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Association of Radiograph-Derived Femoral Neck Fractal Dimension With Bone Mineral Density in Postmenopausal Women

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ABSTRACT

Bone mineral density (BMD) is central to osteoporosis diagnosis but incompletely reflects bone microarchitecture, a key determinant of fracture risk. Fractal analysis of radiographs has been proposed as a low-cost way to characterize trabecular structure, but its relationship with densitometric measures remains uncertain. This study investigated the association between femoral neck fractal dimension (FD) derived from pelvic radiographs and DXA-derived BMD and T-scores in postmenopausal women. This retrospective, cross-sectional study included postmenopausal women who underwent anteroposterior pelvis radiography and DXA within the same year. FD was computed from a standardized femoral neck region of interest using the box-counting method. DXA outcomes were BMD and T-scores at the lumbar spine, femoral neck, and total hip. Associations were evaluated using Spearman correlation and univariable linear regression. A total of 152 women were included; mean femoral neck FD was 1.297 ± 0.083. FD showed no meaningful correlation with DXA-derived measurements (Spearman ρ range, -0.004 to 0.122; all $p > 0.05$; largest at total hip T-score, $\rho=0.122$, $p=0.134$). In univariable regression, FD was not associated with any densitometric endpoint (all $p > 0.05$), with negligible model fit (R^2 range, 0.000–0.010). Radiograph-derived femoral neck FD was not associated with DXA BMD or T-scores and provided essentially no explanatory or predictive value for densitometric outcomes. These findings argue against its use as a surrogate for DXA and support the need for standardized methods with prospective outcome validation.

Keywords: Postmenopausal osteoporosis, Bone mineral density, Fractal analysis, Fractal dimension, Femoral neck.

INTRODUCTION

Osteoporosis is a systemic skeletal disease characterized by reduced bone mineral density (BMD), deterioration of bone microarchitecture, and a consequent increase in fracture risk[1]. Bone loss accelerates markedly after menopause due to estrogen deficiency, rendering postmenopausal women a particularly vulnerable population for osteoporotic fractures[2]. Given the high morbidity, mortality, and healthcare costs associated with fragility fractures, early identification of individuals at increased fracture risk remains a major objective in osteoporosis management[3].

Dual-energy X-ray absorptiometry (DXA) is the gold standard for measuring BMD and diagnosing osteoporosis currently[4]. Despite its well-established utility, DXA has notable limitations. DXA provides a two-dimensional areal measurement of BMD and does not directly capture bone microarchitecture which is a key determinant of bone strength[5,6]. Aside from that, the device cost and restricted accessibility result in its low rate in the population-based screening[7,8]. Notably, a substantial proportion of fragility fractures occur in individuals without densitometric osteoporosis thereby indicating that BMD alone is not adequate to determine skeletal competency[9].

Because trabecular bone plays a major role in mechanical stiffness and fracture resistance, direct assessment of its microarchitecture is limited by the need for invasive or high-cost imaging techniques[10-12]. Therefore, considerable research efforts have focused on developing alternative approaches to indirectly assess trabecular structure using conventional imaging. The application of texture-based analysis on plain radiographs is a recent development and has emerged as a highly efficient, mainly non-invasive approach for indirectly characterizing trabecular structure[13]. Among these methods, fractal analysis (FA) has gained increasing attention as a mathematical technique capable of quantifying the geometric complexity and self-similar patterns of trabecular bone visible on standard radiographs. The fractal dimension (FD) derived from this analysis provides a single numerical descriptor reflecting trabecular organization and connectivity[14]. Experimental and clinical imaging studies suggest that higher FD values may reflect more complex and better-connected trabecular networks with greater mechanical competence, whereas lower FD values are associated with microarchitectural degradation and reduced bone strength[15].

Fractal mathematics are particularly well suited for analyzing biological structures such as trabecular bone, which exhibit complex, irregular patterns across multiple spatial scales. Gray-level radiographic images can be effectively evaluated using fractal models based on fractional Gaussian noise and fractional Brownian motion, approaches that have been successfully applied to the assessment of trabecular texture in skeletal radiographs, including those of the calcaneus[16]. These findings support the potential of FA as a low-cost, image-derived surrogate marker of bone microarchitecture.

Against this background, the present study aimed to compare femoral neck FA derived from pelvis radiographs obtained within the same year with DXA measurements in postmenopausal women. Specifically, we sought to investigate the relationship between FD values and DXA-derived BMD and T-scores, and to evaluate whether FA performed on routinely acquired pelvic radiographs could meaningfully predict osteoporosis status.

MATERIALS AND METHODS

Study Design and Ethics

This single-center, cross-sectional study was carried out at the Izzet Baysal Physical Medicine and Rehabilitation Training and Research Hospital. Medical records of patients evaluated between January 1, 2023 and June 1, 2025 were retrospectively reviewed. The study adhered to the principles detailed in the Declaration of Helsinki and received approval from the Institutional Review Board of Abant Izzet Baysal University.

Participants and Data Source

Data of postmenopausal female patients who underwent both pelvis radiography and DXA measurements within the same year were retrieved from the hospital's Picture Archiving and Communication System (PACS). Only postmenopausal women without bone disorders other than age-related osteoporosis were included. The sample size was determined by the number of eligible patients available in the archive. Assuming a moderate effect size (Cohen's d = 0.5), a minimum sample size of 150 patients was targeted to achieve 80% statistical power at a 5% significance level.

Inclusion and Exclusion Criteria

Inclusion criteria were: (1) postmenopausal status, (2) availability of both pelvis anteroposterior (AP) radiography and DXA data obtained within the same calendar year, (3) age 45 years or older, and (4) pelvis AP radiographs with sufficient image quality to allow evaluation of hip morphology. Exclusion criteria included: (1) history of previous hip arthroplasty surgery, (2) history of trauma, tumor, or infection involving the hip region, (3) radiographs with inadequate image quality for analysis, (4) presence of systemic bone diseases (e.g., Paget's disease, osteomalacia), and (5) diagnosis of inflammatory arthritis.

Data Collection

Demographic data (age, height, weight) and clinical information (comorbidities, medication use, and fracture history) were recorded from the hospital information system. AP radiographs were evaluated using the FA method with the ImageJ software (National Institutes of Health, MD, USA). Trabecular bone characteristics of the femoral neck were assessed using digitally defined regions of interest (ROI).

DXA was utilized to assess BMD, with results expressed as T-scores. In line with World Health Organization (WHO) guidelines, patients were categorized based on the lowest T-score measured at either the lumbar spine (L1-L4), femoral neck, or total femur. Osteopenia was defined as a T-score between -1.0 and -2.5 standard deviations (SD), and osteoporosis as a T-score of ≤ -2.5 SD[17].

Evaluation of the Images

FA was performed on pelvis radiographs with dimensions of 1667 × 957 pixels using the ImageJ software based on White and Rudolph's box-counting method. A 40 × 40 pixel ROI was selected on the left femoral neck (Figure 1).

Fig. 1 — Selection of the region of interest (ROI) on the left femoral neck.

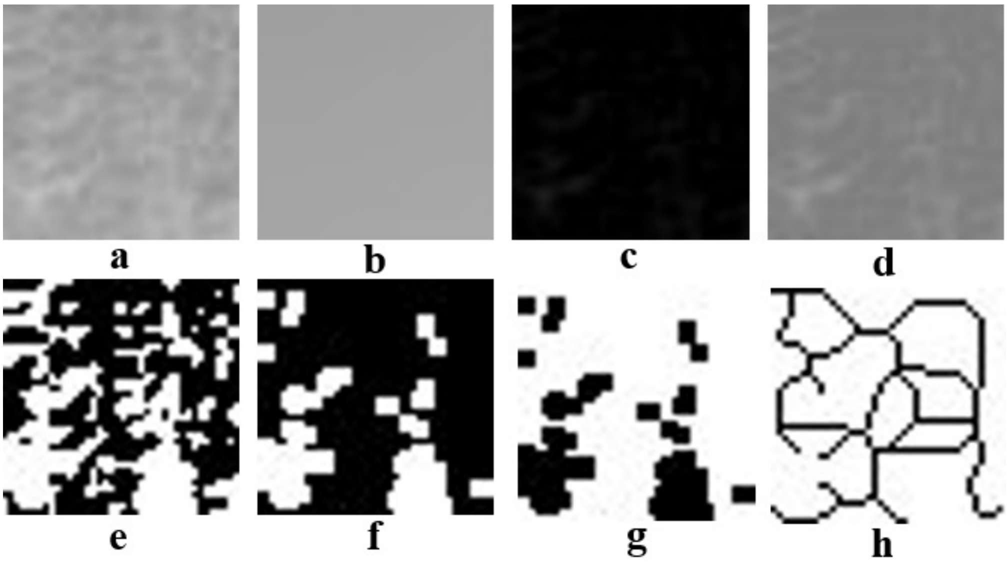

Fig. 2 — Stepwise fractal analysis workflow. (a) Cropped region of interest (ROI). (b) Gaussian blur filter applied to the duplicated ROI. (c) Subtraction of the blurred image from the original. (d) Addition of a constant gray value of 128 to each pixel. (e) Binary image generated through thresholding. (f) Noise reduction using erosion and dilation. (g) Image inversion. (h) Skeletonization.

After duplicating the ROI in JPEG format, soft tissue covering the bone and bright areas caused by variable bone thickness were blurred using a Gaussian blur filter. The blurred image was subtracted from the original image, and a gray value of 128 was added to each pixel. This step enhanced the visualization of trabecular bone and bone marrow.

Using the thresholding option (threshold value: 128), pixels with values equal to or lower than 128 were converted to black, and the remaining pixels were converted to white. Image noise was reduced using erode and dilate operations. The outlines of the trabecular structure were revealed by applying the invert option. The trabecular network was then skeletonized using the skeletonize function, and the FD was calculated using the analyze function[18] (Figure 2). All image processing and FD measurements were performed by a single observer who was blinded to the DXA results.

Statistical Analysis

All statistical analyses were conducted using IBM SPSS Statistics (IBM Corp., Armonk, NY, USA), version 27.0, and Python (Python Software Foundation, Wilmington, DE, USA), version 3.13. Distributional assumptions of continuous variables were evaluated using the Shapiro–Wilk test. Because most variables did not meet normality assumptions, nonparametric methods were applied for association analyses, and relationships were examined using Spearman rank correlation with two-sided p values. When model residuals deviated from normality, heteroskedasticity-consistent HC3 robust standard errors were used for inference. Regression results were reported as unstandardized coefficients with corresponding standard errors, p values, and coefficients of determination (R^2). A two-sided p value <0.05 was considered statistically significant.

RESULTS

A total of 152 participants were included. There were no missing data for variables included in the primary analyses. Median age was 66.00 years (IQR, 60.00–71.00). Mean height was 1.55 ± 0.06 m, and median weight was 73.00 [65.00–79.25] kg; mean body mass index was 30.53 ± 5.44 kg/m^2. Common comorbidities included hypertension in 48 patients, diabetes mellitus in 21 patients, rheumatoid arthritis in 8 patients, and a history of extra-hip fragility fractures in 8 patients. Mean lumbar spine (L1–L4) BMD was 1.014 ± 0.161 g/cm^2 with a corresponding lumbar spine T-score of -1.20 [-1.90–-0.18]. Mean femoral neck BMD was 0.758 ± 0.102 g/cm^2 with a femoral neck T-score of -1.95 [-2.52–-1.40]. Mean total hip BMD was 0.844 ± 0.110 g/cm^2 and total hip T-score was -1.35 [-2.00–-0.80]. The mean femoral neck FD was 1.297 ± 0.083 (Table I).

In unadjusted association testing, Spearman correlations between FD and densitometric measures were uniformly small and not statistically significant (Table II). FD was not correlated with lumbar spine BMD (ρ=0.007, p=0.936) or lumbar spine T-score (ρ=0.029, p=0.722). Similarly, no meaningful association was observed for femoral neck BMD (ρ=0.007, p=0.930) or femoral neck T-score (ρ=-0.004, p=0.958). The largest correlation coefficients were observed at the total hip, but remained non-significant for both total hip BMD (ρ=0.112, p=0.168) and total hip T-score (ρ=0.122, p=0.134).

Patients were further stratified into three categories based on bone mineral density T-scores: normal BMD (n=11), osteopenia (n=85), and osteoporosis (n=56). When analyses were performed separately within each subgroup, no statistically significant correlations were observed between FD and BMD T-scores at the lumbar spine, femoral neck, or total hip (all p > 0.05), indicating that the lack of association between FD and densitometric measures was consistent across BMD-defined clinical categories.

In univariable linear regression models using HC3 heteroscedasticity-robust standard errors (FD scaled per 0.1-unit increase), FD did not predict any BMD or T-score outcome and explained negligible variance (Table III). Estimated effects per 0.1 higher FD were: lumbar spine BMD β=0.000 (SE 0.014, p=0.982, R^2=0.000); lumbar spine T-score β=0.020 (SE 0.119, p=0.869, R^2=0.000); femoral neck BMD β=0.003 (SE 0.009, p=0.775, R^2=0.000); femoral neck T-score β=0.006 (SE 0.080, p=0.935, R^2=0.000); total hip BMD β=0.013 (SE 0.010, p=0.178, R^2=0.009); and total hip T-score β=0.111 (SE 0.080, p=0.164, R^2=0.010).

DISCUSSION

The present findings address a clinically important gap between what densitometry quantifies and what ultimately fails in fragility fractures. This study was intentionally framed as a confirmatory, boundary-defining analysis rather than an exploratory innovation, examining whether FD, derived from standard radiographs, could function as a surrogate for DXA-derived densitometric measures under clinically realistic conditions. In the recalculated analyses, FD showed no meaningful association with BMD or T-scores at the lumbar spine, femoral neck, or total hip, and regression models explained negligible variance in densitometric outcomes, with FD accounting for less than 1% of the variance across all DXA endpoints. Overall, these findings indicate that radiographic FD does not reflect the same skeletal properties as areal BMD. Therefore, within the methodological framework used here, FD cannot replace densitometric measures in clinical assessment, with the observed null associations helping to delineate the limits of radiograph-derived FD for densitometric substitution.

These results align with a substantial portion of the clinical literature in which FD or related texture metrics derived from conventional radiography or cone-beam CT have failed to reliably predict densitometric parameters or to discriminate osteoporotic status[19,20]. At the same time, prior reports have been heterogeneous, with some studies describing

Table I. — Participant characteristics.

Variable	Value
Age (years)	66 [60.00–71.00]
Height (m)	1.55 ± 0.06
Weight (kg)	73.00 [65.00–79.25]
Body mass index (kg/m²)	30.53 ± 5.44
Lumbar spine BMD (g/cm²)	1.014 ± 0.161
Lumbar spine T-score	-1.20 [-1.90–-0.18]
Femoral neck BMD (g/cm²)	0.758 ± 0.102
Femoral neck T-score	-1.95 [-2.52–-1.40]
Total hip BMD (g/cm²)	0.844 ± 0.110
Total hip T-score	-1.35 [-2.00–-0.80]
Femoral-neck fractal dimension	1.297 ± 0.083

Values are mean ± SD for approximately symmetric distributions and median [IQR] for skewed distributions,as prespecified for clinical reporting.

Table II. — Spearman correlations between femoral neck fractal dimension and densitometric measures.

Variable	ρ	p value
Lumbar spine BMD	0.007	0.936
Lumbar spine T-score	0.029	0.722
Femoral neck BMD	0.007	0.930
Femoral neck T-score	-0.004	0.958
Total hip BMD	0.112	0.168
Total hip T-score	0.122	0.134

ρ denotes Spearman rank correlation (two-sided).

Table III. — Univariable linear regression of densitometric measures on femoral neck fractal dimension.

Dependent variable	Model	Beta	SE	p value	R²
Lumbar spine BMD	OLS (HC3)	0.000	0.014	0.982	0.000
Lumbar spine T-score	OLS (HC3)	0.020	0.119	0.869	0.000
Femoral neck BMD	OLS (HC3)	0.003	0.009	0.775	0.000
Femoral neck T-score	OLS (HC3)	0.006	0.080	0.935	0.000
Total hip BMD	OLS (HC3)	0.013	0.010	0.178	0.009
Total hip T-score	OLS (HC3)	0.111	0.080	0.164	0.010

Beta and SE correspond to the change in the dependent variable per 0.1-unit increase in fractal dimension. HC3 indicates heteroskedasticity-robust standard errors (two-sided tests).

weak-to-moderate positive correlations between FD and BMD or osteoporotic phenotypes[15,21,22]. The present findings help adjudicate this inconsistency by emphasizing a key point often obscured by statistical significance testing: even where nominal associations have been reported, the magnitude and robustness of coupling between FD (as computed from two-dimensional clinical images) and DXA outcomes may be insufficient for surrogate validity. In this context, our null findings are not an outlier but a coherent contribution defining the boundary conditions under which FD does not map onto DXA outputs.

Fractal and radiographic texture approaches have been applied to musculoskeletal conditions, including proximal femoral trabecular alterations in hip osteoarthritis, illustrating how such methods have been used in orthopaedic imaging research[18]. Earlier clinical studies have linked DXA-derived bone mineral density to fracture risk, including distal radius fractures, thereby providing an orthopaedic framework for interpreting densitometric parameters in skeletal injury and fragility[23-24]. In addition, investigations using DXA to assess regional or periprosthetic bone remodeling highlight both the clinical utility and inherent limitations of densitometric measurements in orthopaedic practice[25]. Against this background, our study adds a clarifying negative result: when femoral neck FD is computed from routine pelvic radiographs using a standardized box-counting pipeline, it does not meaningfully track DXA BMD or T-scores in postmenopausal women. This boundary-setting evidence helps delimit claims of FD as a densitometric surrogate and underscores the methodological rigor and outcome validation required before any clinical adoption in orthopaedic settings.

A biologically and methodologically grounded interpretation of the null association is that FD and BMD quantify related but non-equivalent constructs. FD is intended to characterize trabecular topology and geometric complexity, whereas areal BMD and derived T-scores measure projected mineral content and are comparatively insensitive to three-dimensional arrangement[9,15]. Thus, a tight monotonic relationship should not be assumed a priori. Indeed, one of the motivations for microarchitectural markers is precisely the observation that structural deterioration and mineral loss can be partially dissociated in clinically relevant phenotypes. If FD captures architectural disorganization that is orthogonal to areal mineral content, then the absence of correlation with BMD/T-scores is not paradoxical; rather, it suggests that FD may not be reducible to, or replaceable by, densitometric measures.

Methodological constraints inherent to radiograph-derived FD may further explain the absence of association observed in this study. Standard radiographs compress three-dimensional trabecular structures into two-dimensional projections, and image acquisition parameters such as exposure, magnification, and soft-tissue attenuation can substantially affect texture measures. This can reduce sensitivity to subtle architectural differences and inflates measurement noise. ROI selection and segmentation thresholds represent a source of variability, especially if they are operator-dependent or not properly standardized, and such variability can completely overshadow a feeble biological signal[20,26]. Another point to consider is the anatomical confounding, which stands out especially in the lumbar region: degenerative changes, osteophytes, endplate sclerosis, and vascular calcification can unreasonably raise spine BMD and thus, by affecting the correlation between microarchitecture and densitometric measures, produce a different situation[27].

Any apparent clustering of the largest coefficients at the total hip should be interpreted conservatively. Although the total-hip models yielded the highest correlations and the largest regression coefficients in this dataset, these effects remained non-significant and explained approximately 1% of the outcome variance, making clinical or predictive utility implausible regardless of proximity to conventional significance thresholds. Given multiple comparisons across skeletal sites and endpoints, such small effects are compatible with stochastic variation[28] and are likely dominated by measurement noise or residual confounding rather than reflecting a true biological signal. At minimum, these findings underscore the necessity of prespecified primary outcomes and independent replication before ascribing biomechanical meaning to weak, unstable statistical signals[29]. Longitudinal designs incorporating standardized imaging protocols and clinical fracture endpoints will be essential to determine whether such trends represent true site-specific structure–mass relationships or random noise.

Hence, the clinical implications of these findings are twofold. First, FD—obtained from standard radiographs and analyzed using the current pipeline—should not be considered a replacement for BMD or T-scores, nor interpreted as a diagnostic or screening alternative for osteoporosis. Accordingly, the present results do not support the substitution of FD for DXA in osteoporosis assessment or therapeutic decision-making. Second, the lack of correlation with densitometric metrics does not disqualify FD as a complementary marker; it simply alters the bar of evidence to what is actually important: that is, if FD provides risk factor for fragility additional to DXA and other risk models. This way of thinking is similar to that of trabecular bone score development, which is not designed to replace BMD but to improve risk assessment by including a structural texture factor[30]. For FD to have clinical significance, it needs to be viewed within this framework of sequentiality—providing documentation of reliability and consistency in measurement, as well as demonstrating important advancements in outcome prediction, calibration, and clinical decision benefit.

The limitations outline the inferences and indicate quite directly what the following steps should be. The cross-sectional design rules out any temporal interpretations about the order of microarchitectural alteration and mineral loss. The lack of longitudinal fracture outcomes constrains the evaluation of FD as a prognostic biomarker for clinically meaningful fragility, which is the endpoint against which any "bone quality" measure should eventually be judged[31]. Variations in imaging acquisition and preprocessing—equipment features, exposure parameters, ROI placement, segmentation thresholds—are possibly the cause of the impact on FD reproducibility and generalizability beyond the conditions evaluated[26]. The unexplained confounding due to factors that affect both density and texture metrics (e.g., body size, medication exposure, and comorbidities) may additionally mask subtle associations, especially in observational cohorts[9].

All in all, these considerations underline that our results ought to be taken as substantial evidence against FD as a densitometric surrogate under the actual implementation, while leaving open the question of whether a standardized, higher-fidelity FD pipeline could contribute meaningfully to outcome prediction.

Future studies should focus on longitudinal designs, standardized acquisition protocols, and clinically relevant outcomes such as incident fractures. Prospective studies with incident fracture endpoints, pre-specified primary hypotheses, and standardized acquisition and analysis pipelines are required to determine whether FD provides independent and clinically valuable information beyond established DXA measurements and risk algorithms. In addition, measurement studies have to quantify the reliability both intra- and inter-observer, device-to-device stability, and the sensitivity to preprocessing choices. This is because it is not possible to use an imaging biomarker in clinical practice unless it is shown to have consistent reproducibility.

CONCLUSION

In the present study, FD derived from standard radiographs showed no meaningful association with lumbar or femoral BMD and T-scores and demonstrated negligible explanatory power for densitometric metrics. These results argue against the use of radiograph-derived FD as a surrogate for DXA-based measures in current clinical practice and underscore that translational adoption should await standardized, reproducible pipelines and evidence of incremental value for predicting fragility fractures beyond established densitometric and clinical risk measures.

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