Neurosurgical Review (2019) 42:671–682
https://doi.org/10.1007/s10143-018-1004-7

ORIGINAL ARTICLE

Characteristics and risk factors for proximal junctional kyphosis in adult spinal deformity after correction surgery: a systematic review and meta-analysis

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Received: 14 February 2018 / Revised: 27 June 2018 / Accepted: 29 June 2018 / Published online: 7 July 2018

Abstract

There are still controversies on characteristics and risk factors for proximal junctional kyphosis (PJK) in adult spinal deformity (ASD) patients. The objective of this study is to explore the characteristics and risk factors for PJK in ASD. A systematic online search in databases including PubMed, EMBASE, Web of Science, and the Cochrane Library was performed to identify eligible studies. OR and weight mean difference with 95% CI were used to evaluate characteristics and risk factors. A total of 31 studies were finally included. ASD patients with PJK had larger proximal junctional angle (PJA), thoracic kyphosis (TK), pelvic incidence minus lumbar lordosis (PI-LL), and sagittal alignment. Age, female gender, and low BMD/osteoporosis were demographic risk factors for PJK. Using hooks at upper instrumented vertebra (UIV) and the selection of UIV above T8 could reduce the occurrence of PJK, while pelvic fixation was significantly associated with increased occurrence of PJK. Preoperative LL, preoperative pelvic tilt (PT), preoperative LL-TK, preoperative PI-LL, preoperative sagittal vertical axis (SVA), preoperative global spine alignment (GSA), postoperative PJA, change in PJA, postoperative TK, change in LL, change in SVA, and postoperative GSA were identified as risk factors for PJK. In conclusion, PJK patients had larger PJA, larger TK, smaller PI-LL, and larger sagittal alignment. Older female ASD patients with low BMD/osteoporosis are more likely to suffer from PJK. We recommend the following: (1) using hooks at UIV; (2) UIV should be chosen above T8, and pelvic fixation should be avoided if possible; (3) ideal correction of sagittal alignment should be performed to prevent the occurrence of PJK.

Keywords Proximal junctional kyphosis · Adult spinal deformity · Meta-analysis

Introduction

Adult spinal deformity (ASD) has become a worldwide spinal disorder, which is characterized by significant low back/leg pain, inferior health-related quality of life (HRQOL) compared with that of the general population, and coronal and sagittal plane malalignment [1]. As the aging population remains active, more attention has been paid to ASD by spine surgeons, hoping to increase ASD patients' life expectancy and improve their HRQOL.

Surgical treatment has been considered as an effective therapy for ASD as a large number of ASD patients could experience substantial benefit from spine surgical intervention [1]. However, surgical correction for ASD is a challenging procedure that is known to carry substantial risk for perioperative and postoperative complications even with an estimated incidence of morbidity and mortality of 31.3 and 0.5%, respectively [2]. Among these complications, proximal junctional kyphosis (PJK) is a common complication in ASD patients following spinal correction surgery [3]. PJK is defined as the final proximal junctional sagittal Cobb angle between the lower endplate of the uppermost instrumented vertebra (UIV) and the upper endplate of two supra-adjacent vertebrae

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(UIV-2), which was 10° and at least 10° greater than the preoperative measurement [4]. The incidence of PJK in ASD patients following correction surgery is reported to range from 10 to 40%, and a meta-analysis showed the incidence of PJK following spinal fusion was 30% [5]. PJK may lead to unsatisfactory radiological and clinical outcomes and require for revision surgery, and it has an influence on satisfaction on ASD surgery as well [5, 6].

Therefore, it is essential to explore the risk factors to allow surgeons to take measures to achieve satisfactory radiological and clinical outcomes as well as minimize the occurrence of PJK. Many studies have been performed to determinate the risk factors for PJK in ASD patients, while the results were still conflicting [3, 5, 7]. Furthermore, a previous meta-analysis [5] has been performed, and the results indicated that age at surgery > 55 years, fusion to S1, T5–T12 > 40°, low BMD, and SVA difference > 5 cm were identified as risk factors for PJK. However, there are many shortcomings in this study, such as confused inclusion criteria, improper pooled analysis of different types of spinal deformity, and omission of other eligible studies [3, 6, 8]. In addition, to the best of our knowledge, no studies have been performed to summarize the characteristics of ASD patients with PJK, which is important to our understanding about this complication.

Thus, we conducted this meta-analysis to make a summary on the characteristics and risk factors for PJK in ASD following correction surgery, in an attempt to improve our understanding about this complication and provide guidance for treatment of ASD.

Materials and methods

Data sources and searches

We searched PubMed, Embase, Web of Science, and the Cochrane Library to identify eligible studies comparing the differences of possible risk factors between PJK group and no PJK group and also investigating these risk factors for PJK in ASD patients. The following search terms were used in our search: "Adult Spinal Deformity" OR "ASD" AND "Proximal Junctional Kyphosis" OR "PJK." Then, one-by-one screening was performed by two authors according to the inclusion and exclusion criteria to collect the data of risk factors. No language restrictions were applied. Secondary searches of eligible studies were conducted by searching the reference lists of the selected studies, reviews, or comments.

Inclusion and exclusion criteria

The inclusion criteria of our meta-analysis were as follows: (1) patients were diagnosed as ASD and underwent correction surgery; (2) at least of 2 years follow-up; (3) ASD patients with PJK should meet the definition of PJK: the final proximal junctional sagittal Cobb angle between UIV and UIV-2 was ≥ 10° than the preoperative measurement [4]; (4) retrospective or prospective studies comparing risk factors in PJK group and no PJK group; (5) sufficient data: mean ± SD (standard deviation) for continuous variables and numbers for count variables. The exclusion criteria were as follows: (1) other types of spinal deformity such as adolescent idiopathic scoliosis (AIS), neuromuscular scoliosis and early onset scoliosis (EOS); (2) other surgeries, such as minimally invasive surgery; (3) no available data reported; (4) duplicated reports. In addition, patients with a previous history of spinal surgery were also excluded.

Data extraction

According to the inclusion and exclusion criteria, data from the eligible studies were extracted by two authors. A consensus was reached by discussion if there exists controversy on data. General characteristics included first author, year of publication, country, type of scoliosis, number of ASD patients with and without PJK, age at surgery, approaches of surgery, follow-up time, and study type. According to the data reported in each eligible study, demographic factors, surgical variables, and preoperative and postoperative radiological parameters were collected and analyzed to explore the risk factors for PJK. Radiological factors at follow-up were analyzed to detect the characteristics of PJK in ASD patients.

Quality assessment

The Newcastle-Ottawa Quality Assessment Scale was used to assess the quality of each study [9].

Data synthesis and statistical analysis

Odds ratios (OR) and weight mean difference (WMD) with 95% CI (confidence interval) were used to evaluate the characteristics and risk factors for PJK. OR and WMD were measured for dichotomous variables and continuous variables, respectively. The heterogeneity of included studies was examined using a Chi-squared-based Q statistical test and quantified using a I^2 metric value. If the I^2 value was > 50% or $P <$ 0.10, OR and WMD values were pooled using a random effects model; otherwise, the fixed effects model was used. A sensitivity analysis was performed to assess the impact of each study on the combined effect of the present meta-analysis. The funnel plot was used to assess the publication bias of the study. Stata 12.0 software (StataCorp, TX, USA) was used, and a P value < 0.05 was considered as statistically significant.

Results

Study selection and characteristics

According to our inclusion and exclusion criteria, a total of 31 studies [3, 6–8, 10–36] were finally recruited in our study. The selection process is shown in Fig. 1, and the characteristics of the included studies are shown in Table 1.

Quality assessment

As shown in Table 2, 19 studies [3, 6, 12–15, 17, 19, 20, 22, 23, 25, 27–29, 31, 33, 34, 36] and 12 studies [7, 8, 10, 11, 16, 18, 21, 24, 26, 30, 32, 35] scored 8 points and 7 points, respectively, indicating that the quality of each study was relatively high.

Results of meta-analysis

Characteristics of PJK

All the abbreviations are listed in Table 3. ASD patients with PJK had larger PJA [WMD (95% CI) = 13.35 (11.31, 15.40), $P < 0.001$], larger TK [WMD (95% CI) = 7.05 (3.63, 10.46), $P < 0.001$], smaller PI-LL [WMD (95% CI) = − 5.64 (− 7.61, − 3.66), $P < 0.001$], and larger GSA [WMD (95% CI) = 10.38 (5.84, 14.91), $P < 0.001$] compared with ASD patients without PJK (Table 4). However, there was no significant difference in LL, PT, SS, and SVA between PJK and no PJK groups (all $P > 0.05$) (Table 4).

Risk factors

Demographic factors

Our meta-analysis showed that age [WMD (95% CI) = 3.26 (2.23, 4.30), $P < 0.001$], female gender [OR (95% CI) = 1.50 (1.21, 1.86), $P < 0.001$], BMD (bone mineral density) [g/cm^2: WMD (95% CI) = − 0.18 (− 0.33, − 0.03), $P = 0.021$; T score: WMD (95% CI) = − 0.71 (− 1.20, − 0.22), $P = 0.004$], and osteoporosis [OR (95% CI) = 2.04 (1.42, 2.93), $P < 0.001$] were significantly associated with occurrence of PJK, while we did not find any significant association between BMI (body mass index) [WMD (95% CI) = 0.56 (− 0.15, 1.27), $P = 0.121$] and smoking status [OR (95% CI) = 1.17 (0.76, 1.81), $P = 472$] and PJK in ASD patients. In addition, we also found that ASD patients older than 55 years old were more likely to suffer from PJK after correction surgery [OR (95% CI) = 1.90 (1.39, 2.60), $P < 0.001$]. All the data were shown in Table 5.

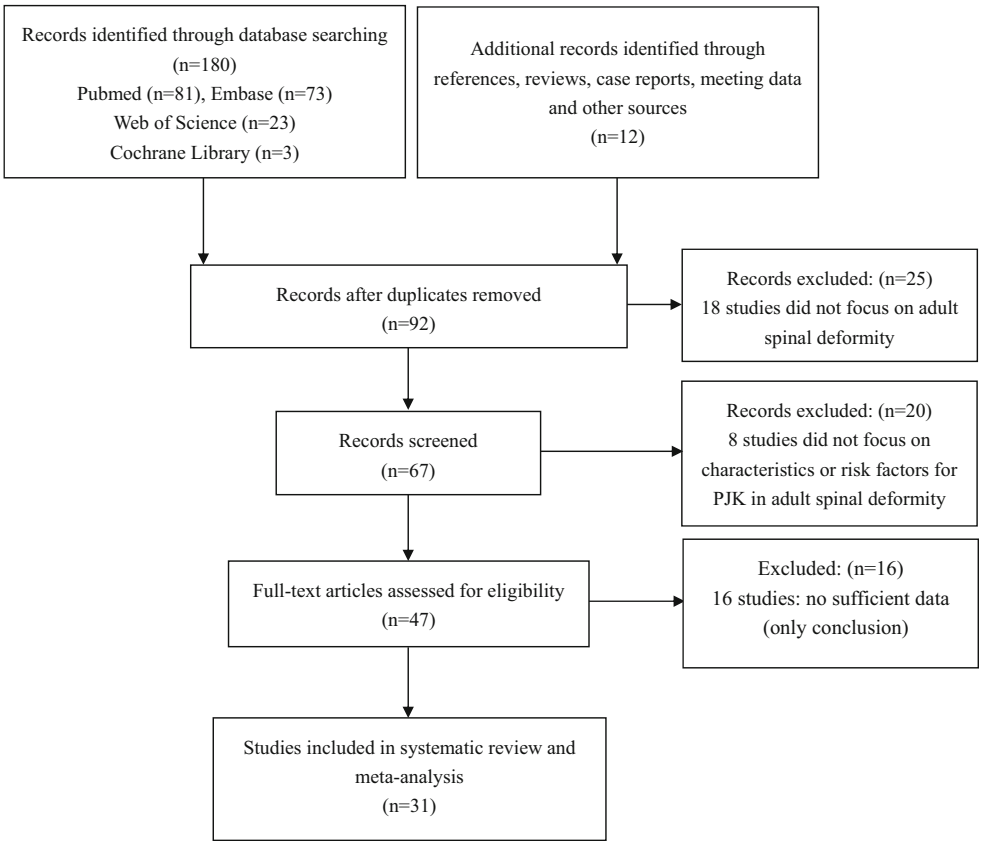

Fig. 1 Flowchart showing the process of selection

Table 1 Characteristics of included studies

Author	Year	Country	Type of scoliosis	*N*		Age (years)	Surgery	Follow-up (month)	Study type
				PJK	No PJK				
Raman et al.	2017	USA	ASD	13	26	PJK: 67.5 ± 5.3 No PJK: 64.6 ± 10	Posterior spinal fusion	67.6 ± 30.9	Prospective cohort study
Yan et al.	2017	China	Degenerative scoliosis	12	15	60.48 ± 6.47	Posterior spinal fusion	31.68 ± 9.36	Retrospective study
Sebaaly et al.	2017	France	Adult scoliosis	64	186	Average 56.67	Posterior reduction and fusion	Average 30	Retrospective study
Sun et al.	2017	China	Degenerative scoliosis	19	55	63.7 ± 4.6	Posterior internal fixation and fusion	Minimum 24 months	Retrospective study
Yasuda et al.	2017	Japan	ASD	19	37	70.0 ± 7.9	Posterior spinal fusion	Minimum 24 months	Retrospective study
Passias et al.	2017	USA	ASD	60	103	54.7 (18–84)	Posterior spinal fusion	Minimum 24 months	Retrospective study
Yagi et al.	2017	Japan	ASD	22	91	At least 20	Corrective spine surgery	Minimum 24 months	Retrospective study
Nicholls et al.	2017	Canada	ASD	281	159	> 18	Posterior long fusion	Average 34	Retrospective study
Lafage et al.	2017	USA	ASD	141	111	Average 61.5	Posterior or combined fusion	24	Retrospective study
Kim et al.	2017	Korea	ASD	16	33	PJK: 62.5 No PJK: 61.9	Segmental spinal instrumented fusion	Average 43.2	Retrospective study
Lafage et al.	2017	USA	ASD	306	373	Average 61	Posterior spinal fusion	Minimum 24 months	Retrospective study
Lafage et al.	2017	USA	ASD	215	243	Average 57.9	Multilevel spinal fusions to the pelvis	Minimum 24 months	Retrospective study
Protopsaltis et al.	2017	USA	ASD	78	189	59.1 (20–82)	Posterior spinal fusion with osteotomy	Minimum 24 months	Retrospective study
Park et al.	2017	South Korea	ASD	56	104	Average 67.6	Long instrumented fusion	Minimum 24 months	Retrospective study
Jamal McClendon Jr. et al.	2016	USA	ASD	18	65	59.7 ± 10.3	Elective spinal fusions	Minimum 24 months	Retrospective study
Wang et al.	2016	China	Degenerative scoliosis	18	81	PJK: 62.3 ± 6.8 No PJK: 62.5 ± 7.5	Long posterior spinal fusion	33.6 (24–72)	Prospective cohort study
Hyun et al.	2016	Korea	Degenerative scoliosis	17	27	PJK: 64.7 ± 7.3 No PJK: 63.4 ± 7.3	Multilevel spinal instrumented fusion	Minimum 24 months	Retrospective study
Scheer et al.	2016	USA	ASD	139	371	57.2 ± 13.9	Posterior spinal fusion	Minimum 24 months	Retrospective study
Smith et al.	2015	USA	ASD	60	113	63.5 ± 13.4	Posterior spinal fusion	Minimum 24 months	Retrospective study
Kim et al.	2014	USA	Adult scoliosis	70	136	PJK: 55.7 ± 14.6 No PJK: 49.9 ± 16.2	Instrumented vertebra	Average 42	Case control study
Lee et al.	2014	Korea	Degenerative scoliosis	28	18	PJK: 66.8 ± 4.2 No PJK: 63.4 ± 5.4	Surgical correction of deformed spine	Average 45.6	Retrospective study
Maruo et al.	2013	Japan	ASD	37	53	Average 64.5	Long instrumented fusion	Average 34.8	Retrospective study
Martin et al.	2013	USA	ASD	5	33	64.4 (41–80)	Posterior spinal fusion	24	Prospective cohort study
Bridwell et al.	2013	USA	ASD	25	675	49.9 ± 12.6	Posterior spinal fusion	42 (24–144)	Retrospective study
Cho et al.	2013	Korea	Degenerative scoliosis	13	38	64.6 (54–84)	Posterior instrumentation	40.8 ± 22.8	Retrospective study
Kim et al.	2013	USA	ASD	144	220	PJK: 53.3 ± 14.5 No PJK: 48.9 ± 15	Posterior spinal fusion	42 (24–72)	Retrospective study
Yagi et al.	2012	USA	Adult scoliosis	17	59	48.8 (23–75)	Long instrumented spine fusion	87.6 (60–168)	Retrospective case series
Mendoza-Lattes et al.	2011	USA	ASD	19	35	59.3 ± 10.1	Reconstructive surgery	26.8 (12–42)	Case control study
Yagi et al.	2011	USA	Adult idiopathic scoliosis	32	125	46.9 (22–81)	Instrumented spinal fusion	51.6 (24–144)	Retrospective case series
Kim et al.	2008	USA	ASD	62	99	45.2 (18–73)	Long posterior spinal fusion	93.6 (60–237.6)	Retrospective study
Glattes et al.	2005	USA	ASD	21	60	45 (23–66)	Posterior spinal fusion	63.6 (24–192)	Retrospective study

ASD adult spinal deformity

Table 2 The quality assessment according to the Newcastle Ottawa Quality Assessment Scale (NOQAS) of each study

Study	Year	Selection	Comparability	Exposure	Total score
Raman et al.	2017	3	2	3	8
Yan et al.	2017	3	2	3	8
Sebaaly et al.	2017	3	2	3	8
Sun et al.	2017	3	2	32	7
Yasuda et al.	2017	3	2	3	8
Passias et al.	2017	3	2	2	7
Yagi et al.	2017	3	2	3	8
Nicholls et al.	2017	3	2	3	8
Lafage et al.	2017	3	2	3	8
Kim et al.	2017	3	2	2	7
Lafage et al.	2017	3	2	3	8
Lafage et al.	2017	3	2	2	7
Protopsaltis et al.	2017	3	2	3	8
Park et al.	2017	3	2	3	8
Jamal McClendon Jr. et al.	2016	3	2	2	7
Wang et al.	2016	3	2	3	7
Hyun et al.	2016	3	2	2	7
Scheer et al.	2016	3	2	3	8
Smith et al.	2015	3	2	2	7
Kim et al.	2014	3	2	3	7
Lee et al.	2014	3	2	3	8
Maruo et al.	2013	3	2	3	8
Martin et al.	2013	3	2	3	8
Bridwell et al.	2013	3	2	3	8
Cho et al.	2013	3	2	2	7
Kim et al.	2013	3	2	3	8
Yagi et al.	2012	3	2	2	7
Mendoza-Lattes et al.	2011	3	2	3	8
Yagi et al.	2011	3	2	3	8
Kim et al.	2008	3	2	3	8
Glattes et al.	2005	3	2	2	7

Surgical variables

As to surgical variables, our study showed that using hooks at UIV could significantly decrease the occurrence of PJK compared with pedicle screws [OR (95% CI) = 0.46 (0.36, 0.60), $P < 0.001$], including both unilateral hooks [OR (95% CI) = 0.58 (0.40, 0.83), $P = 0.004$] and bilateral hooks [OR (95% CI) = 0.47 (0.30, 0.74), $P = 0.001$]. Selection of UIV above T8 [OR (95% CI) = 0.42 (0.24, 0.73), $P = 0.002$] and T5 [OR (95% CI) = 0.72 (0.57, 0.90), $P = 0.005$] were also significantly associated with decreased occurrence of PJK, while no significant association was observed between other locations of UIV and PJK, including T10 [OR (95% CI) = 0.54 (0.26, 1.11), $P = 0.094$] and L1 [OR (95% CI) = 0.66 (0.19, 2.25), $P = 0.502$]. In addition, pelvis fixation [OR (95% CI) = 2.20 (1.73, 2.80), $P < 0.001$] was also identified as a risk factor for PJK. However, we did not find any significant associations between number of instrumented vertebrae, instrumentation type (hooks vs. pedicle screws), surgical approach, osteotomy, cross-links present, thoracoplasty, and occurrence of PJK (all $P > 0.05$; Table 5).

Radiological parameters

As to preoperative parameters, our study showed that smaller preoperative LL (lumbar lordosis) [WMD (95% CI) = − 1.74 (− 2.74, − 0.73), $P = 0.001$], larger preoperative PT [WMD (95% CI) = 1.67 (0.25, 3.08), $P = 0.021$], smaller preoperative LL-TK (lumbar lordosis minus thoracic kyphosis) [WMD (95% CI) = − 10.30 (− 16.27, − 4.34), $P = 0.001$], larger preoperative PI-LL (pelvic incidence minus lumbar lordosis) [WMD (95% CI) = 3.20 (0.48, 5.92), $P = 0.021$], larger preoperative SVA (sagittal vertical axis) [WMD (95% CI) = 16.23 (8.56, 23.90), $P < 0.001$], and larger preoperative GSA (global spine

Table 3 Abbreviations used in this study

Abbreviations	Explanations
ASD	Adult spinal deformity
HRQOL	Health-related quality of life
PJK	Proximal junctional kyphosis
UIV	Uppermost instrumented vertebra
UIV-2	The upper endplate of two vertebrae supra-adjacent
SD	Standard deviation
AIS	Adolescent idiopathic scoliosis
EOS	Early onset scoliosis
OR	Odds ratios
WMD	Weight mean difference
CI	Confidence interval
PJA	Proximal junctional angle
TK	Thoracic kyphosis
PI-LL	PI minus LL
LL	Lumbar lordosis
PT	Pelvic tilt
SS	Sacral slope
SVA	Sagittal vertical axis
GSA	Global spine alignment
BMD	Bone mineral density
BMI	Body mass index
LL-TK	LL minus TK
PMOP	Postmenopausal osteoporosis
RCT	Randomized controlled trials

alignment, TK+LL+PI) [WMD (95% CI) = 16.96 (11.52, 22.39), $P < 0.001$] were significantly associated with increased risk of PJK, while other preoperative radiological parameters including preoperative PJA (proximal junctional angle), preoperative TK, preoperative TLK (thoracolumbar kyphosis), preoperative PI (pelvic incidence), and preoperative SS (sacral slope) were not significant different between PJK group and no PJK group (all $P > 0.05$, Table 5).

Our meta-analysis indicated that larger postoperative PJA [WMD (95% CI) = 6.04 (3.68, 8.40), $P < 0.001$], larger postoperative TK [WMD (95% CI) = 3.08 (0.77, 5.40), $P = 0.009$], larger postoperative GSA [WMD (95% CI) = 11.18 (6.59, 15.76), $P = < 0.001$], greater change in PJA [WMD (95% CI) = 7.23 (2.42, 12.04), $P = 0.003$], greater change in LL [WMD (95% CI) = 5.69 (1.07, 10.30), $P = 0.016$], and greater change in SVA [WMD (95% CI) = 6.12 (1.29, 29.04), $P = 0.023$] were identified as risk factors for PJK. Besides, ASD patients with postoperative GSA ≥ 45° were also more likely to suffer from PJK after correction surgery [OR (95% CI) = 20.19 (7.89, 51.72), $P < 0.001$]. However, we did not find any significant associations between other postoperative parameters and occurrence of PJK (all $P > 0.05$, Table 5).

Sensitivity analysis and publication bias

A leave-one-out analysis was performed to estimate the sensitivity of our study. We found that any single study could be omitted without causing any significant effect on the overall statistical significance, indicating that the results of our meta-analysis were stable. In addition, the shape of the funnel plot was symmetrical, indicating that there was no publication bias in our study (Fig. 2).

Discussion

Characteristics of PJK

In our meta-analysis, ASD patients with PJK had larger PJA compared with ASD patients without PJK. It is

Table 4 Characteristics for PJK in ASD patients

Variables	Test of differences		Model	Test of heterogeneity	
	WMD (95% CI)	*P* value		*P* value	I^2 (%)
PJA (°)	*13.35 (11.31, 15.40)*	*< 0.001*	R	0.001	72.0
TK (°)	*7.05 (3.63, 10.46)*	*< 0.001*	R	0.038	55.0
LL (°)	1.66 (−2.94, 6.26)	0.479	R	< 0.001	74.4
PT (°)	0.29 (−0.91, 1.49)	0.639	F	0.314	15.5
SS (°)	−5.125 (−8.85, −1.40)	0.007	F	0.638	0.0
PI-LL (°)	*−5.64 (−7.61, −3.66)*	*< 0.001*	F	0.287	11.9
SVA (mm)	5.77 (−2.85, 14.40)	0.189	R	< 0.001	72.3
GSA using (TK+LL+PI) (°°)	*10.38 (5.84, 14.91)*	*< 0.001*	F	0.443	0.0

WMD weighted mean difference, *OR* odd ratios, *95% CI* 95% confidence intervals, *F* fixed effect model, *R* random effect model

Italicized data signifies $p < 0.05$, risk factors for PJK in ASD patients

Table 5 Risk factors for PJK in ASD patients

Demographic factors	Test of differences		Model	Test of heterogeneity	
	WMD/OR (95% CI)	*P* value		*P* value	I^2 (%)
Age (year)	*3.26 (2.23, 4.30)*	*< 0.001*	R	< 0.001	64.8
Age ≥ 55 years vs. age < 55 years	*1.90 (1.39, 2.60)*	*< 0.001*	F	0.334	12.6
Gender (female/male)	*1.50 (1.21, 1.86)*	*< 0.001*	F	0.968	0.0
BMI (kg/m^2)	0.56 (− 0.15, 1.27)	0.121	R	0.003	58.0
BMD (g/cm^2)	*− 0.18 (− 0.33, − 0.03)*	*0.021*	R	0.022	68.9
BMD (*T*-score)	*− 0.71 (− 1.20, − 0.22)*	*0.004*	R	< 0.001	85.6
Osteoporosis	*2.04 (1.42, 2.93)*	*< 0.001*	F	0.699	0.0
Smoking status	1.17 (0.76, 1.81)	0.472	F	0.828	0.0
Surgical variables	Test of differences		Model	Test of heterogeneity	
	WMD/OR (95% CI)	*P* value		*P* value	I^2 (%)
Number of instrumented vertebrae	0.03 (− 0.67, 0.74)	0.928	R	< 0.001	87.1
Instrumentation type (hooks vs. pedicle screws)	0.83 (0.51, 1.33)	0.439	F	0.352	4.2
UIV type					
Unilateral hooks vs. pedicle screws	*0.58 (0.40, 0.83)*	*0.004*	F	0.310	16.4
Bilateral hooks vs. pedicle screws	*0.47 (0.30, 0.74)*	*0.001*	F	0.625	0.0
Hooks vs. pedicle screws	*0.46 (0.36, 0.60)*	*< 0.001*	F	0.279	17.9
UIV					
Above T5 vs. below T5	*0.72 (0.57, 0.90)*	*0.005*	F	0.156	37.5
Above T8 vs. below T8	*0.42 (0.24, 0.73)*	*0.002*	R	0.049	58.0
Above T10 vs. below T10	0.54 (0.26, 1.11)	0.094	R	0.007	66.2
Above L1 vs. below L1	0.66 (0.19, 2.25)	0.502	R	0.010	69.7
Pelvic fixation	*2.20 (1.73, 2.80)*	*< 0.001*	F	0.589	0.0
Approach (posterior only vs. posterior and anterior)	0.79 (0.61, 1.02)	0.073	F	0.234	22.7
Osteotomy	1.11 (0.82, 1.50)	0.506	F	0.657	0.0
Cross-links present	1.30 (0.85, 1.99)	0.222	F	0.455	35.7
Thoracoplasty	1.09 (0.53, 2.26)	0.810	F	0.814	0.0
Preoperative radiographic factors	Test of differences		Model	Test of heterogeneity	
	WMD (95% CI)	*P* value		*P* value	I^2 (%)
Preoperative PJA (°)	0.19 (− 1.65, 2.03)	0.839	R	< 0.001	72.2
Preoperative TK (°)	1.13 (− 0.72, 2.98)	0.231	R	0.007	52.6
Preoperative TLK (°)	− 0.01 (− 0.72, 0.71)	0.988	F	0.225	31.2
Preoperative LL (°)	*− 1.74 (− 2.74, − 0.73)*	*0.001*	F	0.258	17.5
Preoperative PI (°)	− 0.07 (− 1.24, 1.09)	0.902	F	0.048	42.3
Preoperative PT (°)	*1.67 (0.25, 3.08)*	*0.021*	R	0.004	57.4
Preoperative SS (°)	− 0.96 (− 3.92, 2.01)	0.527	R	0.044	59.1
Preoperative LL-TK (°)	*− 10.30 (− 16.27, − 4.34)*	*0.001*	F	0.479	0.0
Preoperative PI-LL (°)	*3.20 (0.48, 5.92)*	*0.021*	R	0.001	66.6
Preoperative SVA (mm)	*16.23 (8.56, 23.90)*	*< 0.001*	R	< 0.001	73.6
Preoperative GSA (TK+LL+PI) (°)	*16.96 (11.52, 22.39)*	*< 0.001*	F	0.343	0.0
Postoperative radiographic factors	Test of differences		Model	Test of heterogeneity	
	WMD/OR (95% CI)	*P* value		*P* value	I^2 (%)
Postoperative PJA (°)	*6.04 (3.68, 8.40)*	*< 0.001*	R	< 0.001	82.0
Change in PJA (°)	*7.23 (2.42, 12.04)*	*0.003*	R	< 0.001	97.0
Postoperative TK (°)	*3.08 (0.77, 5.40)*	*0.009*	R	< 0.001	75.6
Change in TK (°)	0.56 (− 5.25, 6.37)	0.581	R	< 0.001	87.5
Postoperative TLK (°)	− 0.28 (− 2.56, 2.01)	0.813	R	0.049	61.8
Postoperative LL (°)	2.58 (− 0.10, 5.27)	0.059	R	< 0.001	75.3
Change in LL (°)	*5.69 (1.07, 10.30)*	*0.016*	R	0.051	54.6
Postoperative PI (°)	1.77 (− 0.79, 4.34)	0.175	F	0.948	0.0
Postoperative PT (°)	0.12 (− 1.07, 1.31)	0.843	F	0.470	0.0
Change in PT (°)	0.61 (− 0.98, 2.21)	0.451	F	0.356	7.4
Postoperative SS (°)	− 0.27 (− 3.04, 2.49)	0.846	R	0.021	65.2
Postoperative LL-TK (°)	− 4.29 (− 18.10, 9.53)	0.543	R	0.001	91.1
Postoperative PI-LL (°)	− 3.31 (− 7.56, 0.95)	0.128	R	0.003	75.0
Postoperative SVA (mm)	− 4.99 (− 11.19, 1.21)	0.115	R	< 0.001	81.2
Change in SVA (mm)	4.33 (− 8.79, 17.45)	0.518	R	< 0.001	89.1
Change in SVA (SVA difference > 50 mm)	*6.12 (1.29, 29.04)*	*0.023*	R	0.003	83.0
Postoperative GSA (TK+LL+PI) (°)	*11.18 (6.59, 15.76)*	*< 0.001*	F	0.535	0.0
Postoperative GSA (GSA ≥ 45° vs. GSA < 45°)	*20.19 (7.89, 51.72)*	*< 0.001*	F	0.470	0.0

WMD weighted mean difference, *OR* odd ratios, *95% CI* 95% confidence intervals, *F* fixed effect model, *R* random effect model

Italicized data signifies $p < 0.05$, risk factors for PJK in ASD patients

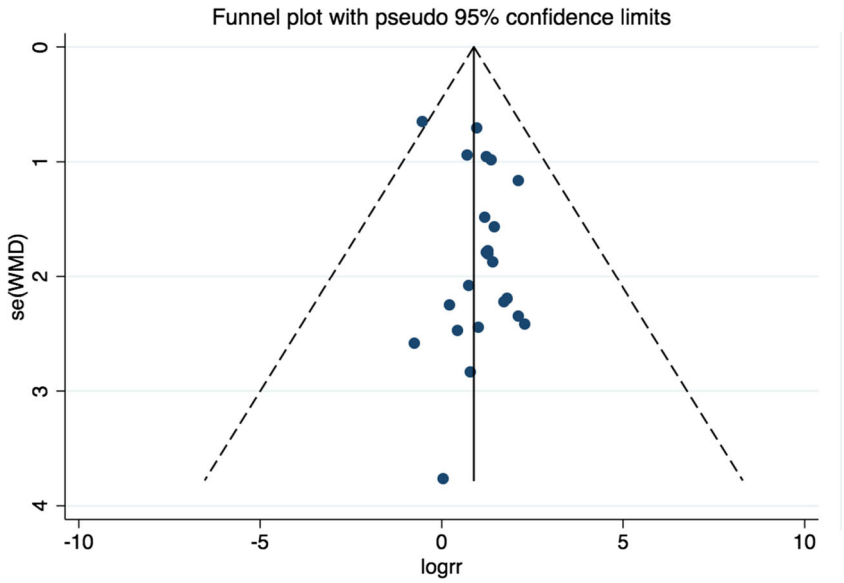

Fig. 2 Publication bias of our study

easily understood why there is significant difference in PJA between ASD patients with and without PJK because of the definition of PJK (PJA ≥ 10° and at least 10° greater than the preoperative measurement) [18]. Larger TK, smaller PI-LL, and larger GSA were also observed in ASD with PJK, verifying that the occurrence of PJK might be a compensatory mechanism for sagittal imbalance [37, 38]. The larger TK and GSA are and the smaller PI-LL is, the more likely the ASD patients will incline toward. Thus, PJK will occur to restore the inclined sagittal alignment. Based on this finding, more and more surgeons suggest sufficient correction and reconstruction of global sagittal alignment after surgery to prevent the occurrence of PJK. Sagittal balance is more than just alignment, and optimal postoperative sagittal alignment may be an important contributor to avoidance of PJK [38].

Risk factors for PJK

Demographic factors

Increasing age has found to be significantly associated with incidence of PJK, specifically for ASD patients who are older than 55 years old. Our results were consistent with many studies [11, 15, 18, 37], suggesting that more attention should be paid to the prevention of PJK in elder ASD patients.

Low BMD (g/cm^2 and *T*-score) and osteoporosis were identified as risk factors for PJK, which was consistent with Yagi et al.'s study [27]. In their study [27], they enrolled 43 patients who started teriparatide therapy immediately after surgery and 33 patients who did not receive teriparatide in this case series, and found that prophylactic teriparatide treatment significantly improved the volumetric BMD (bone volume/tissue volume from 46 to 54%) and fine bone structure at UIV+1, and reduced the incidence of PJF from 15.2 to 4.6%, and they suggested that prophylactic treatments should be considered in ASD patients with low BMD.

Although many studies [6, 10, 13–15] did not show any significant difference in gender between ASD patients with and without PJK, our pooled results suggested that female ASD patients were more likely to suffer from postoperative PJK than male patients. Postmenopausal osteoporosis (PMOP) is a common metabolic bone disorder characterized by low BMD and increased fracture risks in postmenopausal women [39]. Thus, why female gender is found to be a risk factor for PJK in ASD patients is easily understood. However, what should not be ignored is the predominance of female patients in some studies [8], which might also be an important contributor to controversial results between ours and many studies [6, 10, 13–15].

Based on our results, we recommend the following: (1) The evaluation of BMD should be considered an important consideration before surgery in ASD patients, especially for female ASD patients with age older than 55 years old. (2) Surgeons should consider prophylactic measures against PJK/PJF when correcting ASD in patients with a low BMD.

Surgical variables

Many surgical variables are considered as risk factors for PJK, such as approach-related risk factors (disruption of the posterior soft tissues, combined anterior, and posterior approach), rigidity of the construct (the use of all-pedicle screw constructs, fusion to the sacrum/ilium), and choice of the UIV [37]. And several protective methods have been taken according to these surgical risk factors.

Our study demonstrated certain correlations between some surgical variables and PIJK risk, including instrument types of UIV, choice of the UIV, and pelvic fixation. We found that using hooks at UIV could effectively decrease the occurrence

of PJK, including both unilateral hook and bilateral hooks, compared with pedicle screws. Our results were consistent with Kim et al.'s [11] and Hassanzadeh et al.'s study [40]. First, compared with pedicle screws, hooks provide a softer landing and probably produce less mechanical stress on the level above, which is considered as an important contributor to PJK development [40]. Second, there is less risk of violating the facet joint and ligament complex proximal to the UIV when we place hooks, which could provide powerful strengths to prevent the compression of UIV-2 [40]. In addition, vertebral body near UIV will also not be violated by hooks, which might avoid the problem of compression fractures at the UIV [40]. Therefore, although there is a change in surgical techniques from prior hook and hybrid constructs to predominantly pedicle screw constructs, we still recommend using hooks at the UIV to prevent the occurrence of PJK in ASD patients.

Pelvic fixation was also significantly associated with increased incidence of PJK, which was consistent with Bridwell et al.'s [14] and Kim et al.'s study [20]. However, Raman et al. [6], Wang et al. [8], Hyun et al. [10], and Martin et al. [13] did not find significant difference in pelvic fixation between PJK group and no PJK group in their studies. Sample size, selection of study population, measurement errors, and different follow-ups might be contributors to this difference. Long segmental fusion and extension of the fusion to the sacropelvis result in significant increase of stiffness of the construct, especially for modern all-pedicle screws, which is considered as an important contributor to PJK development [16, 37]. Fusion to sacrum and pelvis benefits patients who might suffer from sagittal decompensation and distal junctional degeneration after long instrumented spinal fusion [16]. To avoid sagittal decompensation and distal junctional degeneration in these patients, we still recommend fusion to sacrum in patients who meet the criteria of sacropelvis fusion; however, we should not ignore the devastating impacts of pelvis fixation in ASD patients.

The choice of the UIV also has great influence on the occurrence and development of PJK as our study indicated that the UIV at upper thoracic spine (above T8 and T5) was significantly associated with decreased risk of PJK. Bridwell et al. [14] found similar findings in their study, which demonstrated that shorter constructs (PJK, median 8 levels fused, vs. non-PJK, median 11 levels fused and a UIV [T8-lower]) might increase the risk for PJK. Therefore, extension of the UIV to the upper thoracic spine is recommended to avoid the occurrence of PJK.

However, we did not find any significant association in number of instrumented vertebrae, instrumentation type (hooks vs. pedicle screws), surgical approach (posterior only vs. posterior and anterior), osteotomy, cross-links present, and thoracoplasty between PJK group and no PJK group. Interestingly, Hart et al. [41] identified anterior approaches as an independent risk factor for PJK. However, until now, it is not understood exactly how anterior approaches increase the risk of PJK, which needs further studies.

Radiological parameters

In our meta-analysis, preoperative sagittal malalignment was found to be significantly associated with PJK risk, including smaller preoperative LL, larger preoperative PT, smaller LL-TK, larger PI-LL, larger preoperative SVA, and GSA (TK+LL+PI). Our results were consistent with those of other studies [19, 22, 35, 42], suggesting that ASD patients with preoperative sagittal malalignment are more likely to suffer from PJK after correction surgery. With increased age, lumbar lordosis tends to decrease with pelvis rotation (increased PT) to keep whole sagittal balance, which might result from lumbar degenerative diseases and low back pain [43]. Furthermore, if compensatory mechanisms such as pelvis rotation and extension of adjacent segments and lower limbs could not compensate for sagittal malalignment, patients tend to suffer from anterior sagittal imbalance and have a tendency of anterior inclination. Thus, elder ASD patients might have smaller preoperative LL, larger preoperative PT, smaller LL-TK, larger PI-LL, and larger preoperative SVA and GSA (TK+LL+PI) and it is easily understood why these preoperative radiological parameters are associated with PJK risk. On the other hand, the significant correlations between increasing age and these radiological parameters further verify our previous findings that age is a risk factor for occurrence and development of PJK.

Due to the significant associations between several preoperative sagittal parameters and PJK risk, how to reconstruct the preoperative sagittal alignment during the operation is getting increasing recognition of importance among surgeons, hoping to prevent the occurrence of PJK. ASD patients with PJK had larger postoperative TK and GSA compared with patients without PJK. Sagittal alignment is described as reciprocal curves of TK and LL, and GSA and SVA are common parameters being used to evaluate the sagittal balance [44]. PJK occurs in patients with sagittal malalignment, verifying the theory that PJK might be a compensatory mechanism for sagittal balance [38]. Restoring sagittal alignment after surgery should be considered during the preoperative decision-making.

It is really important to restore sagittal alignment in ASD surgery; however, we should also pay attention to the overcorrection of sagittal alignment. Our results showed that greater correction of PJA, lumbar lordosis, and SVA were identified as risk factors for PJK, which was consistent with Yan et al.'s [3] and Kim et al.'s study [11]. In Yan et al.'s opinion [3], if an ASD patient underwent extensive correction surgery, resulting in sagittal overcorrection such as a larger correction of LL and SVA, the postoperative alignment may not be anatomically sustainable as the body tends to balance itself in all three dimensions with minimal energy expenditure according to Dubousset's conus of economy. Then, patients

with an overcorrected sagittal profile would unconsciously generate compensatory mechanisms to realign the sagittal profile, which are commonly limited to the unfused segments. Therefore, PJK occurs and PJA (angle between UIV and UIV-2) increases as a compensatory mechanism to maintain sagittal balance. Therefore, how to restore the optimal sagittal alignment without overcorrection during the operation should be further studied.

Although we have performed a comprehensive analysis on characteristics and risk factors of PJK in ASD patients after correction surgery, there are some limitations that should be addressed. First, some other risk factors such as disruption of the posterior soft tissues were not analyzed in our analysis due to the insufficient data. Second, the number of described characteristics of PJK was relatively small, and other parameters should be studied to give a more comprehensive summary. Third, we did not analyze the difference of HRQOL between PJK group and no PJK group. In addition, most of these included studies were retrospective studies, although Newcastle Ottawa Quality Assessment Scale was used to assess the quality. Compared with randomized controlled trials (RCT), there are some limitations in retrospective studies, such as observation biases, which might have influences on the pooled results. Therefore, more RCTs with a large sample size should be performed.

Conclusions

PJK patients had larger PJA, larger TK, smaller PI-LL, and larger sagittal alignment. Older female ASD patients with low BMD/osteoporosis are more likely to suffer from PJK. ASD patients with smaller preoperative LL and preoperative LL-TK, larger preoperative PI-LL and preoperative PT, and greater sagittal alignment are more likely to suffer from PJK after correction surgery. We recommend the following: (1) the evaluation of BMD should be considered an important consideration before surgery in ASD patients, especially for female ASD patients with age older than 55 years old; (2) surgeons should consider prophylactic measures against PJK/PJF when correcting ASD in patients with a low BMD; (3) Using hooks at UIV; (4) UIV should be chosen above T8, and pelvic fixation should be avoided if possible; (5) ideal correction of PJA, TK, and LL and sagittal alignment should be performed to prevent the occurrence of PJK.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Jingzhou Central Hospital, Jingzhou City, Hubei Province, China

Informed consent All the authors have approved the publication of this article.

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