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RESEARCH ARTICLE

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An effective strategy for treatment of severe kyphosis secondary to ankylosing spondylitis: one-level modified osteotomy combined with shoulders lifting correction method

Jianzhou Luo[1,2], Tailin Wu[2], Zili Yang[1,2], Chunguang Duan[2] and Huiren Tao[3*]

Abstract

Background Severe kyphosis is a common condition in patients with advanced ankylosing spondylitis (AS). Although two-level osteotomy may serve as a potential alternative, it is often associated with increased blood loss and elevated surgical risks. To date, the optimal treatment for the challenging condition remains unclear. This study aims to introduce an effective strategy for the treatment of severe kyphosis secondary to AS, using one-level modified osteotomy combined with shoulders lifting correction method.

Methods Seventy AS kyphosis who were treated with the strategy from 2012 to 2022, were reviewed retrospectively. All patients were followed up for a minimum duration of 2 years. Spinal and pelvic parameters were measured, including pelvic tilt (PT), pelvic incidence (PI), sacral slope (SS), lumber lordosis (LL), PI and LL mismatch (PI-LL), thoracic kyphosis, global kyphosis (GK), T1 pelvic angle (TPA), sagittal vertical axis (SVA), osteotomized vertebral angle (OVA), and chin-brow vertical angle (CBVA). Parameters of local osteotomized complex were measured and calculated, including the height of osteotomized complex and the length of spinal cord shortening. Clinical outcome was evaluated using Scoliosis Research Society-22 and Oswestry Disability Index scores.

Results Seventy patients with average age of 39.8 years were followed-up for 29.3 months. Average operation time was 373.5 min, and average blood loss was 751.0 ml. Postoperatively, sagittal balance was successfully restored. GK decreased from 90.6° to 35.6°, LL decreased from 8.0° to -35.1°, TPA decreased from 56.8° to 27.8°, and SVA decreased from 24.4 cm to 8.7 cm ($P < 0.05$). A harmonious and matched spinopelvic alignment was achieved. PT decreased from 37.2° to 26.3°, PI-LL decreased from 54.1° to 10.2°, and SS increased from 9.2° to 19.7°($P < 0.05$). Horizontal vision was obtained with postoperative CBVA of 8.8°. Average OVA correction was up to 47.3°, and the spinal cord was shortened by 24.3 mm, with a shortening rate of 36.0%. All patients demonstrated a favorable clinical outcome. No permanent nerve damage, screw loosening, rod breakage and main vascular injury were observed. One case required revision surgery due to screw cap loosening and delayed union. Solid bone fusion was achieved in all other patients.

*Correspondence:
Huiren Tao
1910244002@email.szu.edu.cn; huiren_tao@163.com
Full list of author information is available at the end of the article

Conclusions One-level modified osteotomy combined with shoulders lifting correction method is a safe and effective strategy for the treatment of severe AS kyphosis. This strategy offers a promising alternative for managing severe AS kyphosis, and may be particularly well-suited for individuals with concurrent osteoporosis.

Level of evidence Level IV, therapeutic study.

Keywords Ankylosing spondylitis, Severe kyphosis, Osteoporosis, One-level osteotomy, Shoulders lifting

Introduction

Ankylosing spondylitis (AS) is a chronic inflammatory disease characterized by progressive sacroiliac and spinal arthritis. In advanced stages of the disease, severe thoracolumbar kyphosis commonly develop [1, 2]. Additionally, approximately 60% of AS patients experience complications with osteoporosis, with an even higher prevalence in cases of severe AS kyphosis [3]. These patients often experience limitations in horizontal vision, lying flat, and walking upright, necessitating the need for corrective osteotomy. Two-level osteotomy is usually used to treat this complex condition [4, 5]. However, a two-level osteotomy often comes with a higher risk of surgery-related complications due to larger blood loss and more extensive surgical trauma [4, 6, 7]. Enlarging the magnitude of one-level osteotomy may be a promising strategy for correcting severe AS kyphosis with reduced surgical risks [8, 9].

Pedicle subtraction osteotomy (PSO) is commonly used procedures for kyphotic correction [10]. While one-level PSO is typically appropriate for mild to moderate kyphosis, it may not suffice for the substantial correction required in cases of severe kyphosis. The conventional correction techniques, such as the cantilever method [10–13] and bending rod method [14, 15], utilized in PSO, heavily depend on the pedicle screw holding force to achieve kyphosis correction. This poses a significant challenge for individuals with severe AS kyphosis complicated by osteoporosis.

To address this challenge, our team has developed a surgical strategy aimed at managing the complex condition. This strategy comprises two main components: (1) a modified three-column osteotomy, which involves resecting a partial vertebra and adjacent disc while preserving a portion of pedicle and intact inferior articular process, and implanting a cage; and (2) a shoulders lifting correction method, which involves lifting patient's shoulders as a whole to assist in kyphosis correction. The modified osteotomy is designed to achieve a more substantial correction while safeguarding neurological function. The shoulders lifting correction method is intended to safely correct severe kyphosis in osteoporotic AS patients without compromising the stability of pedicle screws. In this study, we conducted a retrospective analysis of a cohort of patients who underwent this strategy to assess its safety, feasibility, as well as radiographic and clinical outcomes.

Materials and methods

Subjects

The medical records of 174 consecutive patients with AS kyphosis who underwent osteotomy by the same senior surgeon over a 10-year period (2012–2022) were retrospectively reviewed. Inclusion criteria for the study were as follows: (1) preoperative global kyphosis (GK) greater than 80°, (2) one-level modified osteotomy combined with shoulders lifting correction method was performed, (3) a minimum 2-year follow-up, and (4) preoperative L1 computed tomography (CT) attenuation less than 110 Hounsfield units (Hu). CT was recommended for evaluating bone mineral density due to the severity of vertebral heterotopic ossification in AS patients [16, 17]. Patients with L1 CT attenuation less than 110 Hu were considered to have osteoporosis [17, 18]. If Andersson lesions was present in L1, CT attenuation of L2 was measured instead. Patients with previous spine surgery or pathologic fracture were excluded. Ultimately, a total of 70 patients (63 men and 7 women) with an average age of 39.8 years (range, 26–65 years) met the inclusion criteria and were included in this study. The mean L1 CT attenuation was 74.8 Hu (range, 4-110 Hu), and 12 patients had Andersson lesions (Table 1).

Surgical technique

In this study, all patients were treated with the strategy of one-level modified osteotomy combined with shoulders lifting correction method to correct their severe kyphosis. The clear detail of this strategy was as follows.

Under general anesthesia, patients were positioned in the prone position on an adjusted operating table with appropriate postural pads. After disinfecting the entire operative area, the surgical field in the apical region of kyphosis was exposed step by step. Pedicle screws were then implanted into the planned segments of spine, which were at least three levels proximal and distal to the osteotomy site (Figs. 1 and 2). A spceical three-column osteotomy was used in this strategy, which was modified from the original PSO in several ways.

(1) Intact inferior articular processes of osteotomized vertebra were preserved, whereas in the original

Table 1 Demographic and surgical characteristics of patients

Variables	Number
Patients (*n*)	70 (63 men, 7 women)
Age (years)	39.8 ± 8.1
Combined with Andersson lesions (*n*)	12 (17.1%)
CT attenuation of L1 (Hu)	74.8 ± 36.7
Operation time (min)	373.5 ± 92.8
Estimated blood loss (ml)	751.0 ± 289.0
Osteotomy sites (*n*)	
T12	3 (4.3%)
L1	14 (20.0%)
L2	41 (58.6%)
L3	12 (17.1%)
Numbers of fusion level (*n*)	6.5 ± 0.9
Follow-up (months)	29.3 ± 5.2

PSO, they were completely resected. The preservation of these inferior articular processes theoretically provided additional stability to the osteotomized vertebra, preventing sagittal translation [19, 20] (Figs. 2 and 3).

(2) A portion of pedicle and lamina were preserved, whereas they were also completely removed in PSO. The preserved lower part of pedicle served as a protective barrier for the exiting nerve roots, reducing the risk of accidental injury during operation and avoiding bone compression after correction. Additionally, the remaining partial lamina potentially offered an extra area for bone autografts, facilitating spinal fusion (Figs. 2 and 3).

(3) Cranial adjacent disc was removed to prevent instability at the osteotomized site and create additional space for correction.

(4) A cage was implanted into the osteotomized gap to support the height of spine, aiming to avoid the spinal cord shortening dramatically (Figs. 2 and 3).

Osteotomy was performed along the lateral pedicle from posterior to anterior of the vertebra. The upper part of the vertebra (usually 1/2 − 1/3) was removed, including spinous process, transverse processes, upper part of the pedicles and lamina, and the adjacent cranial disc. The intact inferior articular processes and the lower part of pedicle and lamina were meticulously preserved. After completing one side of the osteotomy, a temporary rod was implanted and connected to at least two vertebrae above and below the osteotomy site. The contralateral side was then subjected to the same osteotomy procedure.

After completing bilateral osteotomy, correction was performed with the assistance of bilateral temporary rods. In this surgical strategy, a shoulders lifting correction method was developed for the correction of severe AS kyphosis. This method differed from the typical cantilevered method [10, 11] and the bending rod method [15, 21]. The clear processes of the method were as follows:

Firstly, the spine was moderately closed in situ to shorten the spinal cord, aiming to release tension in the kyphotic spinal cord and create sufficient space for spinal cord elongation during correction (Fig. 1B-a). As the kyphotic spine was gradually corrected, the spinal cord was simultaneously dragged and elongated, transitioning from kyphosis to a straight position. It was crucial to reserve enough space for the cord to prevent traction injury during correction.

Secondly, the shoulders were lifted in conjunction with bending rods for kyphosis correction (Fig. 1B b and c). This step was pivotal in the correction method. The circulating nurses and technicians coordinated their efforts to lift the patients' shoulders while the surgeons manipulated the bending rods for correction. Postural pads were removed, and the operation table was adjusted accordingly to accommodate the change in body posture resulting from the lifting maneuver. In this correction method, the primary corrective force was provided by lifting shoulders, while the bending rods served as a secondary corrective force. This arrangement aimed to decrease the likelihood of pedicle screw dislodgement during correction. And the points of temporary rods at the osteotomized site acted as a hinge, allowing for a greater degree of correction by opening the anterior-middle column of spine.

Thirdly, the spinal alignment was reconstructed by implanting a cage in the osteotomy gap (Fig. 1B-d). Once satisfactory correction was achieved, the temporary rods were replaced with precontoured cobalt chrome rods in a sequential manner. The remaining osteotomy gap was filled with a suitable cage (typically a kidney-shaped PEEK cage, ranging from 16 mm×8 mm×10 mm to 22 mm×12 mm×10 mm) and autogenous bone particles to support the spine. Subsequently, the rods were compressed further to facilitate the sinking and secure anchoring of the cage into the cancellous bone of osteotomized vertebra. The primary objectives of cage implantation were to provide support for spinal height and prevent dramatical shortening of the spinal cord. Furthermore, the implantation of cage also aimed to enhance the stability of osteotomized vertebra and prevent sagittal translation [22].

Finally, two long allogeneic bone plates were used to cover the breach on the lamina of osteotomy site to protect the spinal cord. Subsequently, the surface of posterior column was polished with power drill, and the autogenic bone was paved on the surface to facilitate spinal fusion. A drainage tube was placed, and the surgical incision was sutured. Finally, the kyphosis was completely corrected, and the patient was placed flat on the extended operation

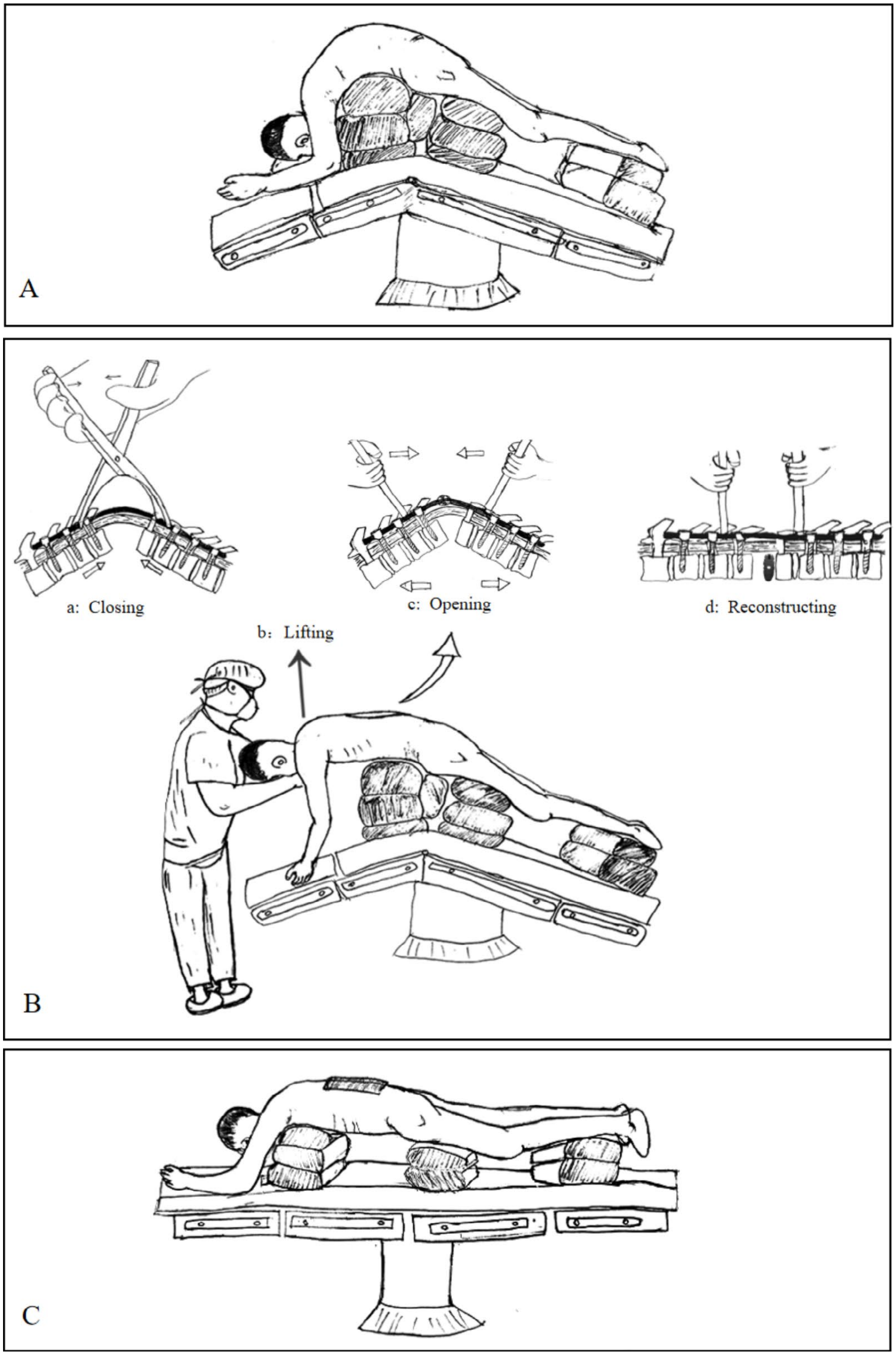

Fig. 1 Procedure of the strategy for treatment severe AS kyphosis. (**A**) Patient is positioned in a prone position on an adjusted operation table with postural pads. (**B**) Following vertebra resection (as described in Fig. 2), the osteotomized ends are slightly closed **(a)** to create space for spinal cord lengthening during correction; the circulating nurse then lifts patient's shoulders **(b)** while bending rods to open the anterior-middle column of spine for correction **(c)**; once satisfactory correction is achieved, a cage is implanted to reconstruct spinal alignment **(d)**. (**C**) Postoperatively, the patient is placed flat on the outstretched operation table

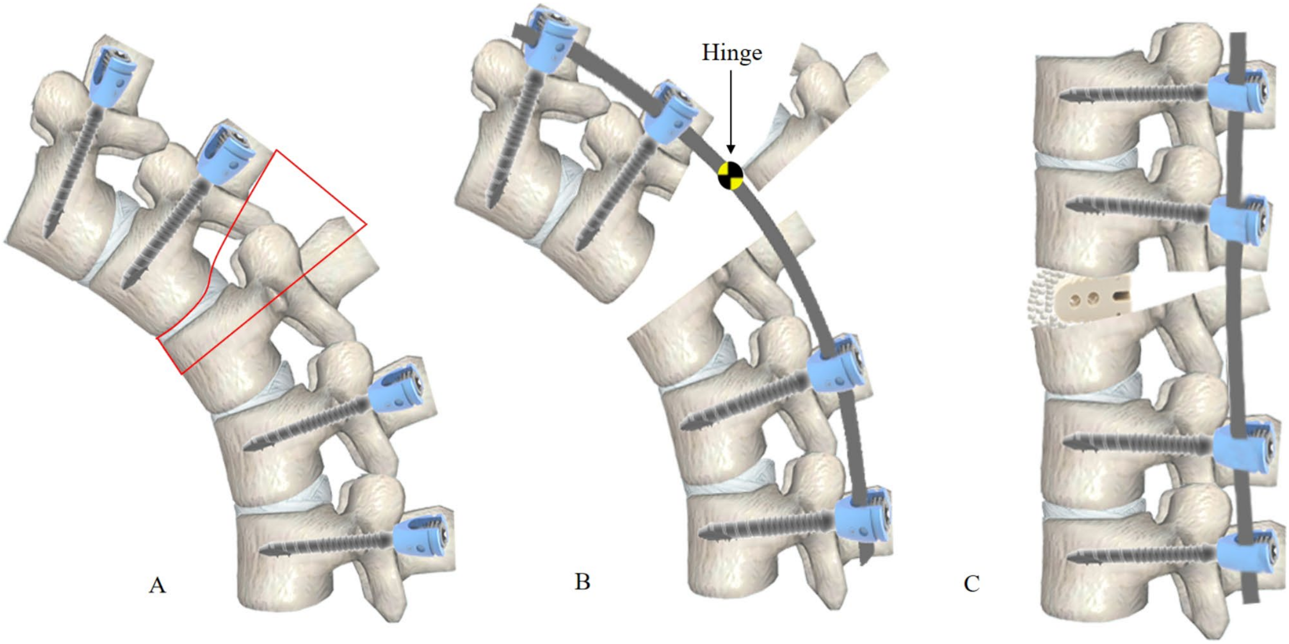

Fig. 2 Schematic illustration of the modified osteotomy. (**A**) Pedicle screws are implanted at the fusion level around the osteotomy area (frame). (**B**) Partial elements of osteotomized vertebra are removed, including spinous process, upper part of pedicle, superior articular processes, and approximately half to one-third of upper part of the vertebral body. Additionally, the inferior articular processes of the adjacent cranial vertebra and the upper disc are resected. (**C**) After kyphosis correction, a cage and autogenous bone are implanted in the osteotomized space to reconstruct and align the spine

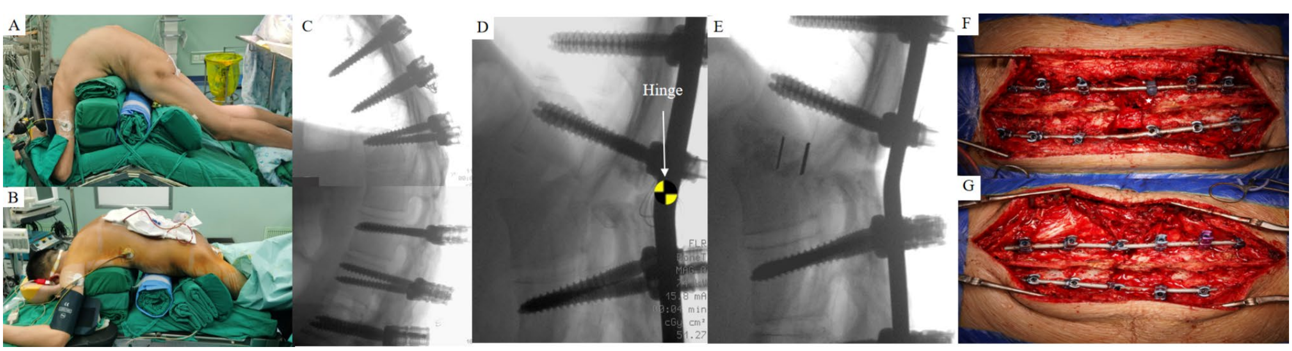

Fig. 3 Intraoperative photographs of the strategy. (**A**) Preoperatively, patient was positioned prone on a flexed operating table with the assistance of positioning pads; (**B**) Postoperatively, the patient was able to lie flat on the operating table. (**C**) Pedicle screws were inserted into three adjacent vertebrae above and below the osteotomy vertebra. (**D**) The lower half of the pedicles, laminae, and completed inferior articular processes in the osteotomized vertebra were preserved. Spine column in front of the hinge of temporary rods was opened for correction. Subsequently, a shortening of the spine was performed to release spinal cord tension and close the gaps of posterior elements. (**E**) Following completion of correction, a cage and autogenous bone particles were placed in the osteotomy space. (**F**) The appearance of incision post-osteotomy, indicating that the lower lamina and inferior articular processes of osteotomized vertebra remained intact (star). (**G**) The appearance of incision post-correction, illustrating that the closure of posterior elements were achieved after the completion of correction

table again. The entire surgical procedure was continuously monitored by somatosensory- and motor-evoked potentials. Around three days after surgery, the patient was permitted to ambulate with a personalized thoracolumbosacral orthosis, typically worn for a duration of six months. Following the operation, calcium supplementation, vitamin D administration, and anti-osteoporosis therapy were continued to improve bone density, support the recovery of the osteotomized vertebra, and aid in the fusion of bone grafts.

Surgical decision-making

Decision-making regarding the strategy for severe AS kyphosis combined with osteoporosis, was primarily based on comprehensive preoperative planning and meticulous intraoperative evaluation. Prior to surgery, the required correction for patients was estimated through lateral radiographic measurements and clinical examination. If the required osteotomized vertebra angle (OVA) was more than 35°, one-level modified osteotomy combined with shoulders lifting correction method was considered. However, the maximum correction in one-level osteotomy should not exceed 70° to prevent excessive spinal cord shortening. Generally, the osteotomy vertebra was selected in the apical vertebral region, closer to the caudal side, to maximize correction of kyphotic deformity and enhance sagittal alignment balance. The evaluation criteria for satisfactory intraoperative correction were as follows: (1) the patient's shoulders were elevated to the level of pelvis horizontally, and (2) the OVA measured in intraoperative radiographs matched the planned degree of OVA. The main goal of surgery was to reconstruct a harmonious and balanced spine.

Outcome measurements and radiographic evaluation

Clinical outcomes were assessed using the Scoliosis Research Society-22 (SRS-22) and Oswestry Disability Index (ODI) questionnaires. Radiographic evaluation was conducted using full-length freestanding lateral spine radiographs. Radiographic parameters included pelvic tilt (PT), pelvic incidence (PI), sacral slope (SS), lumbar lordosis (LL), PI and LL mismatch (PI-LL), thoracic kyphosis (TK), global kyphosis (GK), T1 pelvic angle (TPA), sagittal vertical axis (SVA), chin-brow vertical angle (CBVA), and OVA (Fig. 4). Measurements of local osteotomized complex (comprised of the osteotomized vertebra, adjacent cranial vertebra, and intermediate intervertebral disc) included the distance of anterior column (AC), middle column (MC), and posterior column (PC) (Fig. 4). The height of osteotomized complex (HOC) was calculated using the equation HOC = (AC + MC) / 2, while the length of spinal cord (LSC) was calculated using the equation LSC = (MC + PC) / 2. The percentage of spinal cord shortening (PCS) was calculated using the equation PCS = (change of LSC / preoperative HOC) × 100%. Vertebral subluxation was defined as sagittal translation of the osteotomized vertebra greater than 5 mm [23].

Statistical analysis

Statistical analysis was performed using SPSS software version 22.0 (SPSS Inc., Chicago, IL). All numeric parameters are presented as mean ± standard deviation. Paired t-tests were used to compare the differences in radiographic measurements, ODI, and SRS-22 scores before and after surgery, as well as at the final follow-up. A P value < 0.05 was considered statistically significant.

Results

Operative procedure

One-level modified osteotomy combined with shoulders lifting correction method was performed in all patients, including 3 patients at T12, 14 patients at L1, 41 patients at L2 and 12 patients at L3. The mean operation time was 373.5 min (range, 175–620 min), the average estimated blood loss was 751.0 mL (range, 300–1500 mL), the average number of fused levels was 6.5 (range, 6–12), and the average follow-up was 29.3 months (range, 24–48 months) (Table 1).

Radiographic parameters

With the exception of PI, all other parameters showed significant improvement after surgery (all $P < 0.05$). Overall, the postoperative sagittal alignment was successfully corrected. GK decreased from 90.6° to 35.6° postoperatively, LL decreased from 8.0° to -35.1°, TPA decreased from 56.8° to 27.8°, and SVA decreased from 24.4 cm to 8.7 cm (all $P < 0.05$). The spinopelvic alignment also showed significant improvement. Postoperatively, PT decreased from 37.2° to 26.3°, PI-LL decreased from 54.1° to 10.2°, and SS increased from 9.2° to 19.7°(all $P < 0.05$). TK showed a slight change with an average correction of 1.3° ($P < 0.05$). Horizontal gaze was achieved postoperatively, with CBVA decreasing from 42.6° to 8.8° ($P < 0.05$). Some correction loss was observed at the final follow-up (Table 2; Fig. 5).

Measurements of osteotomized complex

Postoperatively, a substantial correction of OVA was achieved with an average of 47.3° ($P < 0.05$). The anterior column of osteotomized complex was opened, resulting in an average lengthening of 11.9 mm ($P < 0.05$). The height of osteotomized complex decreased from 67.4 mm to 64.4 mm, resulting in an average change of 3.0 mm ($P < 0.05$). The spinal cord was shortened by 24.3 mm after the operation, representing a shortening rate of 36.0% relative to the height of osteotomized complex ($P < 0.05$) (Table 3; Fig. 5).

Clinical outcomes

All domains of SRS-22 showed significant improvement at the final follow-up ($P < 0.05$). The improvements in appearance, mental and satisfaction in SRS-22 were particularly significant, with average increases of 1.70, 1.00, and 1.74, respectively (all $P < 0.05$). The SRS-22 total score increased from 2.72 to 3.89 ($P < 0.05$). Significant improvements were observed in multiple domains of ODI questionnaire, including personal care, walking, standing, sleeping, social life, and traveling (all $P < 0.05$). Among them, the improvements in standing, social life, and traveling were particularly notable, with average improvements of 1.70, 1.24, and 1.36, respectively (all $P < 0.05$). The ODI total score decreased from 18.87 to 9.88 ($P < 0.05$) (Table 4).

Complications

Out of the 70 patients, 15 patients experienced a total of 16 surgical complications. Among these complications, 7 patients had vertebral subluxation with forward vertebral displacement, but none of them had any neurological

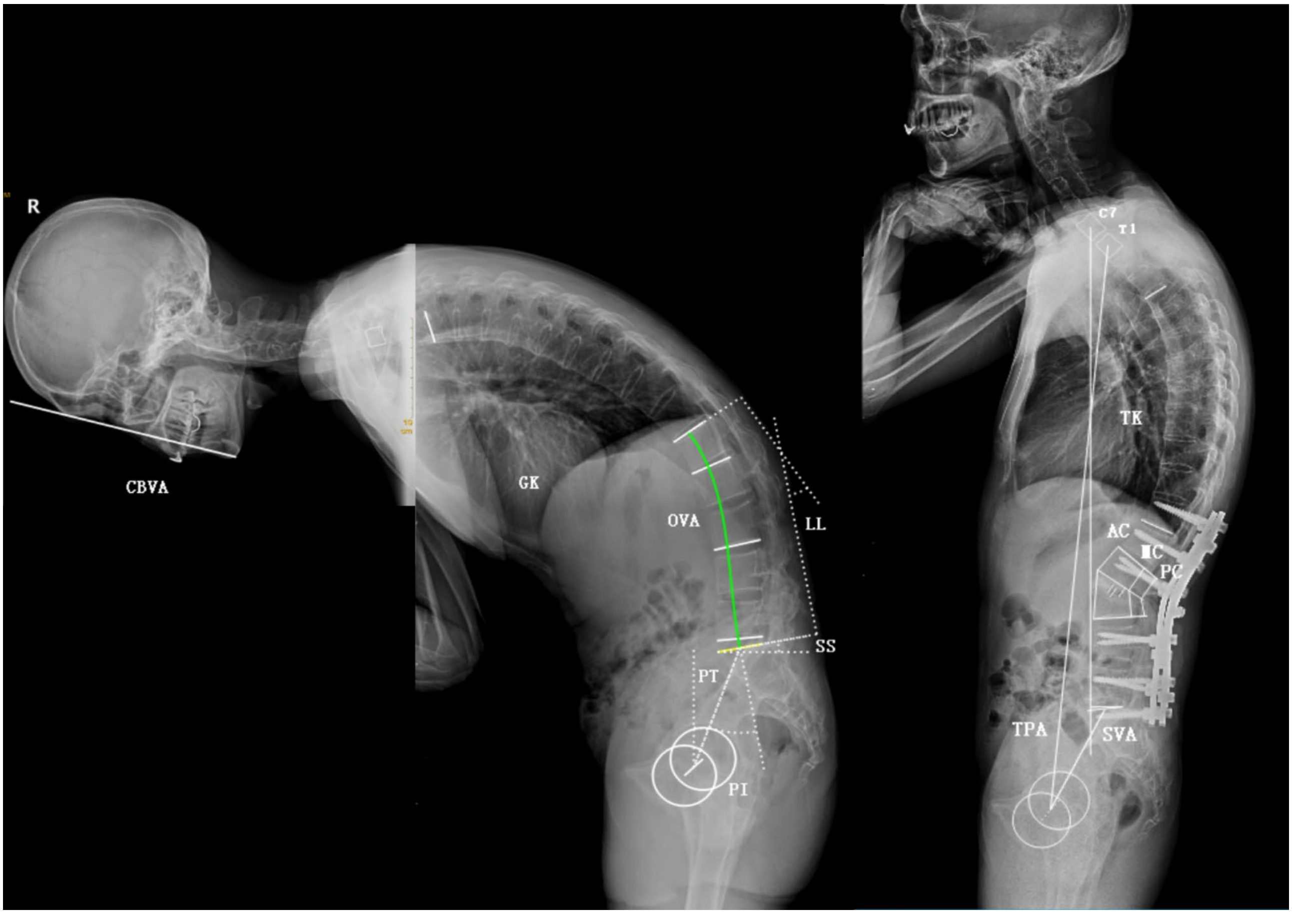

Fig. 4 Illustration of radiographic measurements. Pelvic tilt (PT): the angle between the vertical line and the line connecting the center of the S1 upper endplate to the center of the femoral head axis; pelvic incidence (PI): the angle between the line perpendicular to the S1 upper endplate and the line connecting the center of the S1 upper endplate to the center of the femoral head axis; sacral slope (SS): the angle between the S1 upper endplate and the horizontal line; lumbar lordosis (LL): the Cobb angle measured from the L1 upper endplate to the S1 upper endplate; pelvic incidence and lumbar lordosis mismatch (PI-LL): the pelvic incidence value minus the lumbar lordosis value; thoracic kyphosis (TK): the Cobb angle measured from the T4 upper endplate to the T12 lower endplate; global kyphosis (GK): the angle between the superior endplate of the maximally tilted upper end vertebra and the inferior endplate of the maximally tilted lower end vertebra; T1 pelvic angle (TPA): the angle between a line joining the center of T1 and the femoral head axis, and a line from the center of the femoral head axis to the midpoint of the S1 upper endplate; sagittal vertical axis (SVA): the distance between the C7 plumb line and the posterior-superior corner of S1; chin-brow vertical angle (CBVA): the angle between the line from the chin to the brow and the plumb line; osteotomized vertebral angle (OVA): the angle between the lower endplate of osteotomized vertebra and the upper endplate of adjacent cranial vertebra; anterior column (AC) of osteotomized complex: the distance between the anterior-inferior corner of osteotomized vertebra and the anterior-superior corner of cranial adjacent vertebra; middle column (MC) of osteotomized complex: the distance between the posterior-inferior corner of osteotomized vertebra and the posterior-superior corner of cranial adjacent vertebra; posterior column (PC) of osteotomized complex: the distance between the inferior endplate extension line of osteotomized vertebra and the superior endplate extension line of cranial adjacent vertebra, relative to the posterior wall of spinal canal

deficits. Dural laceration occurred in 7 patients, with 4 cases presenting Andersson lesions at the osteotomy site. Intraoperatively, it was observed that proliferated osteophytes and fibrotic tissues occurred around the site of Andersson lesions, and the dural sacs were adhered to the lamina and ligamentum flavum. In the remaining 3 cases, the dural sac had ossified and fused with the surrounding lamina. All patients with dural lacerations were successfully treated through intraoperative repair and postoperative pressure bandaging, with no persistent cerebrospinal fluid leakage postoperatively. One patient experienced transient neurological deficit due to poor drainage and accumulation of intraspinal hematoma, which was relieved after adjusting the drainage. At 2 years follow-up, one patient required revision surgery as the cap of the LIV pedicle screw was found to be loose and had fallen off, resulting in unstable internal fixation and delayed union. Following the revision surgery, the patient healed without any complications. No permanent nerve damage, vertebral fracture, screw loosening, rod breakage, or main vascular injuries were observed (Table 5).

Table 2 Radiographic measurements of patients before and after surgery

Parameters	Preoperative	Postoperative	Final follow-up	Correction	Loss of correction
PT (°)	37.2 ± 12.3	26.3 ± 11.6	30.9 ± 11.1	10.9 ± 10.4*	4.6 ± 5.8†
PI (°)	46.1 ± 12.5	45.8 ± 12.2	44.8 ± 11.0	0.3 ± 3.3	1.0 ± 4.0
SS (°)	9.2 ± 11.9	19.7 ± 10.7	13.4 ± 13.0	10.5 ± 9.4*	6.3 ± 7.6†
LL (°)	8.0 ± 21.3	-35.1 ± 16.1	-33.3 ± 18.5	43.1 ± 17.3*	1.8 ± 8.2†
PI-LL (°)	54.1 ± 23.2	10.2 ± 16.7	11.0 ± 17.0	43.9 ± 17.6*	0.8 ± 7.9
TK (°)	54.2 ± 16.4	52.9 ± 11.4	52.8 ± 10.4	1.3 ± 13.1*	0.1 ± 5.4
GK (°)	90.6 ± 11.8	35.7 ± 14.0	41.6 ± 16.0	54.9 ± 13.7*	5.9 ± 7.8†
TPA (°)	56.8 ± 18.6	27.8 ± 13.0	30.5 ± 13.0	29.0 ± 11.1*	2.7 ± 4.8†
SVA (cm)	24.4 ± 9.4	8.7 ± 4.9	7.8 ± 5.2	15.7 ± 6.9*	1.0 ± 4.0
CBVA (°)	42.6 ± 28.7	8.8 ± 12.4	6.9 ± 10.2	33.8 ± 24.0*	1.9 ± 10.7

PT, pelvic tilt; PI, pelvic incidence; SS, sacral slope; LL, lumbar lordosis; PI-LL, PI and LL mismatch; TK, thoracic kyphosis; GK, global kyphosis; TPA, T1 pelvic angel; SVA, sagittal vertical axis; CBVA, chin-brow vertical angle. For LL, negative numbers represent lordosis; positive numbers represent kyphosis

*Indicates a statistically significant difference between preoperative and postoperative values ($P<0.05$);

†Indicates a statistically significant difference between postoperative and the final follow-up values ($P<0.05$)

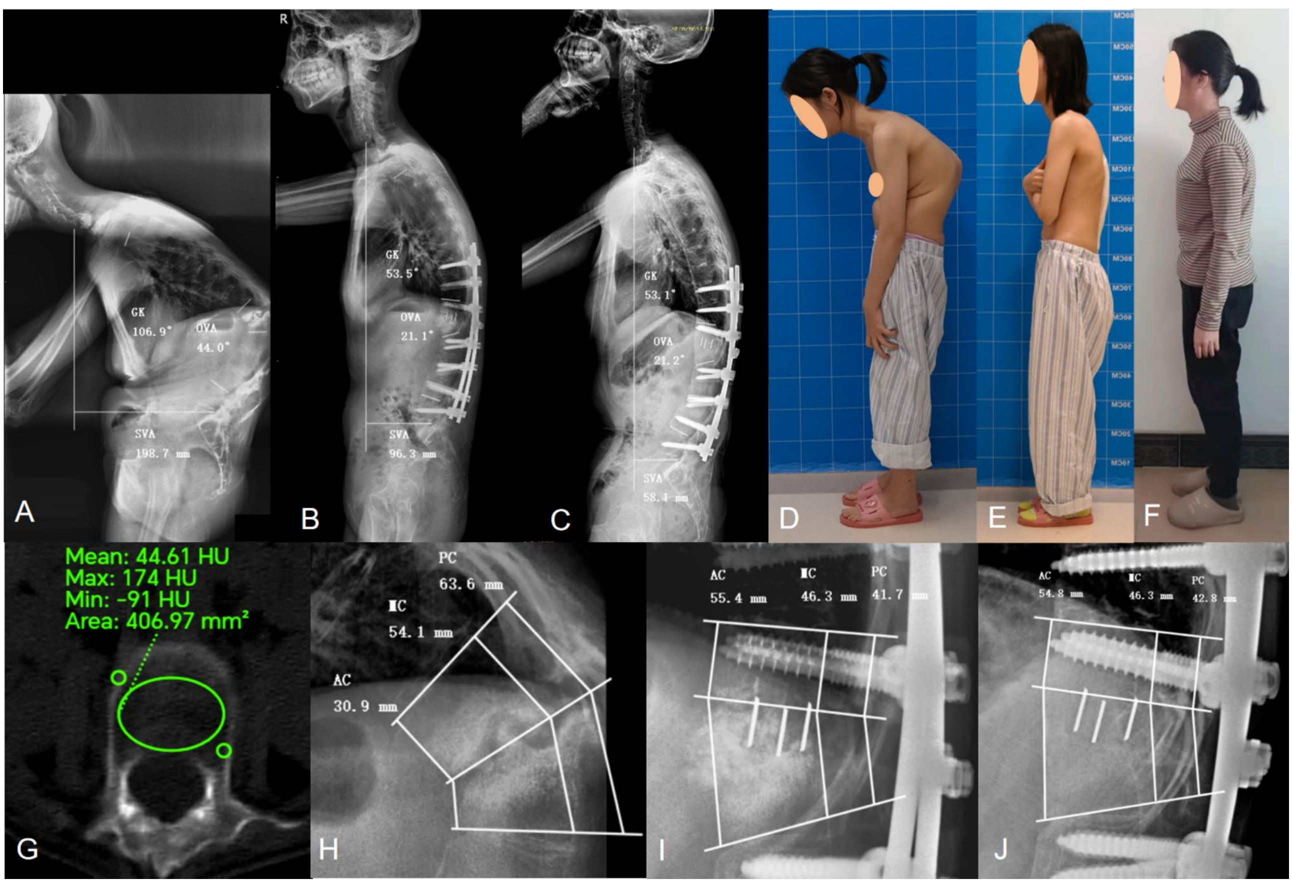

Fig. 5 A 31-year-old woman suffered severe thoracolumbar kyphosis and osteoporosis secondary to AS with T12/L1 Andersson lesions. (**A**) Preoperative standing lateral radiograph demonstrated a severe thoracolumbar kyphosis with GK of 106.9° and SVA of 198.7 mm. (**B**) One-level modified osteotomy combined with shoulders lifting correction method was performed, resulting in a 65.1° OVA correction at L1, with GK of 53.5° and SVA of 96.3 mm. (**C**) At the 2-year follow-up, excellent spinal alignment was maintained, and solid bony fusion was observed at the osteotomy site, with GK of 53.1° and SVA of 58.1 mm.(**D-F**) Clinical photographs illustrated the changes in appearance preoperatively (**D**), postoperatively (**E**), and at the final follow-up (**F**). (**G**) The L2 CT scan revealed severe osteoporosis with an attenuation of 44.6 Hu. (**H-J**) Local X-rays depicted the changes in the height of osteotomized complex in three stages: preoperative (**H**), postoperative (**I**), and final follow-up (**J**)

Table 3 Changes of local osteotomized complex before and after surgery

Parameters	Preoperative	Postoperative	Final follow-up	Change	Loss of change
AC (mm)	60.8 ± 10.1	72.7 ± 8.7	69.5 ± 9.3	11.9 ± 8.8*	3.2 ± 4.2†
MC (mm)	74.0 ± 9.5	56.1 ± 7.2	55.1 ± 8.3	17.9 ± 7.7*	1.0 ± 2.9†
PC (mm)	79.6 ± 10.5	48.9 ± 8.1	49.1 ± 10.0	30.7 ± 9.3*	0.2 ± 3.5
HOC (mm)	67.4 ± 9.2	64.4 ± 7.3	62.3 ± 8.2	3.0 ± 7.3*	2.1 ± 3.3†
LSC (mm)	76.8 ± 9.9	52.5 ± 7.5	52.1 ± 9.0	24.3 ± 8.3*	0.4 ± 3.1†
PCS (%)	-	36.0 ± 10.4	36.6 ± 10.6	-	-
OVA (°)	21.3 ± 11.1	-26.0 ± 10.3	-24.4 ± 13.3	47.3 ± 12.9*	1.6 ± 7.6†

AC, anterior column of the osteotomized complex; MC, middle column of the osteotomized complex; PC, posterior column of the osteotomized complex; HOC, height of the osteotomized complex, calculated with the equation of HOC = (AC + MC)/2; LSC, length of the spinal cord, calculated with the equation of LSC= (MC + PC)/2; PCS, percentage of spinal cord shortening, calculated with the equation, PCS = (Change of LSC/preoperative HOC)×100%; OVA, osteotomized vertebra angle. For OVA, negative numbers represent lordosis; positive numbers represent kyphosis

*Indicates a statistically significant difference between preoperative and postoperative values ($P < 0.05$);

†Indicates a statistically significant difference between postoperative and the final follow-up values ($P < 0.05$)

Table 4 Comparisons of SRS-22 and ODI scores before and after surgery

Variables	Preoperative	Final follow-up	Improvement	*P*-value
SRS-22 pain	3.24 ± 1.00	3.93 ± 0.66	0.68 ± 1.08	0.001
SRS-22 function	2.74 ± 0.88	3.48 ± 0.74	0.75 ± 0.94	< 0.001
SRS-22 appearance	2.05 ± 0.85	3.75 ± 0.65	1.70 ± 0.93	< 0.001
SRS-22 mental	2.93 ± 0.91	3.90 ± 0.68	1.00 ± 1.01	< 0.001
SRS-22 satisfaction	2.65 ± 0.94	4.39 ± 0.58	1.74 ± 1.15	< 0.001
SRS-22 total score	2.72 ± 0.68	3.89 ± 0.51	1.17 ± 0.78	< 0.001
ODI-personal care	1.82 ± 1.16	1.18 ± 1.16	0.64 ± 1.58	0.027
ODI-walking	1.64 ± 1.14	0.67 ± 1.08	0.97 ± 1.42	< 0.001
ODI-standing	2.73 ± 1.21	1.03 ± 0.85	1.70 ± 1.45	< 0.001
ODI-sleeping	1.48 ± 1.30	0.55 ± 0.94	0.94 ± 1.34	< 0.001
ODI- social life	2.48 ± 1.56	1.24 ± 1.41	1.24 ± 2.00	0.001
ODI-travelling	2.21 ± 1.41	0.85 ± 0.94	1.36 ± 1.71	< 0.001
ODI total score	18.87 ± 9.52	9.88 ± 6.04	9.00 ± 11.05	< 0.001

SRS-22: Scoliosis Research Society-22; ODI, Oswestry Disability Index; Significance set as $P < 0.05$

Table 5 Surgical complications

Complications	Cases
Vertebral subluxation	7
Transient neurological deficit	1
Permanent nerve damage	0
Dura laceration	7
Vertebral fracture	0
Screw loosening/ rod breakage	0
Screw cap loosening /delayed union	1
Main vascular injury	0

Discussion

A severe rigid AS kyphosis leads to a forward shift in the center of gravity, resulting in a leaning-forward posture and impaired ability to look straight ahead. In advanced stages, over half of AS patients encounter the complication of osteoporosis, further complicating kyphosis correction through spinal osteotomy [3, 24]. Approximately 33% of AS patients undergoing osteotomy experience pedicle fractures and screw dislocation due to osteoporosis during follow-up, with 4.5% requiring revision surgery due to implant failure [25, 26]. Undoubtedly, osteoporosis presents a growing challenge in the treatment of severe AS kyphosis [27]. Two-level osteotomy is commonly employed in managing this condition. However, the use of two-level osteotomy often entails a higher risk of surgery-related complications due to prolonged operation times and increased blood loss [7]. Therefore, there is an urgent imperative to explore safer and more efficient strategies to address the complex challenge of severe AS kyphosis in the presence of osteoporosis.

One-level PSO is a commonly used procedure for correcting AS-related kyphosis, but it is generally suitable for mild to moderate correction and may not meet the needs of large corrections for severe kyphosis. Some modified PSO techniques have been developed to address severe kyphosis with one-level osteotomy, as demonstrated by Hu et al. [8]. and Gao et al. [19]. These techniques have shown successful correction in cases of post-traumatic thoracolumbar kyphosis. Nevertheless, these approaches were not specifically tailored for severe AS kyphosis accompanied by osteoporosis and may not be suitable for correcting osteoporotic kyphosis.

In this study, a modified osteotomy technique was developed based on PSO, specifically designed for treating severe AS kyphosis with osteoporosis. Several innovative improvements were implemented in this modified osteotomy. Firstly, the upper part of the vertebra, including the adjacent cranial disc, was resected, resulting in an enlarged resection area and allowing for larger degree of correction. Additionally, the removal of the soft tissue of disc enhanced the stability of osteotomized vertebrae, facilitating bone fusion postoperatively [19]. Our data confirmed that the average OVA correction was 47.3°, with the largest correction reaching 71°, indicating a significant potential for correcting severe kyphosis. These results surpass the typical PSO correction range of 30°-43° [12, 28, 29](Table 6). With the exception of one case of delayed union due to LIV screw cap loosening, all other cases achieved solid bone fusion at the final follow-up. Secondly, in this modified osteotomy, the intact inferior articular processes and lower half of the pedicle were meticulously preserved. The preservation of the complete inferior articular processes theoretically provided additional stability to the osteotomized vertebrae, limiting subtle mobility and sagittal translation [19]. And the lower part of the pedicle was preserved to prevent accidental injury to the exiting nerve roots during surgical procedure. In our cases, no neurological damage occurred due to nerve root disturbance. Thirdly, a suitable cage was implanted in the osteotomized gap to support the height of spine, preventing dramatical shortening of spinal cord. The function of the cage in this technique differs from other approaches [11, 30, 31], where the cage is used as a hinge to distract the anterior column for larger correction. In this study, the temporary rods served as pivotal hinges to facilitate the opening of anterior and middle columns of spine, leading to a more substantial correction of kyphosis (Figs. 2 and 3). Key considerations in cage implantation using this approach include actively compressing the cage to ensure its stable fixation within the cancellous bone of osteotomized vertebra, thereby limiting further subsidence or migration, particularly in patients with osteoporosis.

The correction methods employed in PSO typically involve cantilever method [11–13] and bending rod method [14, 15], sometimes supplemented by extending operative table or special spinal frame to achieve kyphosis correction [12, 32, 33] (Table 6). However, in cases of extremely severe AS kyphosis, these methods exhibit limitations. Patients with such severe AS kyphosis are unable to undergo surgery on a standard operating table in a prone position, necessitating the use of a surgical position frame to support the patient's positioning [6]. Additionally, performing surgery in the prone position is not feasible, with only lateral position surgery being a viable option [34]. The utilization of a hinged operating table for correction assistance is not viable for this patient population. While, the "shoulders lifting" correction method serves as a complementary approach that can be applied across all the aforementioned scenarios, providing a more practical surgical solution. This method is adaptable to patients in more surgical positions, allowing for correction of severe kyphosis in multiple directions without constraints related to the operating table area. It is well-suited for addressing highly severe kyphotic deformities, including the "chin-on-thigh" [34] or "chin-on-pubis" deformity [35].

Furthermore, when employing cantilever and bending rod method solely for kyphosis correction, a strong pullout force is concurrently applied to pedicle screws [36, 37]. This necessitates adequate vertebral stiffness and pedicle screw holding force to effectively achieve the desired kyphosis correction. Regrettably, this criterion is frequently unmet in severe AS patients with osteoporosis [1]. Conversely, the "shoulder lifting" correction method can assist in reducing the reliance on corrective force within the vertebral region, making it a favorable option for AS kyphosis patients with osteoporosis. This method involves correcting AS kyphosis by gradually lifting patients' shoulders while utilizing bending rods. The primary corrective force is generated through shoulder lifting maneuvers from the entire body, with minimal localized corrective force applied by bending the temporary rods following the lifting maneuvers. This method theoretically minimizes the pullout force exerted on the pedicle screws, thereby reducing the likelihood of pedicle screw loosening and pseudoarthrosis formation. Within our cohort, there were no cases of pedicle screw loosening, rod breakage, or vertebral fracture observed either intraoperatively or postoperatively.

In this modified osteotomy, the hinge points are located on temporary rods at the osteotomy site, distinguishing it from other osteotomies [14, 19, 22, 31, 38, 39]. In traditional PSO, the hinge is the point where the anterior column cortex is broken [19, 22, 38], while in closing-opening wedge osteotomy (COWO), the hinge is the posterior edge of the vertebral body [14, 39]. Both hinges are located on the vertebral body. However, in our modified osteotomy, the hinge is transferred from vertebral body to temporary rods, allowing for easier opening of the anterior-middle column and achieving greater correction. The alteration in location of hinge proves particularly advantageous for individuals with low bone mineral density, who may not withstand excessive pressure at the vertebral hinge for opening anterior column during correction. Of note, the modified osteotomy method involves a three-column release of spine and allows for unrestricted movement around the hinge on temporary rods. However, if the sagittal rotation angle is excessively large, there exists a risk of vertebral subluxation [39, 40]. Previous studies conducted by Chang et al. [39, 40] indicated that approximately 27%–40% of patients experienced sagittal translation, with 15%

Table 6 Results of clinical and radiographic outcome in different surgical strategy for severe AS kyphosis reported in literatures

Study(year)	Operated cases	Surgical strategy (osteotomy + correction method)	Operation time(min)	Blood loss (ml)	preoperative GK(°)	Final GK(°)	preoperative SVA(cm)	Final SVA(cm)	OVA correction(°)	Complication
Bridwell et al. [10] (2003)	27	PSO + cantilever technique	744	2396	N/A	N/A	17.7 ± 8.0	4.2 ± 6.7	30.3	2 dural tear, 9 pseudarthrosis/implant failure,1 visual field defect in one eye, 2 postoperative respiratory distress, 1 prominent iliac screws.
Chang et al. [12] (2005)	51	one-level PSO + extending operating table	218	1915	N/A	N/A	14.6 ± 6.4	6.9 ± 4.1	38 ± 11	3 dura laceration, 3 paralytic ileus, 1 pneumonia, 3 transient radiculopathy, 3 distal screw loose.
Zhu et al. [37] (2012)	31	one-level PSO + extending bow-shaped frame	N/A	1740	73.7 ± 23.6	33.8 ± 15.7	18.5 ± 4.6	7.7 ± 5.5	43.9 ± 9.7	1 dural tear, 3 nerve root injury, 1 severe neurological deficit.
Qian et al. [14] (2012)	35	one-level PSO + straightening special spinal frame and elevating upper body and thighs	282	2000	75.9 ± 18.7	44.1 ± 19.3	13.9 ± 5.3	4.0 ± 3.6	31.9 ± 7.3	1 dural tears, 1 intraoperative pedicle screw loose, 1 paralytic ileus,1 transient neurological deficit.
Qian et al. [29] (2013)	36	one-level PSO + straightening special bow-type frame	N/A	N/A	73.7 ± 16.5	28.4 ± 11.7	13.3 ± 5.0	4.0 ± 3.4	42.7 ± 10.9	N/A
Xu et al. [4] (2015)	37	one-level PSO + extending operating table and cantilever technique	232	1240	N/A	N/A	18.6 ± 11.6	5.8 ± 6.2	43.2 ± 15.1	3 dura laceration, 2 neurologic deficit, 3 vertebrae translation, 1 vertebrae column fracture.
Hua et al. [5] (2017)	12	one-level PSO	327	1525	75.2 ± 23.2	36.5 ± 14.3	21.7 ± 6.3	10.8 ± 5.7	32.8 ± 18.2	1 dural tear, 1 intraoperative distal pedicle screw loose, 1paralytic ileus.
Qiao et al. [2] (2018)	47	one-level PSO	N/A	N/A	74.3 ± 16.2	29.9 ± 11.6	16.0 ± 6.1	5.2 ± 4.3	29.0 ± 7.2	3 intraoperative subluxation, 1 dural tears, 1 transient neurologic deficit, 1 rod breakage.
Xin et al. [7] (2019)	339	one-level PSO/VCD + extending operating table and cantilever technique.	253	537	55.8 ± 21.3	11.2 ± 7.8	18.0 ± 8.9	5.2 ± 5.0	N/A	12 dural tears, 1 rod broken, 2 pedicle screws loose, 3 pseudarthrosis.
Wang et al. [33] (2019)	25	one–level PSO + adjusting position and operating table	N/A	970	62.3 ± 14.8	26.9 ± 16.0	17.1 ± 3.7	6.2 ± 2.6	33.8 ± 5.2	2 dural tears, 1 transient lower extremity weakness, 3 mild sagittal translation.

Table 6 (continued)

Study(year)	Operated cases	Surgical strategy (osteotomy + correction method)	Operation time(min)	Blood loss (ml)	preoperative GK(°)	Final GK(°)	preoperative SVA(cm)	Final SVA(cm)	OVA correction(°)	Complication
Huang et al. [28] (2020)	100	one-level PSO	332	1821	71.6 ± 15.7	24.0 ± 12.9	16.1 ± 5.9	4.5 ± 3.9	39.2 ± 5.4	7 intraoperative subluxation, 2 dural tears, 2 transient radiculopathy.
Current study	70	One-level modified osteotomy + shoulder lifting correction method	374	751	90.6 ± 11.8	41.6 ± 16.0	24.4 ± 9.4	7.8 ± 5.2	47.3 ± 12.9	7 vertebral subluxation, 1 transient neurological deficit, 7 dura laceration, 1 screw cap loosening /delayed union.

GK, global kyphosis; SVA, sagittal vertical axis; OVA, osteotomized vertebra angle; VCD, vertebral column decancellation; PSO, pedicle subtraction osteotomy; N/A, Not applicable

encountering neurological complications during kyphosis correction using the opening wedge osteotomy. In our study, 7 patients (10%) experienced vertebral subluxation with forward displacement of osteotomized vertebra, yet none of them exhibited neurological deficits. Therefore, caution must be exercised when employing this method to prevent any compromise to neurological function.

Interestingly, in the modified osteotomy, the spinal cord exhibits a tendency to elongate during correction process due to the transfer of hinge to temporary rods. This differs from conventional PSO and COWO procedures, where the spinal cord is typically directly shortened [14, 38, 39]. In the modified osteotomy, the temporary rods function as pivotal hinges, leading to elongation of spinal cord anterior to the juncture during correction procedure. However, the spinal cord is fragile and cannot tolerate excessive lengthening. If the kyphotic spine is straightened too much at once, it can lead to spinal cord traction injury. Without intervention, the cord can be damaged during correction process. To address this issue, we implemented an active shortening of spinal cord to reduce the potential risk of injury that might arise from its elongation. The specific details are as follows: Initially, osteotomized gap is slightly closed by compressing temporary rods to shorten the spinal cord before each correction, which creates enough potential space for spinal cord lengthening. Subsequently, the shoulders are gradually lifted to ensure that spinal cord lengthening is slight and tolerable, based on monitoring observations. Skillfully, the maneuvers of closing and lifting are successively repeated at least 3 times to complete correction, ensuring that every shortening and lengthening of spinal cord is mild and safe. In this study, the spinal cord was ultimately shortened by 24.3 mm, which accounted for a shortening rate of 36.0% relative to the height of osteotomized complex. Consequently, the spinal cord underwent elongation initially, yet through the implementation of a strategy involving multiple active shortenings to prevent spinal cord traction injury, the spinal cord was ultimately shortened. Importantly, the extent of this shortening remained within a safe range [41], and no permanent neurological deficits were observed in this series.

In this study, 7 patients experienced dural laceration, and more than half of them were related to the selection of Andersson lesions as the osteotomy site. The Andersson lesions were characterized by the proliferated osteophytes and fibrotic tissues, causing adhesion of the dural sacs to the lamina and ligamentum flavum. The adhesion increased the risk of dural laceration during surgical separation process. Therefore, for patients with Andersson lesions, if circumstances permit, it is highly recommended to select a non-Andersson lesion area for osteotomy to reduce intraoperative dural sac tears. At the final follow-up, varying degrees of correction loss were observed, which was closely related to osteoporosis. Therefore, it is suggested that AS patients with osteoporosis should regularly take calcium supplements and undergo anti-osteoporosis treatment after surgery to reduce the correction loss [3].

Limitations

Firstly, a control group that underwent traditional PSO combined with cantilever or bending rod correction method was not established for comparison. Secondly, in order to maintain the patients' ability to look ahead postoperatively, some patients with ankylosed cervical spine and small CBVA accepted a limited correction of sagittal alignment. Thirdly, the series of patients had a relatively short follow-up period (<5 years), and a long-term follow-up study on radiographic and clinical results will be required subsequently. Lastly, the study was retrospective, and the sample size was small. A large randomized controlled study will be needed to verify the safety, reliability, and feasibility of the strategy.

Conclusion

One-level modified osteotomy with shoulders lifting correction method is a safe and effective strategy for treating severe AS kyphosis. This strategy has demonstrated the ability to yield satisfactory radiographic and clinical outcomes. Particularly, the shoulders lifting correction method may be well-suited for patients with severe kyphosis and osteoporosis.

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Author contributions
JZ L and TL W collected the radiographic and clinical data, ZL Y and CG D measured parameters. JZ L and ZL Y analyzed the clinical data and measurements. JZ L wrote the manuscript, HR T and JZ L revised the manuscript. HR T conceived the idea and designed the study. All authors reviewed the manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval
This retrospective study involving human data was in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The Human Investigation Committee (IRB) of Shenzhen University General hospital approved this study. This work was performed at Shenzhen University General Hospital, Shenzhen, China.

Consent to publication
The authors affirm that human research participants provided informed consent for publication of the images in Figure(s) 3, 4 and 5.

Consent to participate
Informed consent was obtained from all individual participants included in the study.

Competing interests
The authors declare no competing interests.

Author details
[1]Shenzhen University Health Science Center, Shenzhen 518055, Guangdong, PR China
[2]Department of Orthopedics, Shenzhen University General Hospital, Shenzhen 518055, Guangdong, PR China
[3]Department of Orthopedics, The University of Hongkong-Shenzhen Hospital, Shenzhen 518053, Guangdong, PR China

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