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Association Between Radiological Severity of Lumbar Spinal Stenosis and Spinopelvic Parameters in Adult Patients With Achondroplasia

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BACKGROUND AND OBJECTIVES: Adults with achondroplasia are more vulnerable to suffer from neurogenic claudication because of a congenital narrow spinal canal, which makes them susceptible to lumbar spinal stenosis (LSS). The study aims to investigate the correlations between sagittal alignment parameters and the degree of LSS in patients with achondroplasia with LSS.

METHODS: The radiological data of adult achondroplasts presented to the neurosurgical clinic of our medical center from 2019 to 2022 were collected. Lumbar stenosis was graded using the Schizas scale, and the dural sac cross-sectional area (DSCA) was measured. The angles defining the spinopelvic parameters comprising lumbar lordosis, thoracolumbar kyphosis, sagittal vertical axis, pelvic tilt, sacral slope, and pelvic incidence were measured. Spearman or Pearson correlation was used to investigate the association between sagittal misalignment and LSS.

RESULTS: A total of 34 achondroplastics were enrolled, with a median age of 44.3 ± 15.5 years, ranging from 18.6 to 78.5 years. Larger thoracolumbar kyphosis was associated with more severe stenosis according to the Schizas scale of the L₁₂ lumbar level ($r = 0.44$, $P = .020$, 95% CI [0.08, 0.70]). Larger sagittal vertical axis correlated with a smaller DSCA at L₂₃ ($r = -0.53$, $P = .036$, 95% CI [-0.81, -0.04]) and L₄₅ ($r = -0.66$, $P = .004$, 95% CI [-0.87, -0.26]). Larger pelvic tilt was demonstrated to be associated with a smaller DSCA of the L₃₄ lumbar level ($r = -0.42$, $P = .027$, 95% CI [-0.68, -0.05]) and the L₄₅ lumbar level ($r = -0.47$, $P = .011$, 95% CI [-0.71, -0.12]).

CONCLUSION: The upper LSS may be attributed to an increased kyphosis of the thoracolumbar spine. On the contrary, the lower LSS seemed to be correlated with a more backward tilt of the pelvis.

KEY WORDS: Achondroplasia, Lumbar spinal stenosis, Pelvic rotation, Sagittal balance, Thoracolumbar kyphosis

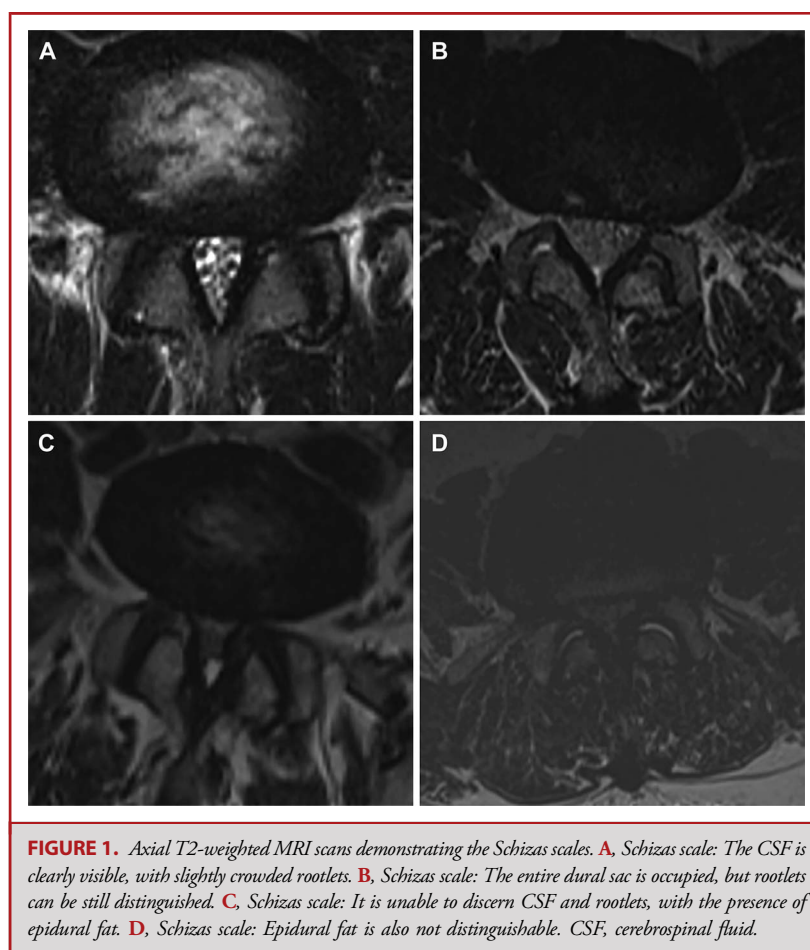
Achondroplasia (Ach) is a genetic disorder characterized by abnormal bone growth and development.^{1–3} Achondroplasts typically experience musculoskeletal manifestations, including rhizomelic limb shortening, macrocephaly, and spinal deformities.¹ A smaller spinal canal makes the adult with Ach more susceptible to lumbar spinal stenosis (LSS) on physiological aging and degeneration of the spine. LSS can lead to clinical symptoms ranging from low back pain with neurogenic claudication to paraplegia with bladder and bowel dysfunction.² The neurological signs enhanced from 8.9% in 10 years to 22.9% at the end of the second decade and to 77.9% by the end of the sixth decade.³

Moreover, the cumulative rate of achondroplasts with lumbar spine surgery was reported to increase from 2.7% by the end of the second decade to 24.1% by the end of the fourth decade.³ In agreement, another study demonstrated that 23% of achondroplast individuals underwent LSS surgery during their lifetime.⁴

In addition, the sacrum of achondroplasts is positioned more horizontally, with an increased sacral slope (SS), and the thoracolumbar junction is frequently kyphotic.^{5,6} In general, thoracolumbar kyphosis (TLK) larger than 20° is deemed pathological in Ach.⁷ Pediatric achondroplasts usually demonstrate TLK, which is associated with lumbosacral backache and/or radicular pain in the lower extremities in adult patients with Ach.⁸ Infantile TLK can resolve spontaneously, with a TLK incidence rate decreasing from 94% in patients under 1 year to 35% in patients aged between 20 and 50 years.⁹

It is hypothesized that the deviating lumbar sagittal balance parameters correlate with the LSS in Ach. An indication for that is that LSS in adult achondroplasts affects the upper lumbar spine

ABBREVIATIONS: Ach, achondroplasia; DSCA, dural sac cross-sectional area; LL, lumbar lordosis; LSS, lumbar spinal stenosis; PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope; SVA, sagittal vertical axis; TLK, thoracolumbar kyphosis.

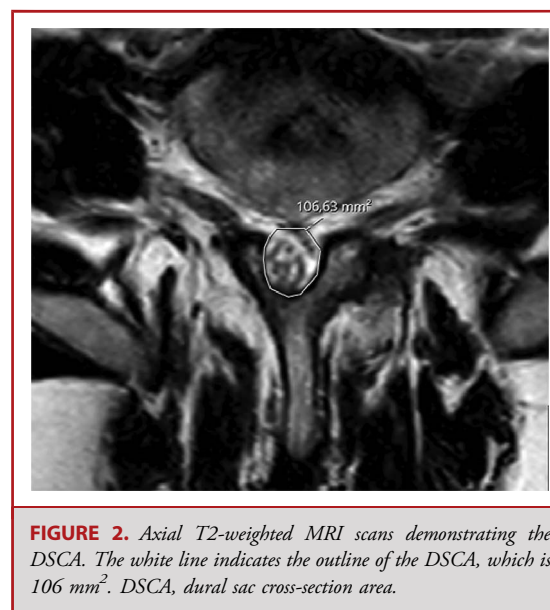


more frequently,¹⁰ in contrast to nonachondroplasts who tend to demonstrate LSS more frequently in the lower lumbar spine.¹¹ As TLK ranges from the T₁₂ to L₂ spinal levels, we speculate that the persistent TLK in Ach is accountable for this phenomenon. The kyphosis at the thoracolumbar level causes excessive forward bending, which is speculated to compress the upper lumbar spinal canal. In addition, this kyphosis can be compensated by lumbar lordosis (LL), which can in turn attribute to stenosis in the lower lumbar canal. However, if LL compensation for TLK is absent, this may be regarded as “lumbar flexion,” which can alleviate the symptoms of LSS.¹² These hypotheses entail a detailed exploration of the correlation between LSS and sagittal balance parameters.

METHODS

Data Source

Radiological images from individuals diagnosed with Ach who were referred to the neurosurgical clinic of our medical center between 2019 and 2022 were assessed in a database. Patients with an age over 18 years



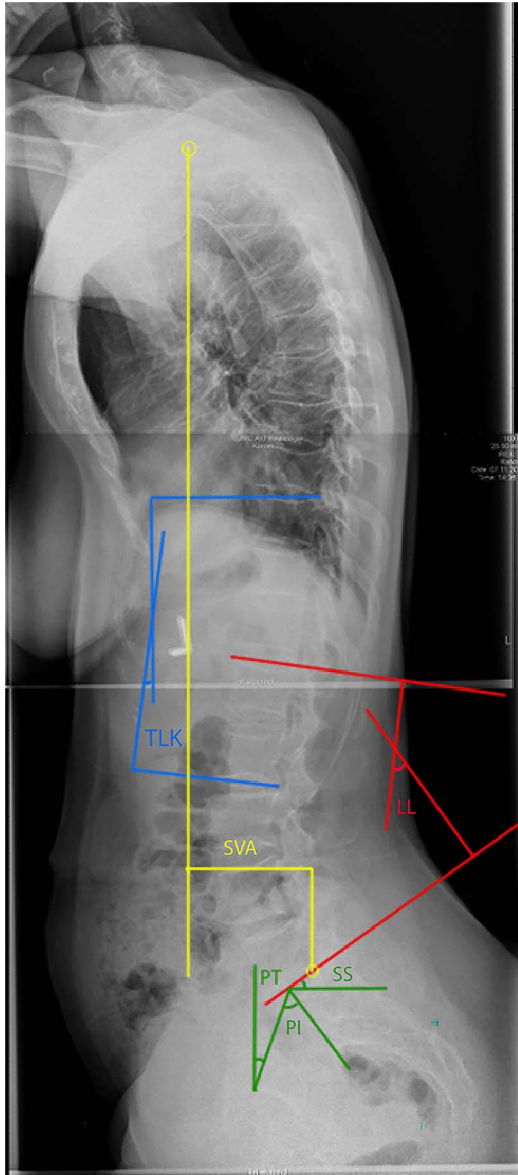


FIGURE 3. Measurement of spinopelvic parameters. The parameters are determined on lateral spine radiographs. SVA is measured as the horizontal distance between a plumb line from the center of C7 and the plumb line from the posterior-superior corner of the sacrum. TLK is the Cobb angle between the superior endplate of T10 and the inferior endplate of L2. LL was measured as the Cobb angle between the superior endplate of L1 and the superior endplate of S1. SS is the angle between the superior endplate of S1 and the horizontal plane. PI is the angle between the perpendicular line to the sacral plate and the line connecting the midpoint of the sacral plate to the midpoint of the femoral heads. PT is the angle between the vertical axis arising from the midpoint of the femoral head and the line from the midpoint of the superior endplate of S1 to the center of the femoral head. LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope; SVA, sagittal vertical axis; TLK, thoracolumbar kyphosis.

TABLE 1. Demographic Information and Agreement Between Two Researchers Assessing the Schizas Scales of Lumbar Spine Levels

	Values
Age (y) ^a	44.31 (15.52)
Age of symptom onset (y) ^a	39 (16)
Sex ratio (M:F)	14:20
Kappa values of the Schizas scales	
T ₁₂ L ₁	0.533
L ₁₂	0.489
L ₂₃	0.580
L ₃₄	0.461
L ₄₅	0.434
L ₅ S ₁	0.427

^aValues are mean (s.d.).

and exhibiting clinical symptoms of neurogenic claudication were selected for analysis. Baseline demographic data were gathered, including the time period that patients had suffered from neurogenic claudication. Patients who were operated before were excluded from this study. Furthermore, patients whose preoperative X-ray and MRI images were not available were also excluded. The informed consent was waived because of the retrospective nature of the analysis, and no IRB/ethics committee approval was sought because it did not involve direct patient contact.

Evaluation of Stenosis

The LSS was evaluated on axial T2-weighted magnetic resonance images at the level of the intervertebral disk, ranging from Th₁₂L₁ to L₅S₁. Screenshots were made and subsequently evaluated by 2 independent

TABLE 2. Schizas Scales and DSCA at Lumbar Levels

	Schizas scales, n				DSCA (mm ²) ^a
	A	B	C	D	
T ₁₂ L ₁	1	8	5	0	105.98 (52.00)
L ₁₂	0	10	17	2	75.00 (32.31)
L ₂₃	1	5	17	7	60.57 (24.48)
L ₃₄	3	13	14	3	67.18 (35.02)
L ₄₅	3	20	8	3	68.57 (25.58)
L ₅ S ₁	18	12	0	1	99.92 (36.52)

DSCA, dural sac cross-sectional area.

^aValues are mean (s.d.).

TABLE 3. Measurement of Sagittal Balance Parameters

	This study		Charles et al ¹⁸
	No. of patients	Mean (SD)	
TLK (°)	34	21.97 (22.79)	
LL (°)	34	46.46 (14.93)	55.9 (12.8)
SVA (mm)	17	29.89 (49.04)	12.3 (33.3)
PT (°)	29	21.03 (18.90)	15.1 (8.2)
SS (°)	34	45.00 (12.11)	37.7 (9.2)
PI (°)	29	64.78 (21.54)	52.7 (12.5)

LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope; SVA, sagittal vertical axis; TLK, thoracolumbar kyphosis.

reviewers (H.C. and C.O.), and a kappa value was determined. Disagreements were conferred with a third reviewer (C.L.A.V.-L.).

Schizas Scale Analysis

The Schizas scale was used to grade stenosis. Schizas et al¹³ defined mild stenosis as grades A1 to A4, moderate stenosis as grade B, severe stenosis as grade C, and complete obliteration of the canal as grade D. However, determining the subgrades of Schizas A was challenging. Previous research simplified the Schizas scales, based on which we adjusted the grading to A to D (Figure 1).¹⁴

Schizas grade A (normal & mild stenosis): Stenosis ranges from normal to mild stenosis; mild stenosis indicates that the nerve roots are clearly distinguishable within the cerebrospinal fluid (CSF) in the dural sac and mild crowding may be present.

Schizas grade B (moderate stenosis): The nerve roots, still being individualized, occupy the whole dural sac. The crowding of the nerve roots causes a “speckled” appearance of CSF interspersed with nerve roots.

Schizas grade C (severe stenosis): No rootlets can be recognized, leading to complete disappearance of CSF signals, but epidural fat is present.

Schizas grade D (complete obliteration): Both nerve roots and epidural fat are not recognizable, demonstrating a homogeneous dark signal.

Cross-Sectional Area Analysis

The dural sac cross-sectional area (DSCA) was the areas occupied by the dural sac (Figure 2). The Picture Archiving and Communication System software (Sectra AB Company) was used for this purpose.

Evaluation of Sagittal Balance

Fluoroscopy of the whole spine was performed in a standing position with fingertips on the clavicles. The measured spinopelvic parameters were C7 sagittal vertical axis (SVA), thoracolumbar kyphotic angle (TLK), LL, SS, pelvic incidence (PI), and pelvic tilt (PT).

C7 SVA represented the horizontal distance between a plumb line drawn from the center of C7 and the plumb line from the posterior-superior corner of the sacrum.¹⁵ Patients were additionally dichotomized into “sagittally balanced” (C7-SVA < 10 mm) and “sagittally imbalanced” (C7-SVA ≥ 10 mm) groups.¹⁶ TLK was the Cobb angle between the superior endplate of T₁₀ and the inferior endplate of L₂.⁷ LL was the Cobb angle between the superior endplate of L₁ and the superior endplate of S₁. SS was the angle between the horizontal line and the line along the superior endplate of S₁. PI was the angle between the perpendicular line from the sacral plate and the line connecting the midpoint of the sacral plate to the midpoint of the femoral heads. PT was the angle between the vertical axis arising from the midpoint of the femoral head and the line running from the

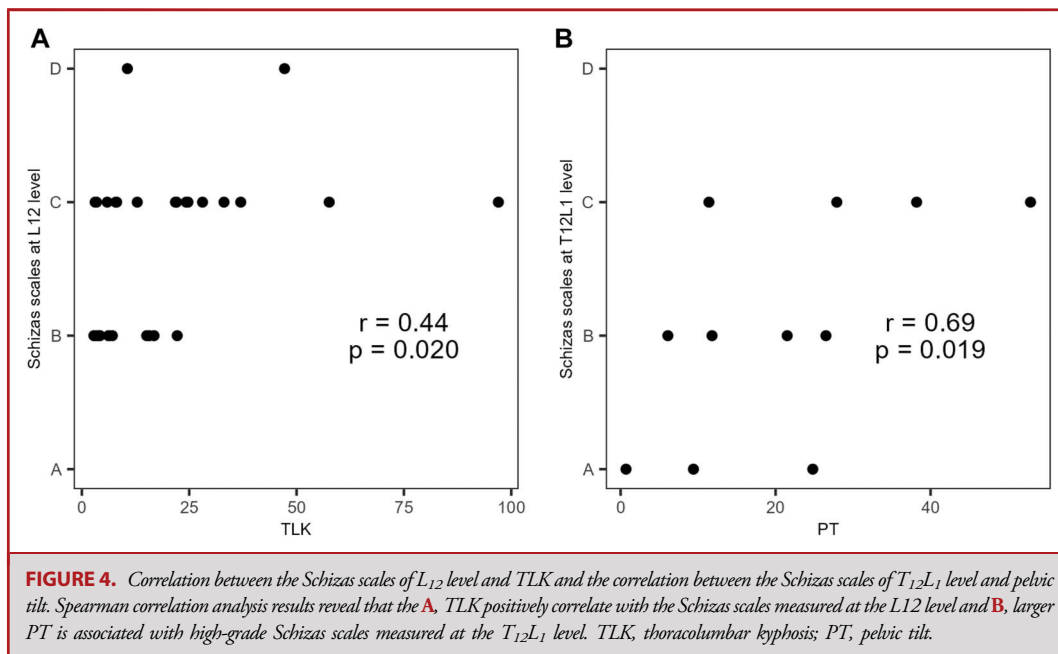


FIGURE 4. Correlation between the Schizas scales of L₁₂ level and TLK and the correlation between the Schizas scales of T₁₂L₁ level and pelvic tilt. Spearman correlation analysis results reveal that the **A**, TLK positively correlate with the Schizas scales measured at the L₁₂ level and **B**, larger PT is associated with high-grade Schizas scales measured at the T₁₂L₁ level. TLK, thoracolumbar kyphosis; PT, pelvic tilt.

TABLE 4. Correlation Between Schizas Scales and Sagittal Balance Parameters

	Schizas scales					
	T12L1	L12	L23	L34	L45	L5S1
TLK						
r (p)	0.10 (0.727)	0.44 (0.020) ^a	0.29 (0.121)	0.14 (0.457)	−0.26 (0.150)	0.07 (0.728)
N	14	29	30	33	34	31
LL						
r (p)	−0.36 (0.203)	−0.12 (0.535)	−0.03 (0.883)	−0.16 (0.373)	−0.27 (0.124)	−0.22 (0.229)
N	14	29	30	33	34	31
SVA						
r (p)	−0.21 (0.624)	0.19 (0.502)	0.15 (0.571)	−0.03 (0.911)	0.42 (0.094)	0.11 (0.700)
N	8	15	16	17	17	15
PT						
r (p)	0.69 (0.019) ^a	0.12 (0.578)	−0.19 (0.349)	−0.02 (0.924)	0.18 (0.362)	0.02 (0.927)
N	11	24	26	28	29	26
SS						
r (p)	−0.26 (0.369)	−0.14 (0.487)	−0.10 (0.589)	−0.07 (0.691)	0.23 (0.193)	−0.09 (0.629)
N	14	29	30	33	34	31
PI						
r (p)	0.55 (0.083)	0.09(0.660)	−0.18 (0.380)	0.07 (0.714)	0.33 (0.077)	−0.02 (0.925)
N	11	24	26	28	29	26

LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope; SVA, sagittal vertical axis; TLK, thoracolumbar kyphosis.

^aCorrelation is significant at the 0.05 level (2-tailed).

midpoint of the superior endplate of S₁ to the center of the femoral head (Figure 3).¹⁷

Statistical Analysis

Continuous variables were expressed as mean and SD, whereas categorical variables were expressed as numbers and percentages. Interobserver agreement regarding the Schizas scales was calculated using weighted kappa values (0-0.20 [slight agreement], 0.21-0.40 [fair agreement], 0.41-0.60 [moderate], 0.61-0.80 [substantial agreement], 0.81-1.00 [almost perfect agreement]). Pairwise Spearman or Pearson correlation was performed to explore the association between sagittal balance parameters and the Schizas scales or DSCA ($r = 0.41$ -0.60 [moderate], $r = 0.61$ -0.80 [good], and $r = 0.81$ -1.0 [strong]). To account for multiple comparisons that the spinopelvic parameters correlated with the degree of stenosis at 6 lumbar disk levels, the Bonferroni correction was also applied, adjusting the significance threshold to 0.0083 (0.05/6). All analyses were conducted using R Statistical Software (v4.1.2; R Core Team 2023). P values < .05 were considered statistically significant.

RESULTS

The database comprised 89 achondroplasts with neurogenic claudication. Six patients were excluded for not reaching adulthood, and 27 were ineligible for the study because of lumbar decompression previous to their first visit to our clinic. In addition, 22 patients were excluded for missing preoperative X-rays. A total of 34 patients were enrolled in this study, 14 males and 20 females. The average age of patients was 44.3 ± 15.5 years with a range from 18.6 to 78.5 years, and the average age of neurogenic symptom onset was 39.00 ± 16 years (range 14-72 years, Table 1). Among the enrolled subjects, 17 patients lacked a full spine high-quality X ray available, but they had an X-ray available that allowed evaluation of the lower thoracic area to the femoral head. In these patients, all sagittal balance parameters, with the exception of the C7-SVA, could be assessed.

A total of 171 lumbar levels were evaluated. Not all lumbar levels could be assessed because not on all MRIs, all lumbar levels

TABLE 5. Correlation Between DSCA and Sagittal Balance Parameters

	DSCA					
	T12L1	L12	L23	L34	L45	L5S1
TLK						
r (p)	−0.20 (0.497)	−0.27 (0.160)	−0.31 (0.107)	0.10 (0.602)	0.04 (0.820)	−0.10 (0.600)
N	14	28	29	32	33	30
LL						
r (p)	0.36 (0.205)	0.01 (0.964)	0.20 (0.288)	0.30 (0.088)	0.27 (0.122)	0.07 (0.712)
N	14	29	30	33	34	31
SVA						
r (p)	−0.36 (0.380)	−0.43 (0.112)	−0.53 (0.036) ^a	−0.22 (0.407)	−0.66(0.004) ^{a,b}	−0.34 (0.205)
N	8	15	16	17	17	15
PT						
r (p)	−0.53 (0.093)	−0.34 (0.105)	−0.23 (0.249)	−0.42 (0.027) ^a	−0.47 (0.011) ^a	−0.00 (1.00)
N	11	24	26	28	29	26
SS						
r (p)	0.071 (0.809)	−0.11 (0.586)	0.06 (0.759)	−0.03 (0.854)	−0.13 (0.478)	0.08 (0.673)
N	14	28	29	32	33	30
PI						
r (p)	−0.51 (0.109)	−0.39 (0.063)	−0.20 (0.321)	−0.40 (0.033) ^a	−0.44 (0.017) ^a	0.11 (0.582)
N	11	24	26	28	29	26

DSCA, dural sac cross-sectional area; LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope; SVA, sagittal vertical axis; TLK, thoracolumbar kyphosis.

^aCorrelation is significant at the 0.05 level (2-tailed).

^bCorrelation persists after the Bonferroni correction, with the adjusted significance level of 0.0083.

were available in the axial plane. The interobserver reliability for the Schizas scale reached moderate agreement. Schizas scales were more reliable in the upper lumbar region (Kappa values range 0.533–0.580; Table 1) than in the lower lumbar region (Kappa value range 0.461–0.427). The L₂₃ level had the highest Schizas scores, with 80% scoring C or D (Table 2).

The DSCA at the lumbar levels varied from 60.57 to 105.98 mm² in the upper lumbar region to 99.92 to 67.18 mm² in the lower lumbar region (Table 2). The most narrow level was the L₂₃ with a corresponding DSCA of 60.57 ± 24.48 mm².

Adult patients with neurogenic claudication had an obvious TLK with a TLK of 21.97° ± 22.79°, which is higher than the circa 0° in nonachondroplasts¹⁸ (Table 3). LL was measured to be 46.46° (±14.93), which was less lordotic in comparison with a nonachondroplast population (55.9° ± 12.8°).¹⁸

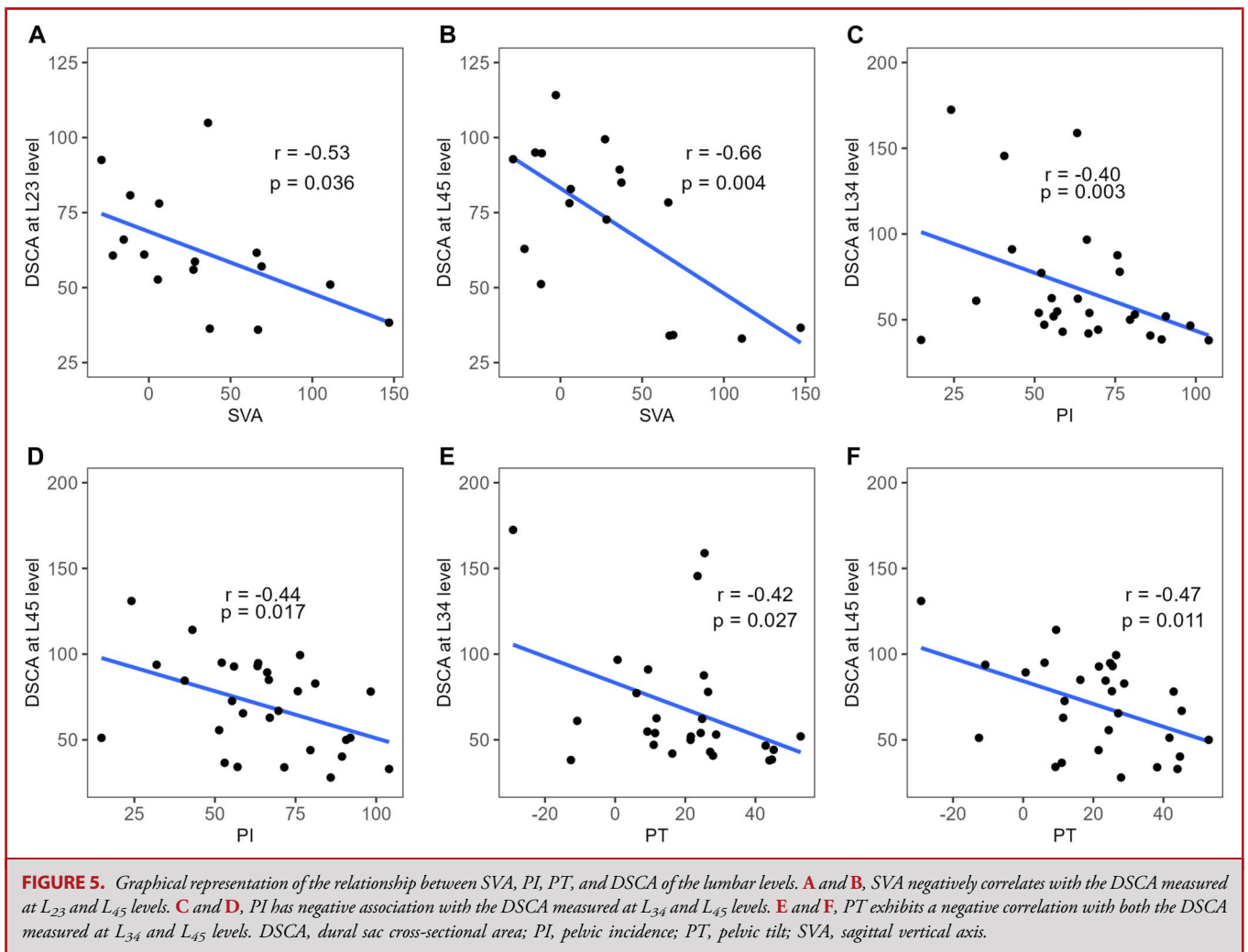
The SVA in the patients in which it could be obtained (n = 17) was larger than that reported in nonachondroplasts (29.89 ± 49.04 mm vs 12.3 ± 33.3 mm). Nine patients had a sagittal

balanced spine (SVA = −10.09 ± 12.52 mm), whereas 8 demonstrated an imbalance (SVA = 65.42 ± 40.67 mm).

To measure the PT and PI, the femoral head has to be clearly defined to determine its midpoint. In 5 patients, this could not be performed. The measured pelvic angles in the 29 patients in which the parameters could be determined adequately were all larger than their counterparts of nonachondroplasts with a PT of 21.03° ± 18.90°, an SS of 45.00° ± 12.11°, and a PI of 64.78° ± 21.54° (Table 3).¹⁸

Association Between the Schizas Scales and Sagittal Balance

In evaluating the grade of stenosis according to the Schizas scale in correlation with the sagittal balance parameter, only TLK demonstrated a significant correlation at the L₁₂ level: the higher the TLK, the higher the grade of stenosis (r = 0.44, P = .020, 95% CI [0.08, 0.70]; Figure 4A). The LL showed no significant correlation with Schizas grade at any lumbar level. For the pelvic



angles, only PT demonstrated a significant correlation: a more severe Schizas scale at the T₁₂L₁ level associated with a larger PT ($r = 0.69$, $P = .019$, 95% CI [0.03, 0.89]; Figure 4B, Table 4). Applying the Bonferroni correction, none of the correlations remained statistically significant.

Association Between DSCA and Sagittal Balance

Unlike the significant correlation between TLK and the Schizas scale at the upper lumbar spine, no association between DSCA and TLK was discerned. Neither was there a correlation between LL and DSCA at any level (Table 5). In the lower lumbar region, however, PT was demonstrated to be negatively associated with the DSCA: A more pronounced PT correlated with a smaller DSCA of L₃₄ and L₄₅ levels ($r = -0.42$, $P = .027$, 95% CI [-0.68, -0.05]; $r = -0.47$, $P = .011$, 95% CI [-0.71, -0.12]). Similarly, PI had inverse correlations with the DSCA of L₃₄ and L₄₅ levels ($r = -0.40$, $P = .033$, 95% CI [-0.67, -0.04];

$r = -0.44$, $P = .017$, 95% CI [-0.69, -0.09]; Figure 5). SVA also significantly correlated with the DSCA at the L₂₃ and L₄₅ levels ($r = -0.53$, $P = .036$, 95% CI [-0.81, -0.04]; $r = -0.66$, $P = .004$, 95% CI [-0.87, -0.26]). After Bonferroni correction, the L₄₅ association remained significant.

Moreover, age at the onset of neurogenic claudication complaints was not associated with any of the sagittal balance parameters.

Subgroup Analysis Dichotomized According to SVA

There were 17 patients in whom the SVA could reliably be assessed. The 9 patients with an imbalanced spine had more severe TLK ($23.93^\circ \pm 18.64^\circ$ vs $15.19^\circ \pm 12.92^\circ$, $P = .275$, 95% CI [-25.26, 7.64]) and more significant forward bending posture (SVA: 65.42 ± 40.67 mm vs -10.09 ± 12.52 mm, $P < .001$, 95% CI [-107.43, -43.59]) than the patients with a balanced spine. In addition, LL was less pronounced ($39.72^\circ \pm 16.03^\circ$ vs $49.10^\circ \pm$

TABLE 6. Correlation Between Schizas Scales and Sagittal Imbalance Parameters in the Imbalanced Group (SVA ≥ 10 mm)

	Schizas scales					
	T12L1	L12	L23	L34	L45	L5S1
TLK						
r (p)	0.63 (0.368)	0.51 (0.155)	0.72 (0.028) ^a	0.34 (0.375)	−0.11 (0.773)	−0.48 (0.186)
N	4	9	9	9	9	9
LL						
r (p)	−0.95 (0.051)	0.19 (0.618)	−0.31 (0.428)	−0.03 (0.946)	−0.85 (0.004) ^{a,b}	−0.15 (0.702)
N	4	9	9	9	9	9
SVA						
r (p)	0.31 (0.684)	0.51 (0.155)	0.09 (0.820)	0.20 (0.599)	0.51 (0.160)	0.41 (0.273)
N	4	9	9	9	9	9
PT						
r (p)	0.95 (0.051)	0.25 (0.502)	0.20 (0.597)	−0.41 (0.276)	0.28 (0.470)	0.15 (0.702)
N	4	9	9	9	9	9
SS						
r (p)	−0.95 (0.051)	0.38 (0.301)	0.59 (0.097)	−0.14 (0.715)	−0.51 (0.158)	0.26 (0.496)
N	4	9	9	9	9	9
PI						
r (p)	0.31 (0.684)	0.12 (0.741)	0.50 (0.163)	−0.44 (0.232)	0.09 (0.807)	0.30 (0.439)
N	4	9	9	9	9	9

LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope; SVA, sagittal vertical axis; TLK, thoracolumbar kyphosis.

^aCorrelation is significant at the 0.05 level (2-tailed).

^bCorrelation persists after the Bonferroni correction, with the adjusted significance level of 0.0083.

12.94°, $P = .202$, 95% CI [−5.62, 24.38]). In imbalanced individuals, TLK was reported to positively correlate with the Schizas scales at the L₂₃ level ($r = 0.72$, $P = .028$, 95% CI [0.11, 0.94]) and the smaller LL was associated with the higher Schizas scales at the L₄₅ level, which was also still significant after the Bonferroni correction ($r = -0.85$, $P = .004$, 95% CI [−0.97, −0.42]; Table 6). Similarly, a smaller LL was associated with a smaller DSCA at the L₄₅ ($r = 0.70$, $P = .037$, 95% CI [0.06, 0.93]) and L₅S₁ levels ($r = 0.77$, $P = .016$, 95% CI [0.21, 0.95]; Table 7).

However, in achondroplasts with a balanced spine, no significant correlation between sagittal balance parameters and LSS degree was found (Tables 8 and 9).

DISCUSSION

In Ach, the upper lumbar levels are more vulnerable to become stenotic than the lower lumbar levels, in contrast to stenosis in

nonachondroplasts.¹⁹ This phenomenon could be objectified by the higher Schizas scales in the upper lumbar region and is in agreement with previous studies.^{10,20} Interobserver variability for the Schizas scales was, however, only moderate, illustrating that it is challenging to score LSS in achondroplasts. Higher agreement in the upper lumbar region suggests greater reproducibility compared with the lower region, possibly because of the shape of the canal, which becomes more elongated from the upper to the lower region. In the lower region, where the shape is usually very elongated, resemblance to a nonachondroplast spinal canal is absent and thus much more challenging to score with a scoring system designed for a nonelongated canal. In the lower region, DSCA is more likely to represent the true space available for the nerve roots, because in the upper region, the conus medullaris is additionally occupying space, which makes the DSCA larger, whereas space for the nerve roots is actually less. We consider the explanation that the Schizas scale demonstrates a correlation with the sagittal balance parameters in the upper region and that the

TABLE 7. Correlation Between DSCA and Sagittal Balance Parameters in the Imbalanced Group (SVA ≥ 10 mm)

	DSCA					
	T12L1	L12	L23	L34	L45	L5S1
TLK						
r (p)	−0.54 (0.463)	−0.50 (0.173)	−0.55 (0.125)	−0.45 (0.218)	−0.26 (0.494)	−0.20 (0.604)
N	4	9	9	9	9	9
LL						
r (p)	0.69 (0.313)	−0.14 (0.726)	0.57 (0.107)	0.57 (0.111)	0.70 (0.037) ^a	0.77 (0.016) ^a
N	4	9	9	9	9	9
SVA						
r (p)	−0.25 (0.744)	0.31 (0.419)	−0.39 (0.302)	−0.44 (0.238)	−0.76 (0.018) ^a	0.46 (0.215)
N	4	9	9	9	9	9
PT						
r (p)	−0.79 (0.202)	−0.02 (0.958)	−0.49 (0.172)	−0.51 (0.164)	−0.33 (0.382)	−0.65 (0.060)
N	4	9	9	9	9	9
SS						
r (p)	0.93 (0.073)	0.47 (0.202)	0.72 (0.029) ^a	0.56 (0.116)	0.38 (0.305)	0.65 (0.057)
N	4	9	9	9	9	9
PI						
r (p)	−0.06 (0.932)	0.27 (0.484)	−0.02 (0.966)	−0.12 (0.756)	−0.07 (0.860)	−0.19 (0.617)
N	4	9	9	9	9	9

DSCA, dural sac cross-sectional area; LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope; SVA, sagittal vertical axis; TLK, thoracolumbar kyphosis.

^aCorrelation is significant at the 0.05 level (2-tailed).

DSCA demonstrates correlations in the lower lumbar region. To overcome these problems, a new scale designed for Ach should be created.

To evaluate our hypothesis that the divergent sagittal balance in Ach contributes to the manifestation of LSS, the degree of LSS correlated with sagittal balance parameters. First, the consequence of the persisting TLK in Ach in lumbar stenosis of the upper lumbar region was evaluated. A deviating alignment of the spine may attribute to a decreased volume of the spinal canal, particularly in those areas where the curvature is most prominent. Spinal stenosis symptoms exacerbate in the extended lumbar spine and are relieved in the flexed position. The TLK induces a compensatory lordosis in the upper lumbar spine, and this study showed that a more pronounced TLK indeed correlated with the stenosis in the upper lumbar spine.

Similarly, an association between the flat sacrum “acutum,” characterized by an increased SS, and more stenosis in the lower lumbar region is presumed. A correlation between stenosis in the lower lumbar region and SS is, however, absent in this study.

Nevertheless, we did observe a change in the main mechanism to compensate for a high SS. Pelvic retroversion is the predominant way to compensate for the increased curvature that is induced by the larger SS: the tilt brings the hip forward.²¹ Posterior rotation of the pelvis is the common response in nonachondroplasts to compensate for LSS to relieve the neurogenic claudication symptoms.¹² Typically, posterior rotation of pelvis in nonachondroplasts is characterized by an increased PT and (a consequently) decreased SS. Indeed, we do observe a correlation between PT and DSCA: a higher PT is associated with a smaller DSCA. According to the geometry relationship, $PI = SS + PT$, the PI correlates similar to the DSCA severity of stenosis.

Initially, no correlation between LL and spinal stenosis was observed. Because this was in contrast to our hypothesis, it was evaluated further whether a correlation could exist if the balanced and imbalanced spines would be evaluated separately. In a previous article, it was demonstrated that LL was more pronounced in the balanced group.¹⁶ It was concluded that the increased TLK in Ach was adequately compensated by a more pronounced LL in

TABLE 8. Correlation Between Schizas Scales and Sagittal Balance Parameters in the Balanced Group (SVA < 10 mm)

	Schizas scales					
	T12L1	L12	L23	L34	L45	L5S1 ^a
TLK						
r (p)	−0.63 (0.368)	0.29 (0.573)	−0.43 (0.325)	−0.22 (0.604)	−0.05 (0.897)	
N	4	6	7	8	8	6
LL						
r (p)	0.63 (0.368)	0.29 (0.573)	0.32 (0.486)	0.08 (0.854)	−0.04 (0.923)	
N	4	6	7	8	8	6
SVA						
r (p)	−0.95 (0.051)	0.49 (0.326)	−0.08 (0.865)	0.06 (0.883)	−0.54 (0.171)	
N	4	6	7	8	8	6
PT						
r (p)	−0.21 (0.789)	0.10 (0.854)	−0.46 (0.301)	0.26 (0.526)	−0.64 (0.083)	
N	4	6	7	8	8	6
SS						
r (p)	0.95 (0.051)	0.29 (0.573)	0.30 (0.515)	−0.03 (0.941)	0.19 (0.648)	
N	4	6	7	8	8	6
PI						
r (p)	0.63 (0.367)	0.29 (0.573)	0.14 (0.766)	0.19 (0.657)	−0.27 (0.510)	
N	4	6	7	8	8	6

LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope; SVA, sagittal vertical axis; TLK, thoracolumbar kyphosis.

^aThe correlation cannot be calculated as the Schizas scales of L₅S1 in the imbalanced group are all grade A.

balanced patients and inadequately compensated and thus less lordotic in imbalanced patients. This study observes again that the LL is higher (more lordotic) in the patients with a balanced spine. Although the number of evaluations is very limited, in the balanced patient group, a significant correlation could be established between LL and grade of lumbar stenosis in the lower lumbar area: the more the lumbar spine compensates for the TLK, the more lordosis exists, which results in a more stenotic lower lumbar level. In patients with an imbalanced spine, the correlation is negative, indicating that in these patients with less lordosis, more stenosis exists. Apparently, the patients with an imbalanced spine (who are unable to compensate for the forward bending of the whole spine [increased SVA]) are also unable to compensate if the lower lumbar levels become symptomatic of stenosis.

Limitations

There are some limitations to this study. The relatively small sample size, multiple correlation, and the absence of a reliable SVA

in half of the patients cause reduced statistical power and limit generalizability. Moreover, stenosis is age-dependent and it would have been optimal if analyses could be corrected for age. To overcome the limitation of lower statistical power, Bonferroni correction is performed, and also, we are consecutively enrolling achondroplasts with LSS to increase the sample size.

CONCLUSION

In summary, we conclude that kyphosis of the thoracolumbar region correlates with spinal stenosis in the upper lumbar region and that an increased PT is an indication for more severe stenosis in the lower lumbar region. Moreover, in a sagittal balanced spine, hyper-LL compensates for the TLK, but this may induce spinal stenosis in the lower lumbar area. In an imbalanced spine, the lumbar lordosis will be less pronounced, but compensatory mechanisms to decrease the progressing stenosis are more likely to fail.

TABLE 9. Correlation Between DSCA and Sagittal Balance Parameters in the Balanced Group (SVA < 10 mm)

	DSCA					
	T12L1	L12	L23	L34	L45	L5S1
TLK						
r (p)	−0.08 (0.917)	−0.06 (0.916)	−0.57 (0.184)	0.34 (0.409)	0.16 (0.708)	0.01 (0.998)
N	4	6	7	8	8	6
LL						
r (p)	−0.33 (0.669)	−0.65 (0.165)	−0.18 (0.705)	−0.18 (0.677)	−0.05 (0.906)	−0.75 (0.085)
N	4	6	7	8	8	6
SVA						
r (p)	0.43 (0.567)	−0.51 (0.298)	0.45 (0.308)	0.05 (0.910)	0.10 (0.807)	−0.28 (0.586)
N	4	6	7	8	8	6
PT						
r (p)	0.68 (0.323)	−0.43 (0.396)	0.01 (0.987)	−0.10 (0.819)	0.30 (0.472)	−0.35 (0.490)
N	4	6	7	8	8	6
SS						
r (p)	−0.63 (0.365)	−0.74 (0.089)	−0.53 (0.220)	−0.11 (0.791)	−0.14 (0.743)	−0.66 (0.149)
N	4	6	7	8	8	6
PI						
r (p)	−0.05 (0.953)	−0.69 (0.125)	−0.28 (0.542)	−0.11 (0.797)	0.14 (0.741)	−0.61 (0.194)
N	4	6	7	8	8	6

DSCA, dural sac cross-sectional area; LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope; SVA, sagittal vertical axis; TLK, thoracolumbar kyphosis.

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