Height Gain Following Correction of Adult Spinal Deformity

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Background: Height gain following a surgical procedure for patients with adult spinal deformity (ASD) is incompletely understood, and it is unknown if height gain correlates with patient-reported outcome measures (PROMs).

Methods: This was a retrospective cohort study of patients undergoing ASD surgery. Patients with baseline, 6-week, and subanalysis of 1-year postoperative full-body radiographic and PROM data were examined. Correlation analysis examined relationships between vertical height differences and PROMs. Regression analysis was utilized to preoperatively estimate T1-S1 and S1-ankle height changes.

Results: This study included 198 patients (mean age, 57 years; 69% female); 147 patients (74%) gained height. Patients with height loss, compared with those who gained height, experienced greater increases in thoracolumbar kyphosis (2.81° compared with −7.37°; $p < 0.001$) and thoracic kyphosis (12.96° compared with 4.42°; $p = 0.003$). For patients with height gain, sagittal and coronal alignment improved from baseline to postoperatively: 25° to 21° for pelvic tilt (PT), 14° to 3° for pelvic incidence − lumbar lordosis (PI-LL), and 60 mm to 17 mm for sagittal vertical axis (SVA) (all $p < 0.001$). The full-body mean height gain was 7.6 cm, distributed as follows: sella turcica-C2, 2.9 mm; C2-T1, 2.8 mm; T1-S1 (trunk gain), 3.8 cm; and S1-ankle (lower-extremity gain), 3.3 cm ($p < 0.001$). T1-S1 height gain correlated with the thoracic Cobb angle correction and the maximum Cobb angle correction ($p = 0.002$). S1-ankle height gain correlated with the corrections in PT, PI-LL, and SVA ($p < 0.001$). T1-ankle height gain correlated with the corrections in PT ($p < 0.001$) and SVA ($p = 0.03$). Trunk height gain correlated with improved Scoliosis Research Society (SRS-22r) Appearance scores ($r = 0.20$; $p = 0.02$). Patient-Reported Outcomes Measurement Information System (PROMIS) Depression scores correlated with S1-ankle height gain ($r = -0.19$; $p = 0.03$) and C2-T1 height gain ($r = -0.18$; $p = 0.04$). A 1° correction in a thoracic scoliosis Cobb angle corresponded to a 0.2-mm height gain, and a 1° correction in a thoracolumbar scoliosis Cobb angle resulted in a 0.25-mm height gain. A 1° improvement in PI-LL resulted in a 0.2-mm height gain.

Conclusions: Most patients undergoing ASD surgery experienced height gain following deformity correction, with a mean full-body height gain of 7.6 cm. Height gain can be estimated preoperatively with predictive ratios, and height gain was correlated with improvements in reported SRS-22r appearance and PROMIS scores.

Level of Evidence: Therapeutic Level III. See Instructions for Authors for a complete description of levels of evidence.

*A list of the International Spine Study Group members is included in a note at the end of the article.

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Adult spinal deformity (ASD) is a growing cause of morbidity worldwide, with debilitating effects on quality of life[1,2]. The prevalence of adult degenerative scoliosis is reported to vary from 32% to as high as 68% in the older population[3]. With an aging population, an estimated 60 million adults will be living with ASD by 2050[3].

Increasing numbers of patients are pursuing surgical correction of ASD despite the complexity of the procedure and its associated high complication rate[4,5]. When compared with nonoperative treatment, ASD surgery reduces pain and disability and improves quality of life[4]. Hayashi et al. found that the ASD surgery satisfaction scores at 2 years were strongly correlated with the revised 22-item Scoliosis Research Society (SRS-22r) Self-Image (SI)/Appearance subdomain[6]. This indicates that appearance is a critical factor to consider when attempting to achieve patient satisfaction after ASD surgery.

Although height loss is a normal physiological change during aging, ASD can cause substantial spinal malalignment and excessive height loss[7]. Shimizu et al. revealed that the mean height loss across their cohort of patients with ASD was 38 mm over 34 years[7]. Surgical treatment of ASD, when indicated, is expected to decompress and realign the spine and may potentially result in height gain. Spencer et al. found that, for adolescent idiopathic scoliosis (AIS), a surgical procedure was associated with a mean height gain of 27.1 mm[8]. A study of patients undergoing posterior instrumentation and fusion for a single idiopathic curve revealed a mathematical formula to estimate height gain based on the preoperative Cobb angle, apical vertebral translation, and number of instrumented segments[9].

Rentenberger et al. investigated spinal height change from C2 to S1 following ASD surgery[10]. However, this did not consider the full-body height change, including changes in the lower extremities. Furthermore, there are no data on the association between height changes and changes in patient-reported outcome measures (PROMs), to our knowledge. The aim of this study was to evaluate if height gain following deformity correction can be estimated preoperatively and correlates with improved patient satisfaction.

Materials and Methods

Study Design

This investigation was a retrospective cohort study of a multicenter, prospective database across 13 spine centers in the United States. The institutional review board at each participating center approved this protocol.

The study sample included patients over 18 years of age with a diagnosis of adult degenerative, idiopathic, or iatrogenic spinal deformity. ASD is classified by the SRS-Schwab classification system[11]. Patients must meet any 1 of the subsequent criteria (points 1, 2, or 3):

1. Radiographic: Pelvic incidence − lumbar lordosis (PI-LL) of ≥25°, T1-pelvic angle of ≥30°, sagittal vertical axis (SVA) of ≥15 cm, thoracic scoliosis of ≥70°, thoracolumbar and/or lumbar scoliosis of ≥50°, and/or global coronal malignment of ≥7 cm.
2. Procedural: Posterior spinal fusion of ≥12 levels and/or 3-column osteotomy (3-CO) or anterior column resection.
3. Geriatric: Age of ≥65 years and ≥7 levels of spinal instrumentation.

Patients with baseline and 6-week postoperative full-body radiographs and PROMs were retained for analysis. Additionally, 1-year full-body postoperative radiographs were examined and assessed for changes in height.

Variables

Patient demographic data were collected at baseline. The primary outcome of this investigation was assessment of the height change following spinal deformity correction. Height gain was measured at different anatomical intervals using full-body radiographs. These included sella turcica-C2, C2-T1, T1-S1, and S1-ankle. These measurements were recorded by independent biomechanical engineers (V.L. and R.L.) and were based on a prior study by Rentenberger et al., in which spinal height was measured as the vertical distance from C2 to S1[10]. The parameters were measured and verified using validated dedicated spinal software[12,13].

Other outcome measures included sagittal and coronal full-body radiographic parameters including pelvic tilt (PT), PI-LL, T10-L2 thoracolumbar kyphosis, T4-T12 thoracic kyphosis, SVA, upper thoracic Cobb angle, thoracic Cobb angle, thoracolumbar Cobb angle, lumbar Cobb angle, lumbosacral Cobb angle, and coronal balance (coronal C7 plumb line position)[14-16]. Lower-extremity parameters were collected, including knee flexion, ankle dorsiflexion, pelvic posterior shift, and global sagittal alignment (GSA). Proximal junctional kyphosis (PJK), defined as a Cobb angle between the upper instrumented vertebra (UIV) and 1 adjacent vertebra of ≥10°, was also recorded as an outcome variable. To investigate the durability of the height gain at the 6-week follow-up, a subanalysis of 67 patients with 1-year follow-up was performed.

PROMs were also collected at baseline and the 6-week follow-up. PROMs included the Oswestry Disability Index (ODI), the Patient-Reported Outcomes Measurement Information System (PROMIS) Physical Health score, the PROMIS Depression score, the PROMIS Anxiety score, and the SRS-22r Appearance score.

Statistical Analysis

Data were recorded in a Microsoft Excel spreadsheet and then were analyzed using SPSS Statistics (version 27.0; IBM). Descriptive statistics were computed to provide the mean regional and global height gain. Differences in radiographic alignment and height from baseline to 6 weeks and from 6 weeks to 1 year were compared utilizing Student paired t tests. Correlation analysis assessed for relationships between height gain and PROMs. A multivariable regression analysis was conducted to preoperatively estimate the regional height gain of the T1-S1 and S1-ankle segments, using measured radiographic parameters (baseline T1-S1

height and thoracic Cobb angle correction, and baseline S1-ankle length and degree of PI-LL correction, respectively). Significance was set at $p < 0.05$

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Funding for this study was provided by the International Spine Study Group Foundation.

Results

Demographic Characteristics

The entire dataset included 510 patients. A total of 198 patients with complete radiographic and clinical outcomes at 6 weeks were included; 147 patients gained height after deformity surgery (74%) and were retained for the height gain subanalysis. All 198 patients had baseline and 6-week PROMs and full-body radiographs. The mean patient age was 57 years and 69% of the patients were female.

Height Loss Subgroup

In the height loss group, the mean change in height was −11.0 cm from baseline to 6 weeks postoperatively. Patients with height loss, compared with patients with height gain, had significantly greater increases in thoracolumbar kyphosis (2.81° compared with −7.37°; $p < 0.001$), greater increase in thoracic kyphosis (12.96° compared with 4.42°; $p = 0.003$), and greater increase in thoracic kyphosis at the unfused segments (24.79° compared with 17.89°; $p = 0.01$). In the coronal plane, patients with height loss had significantly less thoracic Cobb correction (8.61° compared with 16.07°; $p = 0.01$), thoracolumbar Cobb correction (12.72° compared with 19.92°; $p = 0.02$), and lumbosacral Cobb correction (6.23° compared with 11.22°; $p = 0.01$). PJK rates were similar between the 2 groups at the 6-week follow-up (35.85% compared with 33.12%; $p = 0.72$).

Patients in the height loss group had a more caudal UIV on average (T10 compared with T4; $p = 0.02$), with a

TABLE I Comparison Between Patients with Height Loss and Height Gain from Baseline to 6 Weeks Postoperatively

	Height Loss Group* (N = 51)	Height Gain Group* (N = 147)	P Value†
Height change *(cm)*	−11.0	7.6	
Sagittal profile change			
PT	0.98°	3.14°	0.11
PI-LL	10.28°	11.65°	0.66
Thoracolumbar alignment, T10 to L2‡	2.81°	−7.37°	**<0.001**
Thoracic kyphosis, T4 to T12‡	12.96°	4.42°	**0.003**
SVA *(cm)*	3.058	4.240	0.21
PJK angle	6.74°	3.20°	**0.03**
Proximal junctional kyphosis	35.85%	33.12%	0.72
Knee flexion	0.41°	−0.31°	0.28
Ankle dorsiflexion	−0.63°	−2.71°	0.11
Coronal profile change			
Upper thoracic Cobb angle	4.86°	6.35°	0.36
Thoracic Cobb angle	8.61°	16.07°	**0.01**
Thoracolumbar Cobb angle	12.72°	19.92°	**0.02**
Lumbar Cobb angle	13.88°	17.49°	0.22
Lumbosacral Cobb angle	6.23°	11.22°	**0.01**
Maximum Cobb angle	16.15°	22.69°	**0.02**
Coronal balance: C7 plumb line *(cm)*	0.497	0.449	0.91
Surgical technique			
UIV level	T10	T4	**0.02**
Upper thoracic UIV, T1-T5	39.62%	57.79%	**0.04**
Lower thoracic UIV, T6-T11	52.83%	33.12%	**0.04**
LIV level	Ilium	Ilium	0.33
Interbody fusion	63.46%	63.51%	0.99
Osteotomy	88.46%	93.33%	0.26
3-CO	20.75%	22.08%	0.84

*The values are given as the mean change from baseline to 6 weeks postoperatively. †Bold values are significant. ‡Negative values indicate a decrease in the parameter of choice at 6 weeks when compared with baseline.

TABLE II Spinal Alignment at Baseline and 6 Weeks Postoperatively for the Height Gain Subgroup

	Baseline*	Postoperative*	P Value†
Sagittal profile			
PT	24.63° ± 12.11°	21.49° ± 9.97°	**<0.001**
PI-LL	14.48° ± 23.03°	2.83° ± 12.30°	**<0.001**
Thoracolumbar alignment, T10 to L2†	15.04° ± 20.71°	7.67° ± 13.06°	**<0.001**
Thoracic kyphosis, T4 to T12†	39.69° ± 22.72°	44.11° ± 14.70°	**<0.001**
SVA *(cm)*	5.959 ± 6.484	1.719 ± 3.892	**<0.001**
Coronal profile			
Upper thoracic Cobb angle	19.95° ± 12.97°	13.60° ± 9.91°	**<0.001**
Thoracic Cobb angle	34.84° ± 22.22°	18.77° ± 15.05°	**<0.001**
Thoracolumbar Cobb angle	37.09° ± 24.20°	17.17° ± 14.67°	**<0.001**
Lumbar Cobb angle	32.21° ± 19.59°	14.72° ± 13.02°	**<0.001**
Lumbosacral Cobb angle	17.15° ± 8.23°	5.93° ± 5.34°	**<0.001**
Maximum Cobb angle	41.86° ± 24.12°	19.17° ± 15.62°	**<0.001**
Coronal balance: C7 plumb line *(cm)*	−0.223 ± 3.352	−0.345 ± 2.697	0.68

*The values are given as the mean and the standard deviation. †Bold values are significant. ‡Negative values indicate kyphosis, and positive values indicate lordosis.

significantly greater proportion of patients having a UIV at the lower thoracic levels (52.83% compared with 33.12%; p = 0.04). There was no significant difference in the LIV level or use of interbody fusion or osteotomy (p > 0.05) (Table I).

Height Gain Subgroup

For patients with height gain, sagittal alignment improved significantly from baseline to postoperatively: PT, 24.63° to 21.49°; PI-LL, 14.48° to 2.83°; T10-L2 thoracolumbar alignment, 15.04° to 7.67°; T4-T12 thoracic kyphosis, 39.69° to 44.11°; and SVA, 59.59 to 17.19 mm (all p < 0.001).

At the 6-week follow-up, the coronal alignment for these patients improved significantly: upper thoracic Cobb angle, 19.95° to 13.60°; thoracic Cobb angle, 34.84° to 18.77°; lumbar Cobb angle, 32.21° to 14.72°; lumbosacral Cobb angle, 17.15° to 5.93°; and maximum Cobb angle correction, 41.86° to 19.17° (p < 0.001 for all) (Table II). Global coronal balance did not change significantly (−2.23 to −3.45 mm; p = 0.68).

Regional and Global Height Gain Means

The full-body mean height gain was 7.6 cm, distributed as follows: sella turcica-C2, 2.9 mm; C2-T1, 2.8 mm; T1-S1 (trunk gain), 3.8 cm; and S1-ankle (lower-extremity gain), 3.3 cm (p < 0.001) (Fig. 1, Table III).

In the subanalysis of the 67 patients with available data at the 1-year follow-up, the mean total height gain compared with baseline was not significantly different from the height gain at 6 weeks (p > 0.05). Similarly, the height gains from C2-T1 (0.25 cm; p = 0.91), T1-S1 (3.20 cm; p = 0.40), and S1-ankle (2.18 cm; p = 0.74) were not significantly different at the 1-year follow-up (Table IV).

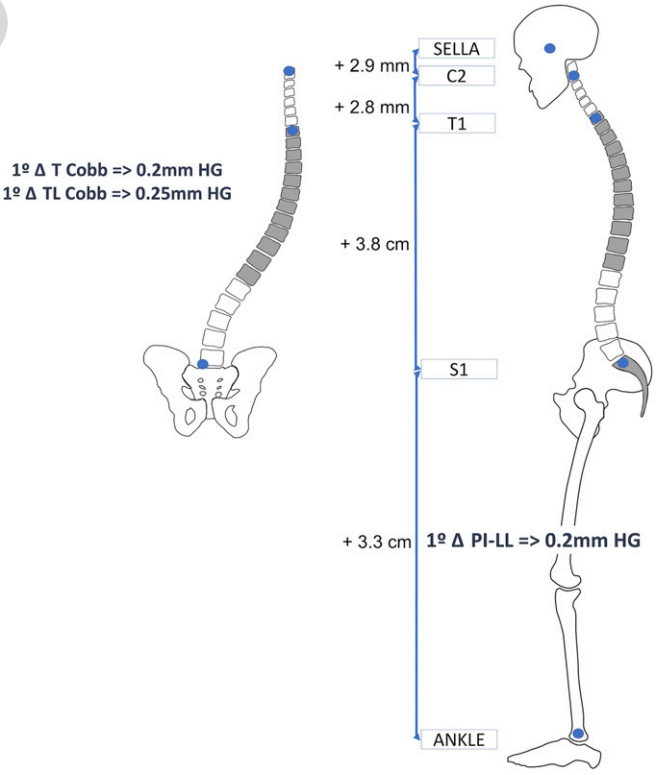

Fig. 1

Representation of the mean regional height gain (HG) in a cohort of patients with spinal deformity at the 6-week follow-up. T = thoracic scoliosis, TL = thoracolumbar, and SELLA = sella turcica.

TABLE III Height at Baseline and 6 Weeks Postoperatively for the Height Gain Subgroup

	Baseline Height*	Postoperative Height*	Height Change*	P Value†
Total height, sella turcica-ankle	148.87 ± 14.13 cm	156.47 ± 16.96 cm	7.60 ± 11.52 cm	**<0.001**
Sella turcica-C2	8.11 ± 0.92 cm	8.40 ± 1.050 cm	0.29 ± 0.74 cm	**<0.001**
C2-ankle	142.63 ± 14.35 cm	150.10 ± 17.12 cm	7.47 ± 10.04 cm	**<0.001**
C2-T1	8.67 ± 1.18 cm	8.94 ± 1.23 cm	0.23 ± 0.93 cm	**<0.001**
T1-S1	39.21 ± 5.03 cm	43.05 ± 5.28 cm	3.84 ± 3.40 cm	**<0.001**
S1-ankle	94.61 ± 9.55 cm	97.94 ± 11.72 cm	3.33 ± 3.33 cm	**<0.001**

*The values are given as the mean and the standard deviation. †Bold values are significant.

Correlation Analysis for Radiographic Outcomes

C2-T1 height gain significantly correlated with C7-S1 SVA ($r = -0.307$; $p < 0.001$), L4-S1 lordosis ($r = 0.188$; $p = 0.02$), T4-T12 kyphosis ($r = 0.228$; $p = 0.01$), and maximum Cobb angle correction ($r = -0.257$; $p = 0.002$).

T1-S1 height gain significantly correlated with T10-L2 alignment ($r = 0.300$; $p < 0.001$), T4-T12 kyphosis ($r = 0.240$; $p = 0.004$), T9 spinopelvic inclination ($r = -0.293$; $p < 0.001$), thoracic Cobb angle correction ($r = -0.362$; $p < 0.001$), and maximum Cobb angle correction ($r = -0.253$; $p = 0.002$).

S1-ankle height gain significantly correlated with correction in PT ($r = -0.621$; $p < 0.001$), PI-LL ($r = -0.555$; $p < 0.001$), SVA ($r = -0.459$; $p < 0.001$), L4-S1 lordosis ($r = 0.566$; $p < 0.001$), T4-T12 kyphosis ($r = -0.169$; $p = 0.04$), T1 spinopelvic inclination ($r = -0.333$; $p < 0.001$), T1 pelvic angle (TPA) ($r = -0.623$; $p = <0.001$), thoracic Cobb angle correction ($r = 0.214$; $p = 0.05$), lumbar Cobb angle ($r = 0.267$; $p = 0.03$), thoracolumbar Cobb angle ($r = 0.363$; $p < 0.001$), lumbosacral Cobb angle ($r = 0.296$; $p = 0.02$), maximum Cobb angle correction ($r = 0.340$; $p < 0.001$), knee flexion correction ($r = -0.499$; $p < 0.001$), ankle dorsiflexion correction ($r = -0.400$; $p < 0.001$), pelvic posterior shift ($r = -0.378$; $p < 0.001$), and global sagittal alignment ($r = -0.530$; $p < 0.001$).

T1-ankle height gain significantly correlated with correction in PT ($r = -0.272$; $p < 0.001$), SVA ($r = -0.184$; $p = 0.03$), T10-L2 alignment ($r = 0.240$; $p = 0.003$), T9 spinopelvic inclination ($r = 0.184$; $p = 0.03$), TPA ($r = -0.266$; $p = 0.001$), knee flexion correction ($r = -0.173$; $p = 0.04$), ankle dorsiflexion correction ($r = -0.180$; $p = 0.03$), pelvic posterior shift ($r = -0.178$; $p = 0.03$), and GSA ($r = -0.209$; $p = 0.01$) (Table V).

TABLE IV Height Gain at 6 Weeks Compared with 1 Year Following ASD Surgery for the Height Gain Subgroup

	Height Gain* *(cm)*		
	6 Weeks	1 Year	P Value
Total, sella turcica-ankle	7.60 ± 11.52	7.36 ± 12.21	0.47
C2-T1	0.23 ± 0.93	0.25 ± 1.08	0.91
T1-S1	3.84 ± 3.40	3.20 ± 4.27	0.40
S1-ankle	3.33 ± 3.33	2.18 ± 7.21	0.74

*The values are given as the mean and the standard deviation.

Correlation Analysis for PROMs

C2-T1 height gain was significantly correlated with improved PROMIS depression scores ($r = -0.176$; $p = 0.05$). T1-S1 height gain was significantly correlated with improved SRS-22r Appearance scores ($r = 0.196$; $p = 0.02$). S1-ankle height gain was significantly correlated with improved PROMIS depression scores ($r = -0.185$; $p = 0.03$) (Table VI).

Regression Analysis

Across all patients, a 1° correction in the thoracic scoliosis Cobb angle resulted in a 0.2-mm gain in height, and a 1° correction in the thoracolumbar scoliosis Cobb angle resulted in a 0.25-mm gain in height. A 1° improvement in PI-LL resulted in a 0.2-mm gain in height.

Discussion

This investigation found that 74% of patients gained height after a surgical procedure to correct ASD, with a mean height gain of 7.6 cm in that group. The predominant area of gain was the trunk (T1-S1, 38.37 mm), followed by the lower extremities (S1-ankle, 33.26 mm). Our study also revealed that both parameters can be estimated utilizing baseline height paired with the planned coronal and sagittal correction obtained for each patient, although this is dependent on surgeons accurately anticipating the actual correction. Finally, our study established an association between trunk and lower-extremity height gain and improvements in SRS-22r Appearance and Depression scores. With sparse data available to counsel patients preoperatively with regard to height gain, this study provides insight into the magnitude, location, and drivers of height change in patients undergoing ASD surgery.

Height gain following deformity surgery has been investigated in patients with AIS, with a mean height gain of 27.1 mm in a study of 116 patients[8]. van Popta et al. similarly found that spinal height from C7-L5 increased by 46.6 mm after AIS correction[17]. Factors associated with the gain in spinal height included the magnitude of curve correction, vertebral levels fused, and preoperative stature. This finding is supported by another study that found that an increase in T1-L5 height was highly correlated

TABLE V Correlations Between Height Gain and Correction of Full-Body Radiographic Parameters Between Baseline and the 6-Week Follow-up for the Height Gain Subgroup*

	Height Gain							
	C2-T1		T1-S1		S1-Ankle		T1-Ankle	
Parameter	R	P Value*	R	P Value*	R	P Value*	R	P Value*
Sagittal plane correction								
PT	−0.06	0.46	0.02	0.78	−0.62	**<0.01**	−0.27	**<0.001**
PI-LL	−0.05	0.55	0.14	0.08	−0.56	**<0.001**	−0.14	0.09
SVA	−0.31	**<0.001**	0.01	0.92	−0.46	**<0.001**	−0.18	**0.03**
L4-S1 lordosis	0.19	**0.02**	−0.13	0.09	0.57	**<0.001**	0.06	0.51
L1-S1 lordosis	0.06	0.48	−0.13	0.11	0.57	**<0.001**	0.15	0.07
T10-L2 alignment	0.01	0.94	0.30	**<0.001**	0.04	0.61	0.24	**0.003**
T4-T12 kyphosis	0.23	**0.01**	0.24	**0.004**	−0.17	**0.04**	0.10	0.25
T1 spinopelvic inclination	−0.29	**<0.001**	0.02	0.78	−0.33	**<0.001**	−0.11	0.21
T9 spinopelvic inclination	−0.10	0.23	−0.29	**<0.001**	−0.15	0.06	0.18	**0.03**
T1 pelvic angle (TPA)	−0.19	**0.03**	0.01	0.88	−0.62	**<0.001**	−0.27	**0.001**
Coronal plane correction								
Thoracic Cobb angle	0.17	0.12	−0.36	**<0.001**	0.21	**0.05**	−0.19	0.08
Lumbar Cobb angle	0.28	**0.02**	−0.18	0.13	0.27	**0.03**	−0.06	0.64
Thoracolumbar Cobb angle	0.33	<0.001	−0.11	0.28	0.36	**<0.001**	0.05	0.63
Lumbosacral Cobb angle	0.02	0.89	0.05	0.74	0.30	**0.02**	0.17	0.20
Maximum Cobb angle	−0.26	**0.002**	−0.25	**0.002**	0.34	**<0.001**	−0.07	0.43
Lower extremity and global sagittal alignment								
Knee flexion	−0.13	0.14	0.10	0.22	−0.50	**<0.001**	−0.17	**0.04**
Ankle dorsiflexion	−0.07	0.44	0.02	0.79	−0.40	**<0.001**	−0.18	**0.03**
Pelvic posterior shift	−0.11	0.20	0.01	0.89	−0.38	**<0.001**	−0.18	**0.03**
GSA	−0.25	**0.003**	0.06	0.52	−0.53	**<0.001**	−0.209	**0.01**

*Bold values are significant.

with the Cobb angle correction[18]. A mathematical formula for estimating height gain in patients with a single idiopathic scoliotic curve has also been derived from patients with a mean age of 16.7 years[9]. However, those studies typically have involved patients with AIS, and there has been sparse evidence regarding height change outcomes following surgery in patients with ASD.

TABLE VI Correlations Between Height Gain and Improvement in PROMs from Baseline to 6 Weeks Postoperatively for the Height Gain Subgroup*

	Height Gain							
	C2-T1		T1-S1		S1-Ankle		T1-Ankle	
Change in PROM	R	P Value*	R	P Value*	R	P Value*	R	P Value
ODI	−0.143	0.09	0.065	0.43	−0.108	0.22	0.018	0.83
PROMIS Physical Domain score	0.056	0.51	−0.108	0.20	0.066	0.44	−0.078	0.36
SRS-22r Appearance score	0.163	0.05	0.196	**0.02**	0.033	0.69	0.146	0.08
PROMIS Depression score	−0.176	**0.04**	−0.059	0.49	−0.185	**0.03**	−0.118	0.16
PROMIS Anxiety score	−0.078	0.36	−0.072	0.40	−0.022	0.794	−0.085	0.32

*Bold values are significant.

Fig. 2

An example of a patient with height gain after ASD surgery. The predicted height gain for this patient was 205 mm, and the actual height gain was measured radiographically as 198 mm.

ASD is associated with height loss in the elderly population[7]. Surgical correction of spinal deformity may potentially lead to height gain, which may be desirable for patients and may increase self-confidence. An example of a patient with height gain following ASD surgery is seen in Figure 2. However, some patients may lose height. Rentenberger et al. demonstrated that >50% of their cohort of patients undergoing ASD surgery lost height, with a mean change of −2.39 mm from C2-S1[10]. Patients who underwent a pedicle subtraction osteotomy were the most likely to exhibit a postoperative height loss. In the present study, a smaller subset of patients experienced height loss following the surgical procedure, although the rates of PJK were similar between this group and the group who gained height. Notably, patients with height loss had a more caudal UIV level and a greater kyphotic change in the unfused segments compared with patients with height gain. Therefore, the reciprocal change in kyphosis above the construct may be responsible for height loss. In current practice, surgeons have little evidence to counsel their patients with regard to an estimate of height gain, in which region the patient is likely to have the greatest height gain, and, importantly, how this may impact PROMs. In our study, 74% of patients undergoing ASD surgery gained height, and this subgroup was the focus of our investigation.

As medical care transforms into a personalized approach for each patient, it would greatly assist surgeons if simple equations could indicate the expected height gain if a patient undergoes surgical correction. In patients with AIS, Keong et al.[19] predicted that increase in height (in cm) as (0.09 × preoperative main thoracic Cobb angle) − (0.04 × fulcrum-bending Cobb angle) – 0.5. Additional research in a similar population of patients with AIS found that those with Lenke types 1 and 2 gain up to 3 cm after the surgical procedure, whereas those with Lenke types 3, 4, and 6 gain >3 cm, accentuating the importance of preoperative parameters and spinal alignment[20]. To our knowledge, the present study is the

first to provide data that can potentially aid clinicians to estimate height gain preoperatively on the basis of surgical planning of the magnitude of correction and anticipated improvement in the lower-extremity compensatory mechanisms. However, as noted by Smith et al., surgeons are not often able to achieve their preoperative alignment targets[21].

Pain and disability are well established as factors for pursuing surgical treatment for ASD. However, as the population has aged, and its social demands have evolved, improved cosmesis has been reported as an additional desirable outcome of ASD surgery. Durand et al. used an artificial intelligence approach to predict which patients would undergo operative management. The most important variable in this model was the SRS-22r Appearance score[22]. Bridwell et al. found that the second most commonly reported reason for pursuing a surgical procedure in patients with AIS was to improve cosmetic appearance[23]. In patients with ASD, improved self-image at 2 years postoperatively was associated with patient satisfaction[6,24]. Our study supports this, as truncal height gain significantly correlated with improved SRS-22r Appearance scores ($r = 0.2$; $p = 0.02$).

Patients with ASD may have coexisting mental health conditions, with 1 study revealing that more than a third of patients with ASD have a psychological disorder[25]. In an additional study, higher rates of surgical complications and revision surgery were found in patients with comorbid depression, anxiety, and other stress disorders at a minimum follow-up of 2 years[26]. Chang et al. found that patients with scoliosis, predominantly in the age group of 18 to 40 years and 41 to 65 years, had a higher risk of depression[27]. However, the surgical correction of deformity may have a role in improving the psychological burden associated with ASD. Poorman et al. investigated patients with cervical deformity and found that, from baseline to 3 months, anxiety and depression levels reported using the EuroQol-5 Dimensions (EQ-5D) scale were significantly higher in the cohort with depression, although, by 1 year, the scores were similar[28]. This may suggest that correction of spinal deformity can lead to subsequent improvements in mental health. Our study corroborates these findings by demonstrating that neck height gain was significantly correlated with improved PROMIS depression scores ($r = -0.18$; $p = 0.04$).

This study provides further evidence for height gain after ASD surgery, and this information can be helpful to surgeons when counseling patients preoperatively. Furthermore, this study adds to prior literature by correlating height gain with PROMs and surgically modifiable radiographic parameters. However, there were several potential limitations. First, the radiographic outcomes were assessed at 6 weeks postoperatively, with a further subanalysis at 1 year. Further follow-up may be required to confirm if height gain is maintained in the longer term and if associated improvements in PROMs are maintained over time. This is also important because some patients may lose height at unfused segments. However, the 6-week time point was chosen to assess the effect of surgical correction, as later height loss may occur from other causes such as compression fracture, deformity progression in the unfused spine, PJK, and degeneration of the lower-extremity joints. Second, the impacts of mechanical complications such as PJK and proximal junctional surgery failure remain to be investigated. Third, accurately estimating height gain would require the surgeon to accurately anticipate the correction magnitude and the amount of relaxation in pelvic and lower-extremity compensatory mechanisms (PT, hip flexion, knee flexion, and ankle dorsiflexion). Although there are ongoing efforts with artificial intelligence to predict alignment outcomes of ASD surgery, the models are imperfect, and, thus, estimating height gain accurately remains challenging. Reliability in measurement also remains an issue. Finally, height change may be considered a surrogate for improvement in sagittal alignment, which could impact PROMs such as the SRS-22r[29]. However, in our study, both patients with height loss and those with height gain experienced postoperative improvements in sagittal alignment. Despite these limitations, our data provide a useful framework for surgeons when counseling patients on appearance prior to ASD surgery and responding to concerns related to height gain after the surgical procedure.

In conclusion, three-fourths of patients undergoing ASD surgery experienced height gain, with a mean full-body gain of 7.6 cm. The correction of coronal alignment increased trunk height, whereas the correction of sagittal malalignment increased lower-extremity height due to the relaxation of a compensatory mechanism that impacts posture and standing height. Height gain was correlated with improvements in reported SRS-22r Appearance and PROMIS scores and can be estimated preoperatively with novel formulas, although this is contingent on accurately anticipating the planned surgical correction. ■

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