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When is Growth the Greatest? Spine and Total Body Growth in Idiopathic Scoliosis Through Sanders Maturation Stages 2, 3A, 3B, and 4

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Background: Sanders maturation stages (SMS) 2 to 4 represent periods of rapid growth and are considered ideal candidates for growth modulation surgery, such as anterior vertebral body tethering. A detailed assessment of spine growth during these stages is essential but limited. This study aimed to clarify the differences in growth rates for spine and total body height across SMS 2, 3A, 3B, and 4, as well as to assess cumulative growth until skeletal maturity for these stages.

Methods: This single-center, retrospective, case-control longitudinal study evaluated consecutive patients with idiopathic scoliosis staged SMS 2 to 4. T1-S1 spine height, total body height, and curve magnitude were measured at each visit. Monthly growth rates for spine and total body height were calculated between baseline and first follow-up visit (6-12 months). In a subset followed to skeletal maturity, cumulative spine and total body height gain were assessed. To account for height loss due to scoliosis, spine and total body height were adjusted for curve magnitude using validated formulas. Multivariate linear regression models were employed to evaluate the relationship between SMS and growth, adjusting for confounding factors.

Results: A total of 517 patients (68% female) were included. Spine height growth was highest in patients at SMS 3A, approximately 1.4 times stage 2, 1.5 times stage 3B, and 1.8 times stage 4. Total body height growth rates were comparable between SMS 2 and 3A, both significantly exceeding SMS 3B and 4. Among 314 patients followed to skeletal maturity, cumulative growth in spine and total body height was greatest in patients at SMS 2.

Conclusions: This study demonstrated that spinal growth was most pronounced in patients at SMS 3A, while total body height growth was greatest during SMS 2 and 3A. Less mature patients exhibited greater cumulative growth potential in both spine and total body height. These findings provide crucial insights for determining the optimal timing of growth modulation surgery.

Level of Evidence: Level III Case-control study. See Instructions for Authors for a complete description of levels of evidence.

Introduction

Anterior vertebral body tethering (AVBT) is a growth modulation surgery for patients with adolescent idiopathic scoliosis (AIS), tethering the convex side of the curve to limit vertebral growth on that side[1,2]. As the concave side continues to grow, the scoliosis may potentially be effectively corrected[3]. Thus, the rate and amount of spinal growth determine the speed and extent of scoliosis correction following the procedure. Understanding the best potential timing for growth modulation is important for the overall success of the procedure.

Chronological age does not accurately predict the timing of peak height velocity (PHV) in adolescents due to individual growth differences. The Risser sign[4], determined with posteroanterior spinal radiographs, typically appears after the onset of PHV. Its manifestation varies among individuals, making it an unreliable indicator of the onset of this critical growth period[5,6]. Conversely, the Sanders maturation stage (SMS), focusing on digital epiphyseal morphology, provides a more accurate approach[7,8]. This system is valuable in predicting bone growth, assessing scoliosis progression, and determining

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the optimal timing for interventions[8-15]. SMS closely aligns with physiological changes during adolescence, making it a valuable tool for tailoring individualized treatment plans in pediatric orthopaedics[16].

Although SMS 2, 3, and 4 correspond to growth spurts and are considered the best candidates for AVBT[1,3], it is unclear which stage exhibits the fastest growth. Studies examining different growth patterns across SMS suggest that PHV often occurs between SMS 2 and 3[6,17-19]. Specifically, a faster rate of height growth and greater degree of postoperative scoliosis correction were reported in patients who underwent AVBT at SMS 2 compared with SMS 3[20]. However, these studies did not include a detailed evaluation of the subcategories within SMS 3, which has been further subclassified into 3A and 3B[7]; SMS 3A shows a larger growth rate[21]. Furthermore, few reports have examined the overall height gain from SMS assessment to skeletal maturity, which theoretically affects the overall amount of scoliosis growth modulation. The purpose of this study was to clarify the differential growth rate in the spine and total body height across SMS 2, 3A, 3B, and 4. In addition, we aimed to assess the cumulative growth until skeletal maturity in those stages.

Materials and Methods

Study Design

This single-center, retrospective cohort analysis identified cases of idiopathic scoliosis between January 2012 and December 2022. Categorization into SMS 2, 3, or 4 was determined based on chart reviews. The Institutional Review Board approved the study protocol. Inclusion criteria included availability of hand radiographs and simultaneous 2-dimensional (2D) posteroanterior radiographic images (EOS Imaging, ATEC Spine) at the baseline visit, availability of posteroanterior EOS images at baseline and follow-up visits, and a follow-up interval of 6- to 12-month postbaseline. Exclusion criteria included a history of prior spine surgery; nonidiopathic scoliosis; failure to meet the SMS classification criteria of 2, 3, or 4; inadequate hand radiographs for distal radius assessment; undergoing scoliosis surgery within 6 months from the baseline visit; and use of whole spine radiographs instead of EOS imaging preventing accurate length measurements. A subset of patients meeting inclusion criteria was followed until skeletal maturity as indicated by SMS 8 or Risser stage fully capped at 4 (4+) or 5. This subset was specifically analyzed to assess cumulative growth from the initial evaluation to skeletal maturity. The patient selection process and proportion of patients followed to skeletal maturity are detailed in Fig. 1.

Demographic Data

Patient demographics including age, sex, race, ethnicity, body mass index, menarchal status, family history of scoliosis, brace treatment status, and visit dates were compiled from chart reviews. In addition, the Risser stage (0-5), status of the triradiate cartilage, and curve location (thoracic, thoracolumbar/lumbar, or double major) were evaluated using posteroanterior EOS 2D images.

Assessment of SMS

In the baseline visit assessment of SMS, all patients were subjected to left hand radiography. Two independent raters analyzed these radiographs to categorize them as SMS 2, 3A, 3B, and 4 utilizing established classification criteria[8,22]. The distinction between SMS 3A and 3B was based on the capping status of the distal radius[7,21].

Outcome Measurement

The Cobb method was used to determine the magnitude of major curves using posteroanterior 2D radiographic images. Spine height was measured as a straight line from the center of the superior endplates from T1 to the center of the superior endplate of S1. Patients undergoing brace treatment were instructed to remove their braces 12 to 24 hours before their appointment and imaging. Total body height measurements were performed by clinic medical assistants using a standardized protocol. To account for potential

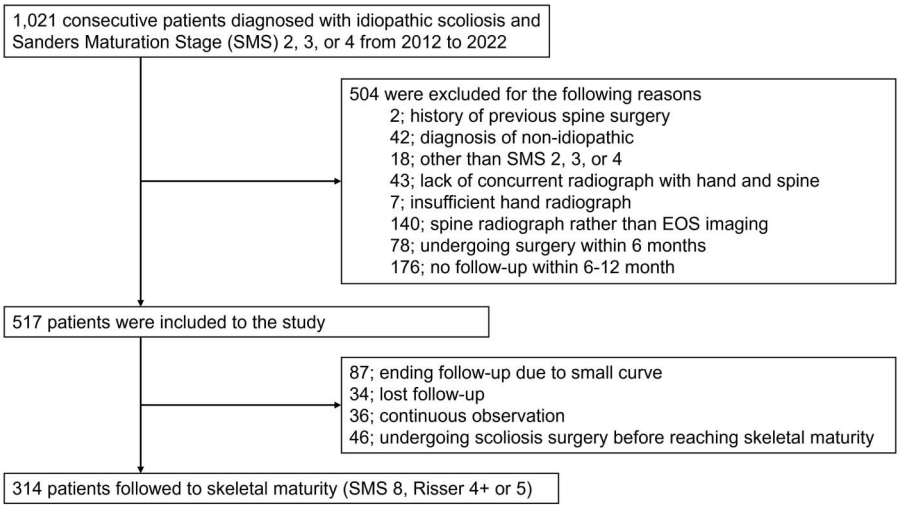

Fig. 1

Flowchart showing details of the patient selection process and the proportion of patients followed to skeletal maturity. SMS = Sanders maturity stage.

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TABLE I Demographics

	SMS 2	SMS 3A	SMS 3B	SMS 4	p
No. of observations	89	123	142	212	
Age (mean ± SD)	11.3 ± 1.3	12.0 ± 1.3	12.6 ± 1.2	12.9 ± 1.3	<0.001
Sex, girls (%)	60	67	70	72	0.179
Menarche (%)	2	2	30	51	<0.001
Race (%)					0.001
White	76	90	87	85	
Black/African American	23	7	9	8	
Other	1	3	4	7	
Ethnicity, Hispanic (%)	3	2	6	6	0.221
Body mass index (mean ± SD)	17.1 ± 3.3	18.5 ± 2.9	19.0 ± 3.1	19.6 ± 3.8	<0.001
Risser stage (%)					<0.001
0	100	92	67	40	
1	0	7	16	22	
2	0	0	14	20	
3	0	1	3	14	
4	0	0	0	5	
Triradiate cartilage close (%)	2	15	56	95	<0.001
Spine height, cm (mean ± SD)	35.6 ± 2.3	37.9 ± 2.8	39.5 ± 2.7	40.3 ± 2.6	<0.001
Total body height, cm (mean ± SD)	149.2 ± 9.1	155.6 ± 9.4	160.4 ± 9.7	162.3 ± 9.2	<0.001
Major curve magnitude (mean ± SD)	19.3 ± 7.6	22.8 ± 9.6	24.5 ± 9.2	25.8 ± 9.1	<0.001
Major curve location (%)					0.114
Thoracic	60	55	43	50	
Lumbar/thoracolumbar	20	16	25	23	
Double major	20	29	32	27	
Family history of scoliosis (%)					0.133
No	37	33	49	44	
Yes	56	62	49	50	
Unknown	7	5	2	6	
Brace treatment (%)	41	50	53	65	<0.001

SMS = Sanders maturation stage. Note: A total of 49 patients contributed data to multiple SMS, resulting in overlapping counts across stages.

height loss due to scoliosis, spinal and total body height were adjusted for curve magnitude using a validated formula calculated as $1.55–0.0471Cobb+0.009Cobb^2$ for single curves and $1.0 + 0.066Cobb+0.0084Cobb^2$ for double curves.[23,24] Growth rates were calculated as the change in spine or total body height divided by the number of months between baseline and the first follow-up visit. The cumulative growth in spine and total body height was measured for those who reached skeletal maturity.

Statistical Analysis

Continuous variables were presented as means ± SD; categorical variables were expressed as percentages. The Kruskal-Wallis test was used to compare continuous variables across groups, with Dunn test and Bonferroni correction applied for post hoc analysis. The Dunn test with Bonferroni correction was performed to identify pairwise differences between groups when significant results were observed in the Kruskal-Wallis test. Categorical variables were examined using either the χ^2 test or the Fisher exact test, as appropriate. Cohen-weighted kappa was used for intrarater and interrater reliability of the SMS classification. Multivariate linear regression models were used to evaluate growth amounts across SMS stages, adjusting for the influence of confounding factors. The confounding factors included in the models are detailed in the corresponding table. Using the developed regression model, predictive equations were created to estimate growth amounts and rates for each SMS, enabling the calculation of expected growth for each stage. Data from the same patient at different stages were treated as independent observations, and dependencies between data points from the same patient were not accounted for in this analysis. All statistical tests were two-tailed, and a p value <0.05 was considered statistically significant. Data analysis was performed using the R statistical software package[25].

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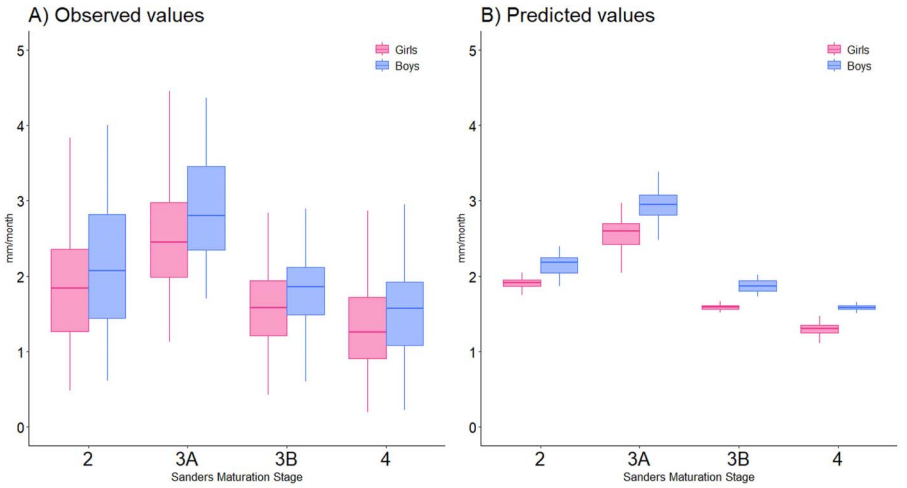

Fig. 2

Monthly spine height changes across Sanders maturation stages observed from baseline to the initial follow-up. **Fig. 2-A** displays observed values, while **Fig. 2-B** shows predicted values derived from the multivariate linear regression model. In both plots, boxes represent the IQR, horizontal lines within the boxes indicate the median, and whiskers extend to 1.5 times the IQR. Outliers are excluded. IQR = interquartile range.

Results

Demographic Data

The study included 517 patients (68% female) of whom 49 were represented in multiple SMS. Among the subset of 314 patients followed to skeletal maturity, 43 were similarly represented in multiple stages. The mean final follow-up age was 15.4 ± 1.6 years for girls and 16.6 ± 1.5 years for boys. The Cohen-weighted kappa demonstrated strong agreement in intrarater (Kw = 0.85 [95% confidence interval [CI] 0.80-0.89]) and interrater (Kw = 0.79 [95% CI 0.69-0.86]) reliability. Detailed demographics are given in Table I. Notably, 98% of girls at SMS 2 and 3A were premenarchal, whereas 30% at stage 3B and more than half at stage 4 were postmenarchal. All patients at SMS 2 and 90% at 3A were at Risser stage 0, while stages 3B and 4 showed more variability. The triradiate cartilage was predominantly open at SMS 2, but closed in 95% by SMS 4.

Growth Rates from Baseline to the Initial Follow-Up Across SMS

Significant differences in monthly spine height change across SMS were observed from baseline to the first follow-up ($p < 0.001$). Post hoc analysis revealed that the highest growth rate was observed in patients at SMS 3A, which was significantly greater than all other stages ($p < 0.001$ for each), as shown in Fig. 2-A. To further explore growth patterns, a multivariate linear regression analysis was conducted. After adjusting for confounding factors, SMS 3A continued to exhibit significantly greater spine height growth compared with other stages. In addition, boys and observation duration were identified as independent factors significantly associated with short-term spine height changes (Table II). Using the developed model, predictive equations were created to estimate spine height changes across SMS. The predicted growth rates, derived from this model, are illustrated in Fig. 2B. The predicted monthly change in spine height at SMS 3A was approximately 1.4 times that of SMS 2, 1.5 times SMS 3B, and 1.8 times SMS 4. Similarly, variations in total body height changes per month were observed across SMS ($p < 0.001$), as shown in Fig. 3-A. Post hoc analysis revealed that patients at SMS 3A experienced significantly greater growth than SMS 3B and SMS 4 ($p < 0.001$ for both), while growth at SMS 3A and SMS 2 was comparable ($p = 0.915$). Multivariate analysis further demonstrated that total body height changes were positively associated with male sex and observation duration, while SMS 3B and SMS 4 were negatively associated compared with SMS 3A (Table III). Using the regression model, the predicted monthly changes in total body height across SMS are depicted in Fig. 3-B.

TABLE II Multivariate Regression Analysis of Factors Associated with Spine Height Change from Baseline to Initial Follow-Up

Explanatory Variables	Estimated Effect (β) (95% CI)	p
Age	0.03 (−0.40 to 0.47)	0.882
Boys (ref: girls)	2.26 (0.99 to 3.53)	<0.001
Race (ref: White)		
Black/African American	0.35 (−1.08 to 1.79)	0.628
Other races	−0.16 (−2.22 to 1.90)	0.879
Baseline spine height (mm)	−0.01 (−0.03 to 0.01)	0.259
SMS (ref: stage 3A)		
Stage 2	−4.81 (−6.29 to -3.33)	<0.001
Stage 3B	−6.46 (−7.75 to −5.18)	<0.001
Stage 4	−8.36 (−9.66 to −7.07)	<0.001
Follow-up duration (months)	1.59 (1.40 to 1.78)	<0.001

CI = confidence interval, ref = reference, and SMS = Sanders maturation stage.

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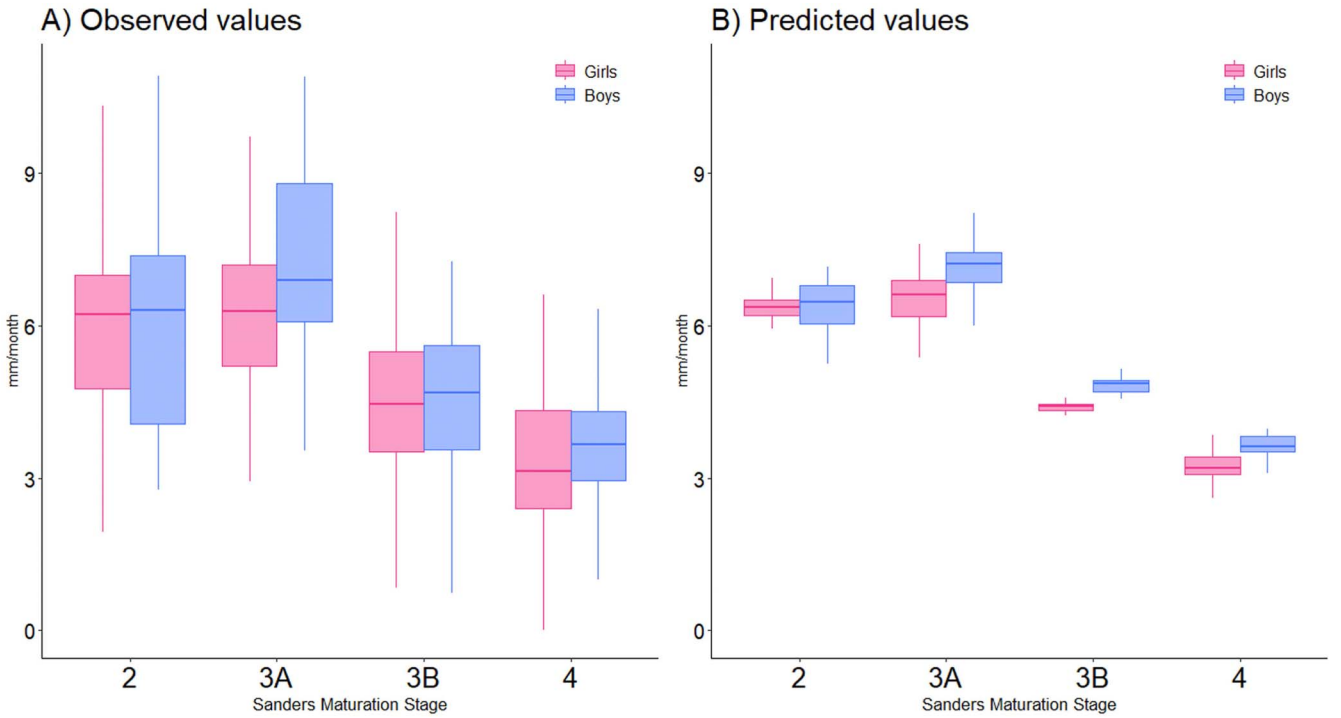

Fig. 3

Monthly total body height changes across Sanders maturation stages observed from baseline to the initial follow-up. **Fig. 3-A** displays observed values, while **Fig. 3-B** shows predicted values derived from the multivariate linear regression model. In both plots, boxes represent the IQR, horizontal lines within the boxes indicate the median, and whiskers extend to 1.5 times the IQR. Outliers are excluded. IQR = interquartile range.

TABLE III Multivariate Regression Analysis of Factors Associated with Total Body Height Change from Baseline to Initial Follow-Up

Explanatory Variables	Estimated Effect (β) (95% CI)	p
Age	−0.50 (−1.66 to 0.67)	0.403
Boys (ref: girls)	3.84 (0.43 to 7.24)	0.027
Race (ref: White)		
Black/African American	1.60 (−2.09 to 5.29)	0.395
Other races	−1.71 (−7.02 to 3.59)	0.526
Baseline total body height	−0.01 (−0.17 to 0.14)	0.858
SMS (ref: stage 3A)		
Stage 2	−2.99 (−6.84 to 0.87)	0.129
Stage 3B	−14.22 (−17.57 to −10.86)	<0.001
Stage 4	−22.06 (−25.37 to −18.76)	<0.001
Follow-up duration (months)	4.32 (3.81 to 4.83)	<0.001

CI =: confidence interval, ref = reference, and SMS = Sanders maturation stage.

The Cumulative Height Gain from Baseline to the Skeletal Maturity Across SMS

For the subset followed to skeletal maturity, spine and total body height gains from baseline to skeletal maturity across different SMS by sex were examined. Fig. 4A demonstrates that cumulative spine height gain differed significantly across SMS ($p < 0.001$), with patients in SMS 2 showing significantly greater gains than those in 3A ($p = 0.019$), 3B ($p < 0.001$), and 4 ($p < 0.001$). After adjusting for potential confounders in the multivariate model, differences in SMS remained significantly associated with cumulative spine height gain (Table IV). Using this model, the predicted cumulative spine height gain for each SMS was estimated (Fig. 4-B). Similarly, Fig. 5-A illustrates significant differences in cumulative total body height gain across SMS ($p < 0.001$), with SMS 2 showing the largest gain compared with other stages ($p < 0.001$ for each). Multivariate analysis confirmed that SMS was independently associated with cumulative total body height gain (Table V). The predicted cumulative total body height gains based on the multivariate model are shown in Fig. 5-B.

Discussion

This study represents a large-scale investigation comparing short-term growth (6-12 months) across SMS 2 to 4 in 517 patients with AIS. We found that spinal growth was most

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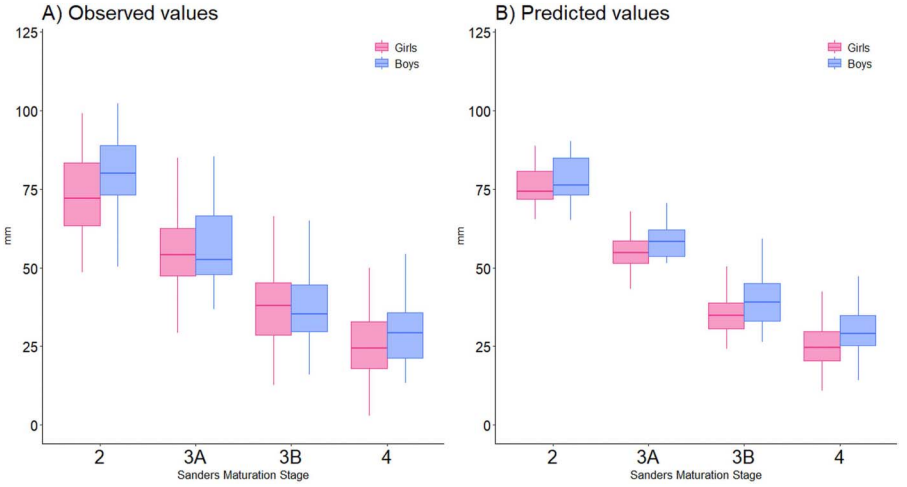

Fig. 4

Cumulative spine height gain across Sanders maturation stages from baseline to skeletal maturity. **Fig. 4-A** displays observed values, while **Fig. 4-B** shows predicted values derived from the multivariate linear regression model. In both plots, boxes represent the IQR, horizontal lines within the boxes indicate the median, and whiskers extend to 1.5 times the IQR. Outliers are excluded. IQR = interquartile range.

rapid in patients at SMS 3A, while total body height growth was greatest in patients at SMS 2 and 3A. Sanders et al.[16] previously demonstrated a uniform pattern of growth spurts among individuals, with 85% to 96% of final height achieved during this period and PHV aligning with 90% of final height. They further showed that SMS is strongly correlated with growth remaining, irrespective of sex, positioning SMS 2 at 85% to 90% of final height, SMS 3 at 90% to 95%, and SMS 4 at approximately 96%, suggesting that PHV occurs immediately after the transition from SMS 2 to 3. Our results align with these observations, showing the highest total body height growth rates in patients at SMS 2 and 3A. However, spine height growth was significantly faster in SMS 3A compared with SMS 2. This difference can be explained by the earlier growth peak of the limbs compared with the spine during puberty. As reported by Dimeglio et al.[26], limb growth typically reaches its peak approximately 6 months before trunk growth, a pattern later confirmed by Sanders et al.[27], further validating these observations.

TABLE IV Multivariate Regression Analysis of Factors Associated with Spine Height Change from Baseline to Skeletal Maturity

Explanatory Variables	Estimated Effect (β) (95% CI)	p
Age	−1.26 (−2.45 to −0.06)	0.039
Boys (ref: girls)	11.19 (7.79 to 14.59)	<0.001
Race (ref: White)		
Black/African American	−9.28 (−13.36 to −5.20)	<0.001
Other races	−1.91 (−7.02 to 3.20)	0.462
Baseline spine height (mm)	−0.11 (−0.16 to −0.06)	<0.001
SMS (ref: stage 2)		
Stage 3A	−14.16 (−18.32 to −10.00)	<0.001
Stage 3B	−28.23 (−32.82 to −23.65)	<0.001
Stage 4	−35.28 (−40.05 to −30.52)	<0.001
Follow-up duration (months)	0.36 (0.29 to 0.43)	<0.001

CI = confidence interval, ref = reference, and SMS = Sanders maturation stage.

The current findings provide critical information for determining the optimal timing for performing AVBT, as accurate assessment of growth potential in skeletally immature patients is essential to the success of growth modulation surgery. Patients at SMS 2 demonstrate the greatest potential for scoliosis correction due to significant remaining growth[20], but this comes with a higher risk of complications, particularly overcorrection[9,28]. Alanay et al.[9] recommended either achieving less correction during surgery or delaying the procedure until SMS 3 to mitigate these risks. SMS 3 has been identified as the optimal stage, offering a balance between effective growth modulation and a lower complication rate[9,28]. Conversely, growth modulation becomes increasingly limited beyond SMS 4. Our findings align with and expand upon these observations by providing additional insights into growth patterns at each stage. SMS 2 represents the period before the peak of spinal growth, offering the highest cumulative growth potential. By contrast, SMS 3A corresponds to the peak of spinal growth, where growth modulation may be most efficiently achieved. By SMS 3B and 4, patients have already passed their growth peaks, making growth modulation less impactful. These findings suggest that patients at SMS 3A represent the ideal candidates for AVBT, as this stage offers the most efficient growth modulation. Although SMS 2 patients possess significant growth potential, the elevated risk of complications

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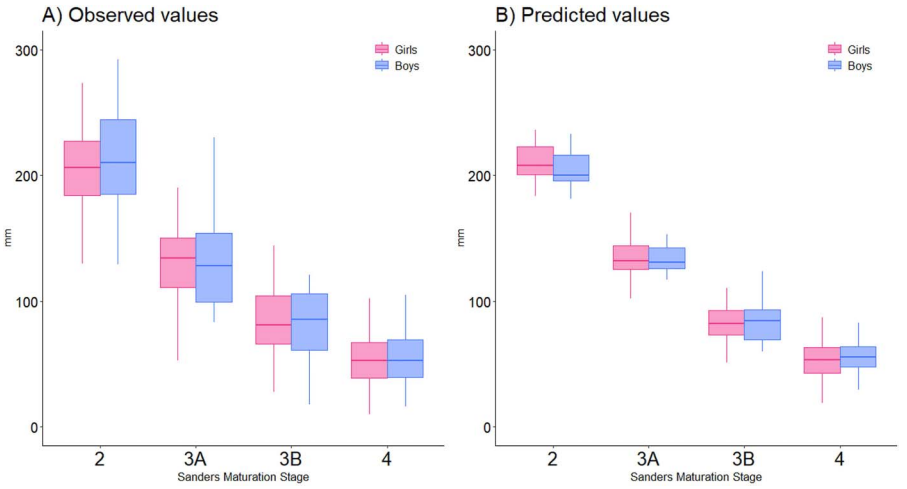

Fig. 5

Cumulative total body height gain across Sanders maturation stages from baseline to skeletal maturity. **Fig. 5-A** displays observed values, while **Fig. 5-B** shows predicted values derived from the multivariate linear regression model. In both plots, boxes represent the IQR, horizontal lines within the boxes indicate the median, and whiskers extend to 1.5 times the IQR. Outliers are excluded. IQR = interquartile range.

such as overcorrection underscores the need for caution. The success of AVBT depends on not only timing but also factors such as curve magnitude, flexibility, fixation range, and degree of intraoperative correction. Future research should focus on developing stage-specific strategies to optimize outcomes.

In this study, closure of the triradiate cartilage began at SMS 3B and was largely complete by SMS 4. This finding appears to contradict the results of Sanders et al.[8], who typically placed closure of the triradiate cartilage at SMS 5, with the Risser sign turning positive at SMS 6. However, several reports have shown deviations from this pattern. Neal et al.[13] found that at SMS 2, 92.5% of subjects were at Risser stage 1, indicating open triradiate cartilage at Risser stage 0, decreasing to 51% at SMS 3, and further decreasing to 7.7% at SMS 4. This indicated that half of the subjects at SMS 3 and most at SMS 4 had closed triradiate cartilage or were at Risser stage 1 or higher. Because triradiate cartilage closure typically occurs at skeletal age 12 years in girls and 14 in boys[26,29], the findings of triradiate cartilage beginning to close by SMS 3B seem plausible and consistent with these observations. Meanwhile, 30% of girls in SMS 3B and 51% in SMS 4 had reached menarche, which typically occurs during the descending phase of adolescent growth[26], confirming previous reports[8,13]. Although there was a significant difference in Risser stages between SMS, substantial variability was observed, highlighting the risk of discrepancy between SMS and Risser stages.[5,13]

TABLE V Multivariate Regression Analysis of Factors Associated with Total Body Height Change from Baseline to Skeletal Maturity

Explanatory Variables	Estimated Effect (β) (95% CI)	p
Age	−5.94 (−9.01 to −2.87)	<0.001
Boys (ref: girls)	19.78 (10.89 to 28.67)	<0.001
Race (ref: White)		
Black/African American	−17.15 (−27.50 to −6.81)	0.001
Other races	−0.91 (−13.96 to 12.15)	0.891
Baseline total body height (mm)	−0.30 (−0.70 to 0.09)	0.128
SMS (ref: stage 2)		
Stage 3A	−62.05 (−72.64 to −51.45)	<0.001
Stage 3B	−102.31 (−113.87 to −90.75)	<0.001
Stage 4	−124.67 (−136.36 to −112.98)	<0.001
Follow-up duration (months)	0.75 (0.57 to 0.92)	<0.001

CI = confidence interval, Ref = reference, and SMS = Sanders maturation stage.

This study has several limitations. First, spine height was measured using simultaneous radiographic imaging in 2D instead of 3D, which may not fully capture the spine's complex nature. Although we adjusted for height loss due to scoliosis using a validated formula, this method might not completely reflect the complexity of spinal deformities, including axial rotation and asymmetric growth. Second, variability in follow-up periods needs consideration. Although there was no significant difference in the interval between each SMS, SMS 2 is typically longer, and growth acceleration may occur later in this stage. Despite this, we approximated short-term growth as linear and used a linear regression model, as adding complexity to the model did not significantly improve accuracy. Future longitudinal studies incorporating nonlinearity and interaction effects are expected to provide more accurate predictions of growth. Third, the growth rates analyzed represent the average over the

6 to 12 months following SMS determination, rather than the instantaneous rate at a specific stage. Some patients may have transitioned to the next SMS stage during the follow-up period. However, assessing growth rates over this interval provides clinically meaningful insights, as growth between evaluations is highly relevant for clinical decision-making. Last, the predominance of White/Caucasian participants in our study raises questions about the generalizability of our findings to other ethnic groups.

In conclusion, this study represents the comprehensive assessment of differences in growth patterns across SMS 2, 3A, 3B, and 4. Although the 6-12-month growth rate for total body height was highest in patients at SMS 2 and 3A, the spine growth rate was most pronounced at SMS 3A, making it the ideal timing for achieving efficient growth modulation. Although patients at SMS 2 have the highest spinal growth potential, their significant remaining growth increases the risk of overcorrection, as reported in clinical studies, necessitating cautious treatment planning. Conversely, patients at SMS 3B and SMS 4 have already surpassed their growth peaks, potentially limiting the benefits of growth modulation surgery at these stages. ■

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