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Prevalence and Clinical Implications of BMD–TBS Discordance in Postmenopausal Women: A Real-World DXA Study

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Abstract: Bone mineral density (BMD) alone may underestimate skeletal fragility, particularly in osteopenic women and in conditions characterized by a disproportionate deterioration of trabecular microarchitecture. Trabecular Bone Score (TBS) and the Bone Resilience Index (BRI) provide complementary information beyond BMD. We aimed to investigate the prevalence and clinical determinants of BMD–TBS discordance in a real-world cohort and to assess its implications for fracture risk reclassification. In this retrospective observa-tional study, we analyzed 110 postmenopausal women who underwent routine dual-energy X-ray absorptiometry (DXA), including lumbar spine TBS assessment and BRI extraction. BMD–TBS discordance was defined as normal or osteopenic hip BMD combined with partially degraded or degraded TBS. Clinical parameters, BMD, TBS, and BRI were evaluated in the entire cohort, while FRAX (Fracture Risk Assessment Tool) was available in a subgroup of patients (n = 34); multivariable regression analyses were per-formed to identify independent determinants of TBS. BMD–TBS discordance was observed in 78 of 110 women (70.9%; 95% CI: 61.5–78.9), peaking among those with hip osteopenia (82.8%). Higher body mass index (BMI) was positively correlated with BMD but inversely correlated with TBS, indicating a density–quality mismatch driven by adiposity-related microarchitectural deterioration. Discordance reached 86.0% in women with low BRI. In the FRAX subgroup (n = 34), 5 women (14.7%) were classified as low risk by FRAX alone despite high-risk microarchitecture, whereas 6 women (17.6%) showed potential risk overestimation, highlighting clinically relevant misclassification. BMD–TBS discordance is highly prevalent in routine clinical practice, particularly among osteopenic women and those with elevated BMI. Integrating TBS and BRI with BMD and FRAX may improve fracture risk discrimination and help avoid both undertreatment and overtreatment.

Keywords: osteoporosis, trabecular bone score, bone resilience index, bone microarchitecture, DXA, fracture risk, osteopenia, postmenopausal women

1. Introduction

Osteoporosis remains a major cause of morbidity in aging populations, with fragility fractures—particularly hip fractures—representing a substantial clinical and socioeconomic burden worldwide [1,2]. Dual-energy X-ray absorptiometry (DXA) remains the gold standard for the diagnosis of osteoporosis and fracture risk assessment through the measurement of bone mineral density (BMD). However, BMD reflects only the mineral component of bone and does not fully account for other key determinants of bone strength, such as trabecular microarchitecture and material properties [3].

Trabecular Bone Score (TBS) is a gray-level texture index derived from lumbar spine DXA images that provides an indirect assessment of trabecular microarchitecture [4,5]. Accumulating evidence demonstrates that TBS predicts fragility fractures independently of BMD and improves risk stratification when combined with clinical

algorithms such as FRAX [3,6–9]. Recent international recommendations now support the use of TBS as a complementary metric in the routine evaluation of osteoporosis, particularly in situations where microarchitectural deterioration may not be adequately captured by BMD alone [1,10,11].

Discordance between BMD and TBS—defined as normal or osteopenic BMD accompanied by partially degraded or degraded TBS—has emerged as a clinically relevant phenomenon that may lead to underestimation of skeletal fragility and potential undertreatment [6,12]. This discordance is particularly prevalent in metabolic and endocrine conditions characterized by impaired bone quality without a proportional reduction in BMD, including type 2 diabetes mellitus, obesity, thyroid disorders, and inflammatory diseases [13–15]. Consequently, a substantial proportion of patients classified as osteopenic by BMD may already exhibit significant structural deterioration, remaining at a "hidden high risk" of fragility fractures [6,12].

In this context, the BRI has recently been proposed as a complementary DXA-derived parameter that integrates densitometric and microarchitectural information into a single metric of overall bone strength [11,16]. Unlike BMD, which primarily reflects mineral content, and TBS, which focuses on trabecular texture, BRI may provide additional insight into skeletal fragility in situations where BMD and TBS yield discordant assessments. Preliminary data suggest that BRI aligns more closely with microarchitectural deterioration than with densitometric thresholds alone, potentially helping to contextualize fracture risk in patients with preserved or borderline BMD but impaired bone quality. As such, BRI may be particularly relevant in the setting of BMD–TBS discordance, where conventional densitometric classification may underestimate true skeletal vulnerability [16,17].

Despite growing evidence supporting the complementary role of TBS in fracture risk assessment, data on BMD–TBS discordance in routine clinical practice remain limited, particularly in populations from Central and Eastern Europe [18]. Moreover, few studies have simultaneously explored the combined contribution of BMD, TBS, BRI, and FRAX to fracture risk stratification in postmenopausal women without densitometric osteoporosis. Therefore, the aim of this study was to investigate the prevalence and clinical determinants of BMD–TBS discordance in a real-world cohort of postmenopausal women, with a particular focus on osteopenic patients, and to explore the potential role of BRI and FRAX in refining fracture risk assessment in this underrepresented population.

2. Results

2.1. Clinical Characteristics

A total of 110 postmenopausal women were included. The mean age was 65.4 ± 7.7 years (range 45–83), mean body mass index (BMI) was 27.4 ± 4.6 kg/m² (range 16.3–40.1), and the mean age at menopause was 48.0 ± 5.3 years (range 23–56). All participants had valid DXA scans of the lumbar spine and both hips, with analyzable TBS and Bone Resilience Index (BRI) parameters, allowing for a comprehensive assessment of bone density and microarchitecture.

2.2. Densitometric Diagnosis by BMD

Based on lumbar spine (L1–L4) T-scores, 14/110 women (12.7%) had normal bone density, 49/110 (44.5%) had osteopenia, and 47/110 (42.7%) had osteoporosis. When classified according to the lowest hip T-score, 13/110 women (11.8%) were normal, 65/110 (59.1%) were osteopenic, and 32/110 (29.1%) were osteoporotic. Figure 1 illustrates the distribution of densitometric categories across skeletal sites.

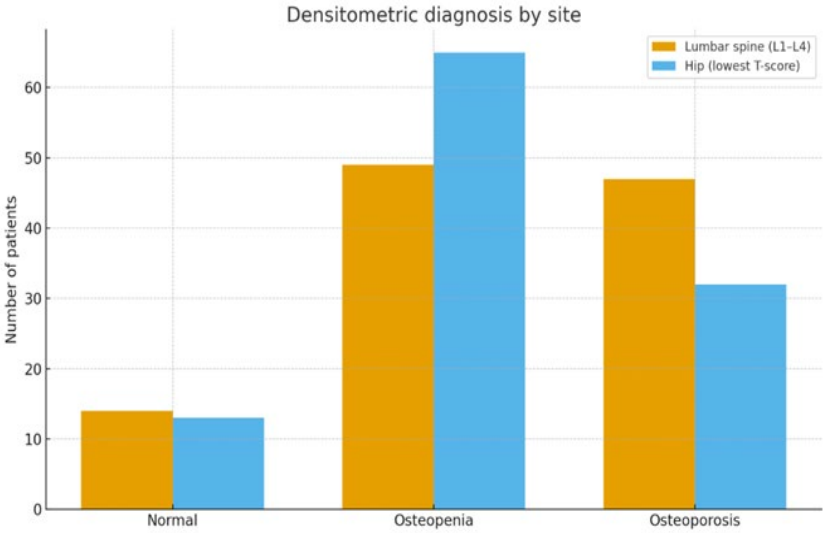

Figure 1. Distribution of densitometric diagnostic categories (normal, osteopenia, osteoporosis) according to lumbar spine and hip BMD.

2.3. TBS and Bone Resilience Index Categories

Lumbar spine TBS indicated normal microarchitecture in 27/110 women (24.5%), partially degraded microarchitecture in 36/110 (32.7%), and degraded microarchitecture in 47/110 (42.7%). Similarly, BRI was classified as normal in 3/110 women (2.7%), moderate in 31/110 (28.2%), low in 50/110 (45.5%), and severely low in 23/110 (20.9%). Taken together, these findings indicate that microarchitectural compromise and reduced bone resilience were highly prevalent in this cohort.

Figure 2 illustrates the distribution of TBS categories (panel A) and BRI categories (panel B).

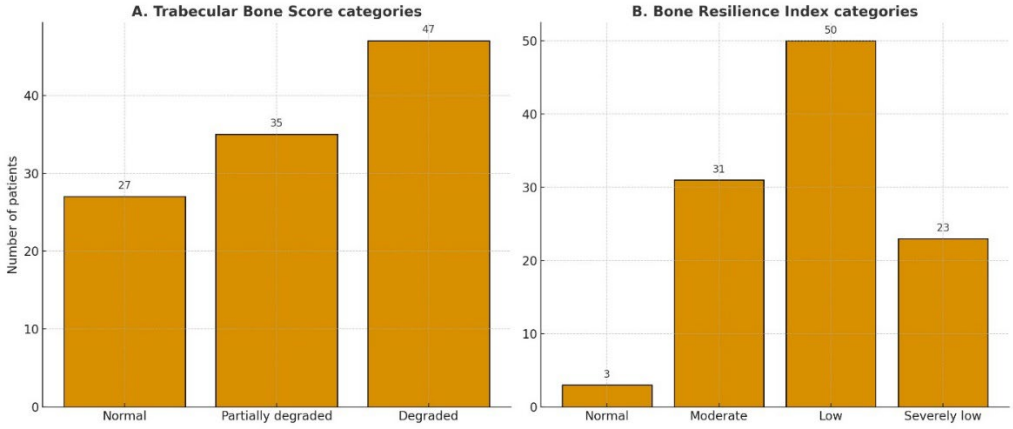

Figure 2. Distribution of trabecular bone score (TBS) categories (A) and Bone Resilience Index (BRI) categories (B) in the study cohort. The majority of women exhibited at least partially degraded trabecular microarchitecture and reduced bone resilience.

2.4. Prevalence of BMD–TBS Discordance

BMD–TBS discordance was highly prevalent, regardless of the skeletal site used for densitometric classification. When assessed using lumbar spine BMD, discordance was observed in 71.4% of women with normal BMD, 81.6% with osteopenia, and 53.7% with osteoporosis. Using the lowest hip T-score, discordance affected 69.2% of women with normal BMD, 82.8% of those with osteopenia, and 42.9% of osteoporotic

women. These findings demonstrate that osteopenia consistently exhibited the highest proportion of discordant cases, highlighting its heterogeneous profile and potentially underestimated fracture risk, whereas lower discordance in osteoporosis reflects greater alignment between densitometric bone loss and microarchitectural deterioration. Figure 3 presents discordance proportions with 95% Wilson confidence intervals.

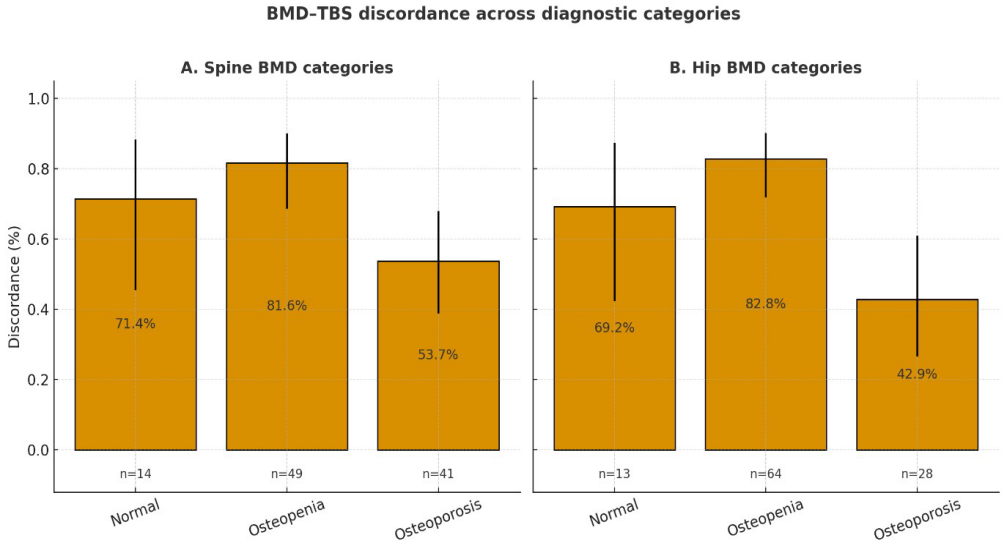

Figure 3. Proportion of BMD–TBS discordance across densitometric diagnostic categories. (A) Lumbar spine BMD (L1–L4). (B) Hip BMD based on the lowest T-score. Bars represent the percentage of discordant cases within each category, with 95% Wilson confidence intervals; n indicates the number of patients per category.

2.5. Relationship between BMI, Height, BMD, and TBS

Body mass index (BMI) was positively correlated with lumbar spine and hip BMD ($r \approx 0.33–0.48$, all $p < 0.001$) but inversely correlated with TBS ($r = −0.21$, $p = 0.03$), indicating a density–quality mismatch in individuals with higher BMI. Height showed weak-to-moderate positive correlations with BMD ($r \approx 0.24–0.37$, all $p < 0.01$) but no association with TBS ($r \approx 0.03$, $p = 0.74$). Consequently, BMD–TBS discordance remained frequent across height categories, with similar rates observed in women <160 cm (68.5%) and ≥160 cm (73.2%).

Figure 4 illustrates the inverse BMI–TBS association (panel A) and the positive BMI–BMD association (panel B).

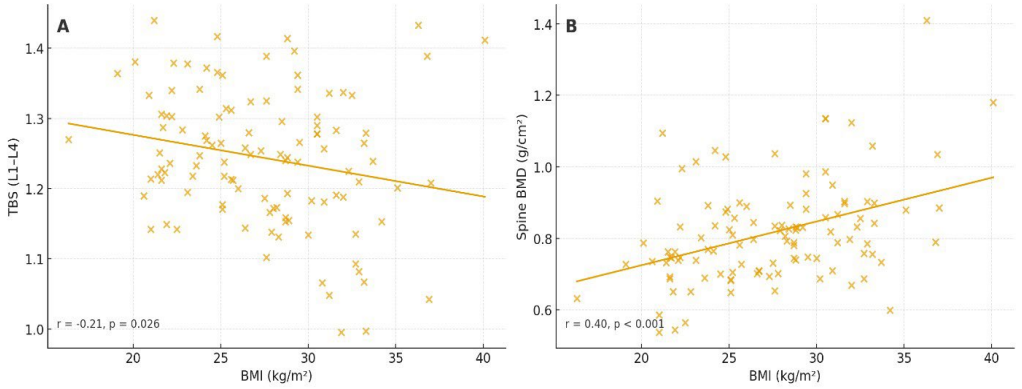

Figure 4. Associations between body mass index (BMI) and (A) TBS and (B) lumbar spine BMD. Pearson correlation coefficients (r) and p values are shown.

2.6. Discordance According to the Bone Resilience Index

The prevalence of discordance increased markedly with decreasing BRI: 33.3% among women with normal BRI, 71.0% in those with moderate BRI, and 86.0% in the low BRI group, before declining to 39.1% among women with severely low BRI. This nonlinear pattern suggests that discordance peaks in women with intermediate structural compromise, in whom BMD remains non-osteoporotic while trabecular microarchitecture is already substantially impaired.

Figure 5 illustrates discordance proportions across BRI categories (χ^2 $p < 0.001$).

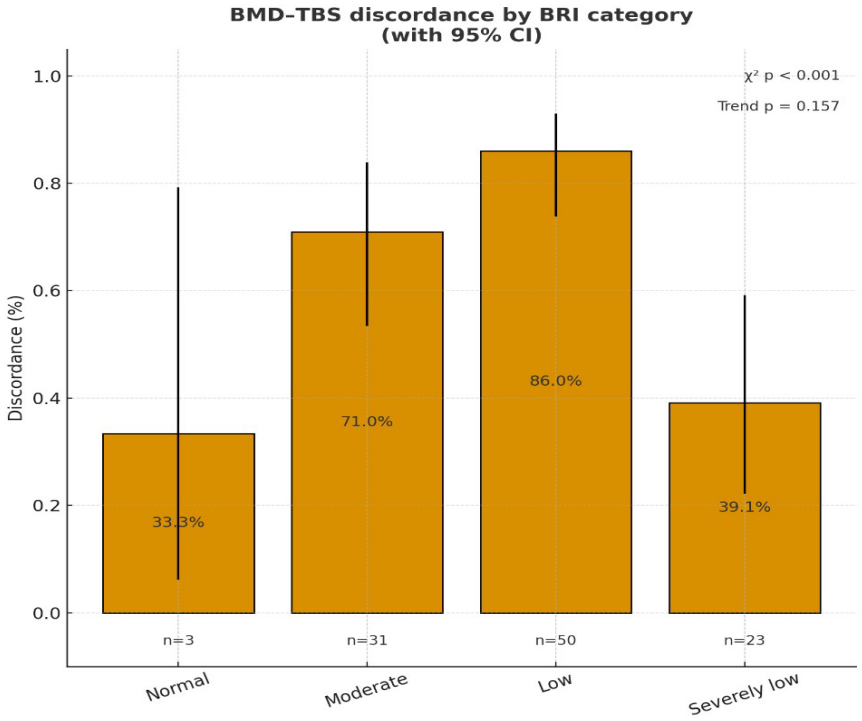

Figure 5. Proportion of BMD–TBS discordance across Bone Resilience Index (BRI) categories, with 95% Wilson confidence intervals. Chi-square (χ^2) statistics and p values for linear trend are reported.

2.6. Independent Determinants of Microarchitectural Deterioration

To better characterize the determinants of microarchitectural deterioration, we evaluated the combined roles of age, duration of menopause, and body mass index (BMI). In univariate analyses, TBS showed a significant decline with increasing duration of menopause, particularly during the first postmenopausal decade (ANOVA, $p < 0.001$), consistent with the rapid loss of trabecular connectivity associated with early estrogen deficiency. However, in multivariable regression models including chronological age and BMI, only BMI remained independently associated with TBS ($\beta = -0.004$, $p = 0.042$). Variance inflation factor analysis confirmed substantial multicollinearity between age and duration of menopause, reflecting their shared contribution to cumulative estrogen deficiency. Consequently, BMI emerged as the dominant independent determinant of trabecular impairment, whereas age-related effects were partially shared with menopausal duration.

Adjusted estimates presented in Figure 6 therefore represent the partial effect of each predictor while holding the others constant, illustrating the relative contributions of adiposity versus menopausal aging. Taken together, these findings support a two-phase model of trabecular deterioration: an initial phase of rapid estrogen-related trabecular loss in early postmenopause, followed by progressive adiposity-related deterioration later in life. This framework may explain the particularly high

prevalence of BMD–TBS discordance observed in overweight postmenopausal women.

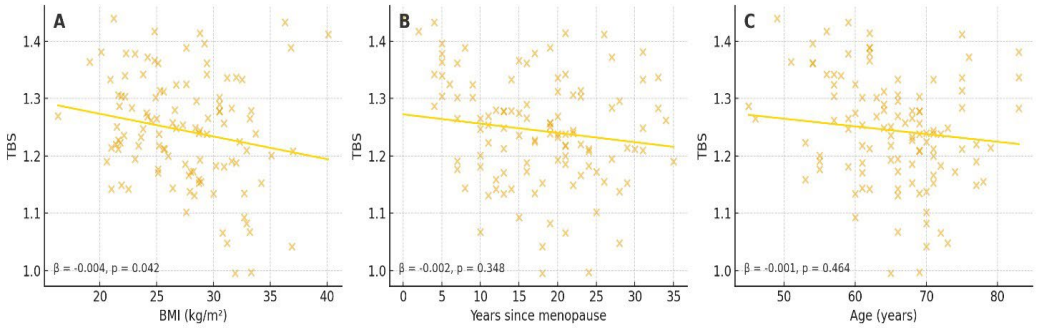

Figure 6 Adjusted partial regression plots illustrating the independent associations between TBS and (A) BMI, (B) years since menopause, and (C) chronological age in multivariable linear regression models. Adjusted β coefficients and p values are shown.

2.7. FRAX and Risk Reclassification

Valid 10-year FRAX probabilities for major osteoporotic fracture were available for 34 women. The distribution of FRAX risk is presented in Table 1. The mean FRAX major fracture risk was 9.6 ± 3.0%, and 17/34 women (50.0%) had a probability ≥10%.

Table 1 Distribution of FRAX risk in the analyzed subgroup (n = 34)

FRAX category (10-year)	n (%)
< 10%	17 (50.0)
≥ 10%	17 (50.0)
Mean FRAX (%)	**9.6 ± 3.0**

A high-risk microarchitectural profile was defined as partially degraded or degraded TBS in combination with low or severely low BRI. Based on this definition, 5 of 34 women (14.7%) were classified as low risk by FRAX alone (<10%) but exhibited high microarchitectural fragility, suggesting risk underestimation when relying exclusively on FRAX [6,19]. Conversely, 6 of 34 women (17.6%) had FRAX probabilities ≥10% but did not meet high-risk microarchitectural criteria, indicating potential risk overestimation in a subset of individuals [7,19].

3. Discussion

In this real-world cohort of postmenopausal women, we observed a high prevalence of BMD–TBS discordance (70.9%), with the highest rate identified among osteopenic women (82.8%). These findings reinforce accumulating evidence that BMD alone frequently underestimates skeletal fragility, particularly in individuals without densitometric osteoporosis [6,12,20,21]. Our results are consistent with multiple studies demonstrating that TBS captures microarchitectural deterioration not reflected by BMD and improves fracture risk assessment [5–7,22].

The hip osteopenia subgroup exhibited the most pronounced discordance, supporting the concept that osteopenia represents a heterogeneous diagnostic category in which fracture risk varies substantially [6,12]. TBS may therefore identify patients with significant structural deficits despite borderline or preserved BMD values, who may require closer clinical surveillance or therapeutic intervention [11,17,20]. We also observed a positive association between BMI and hip BMD, but an inverse association between BMI and TBS, a pattern previously described in obesity and metabolic diseases [13,14,23]. While increased mechanical loading may contribute to higher BMD in obese individuals, soft-tissue artifacts and adiposity-driven inflammatory

pathways may accelerate microarchitectural degradation, leading to a "density–quality mismatch" that contributes to fracture risk despite apparently preserved BMD [13,14,24,25]. Height showed weak-to-moderate correlations with BMD and no association with TBS. Similar observations have been reported in large cohort studies, supporting the notion that greater body size does not necessarily translate into improved trabecular microarchitecture [23,26]. Beyond primary osteoporosis, alterations in TBS have been consistently reported in metabolic and endocrine conditions such as anorexia nervosa, acromegaly, and psoriatic disease [27–29], further supporting its ability to capture skeletal fragility independently of BMD. From a clinical perspective, this density–quality mismatch has important implications for patient management. Reliance on BMD-based thresholds alone may lead to underrecognition of skeletal fragility in osteopenic or overweight women, potentially delaying therapeutic intervention in individuals who already exhibit compromised bone microarchitecture.

Discordance was most frequent among women with low BRI, peaking at 86.0%, and remained elevated in those with moderate BRI, revealing a clear non-linear pattern across BRI categories. This finding suggests that BRI captures an intermediate phase of skeletal deterioration in which BMD may remain non-osteoporotic while trabecular microarchitecture is already substantially impaired. In contrast, women with severely low BRI more frequently exhibited osteoporotic BMD, resulting in greater concordance between densitometric and microarchitectural impairment. This non-linear distribution highlights the potential clinical value of BRI in identifying patients with a pronounced density–quality mismatch who may otherwise be misclassified as lower risk based on BMD alone. Although BRI is still undergoing clinical validation, its close alignment with TBS supports its relevance as a complementary tool for assessing skeletal fragility [11,13,14, 16,18,30,31].

In the subgroup with available FRAX estimates, 14.7% of women classified as low risk by FRAX alone exhibited a high-risk microarchitectural profile, while 17.6% of those with elevated FRAX probabilities preserved trabecular microarchitecture. Although based on a limited subgroup (n = 34), these findings illustrate the potential for discordance between clinical risk algorithms and microarchitectural assessment in routine practice. Rather than providing definitive evidence of FRAX misclassification, these observations highlight areas where fracture risk stratification may benefit from complementary assessment of bone quality, supporting further investigation in larger, systematically assessed cohorts [6,7,11,19].

A key strength of this study is the evaluation of BMD–TBS discordance in a clinical population from Central and Eastern Europe, which remains underrepresented in the literature. Limitations include the retrospective study design, the absence of fracture outcome data, partial availability of FRAX estimates, and the lack of TBS-adjusted FRAX calculations. In addition, causal relationships cannot be inferred due to the cross-sectional methodology.

Overall, reliance on BMD alone may fail to identify a substantial proportion of women with impaired bone quality. Integrating TBS and BRI into routine assessment may improve clinical decision-making and help reduce both undertreatment and overtreatment, particularly among women with osteopenia and elevated BMI.

Among the 29 women with non-osteoporotic hip BMD (normal or osteopenic), 11 of 29 (37.9%) already exhibited compromised microarchitecture and reduced bone resilience. These findings reinforce the notion that fracture risk may be substantially underestimated when BMD is preserved, particularly in osteopenic patients [6,12].

Strengths and Limitations:

The strengths of this study include the integration of multiple complementary indices of skeletal fragility (BMD, TBS, and BRI), the evaluation of a real-world clinical cohort from an underrepresented Central and Eastern European population, and a focused analysis of osteopenic women—a group in which fracture risk stratification and treatment decisions remain particularly challenging.

Limitations include the retrospective and cross-sectional study design, the availability of FRAX estimates only in a subset of the cohort (n = 34), and the lack of fracture outcome validation, which precluded direct assessment of predictive performance. In addition, FRAX values were not adjusted for TBS due to software constraints, which may have contributed to risk misclassification among women with disproportionately impaired microarchitecture.

Clinical Implications:

Our findings reinforce the need to move beyond a BMD-only diagnostic paradigm in routine clinical practice and support the systematic integration of trabecular microarchitectural assessment into fracture risk evaluation. TBS and BRI demonstrated clear added value in detecting "hidden high-risk" skeletal fragility, particularly among older osteopenic women who would otherwise remain classified as low or intermediate risk and potentially undertreated [6,12,20].

Furthermore, because FRAX estimates in this study were not adjusted for TBS due to software limitations, fracture risk was likely underestimated in a subset of patients. Previous research has shown that TBS-adjusted FRAX improves predictive accuracy in clinical populations in which microarchitecture is disproportionately compromised, including type 2 diabetes mellitus, obesity, chronic glucocorticoid therapy, and osteopenia [5,6,19]. Routine implementation of TBS-adjusted FRAX could therefore enhance risk stratification by reducing both under- and overtreatment, aligning clinical decision-making more closely with true skeletal fragility.

4. Materials and Methods

4.1. Study Design and Population

This retrospective observational study included 110 consecutive postmenopausal women who underwent routine dual-energy X-ray absorptiometry (DXA) evaluation at a tertiary care center in Oradea, Romania, between 1 and 30 November 2025. All eligible women undergoing DXA during this period were screened, and no additional selection based on clinical characteristics or fracture risk was applied.

Eligibility was defined by female sex, age ≥40 years, postmenopausal status, availability of valid lumbar spine and hip DXA measurements, and adequate TBS analysis. All included participants fulfilled these criteria, and **no patients were excluded**, as all examinations met predefined quality requirements and complete analyzable data were available for BMD, TBS, and core clinical parameters (age, height, and weight).

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FRAX estimates were available only for patients with complete clinical risk factor data documented in the DXA reports at the time of examination. As FRAX calculation was not systematically performed as part of routine clinical practice during the study period, complete FRAX data could be retrieved for only a subset of the cohort (n = 34).

4.2. DXA Measurements

Lumbar spine (L1–L4) and proximal femur bone mineral density were measured using the same densitometer, Hologic Horizon Wi (Hologic Inc., Marlborough, MA, USA). Results were expressed in g/cm² and as T-scores based on manufacturer reference standards and categorized according to the World Health Organization (WHO) diagnostic criteria:

- Normal: T-score ≥ −1.0
- Osteopenia: −1.0 > T-score > −2.5

- Osteoporosis: T-score ≤ −2.5

The diagnostic category was determined using the lowest hip T-score (total hip or femoral neck), in accordance with current International Society for Clinical Densitometry (ISCD) recommendations [10].

4.3. Trabecular Bone Score and Bone Resilience Index

TBS was extracted from the same lumbar spine DXA acquisitions using dedicated software (TBS iNsight, Medimaps Group)[4,5]. TBS categories were defined as follows:

- Normal microarchitecture
- Partially degraded microarchitecture
- Degraded microarchitecture

The Bone Resilience Index (BRI), a DXA-derived parameter integrating both densitometric and microarchitectural information, was automatically reported by the software and classified as:

- Normal / Moderate / Low / Severely low [11,16]

4.4. Definition of BMD–TBS Discordance

Discordance was defined as the coexistence of normal or osteopenic hip BMD with partially degraded or degraded TBS, reflecting an underestimated skeletal fragility phenotype [6,12]. Concordance was defined when BMD and TBS were aligned within the same diagnostic category.

4.5. FRAX Assessment

The 10-year probability of major osteoporotic fracture (FRAX) was retrieved directly from the DXA report when available. FRAX estimates were not adjusted for TBS, as the available DXA software version did not provide integrated TBS-adjusted FRAX outputs [6,7].

4.6. Statistical Analysis

Continuous variables were expressed as mean ± standard deviation, while categorical variables were presented as frequencies and percentages. Pearson correlation coefficients were used to assess relationships between clinical parameters, BMD, and TBS. Group differences were analyzed using chi-square (χ^2) tests. Multivariable linear regression was applied to identify independent predictors of TBS, including age, duration of menopause, and body mass index (BMI). Statistical significance was set at $p < 0.05$. Analyses were performed using SPSS (version 28.0, IBM Corp.) and Python (version 3.10; statsmodels and scikit-learn packages), and graphical outputs were generated using Matplotlib.

4.7. Ethical statement

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board and the Ethical Council of the Emergency County Clinical Hospital, Oradea, Bihor, Romania (no. 39135/09.11.2023 and 39657/15.11.2023).

5. Conclusions

Among postmenopausal women undergoing routine bone health assessment, BMD–TBS discordance was found to be highly prevalent, particularly in those with osteopenia or elevated body mass index. This pattern reveals a substantial proportion of individuals with "hidden" skeletal fragility who may be underestimated when fracture risk assessment relies primarily on densitometric thresholds, with or without clinical risk algorithms. Consequently, classification strategies based exclusively on BMD may overlook clinically meaningful microarchitectural compromise.

Integrating trabecular microarchitecture through TBS—and complementary indices such as the Bone Resilience Index—provides a more comprehensive reflection of bone strength, improves risk stratification in routine clinical care, and identifies high-risk individuals who may benefit from therapeutic intervention despite non-osteoporotic BMD.

Taken together, these findings highlight the clinical relevance of assessing BMD–TBS discordance and support the integration of microarchitectural parameters into diagnostic pathways and treatment decision-making. Such an approach has the potential to enhance the precision of osteoporosis management in daily practice, while observations related to FRAX-based risk classification should be regarded as exploratory and warrant confirmation in larger, prospectively assessed cohorts.

Author Contributions: Conceptualization, R.B. and A.T.; methodology, R.B.; C.D.N.C., S.D.C.; software, R.B.; validation, S.D.C. and C.D.N.C.; investigation, R.B. and A.T.; data curation, R.B.; writing—original draft preparation, R.B., A.T., S.D.C, C.D.N.C.; writing—review and editing, R.B., A.T., S.D.C., C.D.N.C.; visualization, R.B. and A.T.; supervision, S.D.C. and C.D.N.C.; project administration, R.B.; funding acquisition, R.B. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and ap-proved by the Institutional Review Board and the Ethical Council of the Emergency County Clinical Hospital, Oradea, Bihor, Romania (no. 39135/09.11.2023 and 39657/15.11.2023).

Data Availability Statement: All data are available in the County Emergency Clinical Hospital of Oradea-Romania, Department of Orthopedics and Traumatology.

Conflicts of Interest: The authors declare no conflict of interest

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