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Surgical outcomes of Hemivertebra Resection with Mono-Segment Fusion in Children under 10 years with congenital scoliosis: a retrospective study stratified by the Crankshaft Phenomenon

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Abstract

Background Congenital early-onset scoliosis (CEOS), particularly due to hemivertebra, presents significant challenges in spinal deformity correction. The standard surgical approach, hemivertebra resection combined with short-segment fusion, can be complicated by the crankshaft phenomenon, a progressive deformity that may develop postoperatively. This study aims to evaluate the long-term surgical outcomes of single-stage posterior hemivertebra resection with mono-segment fusion in CEOS, stratified by the presence or absence of the crankshaft phenomenon.

Methods A retrospective analysis was performed on 31 CEOS patients who underwent single-stage posterior hemivertebra resection and mono-segment fusion between 2003 and 2019. Patients were grouped based on the presence ($n=9$) or absence ($n=22$) of the crankshaft phenomenon. Clinical and radiographic outcomes, including main curve correction, compensatory curves, apical vertebral translation (AVT), coronal balance (CB), and sagittal balance (SB), were assessed at preoperative, immediate postoperative, and latest follow-up points. Statistical analyses were performed using SPSS and R software.

Results The cohort showed significant deformity correction with an initial main curve angle reduction from 29.76° to 7.34° (76% correction rate), though some loss of correction was observed at the last follow-up (12.28°). The group with the crankshaft phenomenon exhibited a significantly lower initial correction rate (62%) compared to the non-crankshaft group (82%), with a higher rate of curve progression at follow-up (25.02° vs. 7.06°). Compensatory curves, AVT, and CB showed differences between groups, with those having the crankshaft phenomenon demonstrating worse outcomes. However, no significant differences were found in sagittal parameters (segmental kyphosis, thoracic kyphosis, and lumbar lordosis) between the two groups.

Conclusions The study demonstrates that single-stage posterior hemivertebra resection with mono-segment fusion is effective in correcting deformities in CEOS patients. However, the presence of the crankshaft phenomenon is associated with a poorer long-term surgical outcome, including higher rates of curve progression and worse compensatory curve management. These findings highlight the importance of identifying the crankshaft phenomenon as a potential factor influencing the prognosis of surgical correction in CEOS.

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Keywords Congenital early-onset scoliosis, Crankshaft phenomenon, Single-stage posterior hemivertebra resection, Deformity correction, Mono-segment fusion

Introduction

Early-onset scoliosis (EOS) refers to scoliosis that develops before the age of 10 [1]. Among its various causes, congenital scoliosis (CS) is a prevalent etiology, with hemivertebra being the most common deformity, responsible for about 46% of CS cases [2]. This condition presents significant challenges in spinal surgery due to the variable progression of hemivertebrae. Although the natural course of hemivertebrae can differ, most cases exhibit growth potential, leading to the development of a wedge-shaped deformity that tends to worsen as the patient continues to grow [3].

Hemivertebra should be addressed at the earliest possible age to prevent the progression of the deformity and the development of structural changes in adjacent segments [4, 5]. Early intervention in young children helps to avoid the onset of local deformities and secondary curves, thereby allowing for normal growth in the unaffected regions of the spine [6, 7].

CS caused by a single vertebral deformity, such as a hemivertebra, hemivertebra resection combined with short-segment fusion is considered the gold standard treatment [8]. Numerous studies have shown that hemivertebra resection combined with short-segment fusion can effectively provide stable deformity correction [9–12]. This surgical approach in CS is considered both safe and efficient, ensuring rigid fixation, correction of the deformity, and restoration of spinal balance [13].

However, overly short fusion segments can lead to postoperative curve progression, potentially resulting in the crankshaft phenomenon [10, 14]. The crankshaft phenomenon is a progressive rotational and angular spinal deformity that may develop following posterior spinal surgery [15].

Although extensive research has been conducted on the clinical outcomes of hemivertebra resection combined with short-segment fusion, no studies to date have stratified patients based on the presence of the crankshaft phenomenon to evaluate the surgical outcomes. In response to this gap, the current study aims to assess the long-term surgical results following single-stage posterior hemivertebra resection with mono-segment fusion in congenital early-onset scoliosis (CEOS). This study is unique in that it classifies patients according to the presence or absence of the crankshaft phenomenon, offering a detailed analysis of the surgical outcomes over time.

Methods

Study design and participants

This retrospective study was conducted at a specialized center for scoliosis treatment, where 31 patients were enrolled consecutively between August 2003 and March 2019. The study protocol was approved by the institutional review board, and informed consent was obtained from the parents of all participants. The inclusion criteria were: a confirmed diagnosis of hemivertebra, surgical treatment with posterior hemivertebra resection and single-segment fusion, age under 10 years at the time of surgery, and a minimum follow-up of 5 years as of September 2024, with complete imaging and medical records available. At the last follow-up, the fusion of the fixed segments was stable. Patients with idiopathic, syndromic, or neuromuscular scoliosis were excluded. To ensure consistency in surgical technique and postoperative care, all procedures were performed by the same surgeon specializing in spinal deformities.

Patient demographics and Surgical details

A retrospective review of electronic medical records and radiographic images was performed to gather demographic and surgical information, including age, gender, follow-up duration, type and location of hemivertebra, scoliosis classification, estimated blood loss, and operative time [13].

All patients underwent a single-stage posterior hemivertebra resection combined with mono-segmental fusion. Cross-links were added when necessary to improve postoperative stability [16]. After anesthesia, patients were placed in a prone position, followed by standard disinfection and draping. A subperiosteal dissection was performed on the segments requiring fusion, ensuring preservation of the supraspinous ligament and joint capsules.

Fluoroscopic guidance was used to insert guide pins into the hemivertebra and adjacent pedicles for precise localization. Pedicle screws were then placed according to the preoperative plan. The posterior elements, including the spinous process, lamina, facets, and transverse processes of the hemivertebra, were excised while protecting the spinal cord and nerve roots above and below the affected vertebra.

A bone chisel was used to remove one side of the vertebral body along the pedicle margins, sparing the anterior longitudinal ligament, while the adjacent intervertebral discs were fully excised to expose the bleeding endplates.

Residual bone anterior to the dura was managed directly, either by pushing it forward or excising it.

Pedicle screws on both sides were connected to prebent 4.5 mm titanium rods. Alternating compression and distraction were applied to correct the deformity. In cases of larger hemivertebrae or significant kyphosis where full closure of the osteotomy gap was not possible, a titanium cage filled with autologous bone was used for anterior column reconstruction, followed by compression to stabilize the cage and correct the kyphosis [17]. In smaller hemivertebrae without notable kyphosis, absorbable bone substitutes were employed to close the osteotomy gap.

The laminae and facet joints of the fusion segments were decorticated, and a graft using morselized autologous bone, sometimes mixed with allograft, was performed following Moe's technique. Controlled hypotension was maintained during surgery to minimize blood loss, and all procedures were monitored with continuous spinal cord monitoring to ensure safety.

Radiographic evaluations

Preoperative, immediate postoperative, and most recent follow-up standing full-spine anteroposterior and lateral X-rays were collected for radiographic analysis. Radiographic parameters were evaluated at each follow-up visit using Surgimap Software (Nemaris Co., USA). The methodology for these measurements was previously detailed in the study by Ruf M. et al. [5]. The parameters evaluated included the main curve, compensatory curve, lumbar lordosis (LL), coronal balance (CB), sagittal balance (SB), apical vertebral translation (AVT), segmental kyphosis (SK), and thoracic kyphosis (TK) [18].

Coronal balance (CB) was defined by the deviation of the C7 plumb line from the center sacral vertical line. Apical vertebral translation is defined as the horizontal distances from the midpoint of the apical vertebra to the plumb line. In the thoracic curve, this distance is measured to the plumb line of the neck, while in the thoracolumbar curve, it is measured to the plumb line of the sacrum [19]. Sagittal balance (SB) was measured as the distance from the C7 plumb line to a perpendicular line drawn from the posterosuperior corner of the sacrum. Deviations were categorized as positive (+) when the C7 plumb line was anterior to this point, and negative (−) when it was posterior [9]. Segmental kyphosis (SK) was determined by the angular measurement between the upper and lower endplates surrounding the hemivertebra. Lumbar lordosis (LL) was assessed from the upper endplate of T12 to the upper endplate of the sacrum, while thoracic kyphosis (TK) was measured from the upper endplate of T5 to the lower endplate of T12.

At the final follow-up, the presence of the crankshaft phenomenon was identified if there was an increase of 10 degrees or more in the immediate postoperative Cobb angle, or a rise of 10 degrees or more in the rib-vertebra angle difference (RVAD) at the apical vertebra [15]. All radiographs were independently measured by two authors, with the average of their measurements used for subsequent analysis.

Data analysis

Statistical analyses were conducted using SPSS for Mac (version 27.0.1; IBM) and R for Mac (version 4.4.0; R Foundation for Statistical Computing). Continuous variables were expressed as means with standard deviations, whereas categorical variables were presented as frequencies with percentages. The Welch two-sample t-test and Fisher's exact test were utilized for comparing data between groups. A p-value of less than 0.05 was considered statistically significant for all tests.

Results

Demographic characteristics

The study cohort consisted of 31 participants, with 9 individuals (29.0%) identified as having the crankshaft phenomenon and 22 individuals (71.0%) without. The mean age at initial surgery was 4.66 years (SD 1.94), with a predominance of males (64.5%, $n=20$) over females (35.5%, $n=11$). The mean follow-up duration was 8.35 years (SD 2.82), ensuring extensive postoperative observation. Regarding hemivertebra classification, 61.3% ($n=19$) of participants had fully segmented hemivertebra, 35.5% ($n=11$) had semi-segmented hemivertebra, and 3.2% ($n=1$) had unsegmented hemivertebra. Spinal scoliosis types included kyphoscoliosis in 32.3% ($n=10$) and scoliosis without kyphotic components in 67.7% ($n=21$). The hemivertebra was most frequently located in the lumbar region (64.5%, $n=20$), followed by the thoracolumbar (29.0%, $n=9$) and thoracic (6.5%, $n=2$) regions (Table 1).

Operative data

Operative data revealed a mean estimated blood loss of 248.71 mL (SD 164.39) and a mean operative time of 154.42 min (SD 34.70). Comparing groups with and without the crankshaft phenomenon, no significant differences were observed in estimated blood loss (228.89 mL vs. 256.82 mL; $p=0.589$) or operation time (157.11 min vs. 153.32 min; $p=0.771$) (Table 2).

Table 1 Demographic characteristics

Variable	All participants $N = 31$[1]
Crankshaft Phenomenon	
with	9 (29.0%)
without	22 (71.0%)
Age (years)	4.66(1.94)
Gender	
Female	11 (35.5%)
Male	20 (64.5%)
Follow up duration (years)	8.35(2.82)
Hemivertebra type	
Fully segmented	19 (61.3%)
Semi-segmented	11 (35.5%)
Unsegmented	1 (3.2%)
Spinal scoliosis type	
Kyphoscoliosis	10 (32.3%)
Scoliosis	21 (67.7%)
Location of hemivertebra	
Lumbar	20 (64.5%)
Thoracic	2 (6.5%)
Thoracolumbar	9 (29.0%)

[1] n (%); Mean (SD)

Deformity correction

The overall cohort demonstrated significant deformity correction of the main curve and the compensatory curves. The mean preoperative main curve angle improved from 29.76° (SD 10.10) to 7.34° (SD 5.62) immediately postoperatively, achieving an initial correction rate of 76% (SD 15%). At the last follow-up, the mean main curve angle slightly increased to 12.28° (SD 11.22), corresponding to a final correction rate of 57% (SD 40%). For compensatory curves, the cranial curve angle improved from 10.80° (SD 6.81) preoperatively to 4.23° (SD 2.76) immediately postoperatively and 8.76° (SD 6.81) at the last follow-up. Similarly, the caudal curve angle decreased from 9.61° (SD 7.38) preoperatively to 4.21° (SD 4.51) postoperatively and 6.44° (SD 6.41) at the last follow-up (Table 3).

A comparison between participants with and without the crankshaft phenomenon revealed significant differences in the outcomes of spinal correction. For the main curve, participants with crankshaft phenomenon had a higher mean immediate postoperative angle (12.21° vs. 5.35°, $p = 0.018$) and a significantly lower initial correction rate (62% vs. 82%, $p = 0.003$). At the last follow-up, their mean main curve angle remained significantly larger (25.02° vs. 7.06°, $p < 0.001$) (Fig. 1), with a notably lower final correction rate (13% vs. 75%, $p < 0.001$). Regarding compensatory curves, the cranial curve angles showed no significant differences preoperatively (13.94° vs. 9.51°, $p = 0.217$) or immediately postoperatively (5.81° vs. 3.58°, $p = 0.086$). However, at the last follow-up, participants with crankshaft phenomenon had significantly larger cranial curve angles (14.14° vs. 6.56°, $p = 0.030$) (Fig. 2). For caudal compensatory curves, no significant differences were observed at any time point. The mean preoperative angles were 12.07° for participants with crankshaft phenomenon and 8.60° for those without ($p = 0.283$). Immediately postoperatively, the angles were 5.97° and 3.49°, respectively ($p = 0.189$). At the last follow-up, the angles were 8.23° and 5.71°, respectively ($p = 0.304$) (Table 3).

Apical vertebral translation, Coronal balance, and Sagittal balance

For the overall cohort of 31 participants, significant improvement in apical vertebral translation (AVT) was observed. The mean preoperative AVT decreased from 17.65 mm (SD 10.13) to 4.85 mm (SD 4.64) immediately postoperatively (IMPO) and slightly increased to 10.43 mm (SD 14.04) at the last follow-up. Coronal balance (CB) also improved, with mean preoperative values of 12.81 mm (SD 10.76) reducing to 8.67 mm (SD 7.05) IMPO and further to 7.55 mm (SD 9.23) at the last follow-up. Sagittal balance (SB) showed minimal changes, from a preoperative mean of 3.73 mm (SD 20.36) to −0.08 mm (SD 15.19) IMPO and −1.42 mm (SD 15.80) at the last follow-up (Table 4).

Comparison between participants with and without the crankshaft phenomenon revealed distinct trends. Preoperatively, AVT was higher in the crankshaft group (20.62 mm, SD 14.05) compared to the non-crankshaft group (16.44 mm, SD 8.13, $p = 0.421$). This trend persisted IMPO (6.41 mm, SD 5.54 vs. 4.22 mm, SD 4.20, $p = 0.307$). At the last follow-up, AVT was significantly

Table 2 Operative data

Variable	All participants $N = 31$[1]	With Crankshaft Phenomenon $N = 9$ (29.0%)[1]	Without Crankshaft Phenomenon $N = 22$ (71.0%)[1]	*p*-value[2]
Estimated Blood loss (ml)	248.71 (164.39)	228.89 (96.36)	256.82 (186.63)	0.589
Operation time (ml)	154.42 (34.70)	157.11 (30.43)	153.32 (36.92)	0.771

[1] n (%); Mean (SD)

[2] Welch Two Sample t-test

Table 3 Main curve and compensatory curve

Variable	All participants *N* = 31[1]	With Crankshaft Phenomenon *N* = 9 (29.0%)[1]	Without Crankshaft Phenomenon *N* = 22 (71.0%)[1]	*p-value*[2]
Main curve (°)				
Preoperative	29.76 (10.10)	31.94 (13.21)	28.86 (8.74)	0.533
IMPO	7.34 (5.62)	12.21 (6.89)	5.35 (3.57)	**0.018**
Initial correction rate	76% (15%)	62% (15%)	82% (11%)	**0.003**
Last follow-up	12.28 (11.22)	25.02 (5.24)	7.06 (8.45)	**<0.001**
Final correct ion rate	57% (40%)	13% (33%)	75% (26%)	**<0.001**
Compensatory cranial curve (°)				
Preoperative	10.80 (6.81)	13.94 (9.56)	9.51 (5.05)	0.217
IMPO	4.23 (2.76)	5.81 (3.25)	3.58 (2.31)	0.086
Last follow-up	8.76 (6.81)	14.14 (8.51)	6.56 (4.60)	**0.030**
Compensatory caudal curve (°)				
Preoperative	9.61 (7.38)	12.07 (8.15)	8.60 (7.00)	0.283
IMPO	4.21 (4.51)	5.97 (4.61)	3.49 (4.37)	0.189
Last follow-up	6.44 (6.41)	8.23 (5.74)	5.71 (6.64)	0.304

p Values are less than .05. Significant differences are typed in bold and are accepted for p value less than .05

IMPO immediate postoperative

[1] n(%); Mean (SD)

[2] Welch Two Sample t-test

larger in the crankshaft group (24.29 mm, SD 17.40 vs. 4.76 mm, SD 7.08, $p = 0.010$). For CB, no significant differences were noted preoperatively (11.09 mm, SD 12.71 vs. 13.51 mm, SD 10.10, $p = 0.619$). However, IMPO, participants with crankshaft phenomenon had significantly higher CB (14.10 mm, SD 8.02) than those without (6.45 mm, SD 5.35, $p = 0.023$). This difference diminished at the last follow-up (12.82 mm, SD 12.22 vs. 5.39 mm, SD 6.92, $p = 0.117$) (Table 4).

Sagittal balance showed no significant differences between groups at any time point. Preoperatively, SB was 5.78 mm (SD 25.25) in the crankshaft group and 2.89 mm (SD 18.62) in the non-crankshaft group ($p = 0.761$). IMPO, mean SB was 5.22 mm (SD 16.95) for the crankshaft group and −2.25 mm (SD 14.26) for the non-crankshaft group ($p = 0.265$). At the last follow-up, values were 3.11 mm (SD 13.72) and −3.28 mm (SD 16.51), respectively ($p = 0.283$) (Table 4).

Sagittal plane: segmental kyphosis, thoracic kyphosis, and lumbar lordosis

In the overall cohort of 31 participants, changes in sagittal plane parameters—segmental kyphosis (SK), thoracic kyphosis (TK), and lumbar lordosis (LL)—demonstrated notable trends. Preoperative SK averaged 7.12° (SD 11.53), which decreased to 1.22° (SD 7.37) immediately postoperatively (IMPO) and remained stable at 1.64° (SD 9.90) at the last follow-up. TK showed a gradual increase, with a preoperative mean of 18.47° (SD 12.58), rising to 19.90° (SD 10.00) IMPO and further to 25.79° (SD 13.76) at the last follow-up. Similarly, LL increased from a preoperative mean of 36.94° (SD 14.62) to 38.45° (SD 12.00) IMPO and reached 43.25° (SD 14.78) at the last follow-up (Table 5).

Comparison between participants with and without the crankshaft phenomenon revealed no statistically significant differences in sagittal parameters. Preoperative SK was higher in the crankshaft group (9.44°, SD 9.59) compared to the non-crankshaft group (6.16°, SD 12.32), but the difference was not significant ($p = 0.438$). Similar trends were observed IMPO (2.86°, SD 5.22 vs. 0.55°, SD 8.11, $p = 0.358$) and at the last follow-up (3.89°, SD 7.20 vs. 0.72°, SD 10.82, $p = 0.351$). For TK, the crankshaft group exhibited slightly lower preoperative values (15.69°, SD 15.46) compared to the non-crankshaft group (19.61°, SD 11.42), with no significant difference ($p = 0.505$). This similarity persisted IMPO (19.74°, SD 13.96 vs. 19.96°, SD 8.29, $p = 0.966$) and at the last follow-up (25.87°, SD 15.14 vs. 25.75°, SD 13.53, $p = 0.985$). For LL, preoperative values were higher in the crankshaft group (42.30°, SD 15.20) compared to the non-crankshaft group (34.74°, SD 14.14), though not significantly ($p = 0.221$). This trend continued IMPO (41.92°, SD 10.11 vs. 37.03°, SD 12.63, $p = 0.271$) and at the last follow-up (49.11°, SD 12.65 vs. 40.85°, SD 15.18, $p = 0.138$) (Table 5).

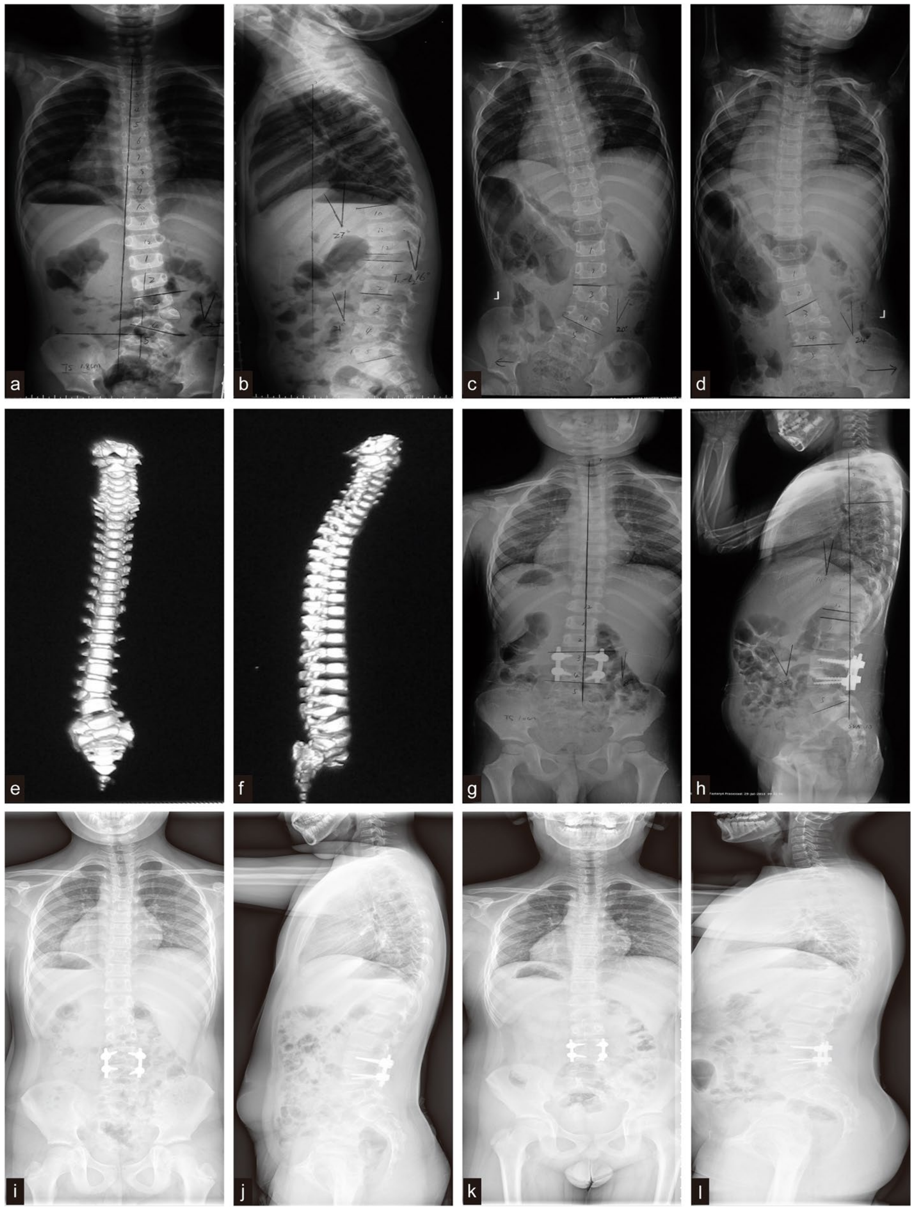

Fig. 1 A 3-year-old male patient diagnosed with scoliosis caused by a fully segmented hemivertebra situated between the right L3 and L4 vertebrae. **a** Preoperative posteroanterior standing X-ray at the age of 3, showing lumbar scoliosis and a hemivertebra between the L3 and L4 vertebrae. **b** Preoperative lateral radiograph. **c**, **d** Lateral bending radiographs obtained in the supine position, commonly known as the left and right bending views. **e**, **f** Preoperative three-dimensional CT reconstructions. **g** Postoperative posteroanterior standing X-ray captured immediately following the surgery. **h** Lateral radiograph taken immediately after surgery, following the posterior resection of the L3/4 hemivertebra and the L3-L4 instrumentation and fusion. **i** Posteroanterior standing X-ray obtained five years postoperatively. **j** Lateral X-ray captured five years after the surgical procedure. **k** The posteroanterior standing radiograph, taken 8 years postoperatively, demonstrates sustained correction and trunk alignment. **l** Lateral X-ray obtained 8 years after the surgical intervention

Discussion

As the leading cause of congenital scoliosis, untreated fully segmented and semi-segmented non-incarcerated hemivertebrae typically progress, resulting in a wedge-shaped deformity during spinal growth. Postponing surgery often necessitates including the rigid compensatory curve in the fusion, thereby increasing the risk of neurological complications [2, 20]. A comparative study by Chang et al. found that patients treated before the age of 6 years achieved significantly better deformity correction compared to those treated after 6 years. Moreover, early intervention did not

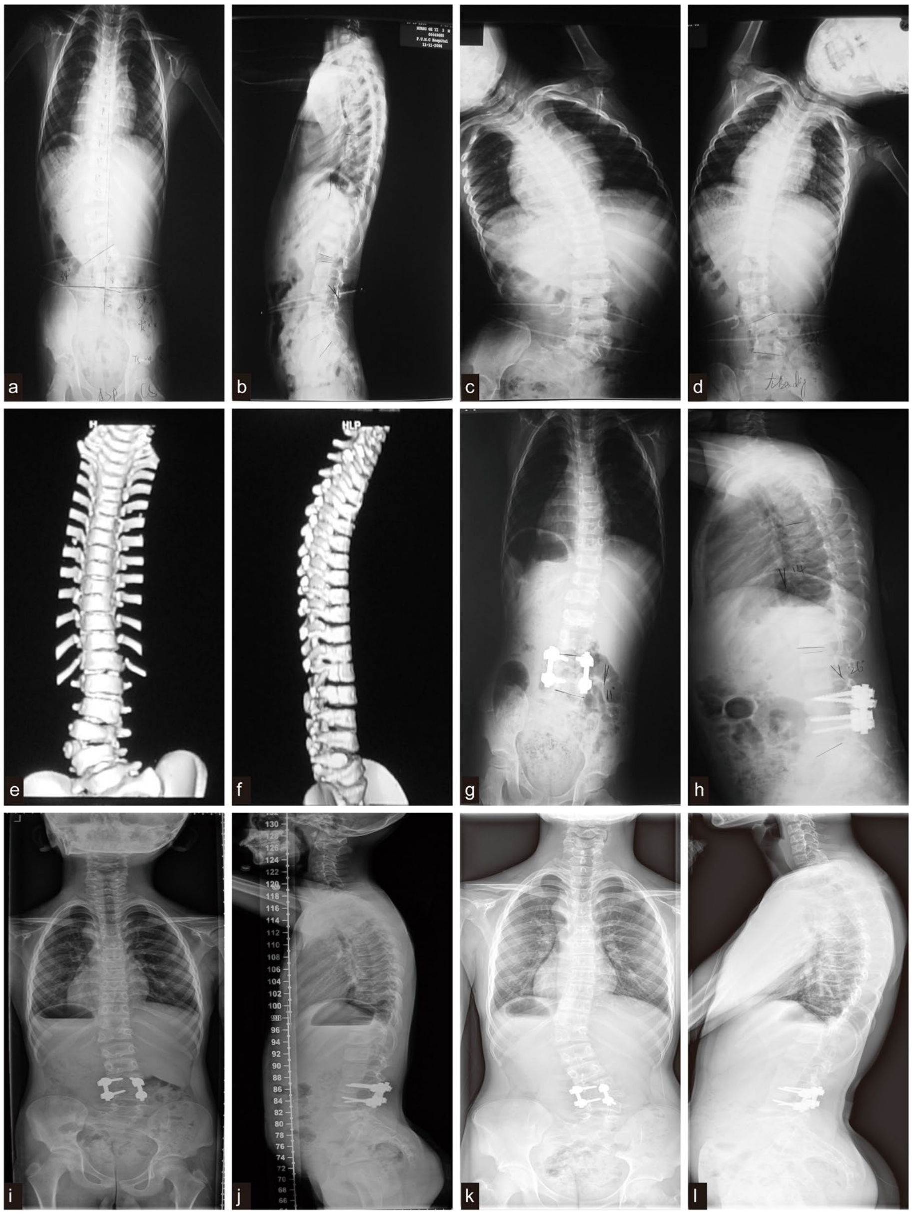

Fig. 2 A 4-year-old male patient presenting with scoliosis resulting from a fully segmented hemivertebra located between the right L3 and L4 vertebrae. **a** Preoperative posteroanterior standing X-ray at the age of 4, displaying lumbar scoliosis accompanied by compensatory curvature. **b** Preoperative lateral radiograph. **c**,**d** Lateral bending radiograph in the supine position, also referred to as the left and right bending views. **e**,**f** Preoperative three-dimensional CT reconstruction images. **g** Postoperative posteroanterior standing radiograph taken immediately after surgery. **h** Immediate postoperative lateral radiograph following the posterior resection of the L3/4 hemivertebra, accompanied by L3-L4 instrumentation and fusion. **i** Posteroanterior standing X-ray taken five years after the surgery. **j** Lateral X-ray image obtained five years following surgery. **k** The posteroanterior standing radiograph taken 11 years after surgery reveals the occurrence of a crankshaft phenomenon, which is being monitored during follow-up. **l** Lateral X-ray image taken 11 years following the surgery

adversely affect the growth of the vertebral body or spinal canal [21]. Therefore, to ensure optimal deformity correction and enhanced spinal mobility in the long term, early surgical intervention is recommended for most congenital scoliosis patients.

However, the Crankshaft Phenomenon is more frequently observed in children with congenital scoliosis, particularly around the age of 10 [22].

The Crankshaft Phenomenon refers to a complication that occurs following posterior spinal fusion in patients

Table 4 Apical vertebral translation, coronal balance, and sagittal balance

Variable	All participants N = 31[1]	With Crankshaft Phenomenon N = 9 (29.0%)[1]	Without Crankshaft Phenomenon N = 22 (71.0%)[1]	p-value[2]
AVT (mm)				
Preoperative	17.65 (10.13)	20.62 (14.05)	16.44 (8.13)	0.421
IMPO	4.85 (4.64)	6.41 (5.54)	4.22 (4.20)	0.307
Last follow-up	10.43 (14.04)	24.29 (17.40)	4.76 (7.08)	**0.010**
CB (mm)				
Preoperative	12.81 (10.76)	11.09 (12.71)	13.51 (10.10)	0.619
IMPO	8.67 (7.05)	14.10 (8.02)	6.45 (5.35)	**0.023**
Last follow-up	7.55 (9.23)	12.82 (12.22)	5.39 (6.92)	0.117
SB (mm)				
Preoperative	3.73 (20.36)	5.78 (25.25)	2.89 (18.62)	0.761
IMPO	-0.08 (15.19)	5.22 (16.95)	-2.25 (14.26)	0.265
Last follow-up	-1.42 (15.80)	3.11 (13.72)	-3.28 (16.51)	0.283

p Values are less than .05. Significant differences are typed in bold and are accepted for p value less than .05

AVT Apical vertebral translation, *CB* Coronal balance, *SB* Sagittal balance, *IMPO* Immediate postoperative

[1] n (%); Mean (SD)

[2] Welch Two Sample t-test

Table 5 Sagittal plane

Variable	All participants N = 31[1]	With Crankshaft Phenomenon N = 9 (29.0%)[1]	Without Crankshaft Phenomenon N = 22 (71.0%)[1]	p-value[2]
SK (°)				
Preoperative	7.12 (11.53)	9.44 (9.59)	6.16 (12.32)	0.438
IMPO	1.22 (7.37)	2.86 (5.22)	0.55 (8.11)	0.358
Last follow-up	1.64 (9.90)	3.89 (7.20)	0.72 (10.82)	0.351
TK (°)				
Preoperative	18.47 (12.58)	15.69 (15.46)	19.61 (11.42)	0.505
IMPO	19.90 (10.00)	19.74 (13.96)	19.96 (8.29)	0.966
Last follow-up	25.79 (13.76)	25.87 (15.14)	25.75 (13.53)	0.985
LL (°)				
Preoperative	36.94 (14.62)	42.30 (15.20)	34.74 (14.14)	0.221
IMPO	38.45 (12.00)	41.92 (10.11)	37.03 (12.63)	0.271
Last follow-up	43.25 (14.78)	49.11 (12.65)	40.85 (15.18)	0.138

IMPO Immediate postoperative, *SK* Segmental kyphosis, *TK* Thoracic kyphosis, *LL* Lumbar lordosis

[1] n(%); Mean (SD)

[2] Welch Two Sample t-test

with remaining growth potential. In this condition, the posterior spine undergoes solid fusion, while the anterior spine continues to grow, leading to the progressive worsening of spinal deformity [23]. The hallmark features of this phenomenon include loss of correction, increased vertebral rotation, and heightened rib prominence [24]. In our study cohort of 31 participants, 9 individuals (29.0%) were found to have the Crankshaft Phenomenon, a result consistent with previous literature. For instance, Terek et al. reported a 30% incidence (7 out of 23 cases) of the Crankshaft Phenomenon following surgery in patients with congenital scoliosis under the age of 10 [25].

Over the past few decades, a variety of surgical approaches have been developed for treating congenital scoliosis. These include combined anterior and posterior epiphysiodesis, anterior and posterior epiphysiodesis with concave distraction, hemivertebra osteotomy using the egg-shell technique, as well as both combined and posterior-only approaches for hemivertebra resection [13, 19, 26]. Ruf and Harms advocated for early intervention through posterior hemivertebra resection with transpedicular instrumentation, emphasizing the safety of using pedicle screws even in very young children [4]. In 2003, they reported on 28 cases of patients under 6 years old, with a mean follow-up of 3.5 years. Of these, 25 cases were treated with bisegmental fusion of adjacent vertebrae, using pedicle screws, and achieved an average scoliosis correction of 71.1% [27]. In 2009, they presented findings from 41 cases involving children under 6 years old, with an average follow-up period of 6 years and 2 months. Among these, 23 underwent bisegmental fusion. For those without bar formation, the main curve demonstrated a correction rate of 80.5% [6]. In our study on single-stage posterior hemivertebra resection with mono-segment fusion in congenital early-onset scoliosis, the mean age at the time of the initial surgery was 4.66 years (SD 1.94), and the average follow-up period was 8.35 years (SD 2.82). The immediate postoperative correction rate achieved was 76%, which is consistent with previous reports in the literature.

However, there is currently no research that addresses the impact of the crankshaft phenomenon on the outcomes of single-stage posterior hemivertebra resection with mono-segment fusion in congenital early-onset scoliosis. Our research found that patients with the crankshaft phenomenon had a significantly lower initial correction rate (62%) compared to those without the phenomenon (82%). Additionally, the crankshaft group demonstrated a higher rate of curve progression during follow-up (25.02° vs. 7.06°). Significant differences in compensatory curves, AVT, and CB were observed between the two groups, with the crankshaft group exhibiting poorer outcomes. However, no substantial differences were noted in sagittal parameters, including segmental kyphosis, thoracic kyphosis, and lumbar lordosis, between the two groups.

Limitations

Retrospective Study Design: The primary limitation of this study lies in its retrospective design, which inherently introduces biases related to patient selection, data collection, and unaccounted confounding variables. Although all patients were treated by the same surgeon, variability in clinical management over the study period may have influenced outcomes. A prospective study design would provide more reliable evidence for the long-term outcomes of this surgical approach.

Sample Size and Power: Despite a relatively large follow-up duration, the study's sample size (31 patients) remains modest. This limits the statistical power of subgroup analyses, particularly when comparing specific outcomes between groups with and without the crankshaft phenomenon. A larger cohort would help clarify the true impact of this phenomenon on surgical outcomes, as well as enable more robust subgroup comparisons.

Radiographic Measurements and Observer Variability: While radiographic parameters were measured using Surgimap Software, the study relied on manual measurements, which may introduce measurement error. Although the use of independent assessments by two authors helped mitigate this potential source of bias, variability in radiographic interpretation is still a concern. Future studies employing advanced imaging techniques or automated measurement systems may help reduce such errors and improve the accuracy of outcomes.

Surgical Technique and Fusion Length: Another limitation of this study is that it primarily focused on the mono-segmental fusion technique, it did not specifically examine the correlation between the extent of wedge deformity, the kyphotic component, and the necessity for multi-segmental fusion. Future research will evaluate the role of multi-segmental fusion in severe vertebral deformities, such as apical torsion and kyphosis, by comparing its clinical outcomes with those of mono-segmental fusion to assess how factors like apical torsion, primary curve severity, and kyphotic angles influence fusion length decisions.

Conclusion

This study highlights the effectiveness of single-stage posterior hemivertebra resection with mono-segment fusion in correcting deformities in congenital early-onset scoliosis. Despite the overall positive results, the presence of the crankshaft phenomenon was associated with poorer long-term outcomes, including greater curve progression and suboptimal compensatory curve management. These findings underscore the need for careful monitoring and consideration of the crankshaft phenomenon as a prognostic factor when planning surgical interventions for CEOS. However, the study's retrospective nature, small sample size, and potential radiographic measurement errors suggest that further, larger-scale, prospective studies are necessary to validate these findings and refine the surgical approach for CEOS patients.

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Clinical trial number

Not applicable.

Authors' contributions
J.Z. conducted surgeries, designed the study, and critically revised the manuscript. Z.P. performed radiographic measurements, data analysis, and drafted the manuscript. H.Z. and S.W. contributed to study design, data collection, and critical revisions. B.H. and Y.D. were responsible for data collection and radiographic measurements. All authors reviewed and approved the final manuscript.

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Data availability
The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Informed consent was obtained from the parents of the patients, and the study received approval from the Institutional Review Board (IRB) of Peking Union Medical College Hospital. This research was conducted in full compliance with the ethical principles outlined in the 1964 Declaration of Helsinki and its later revisions.

Consent for publication
Written informed consent from the parents was obtained for the use of patient data in the publication.

Competing interests
The authors declare no competing interests.

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