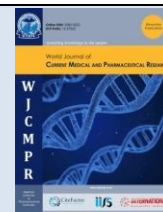




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EVALUATION OF BONE MINERAL DENSITY AND TRABECULAR BONE SCORE AS PREDICTORS OF VERTEBRAL COMPRESSION FRACTURE SEVERITY: A CROSS-SECTIONAL STUDY

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ARTICLE HISTORY	ABSTRACT
Received on: 18-07-2026 Revised on: 16-08-2026 Accepted on: 01-10-2026	Background: Bone mineral density (BMD) is central to osteoporosis assessment, but it may not fully reflect skeletal fragility. Trabecular bone score (TBS) may provide complementary information regarding vertebral fracture severity.
Keywords: Bone mineral density; Trabecular bone score; Vertebral compression fracture; Genant grade; Osteoporosis.	Methods: This hospital-based cross-sectional study included 90 adults with vertebral compression fractures evaluated by dual-energy X-ray absorptiometry and lumbar TBS. Vertebral fractures were graded using the Genant semiquantitative classification, and cumulative fracture burden was assessed using the Spinal Deformity Index (SDI). Associations of BMD and TBS with fracture severity were examined using group comparisons, correlation, logistic regression, and receiver operating characteristic analysis.
Corresponding Author Mohammed Washim Khan Consultant Orthopaedic Surgeon, District Hospital, Directorate of Medical and Health, Moradabad, Uttar Pradesh.	Results: Lumbar spine, femoral neck, and total hip BMD declined with increasing Genant grade. TBS also decreased progressively across grades and was inversely correlated with SDI. Degraded TBS was more frequent in Grade 3 fractures. In adjusted analysis, lower TBS remained associated with severe vertebral fracture after inclusion of age and lumbar BMD. Adding TBS increased model AUC from 0.680 to 0.734.
	Conclusion: TBS complements BMD in characterizing vertebral compression fracture severity and may improve assessment of skeletal fragility.

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INTRODUCTION

Vertebral compression fractures are among the most clinically important manifestations of skeletal fragility. Their importance is not just in the context of the index deformity, as an existing vertebral fracture identifies patients at a higher risk of further fractures. Lindsay et al. showed in a large study of postmenopausal women that having one or more vertebral fractures significantly raised the risk of developing another fracture in the next year, highlighting the need to identify vertebral fracture and its burden [1]. Therefore, it is important to assess the severity of vertebral fracture in the evaluation of osteoporosis. The semiquantitative method developed by Genant and colleagues categorizes vertebral deformities based on the extent of height loss in the vertebrae and is widely used in clinical research as it allows for a reproducible classification of vertebral fractures as mild, moderate, or severe [2]. If multiple levels are involved, adding together the individual fracture grades can also give a numerical measure of the total vertebral fracture burden (Spinal Deformity Index).

Areal bone mineral density (BMD) measurement and classification of skeletal status by T-scores are still based on the standard non-invasive method, dual-energy X-ray absorptiometry (DXA). Low BMD is a strong predictor of fragility fracture risk, and measurements of the proximal femur and lumbar spine are used to assess osteoporosis routinely [3]. But BMD is just one factor of bone strength. Patients with osteopenic or even apparently preserved BMD can still develop fragility fractures, suggesting that other factors affecting the skeleton, which are not fully represented by mineral density, are also important for mechanical failure. The trabecular bone score (TBS) was developed to gain further information from the pixel-level texture of the DXA image of the lumbar spine. While based on the same image as is used for measurement of lumbar BMD, TBS offers information that is only partially correlated with BMD and is regarded as a complementary measure of trabecular skeletal quality. Hans et al. demonstrated in the Manitoba cohort that lower TBS was independently related to incident osteoporotic fractures

even after accounting for BMD, which is consistent with the idea that TBS and mineral density represent different aspects of fracture susceptibility [4]. The benefit of TBS could be especially important in patients with a BMD that does not fulfill the densitometric criteria for osteoporosis. In patients with vertebral fracture, Nassar et al. showed that TBS added value to lumbar spine BMD, especially in those outside the osteoporotic range, and that TBS was associated with the burden and severity of vertebral fractures [5]. The OPUS study also provided prospective evidence that TBS provided extra fracture-risk information beyond lumbar spine BMD, and that the combination of the two improved classification of radiographic vertebral fractures [6]. Pooled analyses of larger studies have confirmed the complementary role of TBS. McCloskey et al. performed an individual-level meta-analysis of 14 prospective cohorts, with a total of 17,809 participants, and found that TBS remained associated with major osteoporotic fracture risk even after adjustment for conventional FRAX probability, although the additional gain in overall discrimination was modest [7]. This is clinically relevant: TBS should not be used as a replacement for BMD but rather as an additional skeletal parameter that can complement existing clinical and densitometric parameters to better characterize risk. The current recommendations from the International Society for Clinical Densitometry also include TBS as an ancillary tool that is associated with vertebral and major osteoporotic fracture risk, but note that it should not be used as a standalone tool for treatment decisions [8]. Although TBS has been increasingly used, there are fewer studies that have specifically investigated the relationship of BMD and TBS with the graded severity of established VCFs and whether there is added value in combining these measures to improve discrimination of severe VCFs. Hence, the present cross-sectional study was carried out at District Hospital, Moradabad, among adults with vertebral compression fractures. It was designed to investigate the relationship of DXA-derived BMD and TBS with the severity of vertebral fracture as determined by the Genant semiquantitative method, to evaluate their association with cumulative fracture burden measured by the Spinal Deformity Index, and to determine if TBS offers any additional discriminatory information for severe vertebral compression fracture (VCF) beyond BMD alone.

METHODS

Study design and participants

The study was a cross-sectional observational study carried out at District Hospital, Moradabad, from June 2024 to June 2026. Patients with vertebral compression fractures (VCF) who were clinically assessed, underwent dual-energy X-ray absorptiometry (DXA), and had lumbar trabecular bone score (TBS) evaluation were included. Demographic and clinical data included age, sex, BMI, menopausal status, previous fragility fracture, chronic use of glucocorticoids, diabetes mellitus, history of vitamin D deficiency and other relevant skeletal risk factors.

Vertebral fracture assessment

The severity of vertebral fracture was classified as Grade 1 (mild), Grade 2 (moderate), or Grade 3 (severe) according to the Genant semiquantitative classification. For patients with multiple fractures, the highest Genant grade was used to determine the maximum fracture severity. The Spinal

Deformity Index (SDI) was determined by adding the Genant grades of all the affected vertebrae. Maximum Genant Grade 3 was considered to be severe vertebral compression fracture (VCF).

Bone mineral density and trabecular bone score

BMD was measured using DXA at the lumbar spine, femoral neck and total hip, and expressed in g/cm² with T-scores provided. The lowest T-score was used to classify BMD status as normal (T-score ≥ -1.0), osteopenia (< -1.0 to ≥ -2.5), or osteoporosis (T-score ≤ -2.5).

Lumbar TBS was measured as a continuous variable and a categorical variable. TBS was classified as degraded (≤ 1.23), partially degraded (> 1.23 to < 1.31), or preserved (≥ 1.31). Only those with an interpretable measurement were included in analyses involving TBS.

Statistical analysis

Continuous variables were presented as mean $\pm$ SD or median [IQR] as appropriate and categorical variables as n (%). One-way analysis of variance or Kruskal-Wallis test was used for continuous variables and chi-square or Fisher's exact test was used for categorical variables between Genant Grades 1–3. Overall group differences were examined and post-hoc pairwise comparisons were conducted when significant, using an adjustment for multiple comparisons. Effect sizes were reported where appropriate. Spearman correlation was used to evaluate the associations of lumbar spine, femoral neck, and total hip BMD and lumbar TBS with SDI. Pearson correlation was used to assess the relationship between lumbar spine BMD and TBS. Odds ratios (ORs) with 95% confidence intervals (CIs) were used to present the associations of osteoporosis and degraded TBS with severe VCF. Binary logistic regression was used to identify factors associated with severe VCF. Univariate analyses were performed for age, sex, BMI, lumbar and femoral neck BMD, TBS, previous fragility fracture, and glucocorticoid use. To limit overfitting, multivariable modelling was parsimonious: Model 1 included age and lumbar spine BMD, while Model 2 additionally included TBS. ORs or adjusted ORs with 95% CIs and p-values were reported. Lumbar spine BMD alone, TBS alone and a combined BMD-plus-TBS model were evaluated for discrimination of severe VCF using receiver operating characteristic analysis. The area under the curve (AUC) with 95% CI was reported and the incremental contribution of TBS was evaluated by comparing AUC and Akaike information criterion (AIC) between models. All tests were two-sided and a p-value of < 0.05 was regarded as statistically significant.

RESULTS

Cohort and vertebral fracture characteristics

Ninety adults with vertebral compression fractures were included. The mean age was 64.6 ± 9.9 years, and 62 (68.9%) were women. Among women, 59 (95.2%) were postmenopausal. Osteoporosis was present in 49 (54.4%) patients, and lumbar trabecular bone score (TBS) was available in 87 (96.7%). Maximum Genant grade was 1 in 31 (34.4%), 2 in 37 (41.1%), and 3 in 22 (24.4%) patients. The median Spinal Deformity Index (SDI) was 2 [2–4]. Overall cohort characteristics are summarized in Table 01.

Bone mineral density and vertebral fracture severity
Lumbar spine, femoral neck, and total hip bone mineral density (BMD) decreased across increasing Genant grades (Table 2). The corresponding T-scores showed similar

gradients. Post-hoc comparisons demonstrated lower BMD in Grade 3 than Grade 1 fractures at all three skeletal sites, while Grade 1 versus Grade 2 and Grade 2 versus Grade 3 comparisons did not remain statistically significant after adjustment for multiple pairwise comparisons. Osteoporosis was more frequent with increasing fracture severity.

Trabecular bone score and fracture severity

Lumbar TBS decreased progressively across Genant grades, with the lowest values observed in Grade 3 fractures (Table 2; Figure 1). Degraded TBS was present in 11 (52.4%) patients with Grade 3 fractures compared with 4 (13.3%) in Grade 1 and 6 (16.7%) in Grade 2. TBS was moderately correlated with lumbar spine BMD (Pearson $r=0.428$), indicating related but non-equivalent skeletal information.

Relationship with cumulative fracture burden

Both BMD and TBS demonstrated inverse relationships with SDI. The magnitude of association was similar for lumbar spine BMD and TBS, with weaker inverse correlations for femoral neck and total hip BMD (Table 3).

Severe vertebral compression fracture and incremental value of TBS

In univariate analyses, lower lumbar spine BMD, lower femoral neck BMD, and lower TBS were associated with Grade 3 fracture, whereas age, sex, BMI, previous fragility fracture, and glucocorticoid use were not statistically significant (Table 4). In the parsimonious adjusted model, lumbar spine BMD was associated with severe fracture when modelled with age. After addition of TBS, lower TBS remained independently associated with severe fracture, while the BMD estimate was attenuated.

Model discrimination and ROC analysis

Adding TBS to the age-plus-BMD model increased the AUC from 0.680 to 0.734 and reduced the AIC from 94.6 to 92.6. The estimated AUC increase was 0.055 (95% CI -0.042 to 0.151). In ROC analyses based on skeletal measures, discrimination was 0.676 for lumbar BMD alone, 0.702 for TBS alone, and 0.736 for the combined BMD+TBS model (Table 04; Figure 02).

Table 01: Overall characteristics of the study cohort (N=90)

Characteristic	Overall
Age, years	64.6 ± 9.9
Female sex	62 (68.9%)
BMI, kg/m ²	24.7 ± 3.5
Postmenopausal among women	59/62 (95.2%)
Previous fragility fracture	22 (24.4%)
Chronic glucocorticoid use	7 (7.8%)
Diabetes mellitus	21 (23.3%)
Vitamin D deficiency history	36 (40.0%)
Number of fractured vertebrae	1 [1–2]
Lumbar spine BMD, g/cm ²	0.782 ± 0.109
Femoral neck BMD, g/cm ²	0.664 ± 0.086
Lumbar spine T-score	-2.24 ± 0.91
Femoral neck T-score	-2.16 ± 0.86
Lumbar TBS	1.299 ± 0.090
Normal BMD	8 (8.9%)
Osteopenia	33 (36.7%)
Osteoporosis	49 (54.4%)
Degraded TBS	21/87 (24.1%)
Partially degraded TBS	26/87 (29.9%)
Normal/preserved TBS	40/87 (46.0%)
Maximum Genant grade 1	31 (34.4%)
Maximum Genant grade 2	37 (41.1%)
Maximum Genant grade 3	22 (24.4%)
Spinal Deformity Index	2 [2–4]

Data are mean ± SD, median [IQR], or n (%). TBS percentages use the 87 patients with an interpretable lumbar TBS. BMD, bone mineral density; SDI, Spinal Deformity Index; TBS, trabecular bone score.

Table 02: Clinical and skeletal characteristics according to maximum Genant grade

Variable	Grade 1 (n=31)	Grade 2 (n=37)	Grade 3 (n=22)	Test statistic	p-value	Effect size
Age, years	61.2 ± 9.4	65.7 ± 8.9	67.4 ± 11.4	F=3.08	0.051	$\eta^2=0.066$
Female sex	20 (64.5%)	26 (70.3%)	16 (72.7%)	$\chi^2=0.46$	0.794	V=0.072
BMI, kg/m ²	24.4 ± 3.2	25.1 ± 3.6	24.4 ± 3.8	F=0.47	0.628	$\eta^2=0.011$
Previous fragility fracture	10 (32.3%)	6 (16.2%)	6 (27.3%)	$\chi^2=2.48$	0.290	V=0.166

Variable	Grade 1 (n=31)	Grade 2 (n=37)	Grade 3 (n=22)	Test statistic	p-value	Effect size
Number of fractured vertebrae	1 [1–2]	2 [1–2]	2 [1–3]	H=5.68	0.059	$\varepsilon^2=0.042$
Multiple vertebral fractures	11 (35.5%)	20 (54.1%)	13 (59.1%)	$\chi^2=3.54$	0.170	V=0.198
Lumbar spine BMD, g/cm ²	0.826 ± 0.109	0.773 ± 0.110	0.734 ± 0.084	F=5.19	0.007	$\eta^2=0.107$
Femoral neck BMD, g/cm ²	0.694 ± 0.088	0.665 ± 0.087	0.619 ± 0.063	F=5.33	0.007	$\eta^2=0.109$
Total hip BMD, g/cm ²	0.750 ± 0.095	0.713 ± 0.097	0.681 ± 0.076	F=3.73	0.028	$\eta^2=0.079$
Lumbar spine T-score	−1.87 ± 0.91	−2.31 ± 0.92	−2.63 ± 0.70	F=5.18	0.007	$\eta^2=0.106$
Femoral neck T-score	−1.86 ± 0.88	−2.15 ± 0.87	−2.61 ± 0.63	F=5.33	0.007	$\eta^2=0.109$
Total hip T-score	−1.82 ± 0.86	−2.16 ± 0.89	−2.45 ± 0.69	F=3.73	0.028	$\eta^2=0.079$
Lumbar TBS	1.332 ± 0.077	1.299 ± 0.090	1.251 ± 0.089	F=5.53	0.006	$\eta^2=0.116$
Osteoporosis	9 (29.0%)	22 (59.5%)	18 (81.8%)	$\chi^2=15.09$	<0.001	V=0.410
Degraded TBS	4/30 (13.3%)	6/36 (16.7%)	11/21 (52.4%)	$\chi^2=12.16$	0.002	V=0.374
Spinal Deformity Index	1 [1–2]	3 [2–4]	4 [3–7]	H=55.93	<0.001	$\varepsilon^2=0.620$

Data are mean ± SD, median [IQR], or n (%). ANOVA was used for approximately normally distributed continuous variables; Kruskal–Wallis testing was used for ordinal/skewed variables; Pearson χ^2 was used for categorical variables. For lumbar spine BMD, femoral neck BMD, total hip BMD, and lumbar TBS, adjusted post-hoc comparisons were significant for Grade 1 versus Grade 3 (adjusted p=0.006, 0.004, 0.023, and 0.004, respectively), but not for adjacent-grade comparisons. TBS denominators reflect three technically uninterpretable measurements.

Table 03: Associations of skeletal measures with fracture burden and severe vertebral fracture

Association	Sample / Event Summary	Effect Estimate (95% CI)	Test Statistic	p-value
Lumbar spine BMD vs SDI	n=90	Spearman $\rho=-0.357$ (95% CI −0.516 to −0.171)	$\rho=-0.357$	<0.001
Femoral neck BMD vs SDI	n=90	Spearman $\rho=-0.294$ (95% CI −0.470 to −0.094)	$\rho=-0.294$	0.005
Total hip BMD vs SDI	n=90	Spearman $\rho=-0.299$ (95% CI −0.465 to −0.102)	$\rho=-0.299$	0.004
Lumbar TBS vs SDI	n=87	Spearman $\rho=-0.364$ (95% CI −0.532 to −0.167)	$\rho=-0.364$	<0.001
Osteoporosis and severe VCF	18/49 vs 4/41 severe	OR 5.37 (95% CI 1.64–17.55)	Fisher exact	0.003
Degraded TBS and severe VCF	11/21 vs 10/66 severe	OR 6.16 (95% CI 2.07–18.31)	Fisher exact	0.001

Severe VCF was defined as maximum Genant Grade 3. Osteoporosis was defined according to the lowest T-score. Degraded TBS was defined as lumbar TBS ≤1.23. CI, confidence interval; OR, odds ratio; SDI, Spinal Deformity Index.

Table 04: Logistic regression and discrimination for severe vertebral compression fracture

Predictor / model	OR / AUC	95% CI	Statistic / operating point	p-value	n / additional information
Univariate logistic regression					
Age, per 10 years	OR 1.48	0.89–2.47	Wald z=1.51	0.130	n=90
Female sex	OR 1.28	0.44–3.71	Wald z=0.45	0.655	n=90
BMI, per 5 kg/m ²	OR 0.86	0.43–1.73	Wald z=−0.41	0.680	n=90
Lumbar spine BMD, per 0.1 g/cm ²	OR 0.52	0.30–0.91	Wald z=−2.29	0.022	n=90
Femoral neck BMD, per 0.1 g/cm ²	OR 0.37	0.18–0.77	Wald z=−2.66	0.008	n=90
Lumbar TBS, per 0.1 unit	OR 0.44	0.24–0.80	Wald z=−2.67	0.008	n=87
Previous fragility fracture	OR 1.22	0.41–3.64	Wald z=0.35	0.723	n=90
Chronic glucocorticoid use	OR 2.53	0.52–12.29	Wald z=1.15	0.251	n=90

Predictor / model	OR / AUC	95% CI	Statistic / operating point	p-value	n / additional information
Model 1: age + lumbar BMD					n=87
Age, per 10 years	aOR 1.10	0.62–1.94	Wald z=0.33	0.741	
Lumbar spine BMD, per 0.1 g/cm ²	aOR 0.48	0.25–0.91	Wald z=-2.26	0.024	
Model 2: age + lumbar BMD + TBS					n=87
Age, per 10 years	aOR 1.02	0.58–1.79	Wald z=0.06	0.955	
Lumbar spine BMD, per 0.1 g/cm ²	aOR 0.55	0.28–1.07	Wald z=-1.75	0.080	
Lumbar TBS, per 0.1 unit	aOR 0.52	0.27–1.00	Wald z=-1.97	0.049	
Model discrimination					
Age + lumbar BMD	AUC 0.680	0.556–0.799	AIC=94.6	—	Reference
Age + lumbar BMD + TBS	AUC 0.734	0.602–0.852	AIC=92.6	—	Δ AUC +0.055 (95% CI -0.042 to 0.151)
ROC: lumbar BMD alone	AUC 0.676	0.539–0.793	Sensitivity 95.2%; specificity 36.4%	—	≤ 0.822 g/cm ² *
ROC: TBS alone	AUC 0.702	0.556–0.825	Sensitivity 71.4%; specificity 66.7%	—	≤ 1.292 *
ROC: lumbar BMD + TBS	AUC 0.736	0.616–0.852	Sensitivity 95.2%; specificity 43.9%	—	Probability ≥ 0.157 *

Severe VCF was maximum Genant Grade 3. Logistic regression results are odds ratios (ORs) or adjusted odds ratios (aORs). Model discrimination is reported as area under the ROC curve (AUC). *Thresholds are exploratory Youden-derived cut-offs and are not proposed as clinical decision thresholds. AIC, Akaike information criterion; BMD, bone mineral density; TBS, trabecular bone score.

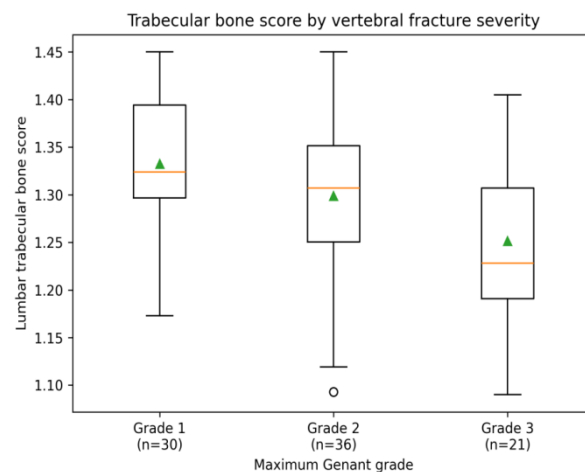


Figure 01: Lumbar trabecular bone score according to maximum Genant grade
Distribution of lumbar TBS across Genant Grade 1, 2, and 3 vertebral compression fractures. TBS values decreased with increasing fracture severity. TBS, trabecular bone score.

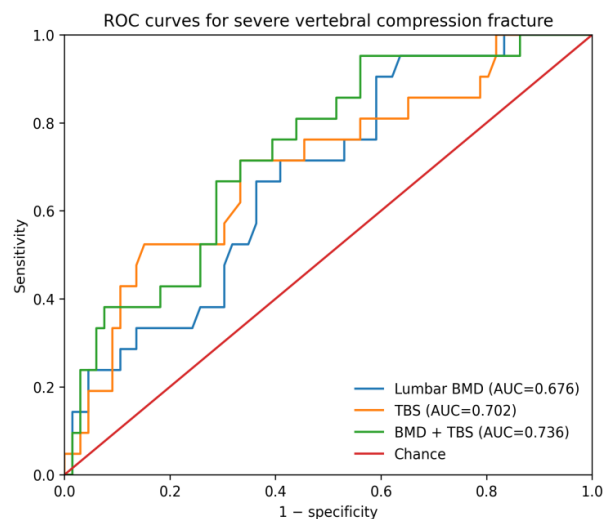


Figure 02: ROC curves for discrimination of severe vertebral compression fracture

Receiver operating characteristic curves for lumbar spine BMD alone, lumbar TBS alone, and the combined BMD+TBS model for discrimination of severe vertebral compression fracture (maximum Genant Grade 3). BMD, bone mineral density; ROC, receiver operating characteristic; TBS, trabecular bone score.

DISCUSSION

Both DXA-derived bone mineral density (BMD) and lumbar trabecular bone score (TBS) were associated with the severity of vertebral compression fracture in this study. The BMD of the lumbar spine, femoral neck, and total hip decreased as the Genant grade increased, and TBS decreased from 1.332 in Grade 1 fractures to 1.251 in Grade 3 fractures. Osteoporosis and degraded TBS were also substantially more frequent among patients with severe fractures. There was an inverse relationship between both lumbar BMD and TBS and cumulative fracture burden as measured by the Spinal Deformity Index (SDI). Importantly, TBS was still associated with severe fracture when adjusted for age and lumbar BMD, indicating that it provides information not fully captured by lumbar BMD.

The progressive decrease in skeletal measures with increasing Genant grades is consistent with structural deterioration that occurs with increasing vertebral deformity. Genant et al. showed that the severity of vertebral fracture was associated with deterioration of trabecular microarchitecture, including decreased trabecular bone volume and connectivity and greater trabecular separation [9]. This is consistent with the current observation that fracture severity is associated with a decrease in mineral density, as well as deterioration in trabecular quality.

However, BMD was still strongly associated with severe fracture in the present study. The prevalence of osteoporosis was 81.8% for Grade 3 fractures compared with 29.0% for Grade 1 fractures, and osteoporosis was associated with more than fivefold higher odds of severe VCF. But some patients with severe fractures did not meet densitometric criteria for osteoporosis. Borgen et al. also found that the prevalence of vertebral fracture and low TBS was high in patients with fragility fractures, including many patients with BMD in the osteopenic range [10]. These results underscore the limitation of relying on BMD alone to characterize skeletal fragility.

The TBS gradient found in our cohort is also similar to previous studies. Omichi et al. reported significantly lower TBS in Japanese adults with vertebral fractures and demonstrated that TBS had discrimination similar to lumbar BMD [11]. In postmenopausal women with osteopenia, Winzenrieth et al. found that TBS was more strongly associated with vertebral fracture than BMD and that the combination of the two measures had better discrimination [12]. Likewise, Pothuau et al. showed that women with fragility fractures had lower TBS even after matching for age and lumbar BMD [13]. The present study showed that lumbar TBS and lumbar BMD were only moderately correlated ($r=0.428$), suggesting that they measure different but related properties of the skeleton.

Cumulative vertebral damage was also related to TBS. It was inversely correlated with SDI ($p=-0.364$), which was similar to that of lumbar BMD ($p=-0.357$). Similarly, Ryang et al. reported that women with prevalent vertebral fractures had lower TBS and that degraded TBS was

associated with subsequent fracture progression [14]. The present cross-sectional study design does not allow for assessment of future fracture risk, but the relationship with SDI indicates that worse trabecular texture is related to higher levels of established vertebral fracture burden.

The categorical TBS analysis also showed that degraded TBS was substantially more frequent in Grade 3 fractures and was associated with over six times the odds of severe VCF. Fixed thresholds should be used with caution, however. Biamonte et al. demonstrated that TBS was lower in women with vertebral fractures, but a substantial percentage of fracture patients did not have TBS values below the conventional degraded-TBS threshold [15]. Therefore, continuous TBS measurements might be more informative than using only categorical cut-offs.

The regression and ROC analyses corroborate the complementary role of TBS. In the age-adjusted model, lumbar BMD was still associated with severe fracture, but this association was reduced when TBS was included in the model, and lower TBS still had an independent association. Incorporating TBS into the age-plus-BMD model improved the AUC from 0.680 to 0.734 and reduced AIC. The confidence interval for the AUC increase, however, included no improvement. Therefore, TBS seems to provide modest additional discriminatory information rather than substitute for BMD. This is in line with Schousboe et al., who showed that TBS added incremental fracture-risk information to conventional measures, but with only modest improvement in classification [16].

One of the strengths of this study is that the severity of vertebral fractures was not just determined as present or absent. SDI was also used to measure cumulative fracture burden, and BMD was measured at multiple clinically relevant skeletal sites. Direct comparison of BMD, TBS, and their combined performance also allowed evaluation of the incremental contribution of TBS.

There are some limitations that should be taken into account. The cross-sectional design does not allow prediction and establishes association only. The number of Grade 3 fractures in the hospital-based cohort was small (22), and multivariable models were limited in complexity and precision. Three of the TBS measurements were technically uninterpretable. Lumbar BMD can also be influenced by degenerative changes in the spine, and TBS is not a direct three-dimensional assessment of bone microarchitecture but an indirect DXA-derived measurement. Lastly, the improvement in discrimination following the addition of TBS was small and needs to be confirmed in larger prospective cohorts.

In general, the results indicated that BMD and TBS provide complementary information about the severity of vertebral compression fracture. TBS could be especially helpful when fracture severity seems out of proportion to BMD and should not be used as a replacement for conventional DXA assessment, but rather as an adjunct.

CONCLUSION

Increasing severity of vertebral compression fracture was associated with decreasing BMD and TBS and increasing cumulative vertebral deformity. TBS continued to be associated with severe fracture after adjustment for age and lumbar BMD and modestly enhanced model discrimination when included with BMD. These results indicate that TBS is a useful complementary tool to assess skeletal fragility, not

a substitute for traditional DXA-based BMD. Further larger prospective studies are required to validate its incremental value in fracture-risk stratification and future vertebral fracture prediction.

Lower BMD and TBS were associated with increasing vertebral compression fracture severity and greater cumulative vertebral deformity. TBS remained associated with severe fracture after adjustment for age and lumbar BMD and modestly improved model discrimination when added to BMD. These findings support TBS as a complementary measure of skeletal fragility rather than a replacement for conventional DXA-derived BMD. Larger prospective studies are needed to confirm its incremental value for fracture-risk stratification and future vertebral fracture prediction.

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AUTHOR CONTRIBUTIONS

All authors are contributed equally.

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