, Kubo KY. Age-related changes in trabecular and cortical bone microstructure. *Internet J Endocrinol*. 2013;2013, 213234.
23. Fields AJ, Keaveny TM. Trabecular architecture and vertebral fragility in osteoporosis. *Curr Osteoporos Rep*. 2012;10(2):132–140.
24. Hans D, Goertzen AL, Krieg MA, Leslie WD. Bone microarchitecture assessed by TBS predicts osteoporotic fractures independent of bone density: the Manitoba study. *J Bone Miner Res*. 2011;26(11):2762–2769.
25. Nauth A, Haller J, Augat P, et al. Distal femur fractures: basic science and international perspectives. *OTA International*. 2024;7(2 suppl l), e320.
26. Joveniaux P, Ohl X, Harisboure A, et al. Distal tibia fractures: management and complications of 101 cases. *Int Orthop*. 2010;34(4):583–588.
27. El Maghraoui A, Zounon AAD, Jroundi I, et al. Reproducibility of bone mineral density measurements using dual X-ray absorptiometry in daily clinical practice. *Osteoporos Int*. 2005;16(12):1742–1748.
28. Lodder MC, Lems WF, Ader HJ, et al. Reproducibility of bone mineral density measurement in daily practice. *Ann Rheum Dis*. 2004;63(3):285–289.
29. Forsen L, Berntsen GK, Meyer HE, Tell GS, Fonnebo V, Group NCR. Differences in precision in bone mineral density measured by SXA and DXA: the NOREPOS study. *Eur J Epidemiol*. 2008;23(9):615–624.
30. Schneider CA, Rasband WS, Eliceiri KW. NIH Image to ImageJ: 25 years of image analysis. *Nat Methods*. 2012;9(7):671–675.
31. Vasilic B, Wehrli FW. A novel local thresholding algorithm for trabecular bone volume fraction mapping in the limited spatial resolution regime of in vivo MRI. *IEEE Trans Med Imag*. 2005;24(12):1574–1585.
32. Gostick JT, Khan ZA, Tranter TG, et al. PoreSpy: a python toolkit for quantitative analysis of porous media images. *J Open Source Softw*. 2019;4(37):1296.
33. Modlesky CM, Subramanian P, Miller F. Underdeveloped trabecular bone microarchitecture is detected in children with cerebral palsy using high-resolution magnetic resonance imaging. *Osteoporos Int*. 2008;19(2):169–176.
34. Li W, Wang W, Zhang M, Chen Q, Li S. Associations of marrow fat fraction with MR imaging based trabecular bone microarchitecture in first-time diagnosed type 1 diabetes mellitus. *Front Endocrinol*. 2024;15, 1287591.
35. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39(2):175–191.
36. Chastin SF, Mandrichenko O, Helbostadt J, Skelton DA. Associations between objectively-measured sedentary behaviour and physical activity with bone mineral density in adults and older adults, the NHANES study. *Bone*. 2014;64:254–262.
37. Lanyon LE, Rubin CT. Static vs dynamic loads as an influence on bone remodelling. *J Biomech*. 1984;17(12):897–905.
38. Borer KT. Physical activity in the prevention and amelioration of osteoporosis in women : interaction of mechanical, hormonal and dietary factors. *Sports Med*. 2005; 35(9):779–830.
39. Bailey CA, Brooke-Wavell K. Optimum frequency of exercise for bone health: randomised controlled trial of a high-impact unilateral intervention. *Bone*. 2010;46 (4):1043–1049.
40. Kistler-Fischbacher M, Weeks BK, Beck BR. The effect of exercise intensity on bone in postmenopausal women (part 1): a systematic review. *Bone*. 2021;143, 115696.
41. Kistler-Fischbacher M, Weeks BK, Beck BR. The effect of exercise intensity on bone in postmenopausal women (part 2): a meta-analysis. *Bone*. 2021;143, 115697.
42. Herbert AJ, Williams AG, Lockey SJ, et al. Bone mineral density in high-level endurance runners: Part B-genotype-dependent characteristics. *Eur J Appl Physiol*. 2022;122(1):71–80.
43. Shigehara K, Izumi K, Kadono Y, Mizokami A. Testosterone and bone health in men: a narrative review. *J Clin Med*. 2021;10(3).
44. Ott SM. Cortical or trabecular bone: what's the difference? *Am J Nephrol*. 2018;47 (6):373–375.
45. Rubin C, Turner A, Mallinckrodt C, Jerome C, McLeod K, Bain S. Mechanical strain, induced noninvasively in the high-frequency domain, is anabolic to cancellous bone, but not cortical bone. *Bone*. 2002;30(3):445–452.
46. Barak MM. Cortical and trabecular bone modeling and implications for bone functional adaptation in the mammalian tibia. *Bioengineering (Basel)*. 2024;11(5).
47. Edwards WB, Taylor D, Rudolphi TJ, Gillette JC, Derrick TR. Effects of stride length and running mileage on a probabilistic stress fracture model. *Med Sci Sports Exerc*. 2009;41(12):2177–2184.
48. Mohammad Rahimi GR, Smart NA, Liang MT, et al. The impact of different modes of exercise training on bone mineral density in older postmenopausal women: a systematic review and meta-analysis research. *Calcif Tissue Int*. 2020;106:577–590.
49. Xie P-P, István B, Liang M. Sex-specific differences in biomechanics among runners: a systematic review with meta-analysis. *Front Physiol*. 2022;13, 994076.