European Spine Journal (2018) 27:2303–2311
https://doi.org/10.1007/s00586-018-5514-3

ORIGINAL ARTICLE

Proximal junctional kyphosis in adult spinal deformity: a novel predictive index

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Received: 16 October 2017 / Revised: 13 December 2017 / Accepted: 4 February 2018 / Published online: 5 March 2018

Abstract

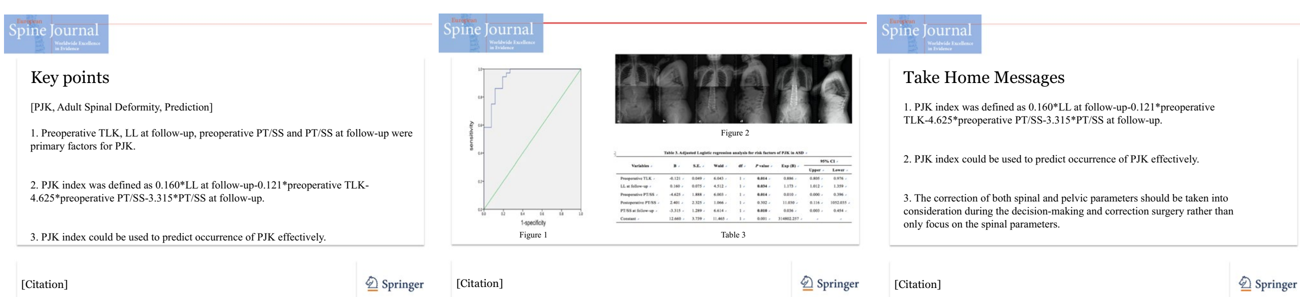
Purpose Proximal junctional kyphosis (PJK) is a devastating complication for adult spinal deformity (ASD) after correction surgery. However, there is no consensus on the risk factors of PJK, and whether it can be predicted remains unknown. The aim of this study is to detect the primary risk factors for PJK in ASD, and introduce a novel index for prediction of PJK.

Methods Medical records of 62 ASD patients receiving correction surgery from January 2010 to January 2015 were analyzed. Spino-pelvic parameters were evaluated on lateral films before surgery, at 2 weeks' and at follow-up. Primary factors for PJK were evaluated. PJK index was proposed and verified.

Results Cervical lordosis at follow-up, postoperative C2-C7 SVA, C2-C7 SVA at follow-up, postoperative T1 slope, T1 slope at follow-up, preoperative TLK, LL at follow-up, preoperative PT, postoperative PT, PT at follow-up, preoperative SS, postoperative SS, SS at follow-up, preoperative PT/SS, postoperative PT/SS and PT/SS at follow-up were significantly different between ASD with and without PJK. Adjusted logistic regression analysis showed that preoperative TLK, LL at follow-up, preoperative PT/SS and PT/SS at follow-up were primary factors for PJK. PJK index was defined as 0.160*LL at follow-up-0.121*preoperative TLK-4.625*preoperative PT/SS-3.315*PT/SS at follow-up. On the basis of ROC curve, if PJK index was smaller and larger than − 2, the occurrence rate of PJK and non-PJK was 82 and 95%, respectively.

Conclusions Preoperative TLK, LL at follow-up, preoperative PT/SS and PT/SS at follow-up were primary factors for PJK. PJK index could be used to predict occurrence of PJK effectively.

Graphical abstract These slides can be retrieved under Electronic Supplementary Material.



Keywords PJK · Adult spinal deformity · Prediction

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Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00586-018-5514-3) contains supplementary material, which is available to authorized users.

Extended author information available on the last page of the article

Introduction

Adult spinal deformity (ASD) is a common disease in aged populations that is characterised by scoliosis, sagittal malalignment, kyphosis and spondylolisthesis, with a significant and measurable impact on health-related quality of life

(HRQOL) [1]. ASD includes many etiologies, such as adult idiopathic scoliosis, and degenerative scoliosis. The prevalence of ASD has been reported to range from 8.3 to 68% [1, 2], with an estimated prevalence of 60 million in 2050 [1].

Nowadays, surgical treatment is getting increasingly more commonplace, whose goals are to decompress the neural elements, restore the sagittal and coronal spinal imbalance and improve patients' HRQOL. Furthermore, it is also considered as the gold standard for ASD patients when conservative therapies are ineffective in alleviating symptoms and correcting the coronal and sagittal malalignment. However, high complication rate has been reported at between 10 and 45%, such as pseudarthrosis, proximal junctional kyphosis (PJK), proximal junctional failure (PJF), and neurological deficit [3, 4].

PJK was first described in Scheuermann's kyphosis [5], which is defined as kyphosis ≥ 10° between the lower endplate of the uppermost instrumented vertebra and the upper endplate of the two supra-adjacent vertebrae, known as the PJK angle [6]. The incidence of PJK in ASD patients receiving long spinal fusions is relatively high, varying from 6 to 59% [4, 7, 8]. Furthermore, what we should pay more attention to is the devastating outcomes of PJK, including upper instrumented vertebra collapse or acute subluxation, also known as proximal junctional failure (PJF) and revision surgery, resulting in great economic burdens on both society and families [4, 9].

To prevent the occurrence of PJK and avoid these devastating outcomes, more and more studies have been performed to explore the risk factors associated with occurrence and development of PJK; while there is lack of consensus on these risk factors [6, 10–13]. In addition, whether PJK could be predicted in ASD patients undergoing long spinal fusions is also unclear. Therefore, we performed this retrospective study to detect the primary risk factors for postoperative PJK in ASD patients, and introduce a novel index for prediction of PJK as well.

Methods and materials

Patient population

Medical records of ASD patients undergoing correction surgery with all-pedicle screw instrumentation in our hospital from January 2010 to January 2015 were collected and analyzed. The inclusion criteria were as follows: (1) patients were diagnosed as ASD; (2) older than 50 years; (3) ASD patients met the indications for surgical treatment; (4) underwent posterior pedicle screw instrumentation and fusion; (5) at least 2 years' follow-up. Patients with history of spinal surgeries, infection or tumors were excluded. In addition, patients without sufficient radiological parameters were also excluded. This study was approved by the Institutional Review Board of our hospital, and all patients in our study provided written informed consent for the study.

Data collection

Demographical information was collected, including age, gender and follow-up time. Other general information such as UIV (upper instrumented vertebra), LIV (lower instrumented vertebra) and UIV-T1 (numbers of segments between UIV and T1) was also recorded.

Spino-pelvic parameters were evaluated on lateral films before surgery, at 2 weeks' and at final follow-up, including preoperative CL (cervical lordosis, the Cobb angle between the lower endplate of C2 and C7), postoperative CL, correction rate of CL, CL at follow-up, preoperative C2-C7 SVA (the horizontal distance between the C2 plumb line and the posterior corner of C7), postoperative C2-C7 SVA, C2-C7 SVA at follow-up, preoperative T1 slope (the angle between the horizontal and the T1 superior endplate), postoperative T1 slope, T1 slope at follow-up, preoperative TK (thoracic kyphosis, the Cobb angle between the upper endplate of T5 and the lower endplate of T12), postoperative TK, correction rate of TK, TK at follow-up, preoperative TLK (thoracolumbar kyphosis, the Cobb angle between the upper endplate of T10 and the lower endplate of L2), postoperative TLK, correction rate of TLK, TLK at follow-up, preoperative LL (lumbar lordosis, the Cobb angle between the upper endplate of L1 and the lower endplate of L5), postoperative LL, correction rate of LL, LL at follow-up, preoperative SVA (sagittal vertical axis, the horizontal offset from the posterosuperior corner of S1 to the vertebral body of C7), postoperative SVA, SVA at follow-up, preoperative PT (pelvic tilt, the angle between the vertical and the line through the midpoint of the sacral plate to femoral heads axis), postoperative PT, PT at follow-up, preoperative PI (pelvic incidence, angle subtended by a perpendicular from the upper endplate of S1 and a line connecting the center of the femoral head to the center of the upper endplate of S1), postoperative PI, PI at follow-up, preoperative SS (sacrum slope, the angle between the horizontal and the sacral plate), postoperative SS, SS at follow-up, preoperative PT/SS (ratio of PT and SS), postoperative PT/SS and PT/SS at follow-up. All these spino-pelvic parameters were measured by two independent surgeons and the average value was calculated.

According to the definition of PJK (proximal junctional angle, PJA > 10 degrees was accepted as PJK), patients were divided into two groups: ASD with PJK and ASD without PJK. General information and spino-pelvic parameters were compared between two groups (univariate analysis). Furthermore, logistic regression was performed using parameters that were found significantly in univariate analysis to determinate the primary contributors to PJK.

PJK index was set according to the results of logistic regression. Then, receiver operating characteristics (ROC) curve was conducted to determine the cut-off value of PJK index as indicators for occurrence of PJK. ROC curve is a graphical plot that illustrates the diagnostic ability of a binary classifier system as its discrimination threshold is varied, which is created by plotting the true positive rate (TPR) against the false positive rate (FPR) at various threshold settings [14]. The area under the curve (AUC) is often used to assess the overall diagnostic accuracy and effectiveness of ROC curve [14]. Cut-off values are the dividing points on measuring scales where the test results are divided into different categories, which could be calculated in ROC curve. The larger AUC is the more effective the cut-off value would be in division of different categories. In addition, the predictive power of the occurrence of PJK using PJK index was also calculated.

Statistical analysis

Descriptive statistics and categorical data were listed in the form of mean and standard deviation and numbers, respectively. Statistical analysis was performed using SPSS 19.0. Independent two-sample t test was used to compare the differences of descriptive statistics between two groups, and χ^2 test was used to compare the differences of count data (univariate analysis). Logistic regression model (Enter) was constructed using variables that were found significant in univariate analysis to find independent risk factors associated with PJK. According to the regression analysis and regression equation, PJK index was calculated. Using this calculated PJK index, ROC curve was constructed to detect the optimal cut-off value of PJK index as indicators for occurrence of PJK. $P < 0.05$ was considered with significant difference.

Results

General information

A total of 62 ASD patients (male/female: 30/32) were recruited in our study, with the mean age of 56.98 ± 5.36 years old. The mean follow-up was 3.89 ± 0.94 years (2.00–5.00 years). The demographical information and the average values of spino-pelvic parameters are shown in Table 1.

Univariate analysis

26 ASD patients (41.9%) suffered from PJK at final follow-up, and other 36 ASD patients (57.1%) were recruited in ASD without PJK group. CL at follow-up (− 23.73 ± 13.55° vs. − 18.25 ± 7.73°, $P = 0.048$), postoperative C2-C7 SVA (19.00 ± 13.08 mm vs. 13.00 ± 9.14 mm, $P = 0.037$), C2-C7 SVA at follow-up (26.54 ± 12.57 mm vs. 19.33 ± 6.04 mm, $P = 0.004$), postoperative T1 slope (21.85 ± 5.98° vs. 17.00 ± 4.06°, $P < 0.001$), T1 slope at follow-up (23.27 ± 6.83° vs. 16.92 ± 3.47°, $P < 0.001$), preoperative TLK (14.65 ± 14.64° vs. 8.97 ± 4.55°, $P = 0.032$), LL at follow-up (− 38.15 ± 6.47° vs. − 29.61 ± 15.63°, $P = 0.007$), preoperative PT (21.04 ± 7.16° vs. 14.00 ± 4.69°, $P < 0.001$), postoperative PT (17.85 ± 5.10° vs. 14.81 ± 4.76°, $P = 0.019$), PT at follow-up (25.35 ± 6.72° vs. 17.75 ± 5.46°, $P < 0.001$), preoperative SS (20.81 ± 5.82° vs. 28.14 ± 4.22°, $P < 0.001$), postoperative SS (24.08 ± 4.72° vs. 27.25 ± 3.56°, $P = 0.004$), SS at follow-up (17.42 ± 5.71° vs. 24.22 ± 4.77°, $P < 0.001$), preoperative PT/SS (1.21 ± 0.91 vs. 0.53 ± 0.28, $P < 0.001$), postoperative PT/SS (0.79 ± 0.32 vs. 0.57 ± 0.27, $P = 0.004$) and PT/SS at follow-up (1.66 ± 0.77 vs. 0.80 ± 0.40, $P < 0.001$) were significantly different between ASD patients with PJK and ASD patients without PJK. However, no significant difference of age, gender, UIV, LIV, UIV-T1, preoperative CL, postoperative CL, correction rate of CL, preoperative C2-C7 SVA, preoperative T1 slope, preoperative TK, postoperative TK, correction rate of TK, TK at follow-up, postoperative TLK, correction rate of TLK, TLK at follow-up, preoperative LL, postoperative LL, correction rate of LL, preoperative SVA, postoperative SVA, SVA at follow-up, preoperative PI, postoperative PI and PI at follow-up were observed in our study (all $P > 0.05$). All the data are shown in Table 2.

Multivariate analysis

Considering that it is difficult to correct cervical spine during almost lumber correction surgery in ASD patients, we excluded CL at follow-up, postoperative C2-C7 SVA, C2-C7 SVA at follow-up, postoperative T1 slope and T1 slope at follow-up in our regression analysis. Preoperative TLK, LL at follow-up, preoperative PT/SS, postoperative PT/SS, PT/SS at follow-up and correction rate of SVA were included in the adjusted logistic regression analysis, and the results showed that preoperative TLK ($P = 0.014$), LL at follow-up ($P = 0.034$), preoperative PT/SS ($P = 0.014$) and PT/SS at follow-up ($P = 0.010$) were primary contributors to the occurrence of PJK in ASD patients (Table 3). According to the results of logistic regression analysis, PJK index was defined as 0.160*LL at follow-up-0.121*preoperative TLK-4.625*preoperative PT/SS-3.315*PT/SS at follow-up.

ROC curve

The AUC was 0.95, indicating the well effectiveness of ROC curve and cut-off value in predicting occurrence of PJK in ASD patients. On the basis of the ROC curve (Fig. 1), the

Table 1 General characteristics and spino-pelvic parameters of recruited patients

Variables	Minimum	Maximum	Mean	Standard deviation
Demographics				
Age (years old)	48.00	68.00	56.98	5.36
Follow-up (years)	2.00	5.00	3.89	0.94
Gender (male/female)	30/32			
UIV (T9/T10/T11/T12/L1)	18/12/16/13/3			
LIV (L4/L5/S1)	36/14/12			
UIV-T1 (segments)	8.00	12.00	9.53	1.25
Spine sagittal parameters				
Preoperative CL (°)	− 32.00	31.00	− 14.32	10.35
Postoperative CL (°)	− 35.00	27.00	− 17.21	10.28
Correction rate of CL (%)				
CL at follow-up (°)	− 44.00	18.00	− 20.55	10.81
Preoperative C2-C7 SVA (mm)	− 6.00	55.00	13.53	10.88
Postoperative C2-C7 SVA (mm)	4.00	60.00	15.52	11.26
C2-C7 SVA at follow-up (mm)	8.00	70.00	22.35	9.93
Preoperative T1 slope (°)	11.00	31.00	16.13	4.46
Postoperative T1 slope (°)	11.00	40.00	19.03	5.47
T1 slope at follow-up (°)	11.00	49.00	19.58	6.00
Preoperative TK (°)	− 8.00	35.00	20.27	9.83
Postoperative TK (°)	− 4.00	39.00	23.97	8.87
Correction rate of TK (%)				
TK at follow-up (°)	1.00	44.00	27.65	8.70
Preoperative TLK (°)	− 11.00	46.00	11.35	10.38
Postoperative TLK (°)	1.00	30.00	10.79	5.78
Correction rate of TLK (%)				
TLK at follow-up (°)	0.00	29.00	9.92	6.02
Preoperative LL (°)	− 50.00	− 19.00	− 32.63	7.38
Postoperative LL (°)	− 55.00	− 24.00	− 36.23	6.15
Correction rate of LL (%)				
LL at follow-up (°)	− 57.00	26.00	− 33.19	12.57
Preoperative SVA (mm)	− 66.00	135.00	11.16	21.97
Postoperative SVA (mm)	− 61.00	140.00	12.68	21.23
SVA at follow-up (mm)	− 57.00	144.00	15.03	21.29
Pelvic parameters				
Preoperative PT (°)	7.00	38.00	16.95	6.77
Postoperative PT (°)	8.00	28.00	16.08	5.09
PT at follow-up (°)	9.00	37.00	20.94	7.06
Preoperative PI (°)	32.00	57.00	42.02	4.92
Postoperative PI (°)	31.00	55.00	42.00	4.55
PI at follow-up (°)	31.00	57.00	42.31	4.74
Preoperative SS (°)	8.00	34.00	25.06	6.12
Postoperative SS (°)	14.00	34.00	25.92	4.34
SS at follow-up (°)	9.00	34.00	21.37	6.15
Preoperative PT/SS (°)	0.20	4.80	0.82	0.70
Postoperative PT/SS (°)	0.30	1.50	0.66	0.31
PT/SS at follow-up (°)	0.31	3.11	1.16	0.72

Table 2 Comparisons of demographics and spino-pelvic parameters between ASD with and without PJK

Variables	Adult idiopathic scoliosis with PJK (*n* = 26), mean ± SD/number	Adult idiopathic scoliosis without PJK (*n* = 36), mean ± SD/number	*P* value
Demographics			
Age	57.88 ± 5.72	56.33 ± 5.07	0.265
Follow-up (years)	3.77 ± 1.07	3.97 ± 0.84	0.407
Gender (male/female)	12/14	18/18	0.765
UIV (T9/T10/T11/T12/L1)	7/8/6/5/0	11/4/10/8/3	0.245
LIV (L4/L5/S1)	16/5/5	20/9/7	0.854
UIV-T1 (segments)	9.35 ± 1.09	9.67 ± 1.35	0.323
Spine sagittal parameters			
Preoperative CL (°)	− 12.00 ± 13.90	− 16.00 ± 6.46	0.134
Postoperative CL (°)	− 15.88 ± 14.08	− 18.17 ± 6.36	0.393
Correction rate of CL (%)	76.48 ± 111.41	37.87 ± 110.01	0.180
CL at follow-up (°)	− 23.73 ± 13.55	− 18.25 ± 7.73	*0.048*
Preoperative C2-C7 SVA (mm)	13.42 ± 14.98	13.61 ± 6.80	0.946
Postoperative C2-C7 SVA (mm)	19.00 ± 13.08	13.00 ± 9.14	*0.037*
C2–C7 SVA at follow-up (mm)	26.54 ± 12.57	19.33 ± 6.04	*0.004*
Preoperative T1 slope (°)	15.81 ± 4.75	16.36 ± 4.28	0.633
Postoperative T1 slope (°)	21.85 ± 5.98	17.00 ± 4.06	*< 0.001*
T1 slope at follow-up (°)	23.27 ± 6.83	16.92 ± 3.47	*< 0.001*
Preoperative TK (°)	17.42 ± 11.08	22.33 ± 8.39	0.051
Postoperative TK (°)	22.08 ± 9.34	25.33 ± 8.39	0.155
Correction rate of TK (%)	− 7.23 ± 85.40	19.00 ± 23.55	0.139
TK at follow-up (°)	28.08 ± 9.27	27.33 ± 8.39	0.743
Preoperative TLK (°)	14.65 ± 14.64	8.97 ± 4.55	*0.032*
Postoperative TLK (°)	10.73 ± 8.30	10.83 ± 3.01	0.946
Correction rate of TLK (%)	− 34.44 ± 98.08	6.13 ± 76.34	0.072
TLK at follow-up (°)	10.85 ± 8.41	9.25 ± 3.41	0.307
Preoperative LL (°)	− 31.46 ± 7.26	− 33.47 ± 7.45	0.294
Postoperative LL (°)	− 36.50 ± 6.79	− 36.03 ± 5.73	0.768
Correction rate of LL (%)	18.20 ± 16.88	10.82 ± 20.31	0.136
LL at follow-up (°)	− 38.15 ± 6.47	− 29.61 ± 15.63	*0.007*
Preoperative SVA (mm)	8.38 ± 32.51	13.17 ± 8.76	0.402
Postoperative SVA (mm)	11.97 ± 32.54	13.19 ± 5.38	0.824
SVA at follow-up (mm)	16.46 ± 32.73	14.00 ± 4.74	0.657
Pelvic parameters			
Preoperative PT (°)	21.04 ± 7.16	14.00 ± 4.69	*< 0.001*
Postoperative PT (°)	17.85 ± 5.10	14.81 ± 4.76	*0.019*
PT at follow-up (°)	25.35 ± 6.72	17.75 ± 5.46	*< 0.001*
Preoperative PI (°)	41.85 ± 6.54	42.14 ± 3.42	0.819
Postoperative PI (°)	41.92 ± 6.01	42.06 ± 3.22	0.911
PI at follow-up (°)	42.77 ± 6.22	41.97 ± 3.37	0.518
Preoperative SS (°)	20.81 ± 5.82	28.14 ± 4.22	*< 0.001*
Postoperative SS (°)	24.08 ± 4.72	27.25 ± 3.56	*0.004*
SS at follow-up (°)	17.42 ± 5.71	24.22 ± 4.77	*< 0.001*
Preoperative PT/SS (°)	1.21 ± 0.91	0.53 ± 0.28	*< 0.001*
Postoperative PT/SS (°)	0.79 ± 0.32	0.57 ± 0.27	*0.004*
PT/SS at follow-up (°)	1.66 ± 0.77	0.80 ± 0.40	*< 0.001*

Table 3 Adjusted logistic regression analysis for risk factors of PJK in ASD

Variables	B	S.E.	Wald	df	*P* value	Exp (B)	95% CI	
							Upper	Lower
Preoperative TLK	− 0.121	0.049	6.043	1	*0.014*	0.886	0.805	0.976
LL at follow-up	0.160	0.075	4.512	1	*0.034*	1.173	1.012	1.359
Preoperative PT/SS	− 4.625	1.888	6.003	1	*0.014*	0.010	0.000	0.396
Postoperative PT/SS	2.401	2.325	1.066	1	0.302	11.030	0.116	1052.035
PT/SS at follow-up	− 3.315	1.289	6.614	1	*0.010*	0.036	0.003	0.454
Constant	12.660	3.739	11.465	1	0.001	314,802.257		

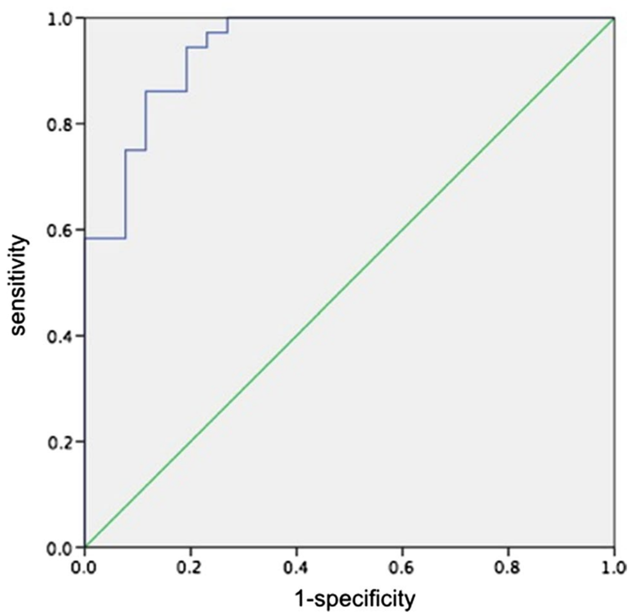

Fig. 1 ROC curve of PJK index (The area under curve (AUC), was 0.95)

optimal cut-off value of PJK index as indicators for occurrence of PJK was − 2. If PJK index was smaller than − 2, the occurrence rate of PJK was 82%. On the contrary, the rate of no PJK was 95%.

A typical case

A typical case was shown in Fig. 2 (a, b: preoperative X-rays; c, d: postoperative X-rays; e, f: X-rays at 5 years follow-up). A 72-year-old female suffered from low back pain, radiating pain in both legs and claudication for 10 years. She was diagnosed as ASD, and underwent correction surgery with pedicle screws from T10–L5. At final follow-up, she complained about low back pain and was diagnosed as PJK with postoperative PJA of 15°. LL at final follow-up, preoperative TLK, preoperative PT/SS and PT/SS at follow-up were − 45°, 30°, 0.75 (15/20) and 0.67 (20/30), respectively. Therefore, PJK index = 0.160*(− 45) − 0.121*30 − 4.625*(15/20) − 3.315*(20/30) = − 16.5.

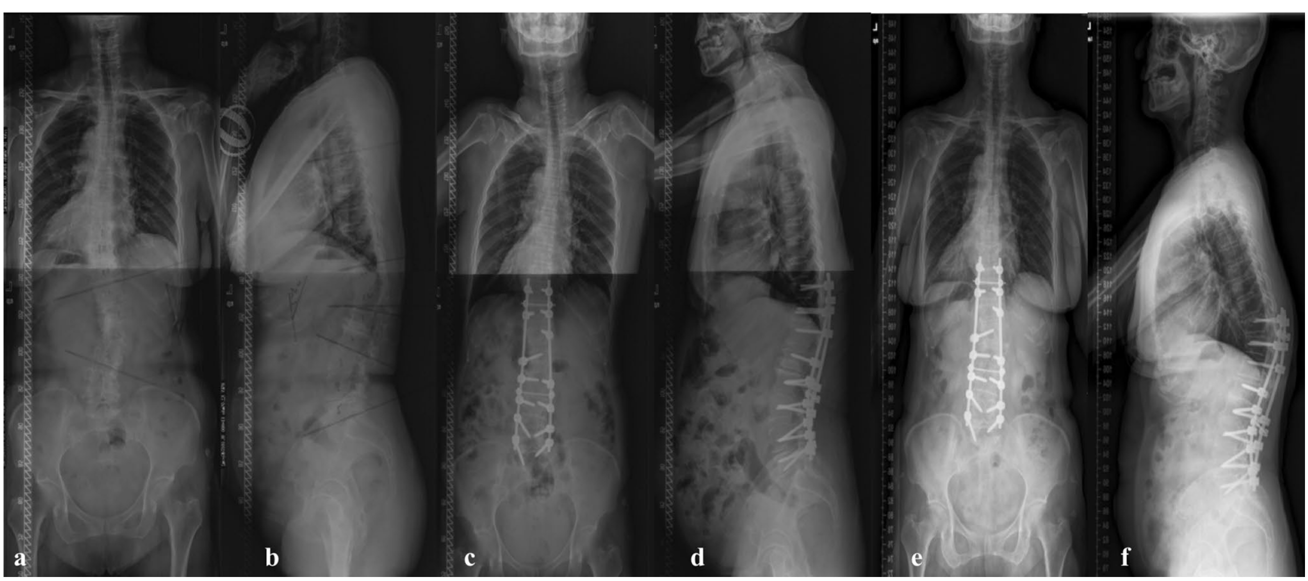

Fig. 2 A typical case. **a**, **b** Preoperative X-rays; **c**, **d** postoperative X-rays; **e**, **f** X-rays at 5 years follow-up

Discussion

PJK is getting increasing recognition of importance because if allowed to develop, it could result in revision surgery, instrumentation breakages, neurologic deficit, upper instrumented vertebra collapse and acute subluxation, known as PJF (proximal junctional failure), and other clinical outcomes [15]. The overall prevalence of PJK in ASD patients after correction ranged from 10 to 45% [3–5, 12]. In our study, PJK was observed in 26 ASD patients with the prevalence of 41.9%, which was larger than that reported in Luo et al. [15] and Liu et al.'s study [13]. In Luo et al.'s meta-analysis [15], ten retrospective studies comprising 1230 patients were included, and total radiographic PJK rate was 32.2%. Liu et al.'s meta-analysis [13] included 14 unique studies containing 2215 patients, and the overall prevalence of PJK was reported to be 30%. Majority of ASD patients recruited in our study underwent surgical treatment in the year from 2010 to 2014. During these years, less knowledge of PJK was achieved among spine surgeons, and less attention was paid to prevention of PJK, which may be important contributors to higher PJK rate in our study. Contemporary concepts and techniques that were not well understood and employed in past decades, such as preservation of interspinous ligaments and facet joints, use of screw anchors, decrease of construct rigidity and UIV selection may also contribute to the higher rate in our study and lower incidence in current series [7, 9, 16]. In addition, sample size, selection of patients and measurement errors may also explain our much higher prevalence.

Due to the devastating outcomes of PJK, surgeons are being devoted to the explorations of risk factors associated with PJK, aiming to minimize the incidence of PJK in ASD patients. However, results from these studies were conflicting [4, 6, 12]. Nicholls et al. [4] found that higher preoperative and postoperative TK, higher preoperative PT and all-screw constructs had a significantly higher rate of PJK. Preoperative BMD (Bone Marrow Density), sagittal imbalance at UIV, and thoracolumbar muscle volume were found to be strongly associated with the presence of PJK in Kim et al.'s study [6]. In addition, although two meta-analyses [13, 15] have been performed to determine the risk factors, there is still no consensus as to which factor is the primary contributor to PJK.

Our univariate analysis showed that preoperative TLK was significantly larger in ASD patients with PJK than that in ASD patients without PJK, suggesting that ASD patients with larger thoracolumbar kyphosis are more likely to suffer from PJK. To the best of our knowledge, thoracolumbar kyphosis is poorly described in the literature, especially in ASD patients with PJK. Our study is the first study that explored the role of thoracolumbar kyphosis in occurrence of PJK in ASD. Thoracolumbar kyphosis, usually measured from T10–L2, is the junctional area of thoracic spine and lumbar spine [17]. Thoracolumbar spine is also the area that transfers force from thoracic spine to lumbar spine. PJK is considered as a compensatory mechanism for sagittal balance [12]. Thus, the larger preoperative TLK is, which might lead to sagittal imbalance, the more likely PJK would occur after correction surgery to compensate for sagittal malalignment. On the other hand, we should also pay attention to the overcorrection of thoracolumbar kyphosis. Overcorrection of the kyphotic deformity can potentially lead to an excessive reduction of lumbar lordosis and the final lumbar lordosis may not match with the patient's PI. This mismatch then leads to an increased risk of PJK [18]. In one word, thoracolumbar kyphosis plays a key role in PJK, and moderate correction of TLK should be performed to prevent occurrence of PJK. LL at follow-up was significantly larger in ASD patients with PJK than that in ASD patients without PJK. The larger LL at follow-up indicated that patients had a trend of backward incline; thus, PJK that might cause forward incline of body occurred to compensate for sagittal balance. Therefore, it could be easily understood why larger LL at follow-up was observed in ASD patients with PJK.

As to pelvic parameters, we also found that preoperative PT, postoperative PT, PT at follow-up, preoperative SS, postoperative SS, SS at follow-up, preoperative PT/SS, postoperative PT/SS and PT/SS at follow-up were significantly different between ASD patients with PJK and ASD patients without PJK, which was consistent with the results by Nicholls et al. [4]. Increasing PT with decreasing SS is a compensatory mechanism for hypolordotic deformity of the lumbar spine [4]. Meanwhile, pelvis rotation involving increasing PT and decreasing SS also occurs in ASD patients with PJK to compensate for the forward incline of sagittal alignment caused by PJK. However, no significant difference in preoperative PI, postoperative PI and PI at follow-up was observed between ASD patients with and without PJK, which was consistent with Lonner et al.'s study [16], further verifying that PI remains constant after adulthood and PI is not a compensatory mechanism for sagittal alignment.

In addition, ASD patients with PJK had significantly larger CL at follow-up, postoperative C2-C7 SVA, C2-C7 SVA at follow-up, postoperative T1 slope and T1 slope at follow-up, indicating that increased cervical lordosis might be a compensatory mechanism for sagittal imbalance caused by PJK. Furthermore, SVA at follow-up was also similar in ASD patients with PJK and ASD patients without PJK, further verifying our concepts that PJK was a compensatory mechanism for sagittal alignment.

However, we did not find any significant difference of UIV between ASD patients with PJK and without PJK. Our results were consistent with the results of Raman et al.'s [9] and Kim et al.'s study [6]. Although no significant difference of UIV was observed between ASD patients with and without PJK, we still recommend that UIV should not be chosen at thoracolumbar kyphosis area if preoperative TLK is larger than 10°, which may increase the incidence of PJK according to our clinical experiences.

Furthermore, our logistic regression analysis showed that preoperative TLK, LL at follow-up, preoperative PT/SS and PT/SS at follow-up were the primary contributors to the occurrence of PJK in ASD patients, further demonstrating the importance of TLK, LL and pelvic parameters. According to the results of logistic regression analysis, PJK index was defined as 0.160*LL at follow-up-0.121*preoperative TLK-4.625*preoperative PT/SS-3.315*PT/SS at follow-up. Before the correction surgery, surgical plans should be made according to our results of regression analysis. First, preoperative TLK should be taken into consideration. If preoperative TLK is larger than 10°, UIV should be chosen across the thoracolumbar kyphosis to avoid PJK. UIV should also not chosen at the apex of thoracolumbar kyphosis. Second, moderate correction of lumbar lordosis should be performed. On the one hand, too large lumbar lordosis after surgery might lead to the backward incline of sagittal plane, leading to the occurrence of PJK to restore the sagittal balance. On the other hand, overcorrection of the kyphotic deformity can also potentially lead to an excessive reduction of lumbar lordosis and the final lumbar lordosis may not match with the patient's PI. This mismatch then leads to an increased risk of PJK. In addition, the correction of TLK and LL determinates the pelvis rotation, namely PT/SS at follow-up. However, preoperative PT/SS already exists before the surgery and could not be changed by the correction surgery. Therefore, our logistic regression analysis illustrated the importance of correction of TLK and LL during correction surgery. Besides, on the basis of ROC curve, if PJK index was smaller than − 2, the occurrence rate of PJK was 82%. On the contrary, the rate of no PJK was 95%. These results indicated that PJK index could be used to predict occurrence of PJK effectively.

Interestingly, we did not find any significant difference of correction rate of CL, TLK, TK and LL between ASD with and without PJK. We also found that there was no significant difference between two groups with regard to postoperative TLK and LL, indicating that correction has been done; however, PJK still happened in some ASD patients. It is believed that PJK might be a compensatory mechanism for sagittal balance. Therefore, more and more attention has been paid to the correction of sagittal alignment and parameters in ASD correction surgery to prevent the occurrence of PJK. Sagittal balance is the results of interactions between sagittal parameters and pelvic parameters. Although we did not find significant difference of postoperative TLK, postoperative LL, correction rate of CL, TLK, TK and LL between two groups, our regression analysis suggested that preoperative TLK, LL at follow-up, preoperative PT/SS and PT/SS at follow-up were primary contributors to PJK in ASD patients. These findings indicate that how to deal the relationships between spino-pelvic parameters is very important in prevention of PJK in ASD patients during the correction surgery rather than only focusing on the correction of spinal parameters (TK, TLK and LL). However, relatively small sample size and measurement errors might also be contribute to the negative impacts of postoperative TLK and LL on occurrence of PJK. Therefore, we recommend that the correction of both spinal and pelvic parameters should be taken into consideration in the correction surgery rather than only focus on the spinal parameters.

Although we found a novel predictor for PJK and evaluate its effectiveness, there are some limitations of this study that should be addressed. First, the sample size in our study was relatively small, and the follow up was relatively short (mean: 3.89 ± 0.94 years). The larger sample size is and the longer follow up is, the more accurate our results would be. Second, only pedicle screws were used in correction surgery rather than other types of instruments, such as hooks, which have also been reported to play a key role in prevention of PJK. Third, BMD, disruption of posterior soft tissues and other factors were also not be analyzed in our study. PJK may depend on osteoporosis, surgical techniques and thoracolumbar muscle mass also. However, due to the insufficient data in our database, we did not analyze these factors in our study, which should be collected and analyzed in our further study. Therefore, large-scale and multicenter studies with longer follow up should be performed to explore the primary factors associated with PJK, and to make a more comprehensive research into the effectiveness of PJK index in predicting PJK.

Conclusion

ASD patients with larger preoperative TLK, LL at follow-up, preoperative PT/SS and PT/SS at follow-up are more likely to suffer from PJK. PJK index defined as 0.160*LL at follow-up-0.121*preoperative TLK-4.625*preoperative PT/SS-3.315*PT/SS at follow-up, could be used to predict occurrence of PJK effectively. Based on our results, we recommend that the correction of both spinal and pelvic parameters should be taken into consideration during the decision-making and correction surgery rather than only focus on the spinal parameters.

Compliance with ethical standards

Conflict of interest None of the authors have a conflict of interest.

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