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The relationship between global spinal alignment and pelvic orientation from standing to sitting following pedicle subtraction osteotomy in ankylosing spondylitis patients with thoracolumbar kyphosis

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Abstract

Introduction To investigate the relationship between the spinal sagittal alignment and arc of pelvic motion from standing to sitting in ankylosing spondylitis (AS) patients with thoracolumbar kyphosis following pedicle subtraction osteotomy (PSO).

Materials and Methods AS patients who underwent PSO for thoracolumbar kyphosis from January 2016 to July 2018 were recruited. EOS standing and sitting images were obtained pre- and postoperatively. Radiographic parameters were measured on the sagittal radiographs, including lumbar lordosis, thoracic kyphosis, pelvic incidence, pelvic tilt, sacral slope, sagittal vertical axis (SVA), spinosacral angle, anterior pelvic plane angle (APPA) and knee flexion angle.

Results Thirty-six patients were enrolled. From standing to sitting, APPA was increased by a mean of 14.7° ($P<0.001$) and 3.0° ($P=0.083$) before and after surgery, respectively. The increase in APPA from standing to sitting was correlated with the standing SVA ($R=0.592$, $P<0.001$) preoperatively. After PSO, the change in APPA was correlated with the change in SSA in both the standing and sitting position ($R=0.381$, $P=0.022$ and $R=0.667$, $P<0.001$, respectively). The APPA from standing to sitting was decreased in 11 patients with standing C7 plumb line posterior to the femoral head postoperatively.

Conclusions In AS patients, pelvic orientation was adjusted by the global spinal alignment. When planning total hip arthroplasty for AS patients, global spinal alignment should be considered to improve the joint stability.

Keywords Ankylosing spondylitis · Thoracolumbar kyphosis · Osteotomy · Anterior pelvic plane · Standing · Sitting

Introduction

Ankylosing spondylitis (AS) is a chronic rheumatic autoimmune disease that could lead to rigid thoracolumbar kyphosis and hip ankylosis [1, 2]. With the progression of spinal deformity, pelvic backward rotation and knee flexion occur in turn to compensate for the thoracolumbar kyphosis [3]. Additionally, further pelvic retroversion could occur during the postural shift from standing to sitting [4, 5].

Due to the patients' daily activity was greatly restricted by the severe thoracolumbar kyphosis, pedicle subtraction osteotomy (PSO) has been widely proposed to restore the spinal alignment [6]. Both the compensated changes in pelvic tilt and knee flexion would be relaxed following the spinal realignment [7, 8].

Moreover, when the hip ankylosis occurred in those AS patients with thoracolumbar kyphosis, total hip arthroplasty (THA) would be also needed [9]. Being a major postoperative complication, dislocation was greatly associated with the inaccuracy of cup positioning. The "safe zone" referred to the anatomical anterior pelvic plane (APP) has been proposed to reduce the dislocation [10]. However, despite the acetabular cup was positioned within the "safe zone", dislocation may occur during the postural changes. This phenomenon revealed that the "safe zone" may not be appropriate for all patients because of the large variations in arc of pelvic motion during the postural shift among individuals [11, 12]. In the patients following THA with a flexible spine, the backward rotation of pelvic occurred from standing to sitting

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so that a more vertical cup could be provided to prevent the posterior dislocation while sitting [11]. However, in patients with a rigid spine, the compensated change in cup orientation may be inadequate to prevent the anterior impingement and posterior dislocation in sitting position [12]. Thus, the pelvic motion during the postural change plays an important role in dislocation.

To date, the change in pelvic orientation from standing to sitting has not been investigated in AS patients with rigid thoracolumbar kyphosis. Therefore, the current study aimed to investigate the arc of pelvic motion from standing to sitting in AS patients with thoracolumbar kyphosis as well as the impact of spinal osteotomy on this arc of pelvic motion.

Materials and methods

Patient population

A single-center prospective study approved by the institutional review committee was conducted. AS patients undergoing corrective surgery for spinal deformities from January 2016 to June 2018 were enrolled. All patients were diagnosed with AS according to the Modified New York Criteria [13]. The inclusion criteria were as follows: (1) AS patients treated with PSO for thoracolumbar kyphosis; (2) age older than 18 years; and (3) available pre- and postoperative EOS (EOS Imaging Inc., Paris, France) 2D images in standing and sitting position. Postoperative EOS images were obtained when patients were able to stand and sit without any assistance after surgery. A freestanding posture with elbows flexed at 45° was used for standing image acquisition. A weight-bearing and comfortable sitting position with thighs parallel to the ground was used for sitting image acquisition. All patients were instructed to have as close to a horizontal gaze as possible during radiographic examinations. The exclusion criteria were as follows: (1) severe radiographic change in the hip joints according to the Bath Ankylosing Spondylitis Radiology Hip Index (BASRI-h) [14]; (2) hip flexion deformity; and (3) prior spinal or hip surgery.

The sequence of spinal osteotomy prior to the THA was proposed in our institution unless the AS patients accompanied with a severe hip flexion deformity [20]. Decision making for PSO was made according to the EOS standing films. Osteotomy angle was calculated to provide patients with an upright posture and horizontal gaze. One-level PSO, including closing wedge osteotomy and closing–opening wedge osteotomy, is adequate for the patients requiring a correction angle < 50°. Furthermore, the greater magnitude of deformity correction is achieved using the two-level PSO [15]. In principle, the apex of the thoracolumbar kyphosis was selected as the PSO level.

Data collection

All radiographic parameters were analyzed using Surgimap software (Nemaris). All radiographic parameters were measured on EOS standing and sitting sagittal radiographs. Regional spinal parameters included lumbar lordosis (LL) (a positive angle indicates lordosis) and thoracic kyphosis (TK) (a positive angle indicates kyphosis) [16]. Global spinal parameters included sagittal vertical axis (SVA) and spinosacral angle (SSA). Pelvic parameters included sacral slope (SS) (a positive angle indicates pelvic rotating forward on sagittal plane), pelvic tilt (PT) (a positive angle indicates pelvic rotating backward on sagittal plane), APP angle (APPA) (a positive angle indicates pelvic rotating backward on sagittal plane) and pelvic incidence (PI) [12, 16]. Both the increases in PT and APPA resulted in the pelvic retroversion (posterior pelvic tilt). Additionally, PT was widely used among the spine surgeon while the APPA among hip surgeons. Since the cup was positioned referred to the APP during THA, functional pelvic orientation was represented by the APPA in the current study [12]. Knee flexion was also analyzed using the knee flexion angle (KFA) [17]. Measuring methods of parameters were presented in Fig. 1. Hip range of motion in flexion was also measured to assess the function of hip joints [18].

Statistical analysis

Data analyses were performed using SPSS Statistics 19.0 software (SPSS, Chicago, IL). All radiographic parameters obtained before and after surgery for the standing and sitting positions were compared using Student's *t* test. Correlations between the variables were analyzed using Pearson's coefficients. P values < 0.05 were considered significant.

Results

Thirty-six patients were recruited in the current study, including 31 males and five females, with a mean age of 37.3 years (range 20–59 years). Single-level PSO was performed at T12 for 2, L1 for 14, L2 for 13 and L3 for 3 patients, with a mean fusion level of 8.6 (range 8–12). Double-level PSO was performed at L1 and L4 for the remaining four patients, with a mean fusion level of 11.0 (range 10–12).

The mean right and left hip ranges of motion are 123.9° and 124.6°. Flexion in all patients was greater than 100°,

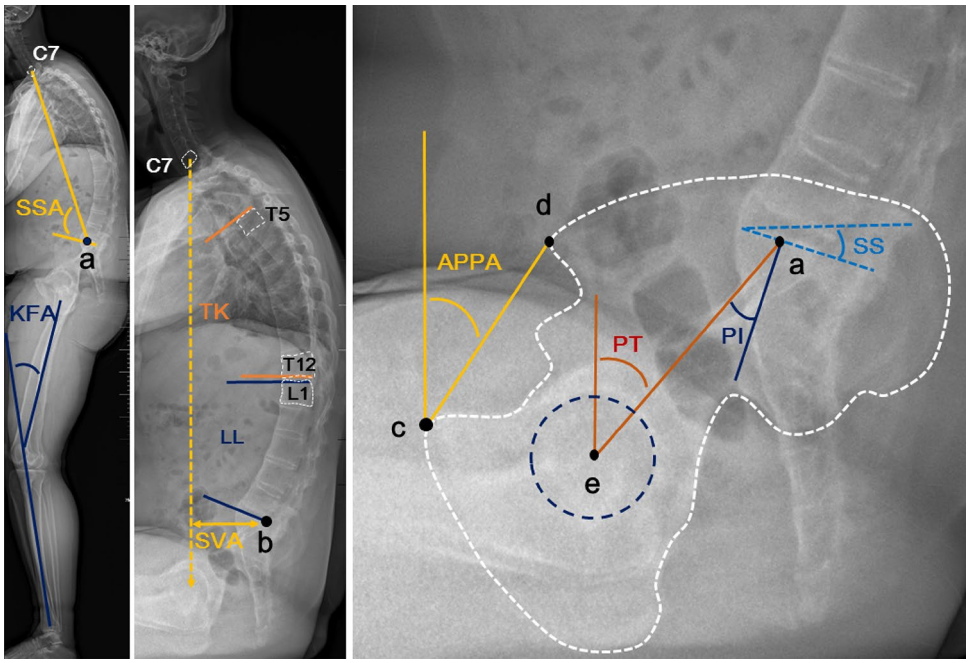

Fig. 1 A radiograph showing the measurements of radiographic parameters on EOS lateral images. Spinosacral angle (SSA) indicates the angle between the sacral plate and a line from C7 to the midpoint of the sacral plate (point a). Knee flexion angle (KFA) was measured as the angle between the mechanical axes of the femur and tibia. Sagittal vertical axis (SVA) was measured as the horizontal distance between the C7 plumb line and the posterior superior corner of S1 (point b). Thoracic kyphosis (TK) was the angle between the superior end plate of T5 and the inferior end plate of T12. Lumbar lordosis (LL) was measured from the sacral plate to the superior end plate of L1. Anterior pelvic plane angle (APPA) was the angle between the vertical and the line connecting the pubis (point c) and the antero-superior iliac spines (point d). Pelvic tilt (PT) was considered as the angle between the vertical and the line drawn from the point a to femoral head axis (point e). Sacral slope (SS) was the angle between the sacral plate and the horizontal. Pelvic incidence (PI) was the angle between the line drawn from point a to point e and the perpendicular to the sacral plate

which is required for the postural shift from standing to sitting [19]. All patients were able to maintain the required positions during the radiographic examinations.

Comparisons between preoperative and postoperative radiographic parameters in the standing and sitting positions are summarized in Table 1. Significant perioperative increases in the LL and SSA and decreases in the TK, SVA and APPA were observed in both the standing and sitting positions ($P < 0.05$ for all). KFA was also decreased significantly ($P < 0.001$).

Sagittal parameters during the postural shift from standing to sitting before and after surgery were also analyzed. Both

Table 1 Comparisons between preoperative and postoperative radiographic parameters in the standing and sitting positions

	Standing			Sitting		
	Preoperative	Postoperative	*P* value	Preoperative	Postoperative	*P* value
LL(°)	3.5 ± 25.1	46.3 ± 15.8	< 0.001	2.3 ± 25.6	44.1 ± 14.2	< 0.001
TK(°)	50.1 ± 18.7	44.5 ± 15.9	0.026	50.3 ± 18.4	45.0 ± 16.1	0.032
PI(°)	44.4 ± 10.5	45.5 ± 10.9	0.010	45.3 ± 11.9	46.4 ± 11.8	0.052
PT(°)	35.0 ± 9.5	19.4 ± 9.7	< 0.001	49.0 ± 14.3	24.1 ± 10.1	< 0.001
SS (°)	9.5 ± 12.2	26.3 ± 11.4		− 3.8 ± 15.7	22.2 ± 12.2	< 0.001
SVA (mm)	163.3 ± 72.1	55.8 ± 34.7	< 0.001	81.9 ± 42.2	34.2 ± 29.2	< 0.001
SSA (°)	76.8 ± 18.2	110.1 ± 11.6	< 0.001	75.7 ± 19.7	109.4 ± 11.3	< 0.001
APPA (°)	23.2 ± 12.7	6.7 ± 10.8	< 0.001	37.9 ± 15.5	9.7 ± 10.4	< 0.001
KFA (°)	21.7 ± 9.6	8.6 ± 8.3	< 0.001	–	–	–

Values are presented as the mean ± SD

LL lumbar lordosis, *TK* thoracic kyphosis, *PI* pelvic incidence, *PT* pelvic tilt, *SS* sacral slope, *SVA* sagittal vertical axis, *SSA* spinosacral angle, *APPA* anterior pelvic plane angle, *KFA* knee flexion angle

the pre- and postoperative TK and LL remained unchanged from standing to sitting. Significant postural decrease in SVA was found before and after surgery ($P < 0.05$ for both). The preoperative APPA was significantly increased by 14.3° from standing to sitting position ($P < 0.001$). However, the postural change in APPA was significantly reduced to 3.0° postoperatively ($P < 0.001$).

Correlations between perioperative changes in spinopelvic parameters and that in the APPA in the standing and sitting positions are shown in Table 2. The perioperative change in the SSA was strongly correlated with that in the APPA in the sitting position ($R = 0.667$, $P < 0.001$). Notably, this correlation between the perioperative changes in the SSA and APPA in the standing position was weak ($R = 0.381$, $P = 0.022$). Moreover, linear regression analysis revealed that 1° decrease of standing PT occurred with 0.910° decrease of standing APPA following PSO ($R = 0.694$, $P < 0.001$). Meanwhile, the perioperative change of 1° in PT occurred with 0.965° in APPA while sitting ($R = 0.787$, $P < 0.001$).

Correlations between the standing spinal parameters and postural change in the APPA from standing to sitting were also analyzed. Standing SVA was correlated with the postural changes in the APPA from the standing to sitting before ($R = 0.592$, $P < 0.001$) and after ($R = 0.397$, $P = 0.017$) PSO, respectively.

Table 2 Correlations between perioperative changes in spinal parameters and change in APPA in the standing and sitting positions

	Standing	Sitting
ΔLL(°)	0.368 (0.027)	0.641 (<0.001)
ΔTK(°)	−0.036 (0.836)	−0.353 (0.035)
ΔPI(°)	0.185 (0.281)	0.077 (0.657)
ΔPT(°)	0.694 (<0.001)	0.787 (<0.001)
ΔSS(°)	0.638 (<0.001)	0.762 (<0.001)
ΔSVA(mm)	−0.021 (0.905)	0.001 (0.998)
ΔSSA(°)	0.381 (0.022)	0.667 (<0.001)

Values are presented as correlation coefficient (*P* value)

APPA anterior pelvic plane angle, *LL* lumbar lordosis, *TK* thoracic kyphosis, *PI* pelvic incidence, *PT* pelvic tilt, *SS* sacral slope, *SVA* sagittal vertical axis, *SSA* spinosacral angle

Subanalysis of postural changes in the APPA after PSO

From the standing to sitting positions, postoperative APPA was increased in 25 patients, while the remaining 11 showed a decrease in APPA. All of the patients with a decreased APPA had a standing C7 plumb line located posterior to the center of femoral heads. Oppositely, the standing C7 plumb line was located anterior to the center of femoral heads in the remaining 25 patients. Comparisons of the postoperative SVA and APPA in the standing and sitting positions between patients with C7 plumb line anterior and posterior to the femoral heads are presented in Table 3.

Discussion

AS patients are a special population cohort who may require both spinal osteotomy and THA. Higher dislocation rate has been reported after THA in AS patients [11]. Anterior dislocation could be caused by the excessive posterior pelvic tilt compensated to the thoracolumbar kyphosis [20]. When the prostheses were placed within the "safe zone" referred to the anatomical APP, a greater "anterior opening" cup would be expected in the patients with excessive pelvic retroversion, then the anterior dislocation may occur. To decrease the risk of dislocation, hip surgeons advocated a more horizontal cup based on the "safe zone" to match the excessive pelvic retroversion while the spine surgeons considered that a spinal osteotomy prior to the THA could restore a normal functional pelvic orientation for the cup positioning [9, 20]. However, both the radiographic analyses in their studies were based on the standing position without considering the pelvic motion during the postural changes. Given that the range of pelvic motion was decreased in rigid spine [12], it is necessary to investigate the functional pelvic orientation in both the standing and sitting positions in AS patients.

Table 3 Comparison of the postoperative SVA and APPA in the standing to sitting positions between patients with C7 plumb line (spinopelvic axis) anterior and posterior to the femoral heads

	Patients with C7 plumb line anterior to femoral heads ($N = 25$)	Patients with C7 plumb line posterior to femoral heads ($N = 11$)	*P* value
SVA (mm)			
Standing	71.2 ± 29.3	22.7 ± 15.2	< 0.001
Sitting	33.4 ± 33.2	34.5 ± 17.8	0.919
APPA (°)			
Standing	5.5 ± 10.3	8.8 ± 11.6	0.400
Sitting	12.2 ± 9.5	4.9 ± 10.6	0.048

Values are presented as the mean ± SD

SVA sagittal vertical axis, *APPA* anterior pelvic plane angle

Moreover, the effect of spinal osteotomy on the arc of pelvic motion from standing to sitting positions was also analyzed.

In the current study, both the compensation mechanisms of pelvic retroversion and knee flexion were relaxed after the spinal osteotomy. The perioperative change in APPA was correlated with the changes in the spinal sagittal parameters (TK, LL and SSA). As previously demonstrated, the stiff spine in AS patients could be considered as a single rigid beam; to maintain the sagittal balance, the beam-like spine can be readjusted only by pelvic rotation around the hips [5, 21]. Compared to the correlation between the perioperative changes in regional spinal parameters (TK and LL) and that in APPA, the superior correlation between the changes in the global spinal parameter (SSA) and APPA, suggested that the APPA is modified by the global spinal alignment in AS. Regarding the weaker correlation between the perioperative changes in SSA and APPA compared while sitting, it could be attributed to the knee flexion in the standing position which shared the responsibility for the compensation to spinal deformity with pelvic retroversion [3].

In the healthy individuals, further pelvic retroversion from standing to sitting positions was generated by the flexion of lumbar spine [22]. Theoretically, pelvic retroversion would not occur from standing to sitting in the patients with rigid spine [23]. However, despite the LL remained unchanged during the postural shift, a mean increase of 14° in APPA was observed in the current study preoperatively (Fig. 2). Moreover, the strong correlation between standing SVA and the change in APPA revealed that instead of the spinal flexibility, the pelvic retroversion was induced by the spinal imbalance. In the context of preoperative standing posture with knee flexion, adequate pelvic retroversion was not available to maintain the spinal balance due to the full extension of the hip joint. However, because of the flexion contracture of hip joints in the seated position, further pelvic backward rotation could occur from standing to sitting [5]. Since the C7 plumb line was located over the femoral heads in the balanced sitting position, further pelvic retroversion during the postural shift would be observed in AS patients with standing C7 plumb line located anterior to the femoral heads. In addition, the range of pelvic motion would be greater in patients with more severe spinal malalignment.

As expected, change in the APPA from standing to sitting was decreased following PSO. It could be explained by that since the standing SVA was decreased with the spinal realignment, further pelvic retroversion was no longer needed from standing to sitting. Interestingly, there were 11 patients showed a decrease in postoperative APPA from the standing to sitting position. The decreased APPA in the 11 patients could be attributed to the location of standing C7 plumb line. Considering that the neutral balance of C7 plumb line projected on the femoral heads while sitting

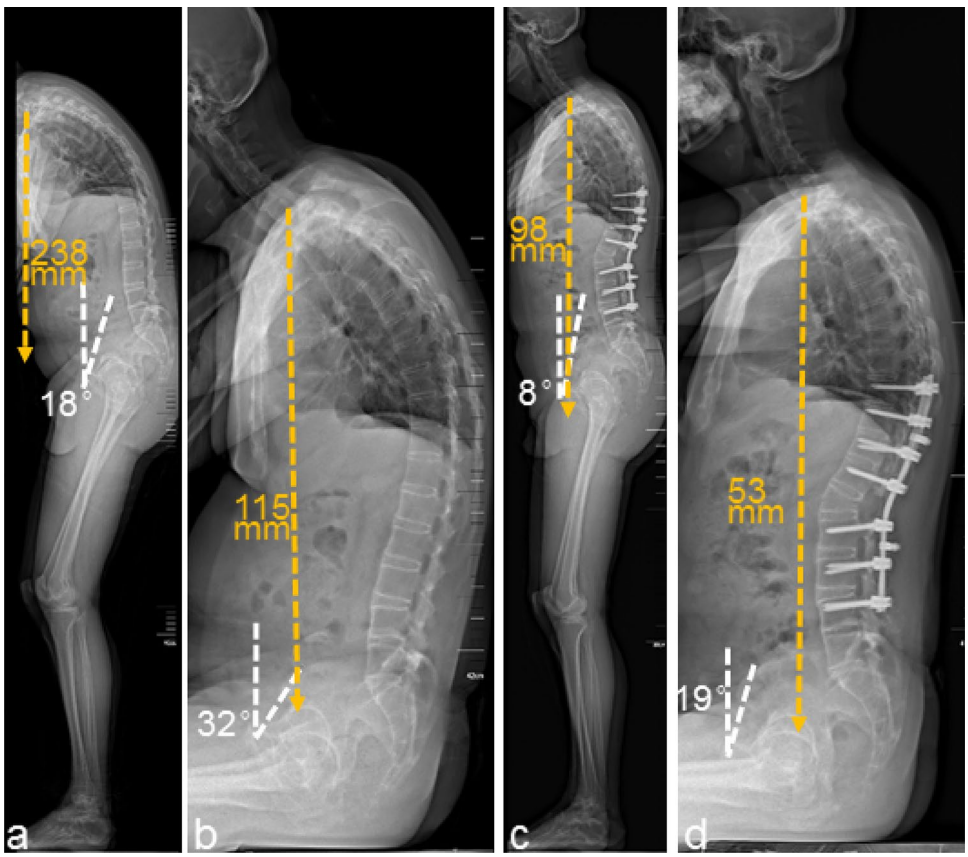

Fig. 2 A 57-year-old male AS patient with thoracolumbar kyphosis who underwent PSO at L1. **a** In the standing position, the SSA was 80°, the SVA was 238 mm, and the APPA was 18°. **b** In the sitting position, the SSA remained unchanged, and the SVA decreased to 115 mm as the APPA increased to 32°. **c** After surgery, the standing SSA was improved to 101°, and the SVA decreased to 98 mm as the APPA decreased to 8°. **d** From the standing to sitting positions, the postoperative SSA remained constant, and the SVA decreased to 53 mm as the APPA increased to 19°

[5], forward movement of the upper body associated with an increase in SVA from standing to sitting would occur in the patients with standing C7 plumb line located posterior to the femoral heads (Fig. 3). The forward movement of the upper body from standing to sitting was resulted from the flexion of lumbar spine in the healthy individuals. However, this increase in SVA in AS patients with rigid spine could be only ascribed to the pelvic forward rotation. Additionally, a more posterior location of standing C7 plumb line would lead to a greater magnitude of pelvic forward rotation from standing to sitting.

Therefore, the arc of pelvic movement from standing to sitting was determined by the global spinal alignment (Fig. 4). In clinical practice, when planning THA for AS patients, adjusting the cup positioning angle according to the functional APP in the static standing position is definitely not enough. The global spinal alignment should be also taken into consideration to optimize the hip range of motion and stability during daily activities, especially for

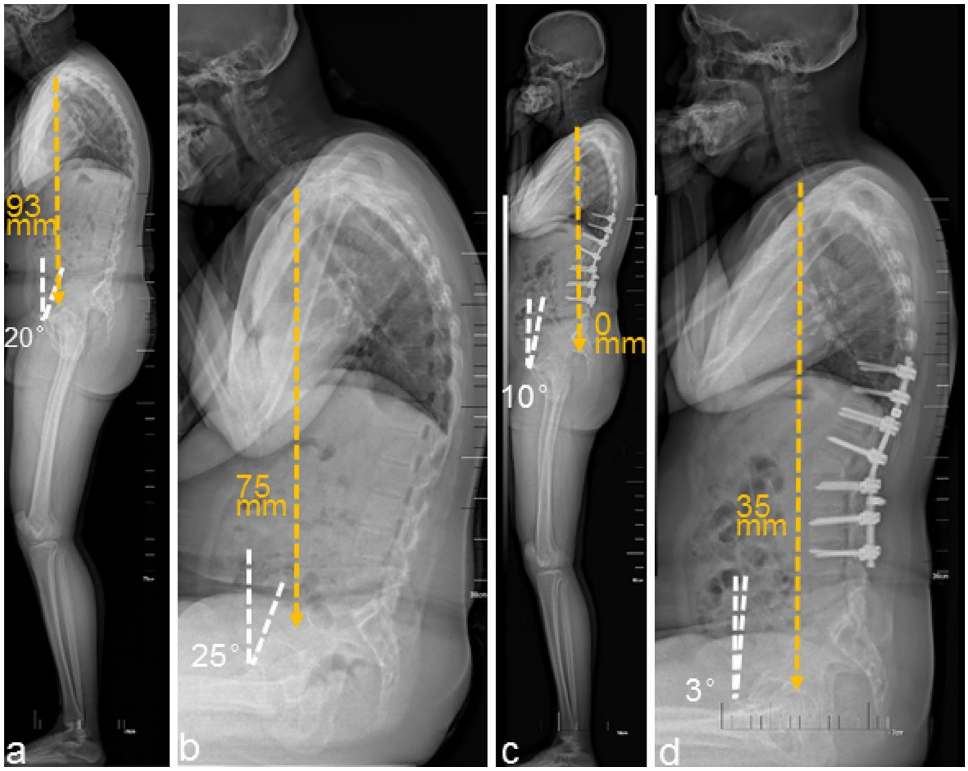

Fig. 3 A 30-year-old male AS patient who underwent PSO at L1 for thoracolumbar kyphosis. **a** In the standing position, the SSA was 85°, the SVA was 93 mm, and the APPA was 20°. **b** In the sitting position, the SSA remained unchanged, and the SVA decreased to 75 mm as the APPA increased to 25°. **c** After surgery, the standing SSA was improved to 109°, and the SVA decreased to 0 mm as the APPA decreased to 10°. **d** From the standing to sitting positions, the postoperative SSA remained constant, and the SVA increased to 35 mm as the APPA decreased to 3°

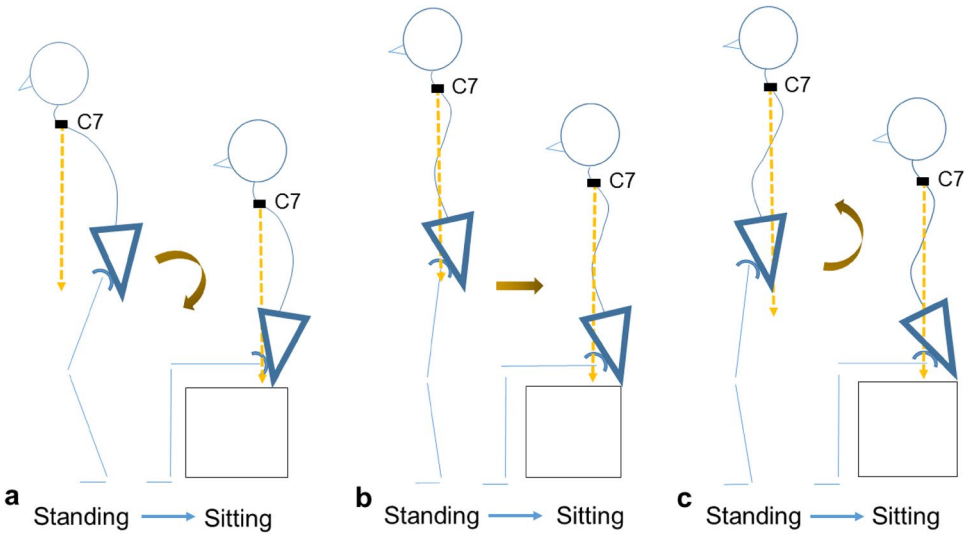

Fig. 4 Three arc types of pelvic motion from standing to sitting positions. **a** When the standing C7 plumb line located anterior to the femoral heads, the pelvic retroversion occurs from standing to sitting. **b** In the patients with standing C7 plumb line located over the femoral heads following PSO, the pelvic orientation remained unchanged during the postural shift. **c** However, if the postoperative standing C7 plumb line located posterior to the femoral heads, the pelvic forward rotation occurs to maintain the sagittal balance while sitting

AS patients following PSO with a standing C7 plumb line posterior to the femoral heads. Considering the abnormal anterior rotation of pelvic from standing to sitting in these patients, a relative more vertical cup based on the standing APPA-adjusted cup positioning angle should be suggested to prevent the anterior impingement and posterior dislocation while sitting [9]. On the other hand, for the patients already performed with THA, the acetabular cup orientation should be kept in mind when planning PSO. For example, in patients with a relative horizontal cup following THA, a higher risk of posterior dislocation while sitting may be expected in the patients following PSO with the standing C7 plumb line located posterior to the femoral heads.

There were several limitations in the current study. First, the postoperative spinal alignment was analyzed based on the radiographs taken at 2 weeks after surgery. Although the patients were able to stand and sit on their own, the standing and sitting postures may be changed during the patients' functional recovery period. And, further investigation with longer follow-up was needed. Second, due to the patients enrolled has not been performed with THA, the effect of THA on the spinopelvic sagittal alignment was not analyzed. However, the spinopelvic parameters were reported to be unchanged before and after the THA [11, 24]. Third, acetabular alignment was not assessed because the measure of acetabular parameters was not available on the EOS 2D images. Future investigations with more comprehensive analyses are certainly warranted.

Conclusions

In AS patients with thoracolumbar kyphosis, the functional pelvic orientation is adjusted by global spinal alignment. Instead of the lumbar flexion, the spinal malalignment induced the pelvic movement from standing to sitting positions in AS. The magnitude of pelvic motion during the postural shift was decreased after the spinal osteotomy. When making the THA strategies for AS patients, the spinal sagittal alignment should be considered to provide better joint motion and stability.

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Compliance with ethical standards

Ethical approval All methods were performed in accordance with the relevant guidelines and regulations.

Conflict of interest Shi-zhou Zhao, Bang-ping Qian, Yong Qiu, Mu Qiao, Zhuo-jie Liu, and Ji-chen Huang declare that they have no conflict of interest.

Research involving human and/or animal participants This article does not contain any studies with human participants or animals performed by any of the authors.

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

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