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Research Article

Facet tropism is not associated with lumbar spondylolysis: a computed tomography-based three-dimensional morphometric case–control study

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ABSTRACT

Objective: Facet tropism has been proposed as a morphologic modifier of posterior element loading, but prior evidence in lumbar spondylolysis is inconsistent and often based on 2D measurements. This study aimed to evaluate whether facet tropism differs between patients with lumbar spondylolysis and controls using a CT-based three-dimensional (3D) morphometric workflow with vertebra-anchored reference planes.

Methods: This retrospective case–control study included 39 individuals: 19 with CT-confirmed lumbar spondylolysis and 20 controls (age and sex comparable). Vertebrae L1-L5 were segmented, 3D surface models were generated, and best-fit planes were computed for each superior and inferior facet surface bilaterally. Facet orientation was quantified relative to sagittal, frontal, and transverse planes. Facet tropism (FT) was defined as the absolute right–left difference in facet angles for the same level and facet type; FT presence was descriptively defined as >5°, while hypothesis testing used continuous FT values. Group comparisons were performed across L1–L5 and for prespecified lowerlumbar segment metrics (L4-L5 facet-plane mismatch and L5 intra-vertebral mismatch).

Results: Spondylolysis involved L5 in 18/19 patients (4 unilateral, 14 bilateral) and L4 in 1/19. Across L1-L5, facet tropism (FT) did not differ between groups for either superior or inferior facets in any plane (all $p > .05$). The greatest numerical difference was observed for L5 inferior FT on the sagittal plane (controls 10.38 ± 9.40 vs. patients 7.51 ± 10.93), but this comparison did not reach statistical significance ($p = .092$). Lower-lumbar segment-focused mismatch measures also showed no between-group differences (all $p > .05$). Frontal-plane and sagittal-plane angles showed strong positive correlations in both groups (controls: $r = 0.811$-0.998; patients: $r = 0.851$-0.995; all $p < .05$), whereas transverse-plane parameters showed no meaningful associations.

Conclusion: Using CT-based 3D morphometry, no statistically significant association between facet tropism and lumbar spondylolysis was demonstrated in the present study population, and facet tropism did not discriminate cases from controls across lumbar levels or lowerlumbar segmental mismatch metrics. In this cohort, which was predominantly characterized by L5 involvement and frequent bilateral defects, side-to-side facet asymmetry did not appear to represent a major independent morphologic marker when measured with a standardized 3D framework.

Level of Evidence: Level III, Prognostic Study.

Introduction

Lumbar spondylolysis is a defect of the pars interarticularis that is most often conceptualized as a stress-related injury of the posterior elements, particularly in physically active adolescents and young adults, and it may remain clinically silent or present with activity-related low back pain and functional limitation. The condition is also clinically relevant because pars defects can contribute to the continuum of isthmic spondylolisthesis in a subset of patients, with long-term trajectories influenced by age, level involvement, and mechanical demand. Contemporary syntheses emphasize that repetitive extension–rotation loading and segment-specific stress concentration are central to pathogenesis; yet, they also highlight substantial inter-individual variability that cannot be explained by exposure alone, implying a potential role for patient-specific morphologic modifiers of lumbosacral biomechanics.[1-3]

The lumbar facet (zygapophyseal) joints are key posterior stabilizers that constrain axial rotation and shear while sharing load with the intervertebral disc, and their morphology varies across individuals and spinal levels. Two related descriptors are commonly studied: facet orientation (the absolute angulation of each facet surface relative to a defined anatomical reference) and facet tropism (side-to-side asymmetry in facet orientation within the same motion segment).[4] Because unilateral or asymmetric guidance of motion can plausibly redistribute stresses across the posterior arch and disc, facet tropism has been investigated across multiple spinal phenotypes, including disc herniation, disc degeneration, and degenerative lumbar spinal stenosis. However, evidence remains mixed, in part because operational definitions (including cut-offs for “tropism”) and imaging measurement conventions differ between studies, and meta-analytic syntheses suggest that observed associations can be level specific and method dependent.[5-8]

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When the focus is narrowed to spondylolysis, the literature is similarly heterogeneous. Some investigations—particularly those examining unilateral pars defects—support the notion that asymmetric facet morphology (often described as relatively more coronal orientation on the affected side) may be associated with lesion laterality, consistent with a biomechanical pathway in which asymmetric posterior guidance concentrates stress on one side of the posterior arch. In contrast, large community-based multidetector CT analyses have reported that the association between facet orientation/tropism and spondylolysis is not straightforward, challenging a simple "tropism predisposes to pars defect" model. Adding to this uncertainty, more recent work using 3D bone-model approaches in early-stage/isthmic spondylolysis has reported negative findings regarding facet tropism as a predisposing factor, suggesting that any relationship—if present—may be contingent on developmental stage, disease phase, or measurement methodology.[9-11]

A major explanation for conflicting results is methodological: many prior studies estimate "facet angle" from limited two-dimensional axial slices, where slice selection, vertebral rotation, and reference-line choice can materially influence the measured value, and where a complex three-dimensional articular surface is reduced to a single planar proxy. Computed tomography–derived 3D modeling and registration frameworks can mitigate these issues by enabling plane-specific and coordinate-system–anchored measurements, potentially improving reproducibility and anatomical validity. Therefore, the present study evaluates facet tropism in patients with lumbar spondylolysis versus controls using CT-based 3D anatomical models and a standardized multi-planar assessment strategy, aiming to clarify whether side-to-side facet asymmetry is meaningfully associated with spondylolysis when measured with a method better aligned with three-dimensional joint morphology.[10,12]

Materials and methods

This study was designed as a retrospective case–control analysis based on computed tomography (CT) examinations. This study was approved by the Ethics Committee of İstanbul Medipol University (Approval No: 750, Date: September 14, 2023).

The researchers hypothesized that facet tropism quantified using a CT-based 3D morphometric workflow would differ between individuals with lumbar spondylolysis and controls, with a prespecified focus on lower lumbar levels (L4-L5 and L5).

Patients were identified from İstanbul Medipol University's institutional radiology and/or clinical database within the predefined study period. The case group comprised individuals with a clinical diagnosis of lumbar spondylolysis and CT-confirmed pars interarticularis defect(s). The control group consisted of individuals who underwent lumbar CT during the same period and had no evidence of spondylolysis or other exclusionary spinal pathology on imaging review.

A total of 39 individuals were included: 19 patients with spondylolysis and 20 controls.

Inclusion criteria

- **Controls:** Individuals without a prior diagnosis or imaging evidence of a musculoskeletal/spinal pathology relevant to the study question (i.e., no spondylolysis/spondylolisthesis and no major structural deformity on review).
- **Spondylolysis group:** Individuals with clinically diagnosed and CT-confirmed lumbar spondylolysis.

Exclusion criteria

Participants were excluded if they had imaging evidence or a clinical history consistent with congenital spinal stenosis, vertebral fractures, tumors, Paget's disease, marked spinal deformity (e.g., scoliosis with Cobb angle >20°), or other conditions expected to alter facet morphology. Individuals with spondylolisthesis were excluded from both groups (and in addition, controls were excluded if spondylolysis was present). Patients receiving systemic steroid therapy and those with severe degenerative osteoarthritic changes that could distort facet anatomy were excluded.

All lumbar CT examinations were retrieved in Digital Imaging and Communications in Medicine (DICOM) format. Scans with incomplete coverage of the lumbar vertebrae required for analysis, pronounced motion artifacts, or insufficient image quality to delineate facet joint cortical margins were excluded. CT acquisition parameters (including slice thickness, reconstruction kernel, and in-plane resolution/voxel size) were extracted from the DICOM metadata and reviewed to ensure adequate image quality for facet surface segmentation. Across the included CT examinations, reconstructed slice thickness was approximately 0.625 mm, and images were reconstructed using the Philips B standard reconstruction kernel. In-plane pixel spacing was approximately 0.49 × 0.49 mm, yielding reconstructed voxel dimensions of approximately $0.49 \times 0.49 \times 1.5$ mm and an approximate voxel volume of 0.36 mm^3. These parameters were considered adequate for segmentation-based assessment of the lumbar facet articular surfaces.

The overall workflow consisted of (i) lumbar vertebral segmentation and surface model generation, followed by (ii) geometric processing and angle computation in an engineering environment. Lumbar vertebrae were segmented using 3D Slicer. Semi-automatic threshold-based segmentation was performed on each CT series to isolate osseous structures, followed by manual refinement to correct cortical boundaries and remove non-target structures. Vertebral bodies from L1 to L5 were segmented and individually labeled (Figure 1). The resulting 3D surfaces were exported in stereolithography (STL) format and archived in a structured dataset for downstream processing, consistent with previously described CT-based patient-specific three-dimensional spine modeling workflows.[13]Stereolithography models were imported into ANSYS Workbench/SpaceClaim. To ensure standardized, reproducible measurement across subjects, a Cartesian coordinate system was established for each vertebra. The reference planes—sagittal, coronal (frontal), and transverse—were defined using consistent anatomical landmarks and vertebral orientation cues, aligned to the vertebral geometry (e.g., posterior vertebral wall and other reproducible posterior element references), following

HIGHLIGHTS

- In this computed tomography-based (CT-based) three-dimensional (3D) case–control study, facet tropism (FT) was not significantly associated with lumbar spondylolysis.
- Superior and inferior FT values were comparable between groups across L1-L5 in sagittal, frontal, and transverse planes.
- Lower-lumbar facet mismatch parameters also did not differ significantly between patients and controls.
- The 3D morphometric protocol provided a consistent multiplanar assessment of lumbar facet orientation.
- These findings suggest that facet asymmetry alone may not be a major anatomic factor in lumbar spondylolysis.

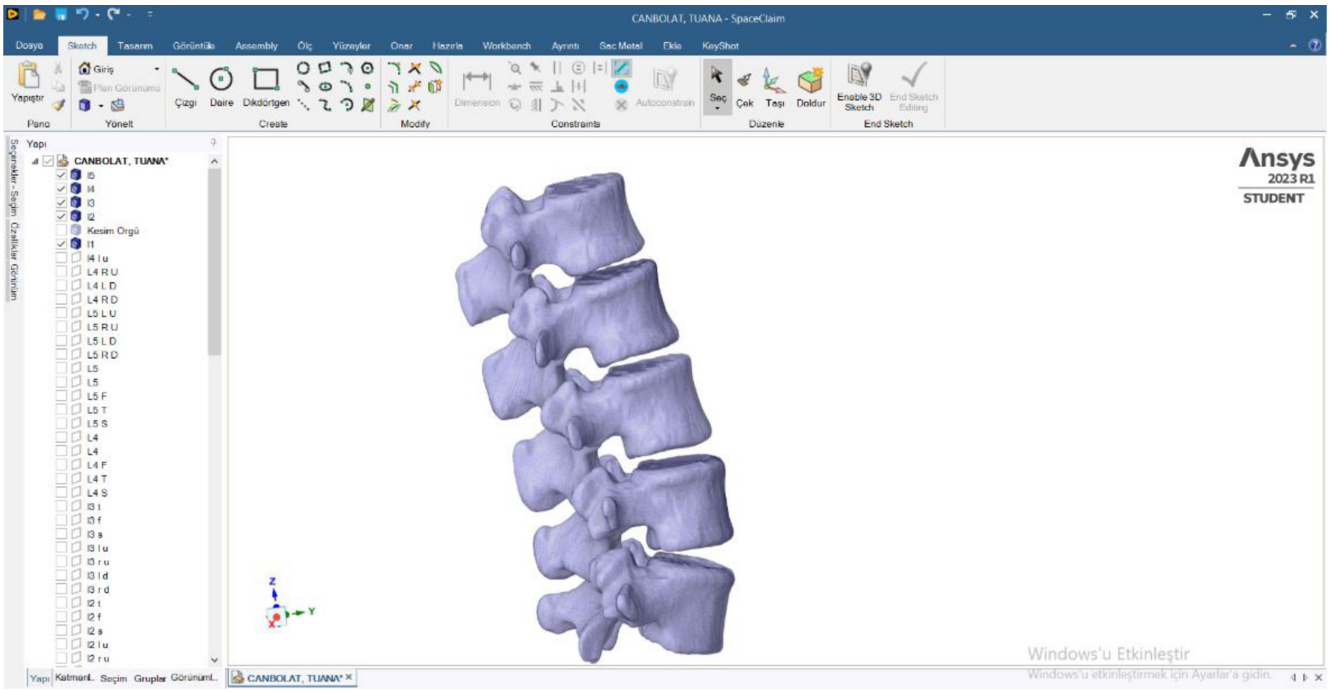


Figure 1. Appearance of the lumbar vertebrae between L1 and L5 after segmentation.

a previously described morphometric framework adapted for lumbar vertebrae[14] (Figure 2). This step aimed to minimize artifacts from vertebral rotation and slice selection inherent to 2D measurement approaches. To assess repeatability of the 3D facet plane fitting and angle extraction workflow, a random subset of 10 participants (5 spondylolysis, 5 controls) was reprocessed. The same observer repeated the segmentation/plane fitting and angle computation after a 2-week washout period (intraobserver reliability). A second independent observer repeated the workflow in the same subset (interobserver reliability). Reliability was quantified using the intraclass correlation coefficient (ICC) with a two-way random-effects model and absolute agreement (ICC[2,1]) and is reported with 95% CIs. The authors additionally calculated the standard error of measurement (SEM=SD × √(1−ICC)) and the minimal detectable change at 95% confidence (MDC95=1.96 × √2 × SEM).

For each vertebral level (L1-L5), facet joint surfaces were evaluated bilaterally for both the superior and inferior articular processes, yielding 4 facet surfaces per vertebra (right superior, left superior, right inferior, and left inferior). For each facet, the articular region was isolated on the 3D model and sampled as a dense set of surface points ("surface scanning"). A best-fit facet plane was then generated using a least-squares fitting approach, which represented the dominant orientation of the articular surface.

To standardize measurements across subjects, each vertebra was positioned within a vertebra-specific right-handed Cartesian XYZ coordinate system (Figure 3). Following established 3D morphometric frameworks, the origin/reference point was defined at the center (centroid) of the superior endplate, and the vertebral orientation was normalized by defining the XY plane using the posterior wall of the vertebral body as the anatomical reference; the Z axis was defined through the superior endplate center (cranio-caudal direction)

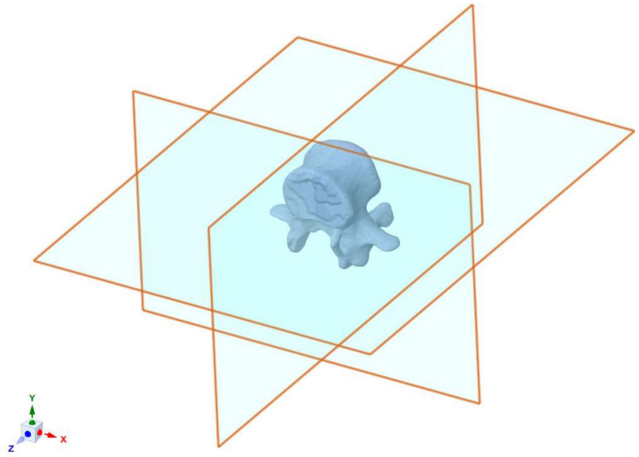


Figure 2. Obtaining the sagittal, transverse, and frontal planes.

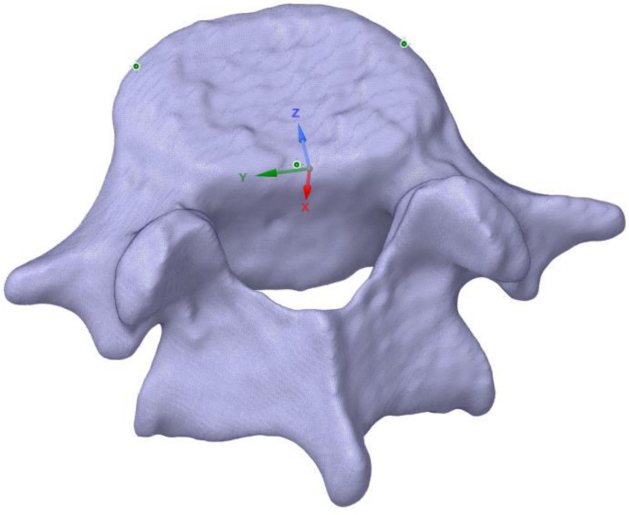


Figure 3. Position of the vertebra in the Cartesian XYZ coordinate system.

relative to this plane definition. Accordingly, the anatomical planes used for angle calculations were defined as: transverse plane=XY, sagittal plane=XZ, and frontal (coronal) plane=YZ (Figure 3).

Facet orientation was quantified in a multi-planar manner by computing the angle between each facet plane and each of the three reference planes (sagittal, frontal, and transverse). Thus, for every facet plane, 3 plane-specific facet angles were obtained: (i) the sagittal facet angle (angle between the facet plane and the sagittal plane), (ii) the frontal facet angle (angle between the facet plane and the frontal plane), and (iii) the transverse facet angle (angle between the facet plane and the transverse plane) (Figures 4,5).

Facet tropism (FT) was defined as the absolute side-to-side difference between the right and left facet angles for the same vertebral level and the same articular process (superior or inferior), calculated separately for each reference plane (sagittal, frontal, and transverse):

FT = $|\theta_{Right} - \theta_{Left}|$ (degrees)

According to the predefined rule, FT was considered present when the right–left difference exceeded 5° for the relevant plane and facet type. For hypothesis testing, FT was analyzed as a continuous variable.[15]

Therefore, for each level (L1-L5), the following were derived for each plane:

- Superior FT (right–left difference of superior facet angles),
- Inferior FT (right–left difference of inferior facet angles).

To contextualise morphology at clinically relevant lower-lumbar levels, additional segmental parameters were computed as follows:

1. **L4-L5 superior facet plane mismatch:** the absolute angular difference between the **L5 superior** facet plane and the **L4 superior** facet plane on the same side (left and right), computed separately for each reference plane (Figure 6A).
2. **L4-L5 inferior facet plane mismatch:** the absolute angular difference between the **L5 inferior** facet plane and the **L4 inferior** facet plane on the same side (left and right), computed separately for each reference plane.
3. **L5 intra-vertebral facet plane mismatch:** the absolute angular difference between the **L5 superior** and **L5 inferior** facet planes on the same side (left and right), computed separately for each reference plane (Figure 6B).[16,17]

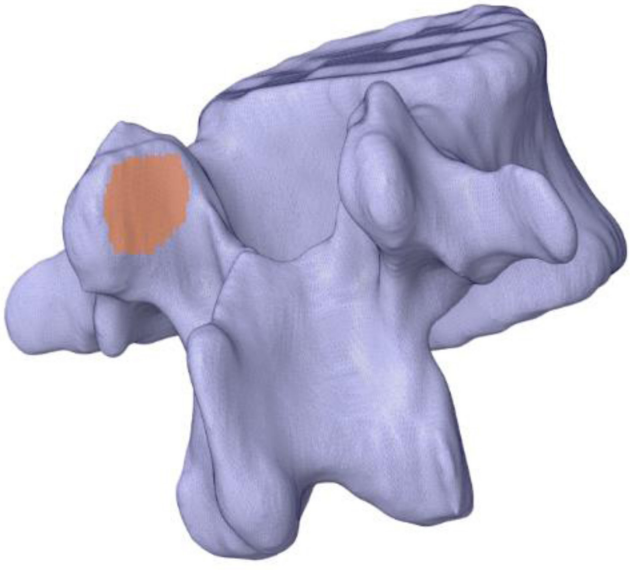


Figure 4. Scan image of the facet surface.

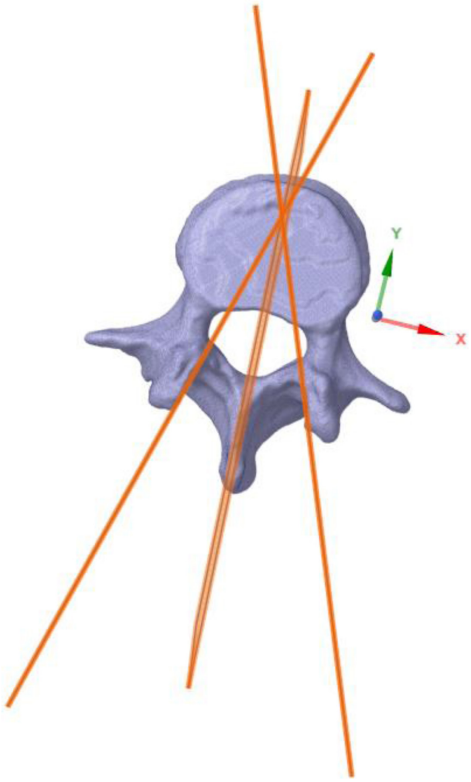


Figure 5. Angles formed by facet surface planes relative to the midsagittal plane.

All measurements were generated using an identical, standardized workflow and identical reference definitions across subjects to minimize methodological variance.

Statistical analysis

Data were analyzed using SPSS software (ver. 22.0; IBM Corp., Armonk, NY, USA). Continuous variables were assessed for normality using the Shapiro–Wilk test together with distributional inspection (histograms and Q–Q plots). Normally distributed data are reported as mean ± SD, whereas non-normally distributed data are reported as median [IQR]. Categorical variables are presented as counts and percentages.

Between-group comparisons were conducted as follows: (i) independent-samples *t*-test for normally distributed continuous variables and Mann–Whitney *U*-test otherwise; (ii) chi-square or Fisher's exact test for categorical variables, as appropriate. Alongside *P*-values, effect estimates are presented as between-group differences (mean or median difference, as appropriate). Because several level- and plane-specific facet tropism variables were non-normally distributed, the facet tropism parameters in Table 1 were summarized as median and compared between groups using the Mann–Whitney *U*-test. Correlations between plane-specific facet parameters were assessed using Spearman's rank correlation coefficient (r). Correlation magnitude was interpreted as high ($|r| \geq 0.70$), moderate ($|r| = 0.50$-0.69), and low ($|r| < 0.50$). Given

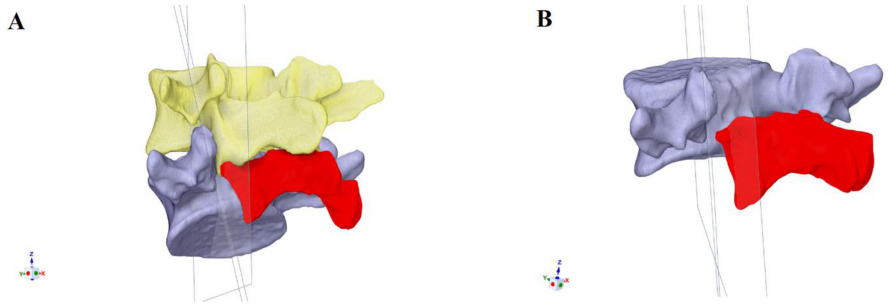


Figure 6. (A) The angle between the superior facet surface plane of L5 and the superior facet surface plane of L4 on the same side (yellow). (B) The angle between the superior and inferior facet surface planes of the L5 vertebra on the same side. The fractured L5 fragment (bilateral pars defects) is shown in red.

the multilevel and multiplanar structure of the dataset, they prespecified lower-lumbar outcomes (L4-L5 mismatch metrics and L5-related measures) as primary analyses, whereas comparisons across upper levels (L1-L3) were considered exploratory. The authors therefore interpret exploratory *P*-values cautiously and emphasize effect estimates for prespecified lower-lumbar outcomes. A sensitivity power analysis was additionally performed for the available sample size. With 19 patients with spondylolysis and 20 controls, assuming a two-sided α of 0.05 and 80% power, the study was powered to detect a large between-group effect size of approximately Cohen's d=0.92. All tests were two-sided and $P < .05$ was considered statistically significant.

Results

A total of 39 participants were included: 19 patients with spondylolysis (mean age 28.68 ± 15.68 years; 10 males/9 females) and 20 controls (mean age 30.30 ± 7.45 years; 14 males/6 females). Group characteristics were comparable with respect to age (P=.686) and sex distribution (P=.333) (Table 2).

Within the spondylolysis group, the defect involved L5 in 18/19 patients and L4 in 1/19 patients. Specifically, 18 patients had an L5-S1 pars defect **(**4 unilateral**,** 14 bilateral**),** whereas one patient had a unilateral L4-L5 defect.

Facet tropism values (absolute right–left angular difference) were compared between groups across L1-L5 for the sagittal, frontal, and transverse reference planes using the Mann–Whitney *U*-test. Facet tropism values showed measurable side-to-side variability across planes and levels, but without consistent separation between the spondylolysis and control groups. Across all lumbar levels, no statistically significant between-group differences were observed for either superior or inferior facets in any reference plane (all $P > .05$) (Table 1). The largest numerical between-group separation was observed for L5 inferior facet tropism on the sagittal plane; however, this comparison did not reach statistical significance (P=.092) (Table 1).

Given that defects were predominantly located at L5**,** additional lower-lumbar segmental parameters were examined. Comparisons of L4-L5 superior facet angles (left/right), L4-L5 inferior facet angles (left/right), and within-vertebra L5 superior–inferior facet angular mismatch (left/right) demonstrated no significant between-group differences (all $P > .05$) (Table 3). Spearman rank correlations demonstrated strong concordance between frontal-plane and sagittal-plane measurements in both groups (controls: r=0.811-0.998; patients: r=0.851-0.995; all $P < .05$) (Table 4), whereas transverse-plane parameters showed no meaningful associations with sagittal- or frontal-plane measures ($P > .05$).

Discussion

In this CT-based 3D morphometric case–control study, they did not demonstrate a statistically significant difference in facet tropism—defined as the absolute right–left asymmetry in facet orientation—between individuals with lumbar spondylolysis and controls, either across L1-L5 or within clinically relevant lower-lumbar segmental measures. This negative finding remained consistent across anatomical reference planes and facet types, and it was supported by the absence of group differences in segment-focused mismatch metrics. Collectively, these results suggest that side-to-side facet asymmetry did not emerge as a dominant, stand-alone morphologic factor associated with spondylolysis in the present study population when assessed using a method aligned with three-dimensional joint geometry. Notably, tropism was derived from best-fit planes of the articular surfaces and referenced to vertebra-anchored coordinate systems, reducing slice-selection bias inherent to 2D measurements.

A key reason the published evidence appears inconsistent is that "spondylolysis" encompasses distinct phenotypes—particularly early-stage pars stress injuries in adolescent athletes versus established defects in older or mixed-age populations. Contemporary imaging frameworks emphasize that the early diagnosis and staging of pars stress injuries are clinically meaningful because healing potential and clinical trajectories vary with phase and maturation.[18] In adolescent cohorts, posterior element stress injuries are also shaped by sport-specific repetitive loading, and imaging studies in young athletes demonstrate that relevant structural findings may occur even in minimally symptomatic or asymptomatic settings.[19] These considerations support the interpretation that if facet asymmetry influences pars stress, its effect may be conditional, manifesting in selected contexts (e.g., unilateral lesions, very early phase, and sport-specific mechanics) rather than as a uniform risk marker across all spondylolysis presentations.

Relatedly, evidence suggests that facet morphology may not simply "cause" unilateral or bilateral defects; rather, it may interact with developmental anatomy and loading. For example, an adolescent-focused analysis evaluating facet joint morphology in unilateral and bilateral spondylolysis did not support a simplistic model in which facet configuration alone explains defect pattern.[20] Their cohort—characterized predominantly by L5 involvement and including many bilateral defects—may therefore represent a phenotype in which global alignment and segmental shear dominate over small right–left differences in facet orientation.

Facet "angles" have historically been estimated from 2D axial slices, which are vulnerable to slice selection and vertebral rotation effects.

Table 1. Comparison of facet tropism values between the spondylolysis and control groups across sagittal, frontal, and transverse planes

Parameter*	Sagittal control, median [IQR]	Sagittal spondylolysis, median [IQR]	*P*	Frontal control, median [IQR]	Frontal spondylolysis, median [IQR]	*P*	Transverse control, median [IQR]	Transverse spondylolysis, median [IQR]	*P*
Superior L5	5.64 [3.83-8.31]	4.70 [2.49-8.86]	.299	5.83 [3.91-8.70]	4.92 [2.70-8.98]	.332	2.27 [1.45-3.55]	3.06 [1.89-4.95]	.339
Inferior L5	7.69 [4.57-12.97]	4.25 [2.07-8.73]	.092	7.64 [4.57-12.78]	4.72 [2.51-8.86]	.106	2.49 [1.49-4.15]	2.70 [1.71-4.26]	.811
Superior L4	6.45 [4.04-10.29]	6.22 [4.28-9.04]	.955	6.62 [4.24-10.34]	5.59 [3.67-8.51]	.593	3.28 [2.19-4.91]	3.14 [2.13-4.64]	.933
Inferior L4	3.77 [2.34-6.06]	4.70 [2.93-7.52]	.613	4.11 [2.64-6.38]	4.62 [2.94-7.28]	.715	2.23 [1.38-3.61]	3.34 [1.94-5.76]	.273
Superior L3	4.53 [3.03-6.77]	5.83 [3.67-9.26]	.354	4.86 [3.27-7.23]	5.97 [3.76-9.45]	.384	2.93 [1.80-4.78]	1.87 [1.13-3.09]	.103
Inferior L3	5.84 [3.40-10.04]	4.88 [2.91-8.19]	.653	6.08 [3.59-10.30]	5.24 [3.17-8.67]	.715	2.63 [1.56-4.45]	2.19 [1.41-3.40]	.613
Superior L2	4.65 [3.10-6.97]	6.24 [4.15-9.38]	.216	5.02 [3.48-7.24]	6.41 [4.27-9.62]	.339	2.18 [1.46-3.25]	2.47 [1.63-3.75]	.603
Inferior L2	3.76 [2.30-6.12]	5.07 [3.25-7.92]	.500	4.08 [2.51-6.63]	5.15 [3.31-8.01]	.509	4.41 [3.01-6.47]	2.88 [1.92-4.31]	.081
Superior L1	7.35 [4.23-12.77]	5.74 [3.24-10.17]	.536	7.33 [4.21-12.77]	6.02 [3.54-10.26]	.653	2.14 [1.27-3.61]	3.77 [2.37-5.99]	.196
Inferior L1	5.30 [3.41-8.26]	3.49 [2.18-5.59]	.136	5.34 [3.13-9.11]	3.44 [2.18-5.44]	.129	3.45 [2.27-5.24]	2.84 [1.90-4.24]	.565

*Facet tropism is reported as the absolute right-left difference in facet angles. Because several facet tropism variables were non-normally distributed, values are presented as median [interquartile range], and between-group comparisons were performed using the Mann–Whitney *U*-test. Two-sided $P < .05$ was considered statistically significant.

Table 2. Baseline characteristics of the study groups*

Variable	Control (n=20)	Spondylolysis (n=19)	*P*
Age, years (mean ± SD)	30.30 ± 7.45	28.68 ± 15.68	.686†
Sex, n (%)			.333‡
Male	14 (70)	10 (52.6)	
Female	6 (30)	9 (47.4)	

† Welch's t-test.
‡ Fisher's exact test (two-sided).
*Data are presented as mean ± standard deviation or n (%). Continuous variables were compared using the independent-samples *t*-test when normally distributed and the Mann–Whitney *U*-test otherwise. Categorical variables were compared using the chi-square test or Fisher's exact test, as appropriate.

In contrast, their workflow relied on CT-derived 3D surface models and standardized vertebra-anchored reference definitions to better reflect true joint morphology. This approach aligns with broader trends in quantitative spine morphometry and 3D/registration-based analysis for lumbar facet assessment and motion characterization.[12,21,22] The persistence of a null association under a 3D framework supports the possibility that some prior positive findings may be partly attributable to measurement convention rather than a robust anatomical signal.

The strong correlations they observed between sagittal- and frontal-plane measures are also biologically plausible: different plane-referenced angles are essentially projections of a single underlying 3D facet surface orientation and thus may covary, independent of pathology. Conversely, the lack of meaningful associations involving transverse-plane parameters may reflect that transverse components capture a different geometric axis or offer less discriminative variability within the anatomic range present in their sample.

Negative findings require careful framing. Although the sample size limits detection of very small effects, the consistency of null results across levels, planes, and secondary mismatch metrics argues against a clinically meaningful between-group separation in facet tropism. This is particularly relevant because recent systematic syntheses of imaging predictors for progression from spondylolysis to spondylolisthesis highlight that meaningful prognostic signals more commonly involve defect- and alignment-related parameters rather than isolated facet asymmetry.[23] Accordingly, their findings support the view that facet tropism, when treated as a continuous morphometric variable, may not be a high-yield discriminator for spondylolysis susceptibility in mixed-age or predominantly L5/bilateral phenotypes. Even if small differences exist, their magnitude is likely limited and unlikely to be clinically actionable as a stand-alone marker.

The pars interarticularis is exposed to complex combined loading (extension, rotation, and shear). Finite element investigations consistently demonstrate that pars stresses increase under rotational and extension-related demands and that unilateral defects can shift stresses contralaterally; more recent FE work further suggests that muscle weakness and loading conditions can materially affect stress

Table 3. Comparison of L4-L5 and L5 superior, inferior facet parameters in the patient and control groups

		Control (n=20)	Patient (n=19)	
		mean ± SD	mean ± SD	Sig.
L4-L5 Sup. F. angle	Left	16.03 ± 6.85	18.08 ± 7.11	0.365
L4-L5 Sup. F. angle	Right	15.53 ± 8.48	16.63 ± 1.59	0.661
L4-L5 Inf. F. angle	Left	13.43 ± 8.20	13.87 ± 9.60	0.878
L4-L5 Inf. F. angle	Right	13.61 ± 7.24	16.51 ± 8.01	0.242
L5 Sup.-Inf. F. angle	Left	11.39 ± 6.17	12.62 ± 7.74	0.587
L5 Sup.-Inf. F. angle	Right	12.89 ± 8.54	15.52 ± 9.29	0.364

*Segment-focused mismatch measures are reported as absolute angular differences (degrees). Group comparisons were performed using the Mann–Whitney *U*-test. Values are mean ± standard deviation.

Table 4. Correlation coefficients (r) between frontal-plane and sagittal-plane (FP: frontal plane; SP: sagittal plane) measurements in both patient and control groups

Parameters		Control (n=20)	Patient (n=19)
FP Superior L5	SP Superior L5	*r=0.980**	r=0.980*
FP_Inferior_L5	SP_Inferior_L5	*r=0.975**	r=0.989*
FP Superior L4	SP Superior L4	*r=0.945**	r=0.983*
FP_Inferior_L4	SP_Inferior_L4	*r=0.811**	r=0.961*
FP Superior L3	SP Superior L3	*r=0.985**	r=0.966*
FP Inferior L3	SP Inferior L3	*r=0.994**	r=0.995*
FP Superior L2	SP Superior L2	*r=0.998**	r=0.974*
FP_Inferior_L2	SP_Inferior_L2	*r=0.991**	r=0.960*
FP Superior L1	SP Superior L1	*r=0.985**	r=0.991*
FP_Inferior_L1	SP_Inferior_L1	*r=0.992**	r=0.851 *

*Correlations were assessed using Spearman's rank correlation. Values are reported as correlation coefficients (r); *indicates $P < .05$ (2-sided). Correlation strength was interpreted as high ($|r| \geq 0.70$), moderate ($|r| = 0.50$-0.69), and low ($|r| < 0.50$).

distribution across unilateral and bilateral defect models.[24,25] This supports a multifactorial pathomechanics model in which global alignment and subject-specific loading may dominate over facet asymmetry alone.

In this context, sagittal spinopelvic morphology is particularly relevant. Classic and widely validated frameworks demonstrate that pelvic incidence and global spinopelvic balance are strongly related to shear environment and spondylolisthesis patterns, and contemporary syntheses continue to reinforce sagittal balance as a central biomechanical axis for spinal disorders.[26-28] Although the authors excluded spondylolisthesis to isolate pars defects, these data collectively suggest that future models of spondylolysis susceptibility should integrate tropism within a broader morpho-mechanical context rather than expecting a direct one-to-one relationship.

This study has some limitations. First, although they compared patients with spondylolysis to a control group, the retrospective design and the modest cohort size limited statistical power and restricted phenotype-specific subgroup analyses (e.g., strictly unilateral defects, very early/early-stage lesions, or level- and stage-stratified comparisons). A sensitivity power analysis indicated that, with 19 patients with spondylolysis and 20 controls, the study was powered to detect only large between-group effects, approximately Cohen's $d=0.92$ at $\alpha=0.05$ and 80% power; therefore, small or moderate morphometric differences cannot be excluded. In addition, because multiple planes, vertebral levels, and morphometric parameters were analyzed, the risk of type I error and overinterpretation of isolated P-values should be acknowledged. For this reason, analyses beyond the prespecified lower-lumbar outcomes should be interpreted as exploratory. Because their cohort predominantly comprised L5-level and bilateral defects, the findings may not be generalizable to all spondylolysis phenotypes, particularly strictly unilateral defects, early-stage pars stress reactions, or adolescent very-early lesions. Second, because defect chronicity and healing status were not systematically staged, they could not evaluate whether the relationship between facet morphology and pars defects varies across disease phases. Third, while they used a CT-derived 3D surface-modeling workflow with standardized reference definitions, their approach still represents a geometric approximation of a complex articular surface; future work could further refine three-dimensional characterization by integrating higher-resolution surface registration and coordinate-system embedding strategies tailored to the facet articular plane. In addition, although this 3D morphometric workflow provides detailed and reproducible geometric assessment, it requires dedicated segmentation software, engineering-based image processing, and operator expertise. Therefore, its direct applicability to routine clinical practice may currently be limited, and further simplification or automation would be needed before broader clinical implementation. Finally, they did not incorporate exposure- or function-related variables (e.g., sport participation patterns, kinematic factors, or muscle performance), which may interact with bony morphology and influence pars loading; therefore, prospective studies combining detailed 3D morphometry with subject-specific loading and functional assessments are warranted.

In this CT-based 3D morphometric case–control study, no statistically significant difference in facet tropism—defined as the absolute right–left asymmetry in facet orientation—was demonstrated between individuals with lumbar spondylolysis and controls across L1-L5 and across sagittal, frontal, and transverse reference planes. Lower-lumbar, segment-focused metrics, including L4-L5 facet-plane mismatch and L5 intra-vertebral superior–inferior facet-plane mismatch, likewise showed no between-group differences. These findings suggest that, in the present study population, side-to-side facet asymmetry did not appear to represent a dominant, stand-alone morphologic marker of lumbar spondylolysis when quantified using vertebra-anchored coordinate systems and best-fit facet surface planes.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Artificial Intelligence Usage Statement: This study used ChatGPT (OpenAI) 5.3 to improve language, grammar, and readability during the preparation of the manuscript.

Ethics Committee Approval: Ethical committee approval was received from the Ethics Committee of İstanbul Medipol University (Approval no: 750, Date: September 14, 2023).

Informed Consent: Verbal informed consent was obtained from the patients who agreed to take part in the study.

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