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The Relationship of Lumbar Degenerative Scoliosis with Postmenopausal Osteoporosis and Vitamin D

Lomber Dejeneratif Skolyozun Menopoz Sonrası Osteoporoz ve D Vitamini ile İlişkisi

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Abstract

Objective: To investigate whether adult lumbar degenerative scoliosis in postmenopausal women with osteoporosis is associated with hip bone mineral density and serum 25-hydroxyvitamin D levels.

Materials and Methods: This prospective observational cross-sectional study included 80 women aged 50-85 years with postmenopausal osteoporosis. Standing lumbosacral radiographs were used to measure the Cobb angle. Hip bone mineral density was assessed by dual-energy X-ray absorptiometry, and serum 25-hydroxyvitamin D was measured by chemiluminescence immunoassay.

Results: Forty women had adult lumbar degenerative scoliosis and 40 served as controls. The scoliosis group had lower femoral neck and total hip bone mineral density and T-scores, lower serum 25-hydroxyvitamin D levels, and vertebral fractures were observed only in this group. In women with scoliosis, the Cobb angle was negatively correlated with total hip bone mineral density and T-score and strongly inversely correlated with serum 25-hydroxyvitamin D. In logistic regression analysis, total hip T-score and serum 25-hydroxyvitamin D were independently associated with scoliosis.

Conclusion: In postmenopausal women with osteoporosis, adult lumbar degenerative scoliosis was associated with lower hip bone mineral density and lower serum 25-hydroxyvitamin D levels.

Keywords: Adult degenerative scoliosis, postmenopausal osteoporosis, hip bone mineral density, vitamin D, vertebral fracture

Öz

Amaç: Bu çalışmada, postmenopozal osteoporozlu kadınlarda erişkin lomber dejeneratif skolyoz varlığının kalça kemik mineral yoğunluğu ve serum 25-hidroksivitamin D düzeyleri ile ilişkisini araştırmak amaçlandı.

Gereç ve Yöntem: Bu prospektif, gözlemsel, kesitsel çalışmaya 50-85 yaş arasında, postmenopozal osteoporoz tanılı 80 kadın dahil edildi. Ayakta çekilen lumbosakral grafilerde Cobb açısı ölçüldü. Kalça kemik mineral yoğunluğu dual-enerji X-ışını absorbsiyometrisi ile, serum 25-hidroksivitamin D düzeyleri ise kemilüminesans immünolojik yöntemle değerlendirildi.

Bulgular: Kırk kadında erişkin lomber dejeneratif skolyoz saptandı ve 40 kadın kontrol grubunu oluşturdu. Skolyoz grubunda femur boynu ve total kalça kemik mineral yoğunluğu ile T-skorları ve serum 25-hidroksivitamin D düzeyleri daha düşüktü; vertebral kırıklar yalnızca bu grupta gözlendi. Skolyozu olan kadınlarda Cobb açısı, total kalça kemik mineral yoğunluğu ve T-skoru ile negatif; serum 25-hidroksivitamin D düzeyi ile güçlü negatif korelasyon gösterdi. Lojistik regresyon analizinde, total kalça T-skoru ve serum 25-hidroksivitamin D düzeyi, aynı model içinde skolyoz varlığı ile ilişkili bulundu.

Sonuç: Postmenopozal osteoporozlu kadınlarda erişkin lomber dejeneratif skolyoz, daha düşük kalça kemik mineral yoğunluğu ve daha düşük serum 25-hidroksivitamin D düzeyleri ile ilişkilidir.

Anahtar kelimeler: Erişkin dejeneratif skolyoz, postmenopozal osteoporoz, kalça kemik mineral yoğunluğu, vitamin D, vertebra kırığı

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Introduction

Why some postmenopausal women develop adult lumbar degenerative scoliosis (ALDS) while others do not remains unresolved. Adult degenerative scoliosis (ADS) is a three-dimensional spinal deformity recognized in skeletally mature adults and is generally defined by a coronal Cobb angle of ≥10° (1,2). ADS may result from the progression of idiopathic scoliosis that began earlier in life or may develop *de novo* in adulthood because of degenerative changes in the spine (2). Primary degenerative, or *de novo*, curves most often involve the lumbar or thoracolumbar spine, and meta-analytic data for *de novo* adult scoliosis indicate that prevalence increases with age and is higher in women and in adults older than 60 years (2,3). This *de novo* degenerative form is characterized by asymmetric degeneration of the intervertebral discs and facet joints and may present with axial back pain, radicular symptoms, and neurogenic claudication (1,2); these symptoms may contribute to disability and reduced quality of life (1).

Postmenopausal osteoporosis (PO) is a form of primary osteoporosis that occurs after menopause and is characterized by compromised bone strength, which increases the risk of fracture (4). Estrogen deficiency plays a central role in its pathophysiology, as menopause increases bone resorption and creates a relative imbalance between bone resorption and bone formation (5). Because vertebral and hip fractures are associated with substantial morbidity in postmenopausal women, PO remains an important clinical problem (4,6). Whether PO may contribute to the development or progression of ALDS remains unclear. Available findings have been conflicting, and a systematic review of *de novo* degenerative lumbar scoliosis did not identify osteoporosis as a consistent predictor of curve progression (7). At the same time, lumbar degenerative changes may artifactually increase spinal dual-energy X-ray absorptiometry (DXA) measurements, leading to discordance between spinal and hip bone mineral density (BMD) values and complicating interpretation of the association between scoliosis and osteoporosis (8). In keeping with this, lumbar scoliosis in postmenopausal women appears to increase with age but not to show a significant independent association with femoral neck or total hip bone density measures (9).

Vitamin D may be another biologically relevant factor in this context. Because vitamin D is essential for intestinal calcium absorption and skeletal mineralization, deficiency can lead to secondary hyperparathyroidism, increased bone turnover, bone loss, and fractures (10,11). However, the available synthesis-level evidence does not directly address ALDS. The quantitative syntheses cited here focus on adolescent idiopathic scoliosis (AIS) rather than ADS. In AIS, vitamin D deficiency and insufficiency appear common, but pooled analyses do not show a significant association with curve magnitude, and the overall association between serum vitamin D levels and AIS appears weak or inconsistent (12,13). In contrast, the available review literature in adult spinal deformity has focused primarily on perioperative bone-health optimization and fusion-related outcomes rather than on the etiologic relevance of vitamin D to *de novo* lumbar degenerative scoliosis (14). Therefore, the relevance of vitamin D to ALDS in postmenopausal women with osteoporosis remains insufficiently defined.

These gaps provide the rationale for the present study. Previous work has mainly addressed curve progression, the interpretive limitations of lumbar DXA in scoliotic patients, or bone-health optimization in adult spinal deformity, whereas evidence jointly evaluating hip-region BMD and serum 25-hydroxyvitamin D [25(OH)D] in postmenopausal women with established osteoporosis appears limited (7-9,14). In this prospective observational study, we investigated whether the presence of ALDS in postmenopausal women with established osteoporosis was associated with hip-region BMD values and serum 25(OH) D levels. We further examined whether these variables were independently associated with ALDS.

Materials and Methods

Study Design and Ethics Committee Approval

This prospective, observational, cross-sectional study was planned and approved by the University of Health Sciences Türkiye, Elazığ Fethi Sekin City Hospital Non-Interventional Research Ethics Committee with decision number 2024/5-20, dated 05.12.2024. The study was conducted in accordance with the principles of the Declaration of Helsinki, and written informed consent was obtained from all participants.

Patient Selection and Groups

Women aged between 50 and 85 years who were diagnosed with PO and who applied to University of Health Sciences Türkiye, Elazığ Fethi Sekin City Hospital Physical Therapy and Rehabilitation Outpatient Clinics were included in the study. Patients with a history of traumatic spine injury, active malignancy, or known serious systemic disease (lung, liver, kidney) were excluded from the study. After radiological evaluation, participants were divided into two groups according to the presence of ALDS: Group 1 (scoliosis group) consisted of patients with ALDS; Group 2 (control group) consisted of patients without ALDS. All included participants underwent standing radiography, DXA, and serum 25(OH)D assessment and had complete data for analysis.

Study Size

No formal a priori sample size calculation was performed. The study size was determined by the number of eligible postmenopausal women with PO who completed radiographic evaluation, DXA measurement, and serum 25(OH)D assessment during the study period. The final analytic sample comprised 80 participants, including 40 women with ALDS and 40 controls.

Data Collection Procedures

Demographic and Anthropometric Data

Demographic and anthropometric characteristics of the participants, such as age, height and body weight, were recorded at the time of application; body mass index [(BMI), kg/m^2] was calculated from these data.

Radiological Evaluation

Standing lumbosacral anteroposterior (AP) and lateral plain radiographs were obtained for all participants. The Cobb angle, the angle between lines drawn parallel to the endplates of the most curved upper and lower vertebrae on the AP radiograph, was used to measure curvature in the coronal plane. Angles greater than 10° were defined as adult lumbar scoliosis. For the diagnosis of ALDS, in addition to these criteria, the presence of at least one degenerative finding, such as disc space narrowing (DSN), facet arthropathy, osteophyte formation, lateral listhesis, or rotatory subluxation, was required. This definition aims to focus the study on curves that develop *de novo* after skeletal maturity and to distinguish AIS from its progression into adulthood (1,2). All radiographs were evaluated by a single physical medicine and rehabilitation specialist.

BMD Measurement

BMD measurements were made using the DXA method. Densitometric diagnosis of osteoporosis was made in accordance with the 2023 guidelines of the International Society for Clinical Densitometry. Accordingly, the lowest T-score measured at any of the lumbar spine (L1-L4, excluding artifactual vertebrae), femoral neck, or total hip regions was taken as the criterion of ≤-2.5 (15). All DXA measurements in the study were performed with the same model of DXA device used in our hospital [GE Lunar Prodigy DXA system (GE Healthcare, Madison, WI, USA)], and by the same experienced technician.

Biochemical Analysis

Participants' serum 25(OH)D levels were measured by chemiluminescence immunoassay, a standard method in our hospital's biochemistry laboratory. The results were classified according to the literature as follows: <20 ng/mL deficiency, 21-29 ng/mL insufficiency, and ≥30 ng/mL sufficiency (11).

Statistical Analysis

IBM SPSS Statistics for Windows, Version 22.0 (IBM Corp., Armonk, NY, USA) was used to analyze the data. Distributional properties of continuous variables were evaluated with the Shapiro-Wilk test; data were presented as mean ± standard deviation for normally distributed variables and as median (25^{th}-75^{th} percentile) for non-normally distributed variables. Categorical variables were expressed as numbers and percentages (n %). In intergroup comparisons, the independent sample t-test was used for continuous variables that met the normal distribution assumption, and the Mann-Whitney U test was used for those that did not meet the normal distribution assumption. The chi-square test was used to compare categorical data, and Fisher's exact test was used in cases where the expected number of cells was insufficient. To examine the relationships between variables, Pearson or Spearman correlation coefficients were calculated based on distributional characteristics. To assess independent predictors associated with the presence of ALDS, binary logistic regression analyses were performed using the presence of scoliosis as the dependent variable (1= scoliosis, 0= no scoliosis). Total hip T-score and serum 25(OH)D levels were included in the first model, and age and BMI were simultaneously included in the second model using the Enter method. Statistical significance was set at $p<0.05$ in all analyses.

Results

The study included 40 postmenopausal women with lumbar ADS and 40 without ADS. The participant flow is summarized in Figure 1. The baseline characteristics of the groups are shown in Table 1. While age was higher in the scoliosis group, no significant differences were observed in height, weight, or BMI. Conversely, BMD/T-scores for the femoral neck and total hip region were significantly lower in the scoliosis group, and serum 25(OH)D levels were lower. As expected, the Cobb angle was significantly higher in the scoliosis group (Table 1). In the scoliosis group, convex curvature was observed to the right in 22 patients (55%) and to the left in 18 patients (45%), and no apparent dominant side was observed in terms of scoliosis direction.

Vertebral fractures (VF) were observed only in the scoliosis group, and this distribution demonstrated a significant association between scoliosis and the presence of fractures (Table 2). Categorical analysis of vitamin D status revealed an increased rate of deficiency and a decreased rate of sufficiency in the scoliosis group (Table 3).

Correlation analysis revealed significant negative correlations between the Cobb angle and total hip T-score and BMD in the scoliosis group, and a strong inverse correlation between the Cobb angle and 25(OH)D. No significant correlation was found between the Cobb angle and either BMD parameters or vitamin D levels in the control group (Table 4).

In the logistic regression analysis, when total hip T-score and 25(OH)D level were included in the model together, both variables were independently associated with the presence of ALDS, and the model demonstrated good explanatory power (Model 1a, Table 5). In the model including age and BMI, only age was significantly associated with scoliosis, while BMI was not an independent predictor, and the model's explanatory power was lower (Model 2b, Table 5).

Discussion

Current findings suggest that ALDS is not solely attributable to aging and may also be associated with osteoporosis, vitamin D deficiency, and osteoporotic VFs. However, the cross-sectional design of the study does not allow to definitively demonstrate

the causal relationship; it raises the possibility that the interaction between scoliosis, osteoporosis, and vitamin D deficiency is a bidirectional and dynamic process. When the significantly lower BMD found in the scoliosis group, the significantly low vitamin D levels, and the fact that osteoporotic VFs were observed only in this group are evaluated together, these findings suggest that bone fragility and vitamin D insufficiency may contribute to a "brittle bone" profile in patients with ALDS.

Adult spinal deformities are reported to affect approximately one-third of individuals over the age of 50 and more than two-thirds of the population over the age of 70 (16). In McAviney et al.'s (3) systematic review and meta-analysis examining the frequency of *de novo* scoliosis in adults, data from four cross-sectional and one cohort study (total 4069 participants; age range 41-94 years, 66.6% female) that evaluated scoliosis in the general population using imaging

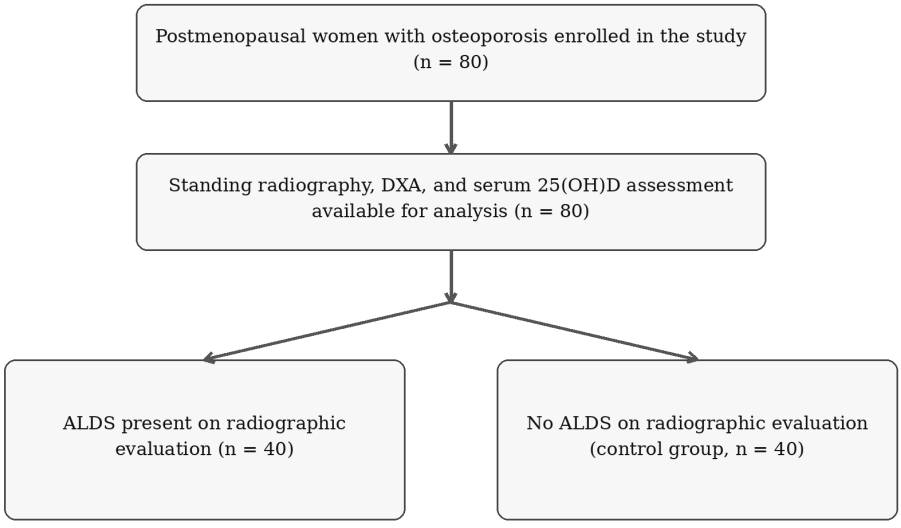

Figure 1. STROBE-oriented participant flow diagram
ALDS: Adult lumbar degenerative scoliosis, DXA: Dual-energy X-ray absorptiometry, 25(OH)D: 25-hydroxyvitamin D

Table 1. Demographic and clinical characteristics of the study groups

Variable	Scoliosis (n=40)	Control (n=40)	Test statistic (t/z)	p-value
Age, years*	69.55±6.86	65.47±7.10	t=2.61	0.011
Height, cm*	160.56±5.72	162.06±5.58	t=-1.18	0.240
Weight, kg*	70.11±10.27	69.69±11.82	t=0.17	0.867
BMI, kg/m²*	27.29±4.37	26.62±4.85	t=0.65	0.518
Femoral neck T-score*	-2.31±0.96	-1.57±0.83	t=-3.69	<0.001
Femoral neck BMD, g/cm²*	0.71±0.12	0.80±0.10	t=-3.29	0.001
Total hip T-score†	-2.05 (-3.35–1.60)	-1.45 (-2.00–0.90)	z=-3.37	0.001
Total hip BMD, g/cm²†	0.77 (0.61-0.84)	0.83 (0.76-0.90)	z=-2.59	0.009
Cobb angle,°†	14.50 (12.00-18.50)	5.00 (4.00-6.50)	z=-7.72	<0.001
25(OH)vitamin D, ng/mL†	14.00 (8.00-19.00)	22.50 (17.00-28.00)	z=-4.59	<0.001

Data are presented as mean ± standard deviation for normally distributed variables and as median (25^{th}-75^{th} percentile) for non-normally distributed variables.
*: Independent samples t-test, †: Mann-Whitney U test. "Test statistic" column shows the corresponding t or z values for each comparison, BMI: Body mass index, BMD: Bone mineral density

Table 2. Distribution of vertebral fractures between groups

Vertebral fracture	Scoliosis (n=40)	Control (n=40)	Total (n=80)	Test/statistic	p-value
Present	8 (20.0%)	0 (0.0%)	8 (10.0%)	Fisher's exact	0.005
Absent	32 (80.0%)	40 (100.0%)	72 (90.0%)		

Data are presented as n (%). Because 50% of cells had an expected count <5, group comparison was performed using Fisher's exact test (Pearson χ^2 =8.89, df =1, asymptotic p=0.003)

Table 3. Distribution of vitamin D status between groups					
25(OH)vitamin D status	**Scoliosis (n=40)**	**Control (n=40)**	**Total (n=80)**	**Test statistic (χ^2)**	**p-value**
Deficiency	31 (77.5%)	16 (40.0%)	47 (58.8%)	13.79	0.001
Insufficiency	9 (22.5%)	18 (45.0%)	27 (33.8%)		
Sufficiency	0 (0.0%)	6 (15.0%)	6 (7.5%)		
Data are presented as n (%). Group comparison was performed using Pearson's chi-square test (χ^2=13.79, df =2, p=0.001; minimum expected count =3.0)					

Table 4. Spearman correlation between Cobb angle and clinical variables in scoliosis and control groups		
Variable	**Scoliosis group (n=40) Spearman r (p-value)**	**Control group (n=40) Spearman r (p-value)**
BMI, kg/m²	0.116 (p=0.477)	0.323* (p=0.042)
Femoral neck T-score	-0.224 (p=0.165)	0.011 (p=0.944)
Femoral neck BMD, g/cm²	-0.286 (p=0.074)	0.003 (p=0.987)
Total hip T-score	-0.328* (p=0.038)	0.053 (p=0.745)
Total hip BMD, g/cm²	-0.359* (p=0.023)	0.056 (p=0.729)
25(OH)vitamin D, ng/mL	-0.754** (p<0.001)	-0.119 (p=0.465)
Data are presented as Spearman's rank correlation coefficients (r) with corresponding p-values. *: p<0.05, **: p<0.01, BMI: Body mass index, BMD: Bone mineral density		

Table 5. Multivariable logistic regression models for factors associated with lumbar degenerative scoliosis				
Variable	**Model 1a OR (95% CI)**	**Model 1a p-value**	**Model 2b OR (95% CI)**	**Model 2b p-value**
Total hip T-score (femur total)	0.41 (0.20-0.82)	0.012	–	–
25(OH)vitamin D, ng/mL	0.86 (0.79-0.94)	<0.001	–	–
Age, years	–	–	1.10 (1.02-1.18)	0.012
BMI, kg/m²	–	–	1.05 (0.95-1.17)	0.326
Dependent variable: presence of lumbar degenerative scoliosis (1= scoliosis, 0= control). Data are presented as odds ratios (OR) with 95% confidence intervals (CIs) and p-values. Model 1a: predictors = total hip T-score and 25(OH) vitamin D [χ^2(2) =32.64, p<0.001; Nagelkerke R^2=0.45; Hosmer-Lemeshow p=0.97; overall accuracy =73.8%]. Model 2b: predictors = age and BMI [χ^2(2) =7.69, p=0.021; Nagelkerke R^2 =0.12; Hosmer-Lemeshow p=0.28; overall accuracy =56.3%). BMI: Body mass index				

methods and excluded individuals previously diagnosed with scoliosis/spine disease were analyzed as a result of a search of MEDLINE, Embase, CINAHL, Web of Science, and PubMed databases up to March 28, 2018. The prevalence of scoliosis was found to be significantly higher in women and individuals over 60 years of age, suggesting that older age and female sex represent higher-prevalence groups for adult *de novo* scoliosis (3).

Xu et al. (17) found the prevalence of ALDS to be approximately 13.3% in 2395 Chinese Han individuals over 40 years of age who applied to a DXA clinic and had no history of previous spinal trauma, surgery or scoliosis; they reported that the presence of ALDS was significantly associated with age, gender and BMD, whereas the severity of the curve was not associated with age, gender, BMI and BMD. In the current study, the significantly higher age found in the scoliosis group compared to the control group is consistent with the age-related increase in risk reported in the literature. The increased prevalence of ALDS with age is thought to be due to cumulative disc and facet joint degeneration, ligamentous laxity, paraspinal muscle weakness, and accompanying bone fragility progressing over time, disrupting spinal balance (1-3,7). However, the lack of a significant difference between groups in terms of BMI and the lower explanatory power of the age-and-BMI model suggest that the degree of curve cannot be explained solely by aging or body composition. This finding suggests that multiple factors beyond age, such as disc and facet joint degeneration, and bone quality deterioration, contribute to the severity of the deformity, and that scoliosis progression reflects a more complex biomechanical process (1,2,7,18,19).

In their retrospective study evaluating the relationship between ALDS and osteoporosis in adult patients, Huang et al. (18) compared 53 lumbar degenerative scoliosis patients treated between 2012 and 2016 with a control group of 53 individuals without scoliosis. Scoliosis diagnosis was confirmed by radiography and magnetic resonance imaging (MRI), Cobb angles were measured, and T-scores were obtained by DXA at the L_2-L_4, femoral neck, Ward's triangle, and trochanter regions in all patients. Analyses showed that T-scores were significantly lower in scoliosis patients compared to the control group, indicating more pronounced osteoporosis in this group; however, no significant correlation was found between segmental T-scores and the Cobb angle (18). In a retrospective study by Wang et al. (19), the relationship between paraspinal

muscle sarcopenia, osteoporosis, and vertebral rotational subluxation (VRS) was examined in 166 patients with ALDS; VRS was detected in 54.2% (n=90). Coronal (Cobb angle, coronal balance distance, lateral translation) and sagittal [thoracic kyphosis, lumbar lordosis, sagittal vertical axis (SVA)] spinal parameters were measured from upright anteroposterior-lateral radiographs. Bilateral paraspinal muscle cross-sectional area and fat infiltration rate (%) at the L1-S1 levels were assessed using lumbar MRI. Vertebral rotation angles and Hounsfield unit (HU) values were calculated from axial computed tomography (CT) scans, and L1 HU ≤110 was used as the osteoporosis criterion. As a result of the study, it was stated that VRS in ALDS patients was characterized by an asymmetric paraspinal muscle sarcopenia pattern with a diagonal distribution and vertebral osteoporosis, and these structural/tissue level changes may play an important role in curve progression (19). There are also studies emphasizing that falsely high BMD can be detected in lumbar DXA measurements due to degenerative changes and therefore hip-based BMD measurements may provide a less confounded estimate of skeletal fragility in these patients (8).

In the current study, the finding that femoral neck and total hip T-scores and BMD values were significantly lower in the scoliosis group and that only the total hip T-score emerged as an independent predictor in the multivariate model predicting the presence of scoliosis is consistent with these literature findings. A possible pathophysiological explanation is that reduced bone mass and microarchitectural deterioration may increase susceptibility to lumbar degenerative scoliosis, particularly in the postmenopausal period. Conversely, the lack of correlation between femoral neck T-score/BMD values and Cobb angle severity, while the significant correlation between total hip T-score/BMD values and the degree of curve, may indicate that hip-based measurements, particularly total hip in our dataset, are less influenced by lumbar degenerative artifacts and may better reflect systemic skeletal fragility in this setting (8).

In a longitudinal study by Ye et al. (20) using data from the Framingham Heart Study Offspring and Third Generation Multi-Detector CT, the progression of spinal degeneration [facet joint osteoarthritis (FJOA) and intervertebral DSN] was evaluated during follow-up in individuals with vertebral compression fractures at baseline. A total of 370 (31%) of 1197 participants had an existing VCF at baseline. Although the DHN summary index increase appeared to be associated with VCF in the analysis, it lost significance after multivariate adjustment. On the other hand, the presence of VCF was associated with FJOA progression, especially in severe (grade 3) VCF cases, and as the severity of VCF increased, the worsening of FJOA increased. In summary, this study supports that VCFs may accelerate spinal osteoarthritis, especially in severe cases (20). Savarese et al. (21) investigated the relationship between spinopelvic alignment and VFs in 93 postmenopausal women with osteopenia/osteoporosis using a retrospective, cross-sectional design. Pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS), SVA, global tilt (GT), spinosacral angle (SSA), T1 pelvic angle (TPA), lumbar lordosis (LL), and thoracic kyphosis (TK) were measured from lateral spine-pelvis radiographs using Surgimap software. Fractures were graded according to the Genant classification, and the spinal deformity index (SDI) was calculated from the sum of these. Their analysis reported that GT was the only parameter significantly associated with the presence of VFs, with each 1° increase in GT increasing the prevalence of fractures by approximately 2.1%. However, no significant association was found between SS, PT, PI, LL, TK, SVA, or SSA and the presence of fractures. It has also been reported that GT values are higher in patients with fractures and that SDI shows a significant correlation with GT, which reflects global sagittal balance (21,22). The significant association between scoliosis and the presence of VFs in the current study supports these literature findings. It is plausible that the impaired global sagittal balance and asymmetric loading associated with degenerative scoliosis may increase the risk of VCF by increasing segmental stresses on the vertebral body. When a fracture develops, it may further aggravate the progression of FJOA, particularly in severe (grade 3) cases, and could thereby contribute to progression of the deformity over time. Therefore, the association between scoliosis and VFs may reflect a plausible two-way pathomechanism operating through a two-way "vicious cycle" (deformity → fracture risk ↑; fracture → degeneration/deformity progression ↑).

In a recent review of adult scoliosis, calcium and vitamin D supplementation was described as a supportive strategy for improving bone health and reducing fracture risk, which may indirectly help limit deformity progression in osteoporotic patients (23). In a study by Aspell et al. (22) based on the English Longitudinal Study of Ageing cohort, the relationship between vitamin D deficiency and impaired muscle strength and physical performance in community-dwelling elderly individuals was examined. Muscle strength was assessed using a handgrip dynamometer and physical performance was assessed using the short physical performance battery in 4157 participants aged 60 years and older (mean age 69.8±6.9 years). Vitamin D deficiency, defined as a serum 25(OH)D level <30 nmol/L, was reported to be significantly associated with reduced muscle strength and impaired physical performance (22). In a recent review summarizing approaches to the prevention of ADS, it was emphasized that maintaining bone health through adequate calcium and vitamin D intake is one of the basic strategies to reduce the risk of developing vertebral deformities due to osteoporosis (23). In the current study, the finding that serum 25(OH)D levels were significantly lower in the scoliosis group compared to the control group is consistent with these data. When evaluated together with our study and previous studies, it can be suggested that vitamin D deficiency may impair postural balance through decreased BMD and loss of muscle strength, facilitate repetitive microtrauma, and through these mechanisms, may both increase the risk of VFs and predispose to spinal deformity progression. In this context, the correlation of vitamin D levels with Cobb angle severity observed in our cohort may indicate that lower vitamin D status accompanies greater

impairment in bone-muscle health; however, this interpretation should be considered exploratory, as direct evidence linking vitamin D deficiency to curve severity in ADS remains limited.

The logistic regression findings should be interpreted with caution. In the model that included total hip T-score and serum 25(OH)D, both variables were independently associated with the presence of ALDS. In a separate model, age was associated with ALDS whereas BMI was not, and this age-and-BMI model showed lower explanatory power. Accordingly, our results suggest that lower total hip BMD and lower 25(OH)D levels are important correlates of ALDS, but they do not establish independence from age because all variables were not entered into the same model. Nevertheless, the findings suggest that reduced bone strength and low vitamin D status may play an important role in the biological background of ALDS.

Strengths of the Study

The present study has several strengths. It prospectively enrolled a clinically homogeneous cohort of postmenopausal women with densitometric osteoporosis, evaluated hip rather than lumbar BMD to reduce the effect of degenerative measurement artifacts, and assessed radiographic deformity, DXA parameters, serum 25(OH)D levels, and VF within the same analytical framework. In addition, all DXA examinations were performed using the same device and by the same experienced technician, and all radiographs were evaluated by a single specialist, which reduced measurement variability.

Study Limitations

Our study has several limitations. First, due to its cross-sectional design, relationships between variables cannot be interpreted at the causal level. Second, the scoliosis group had a higher mean age than the control group; therefore, residual confounding by age cannot be fully excluded despite the supplementary model that included age and BMI. Furthermore, the relatively limited sample size may have limited statistical power, particularly in subgroup analyses. Another limitation of the study is the lack of assessment of muscle mass/sarcopenia parameters, which are known to play an important role in the development and progression of scoliosis. Similarly, radiographic deformity indicators such as the lumbar osteophyte score, which are among the structural changes that may influence scoliosis, and other degenerative measures such as FJOA, and intervertebral DSN, were not systematically analyzed in this study. Another limitation is the lack of grading for VCF, which have significant prognostic significance in spinal deformities. Therefore, our findings need to be supported by multicenter studies with larger samples, longer-term follow-up, and incorporating muscle mass, detailed degenerative scoring, and VCF grading.

Conclusion

The current study revealed that, among postmenopausal women with osteoporosis, ALDS was associated with lower total hip BMD and lower serum 25(OH)D levels. In addition, the detection of osteoporotic VFs only in the scoliosis group suggests that ALDS and VFs may cluster within the same "brittle bone" phenotype and may be associated with common pathomechanisms.

These findings suggest that routine assessment of bone quality (especially total hip BMD) and vitamin D levels, screening for VFs, and planning appropriate osteoporosis treatment when necessary may be key elements to consider in clinical management in postmenopausal women with scoliosis.

Ethics

Ethics Committee Approval: This prospective, observational, cross-sectional study was planned and approved by the University of Health Sciences Türkiye, Elazığ Fethi Sekin City Hospital Non-Interventional Research Ethics Committee with decision number 2024/5-20, dated 05.12.2024.

Informed Consent: Written informed consent was obtained from all participants.

Footnotes

Authorship Contributions

Concept: M.Ş.E., M.K., N.Y., Design: M.Ş.E., Data Collection or Processing: M.Ş.E., M.K., N.Y., Analysis or Interpretation: M.Ş.E., Literature Search: M.K., N.Y., Writing: M.K., N.Y.

Conflict of Interest: No conflict of interest was declared by the authors.

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