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ORIGINAL ARTICLE

Proximal junctional kyphosis in adult scoliosis: comparison of four radiological predictor models

Amer Sebaaly[1,2] · Guillaume Riouallon[3] · Ibrahim Obeid[4] · Pierre Grobost[1] · Maroun Rizkallah[2] · Fethi Laouissat[1] · Yann-Phillippe Charles[5] · Pierre Roussouly[1]

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Abstract
Objective The objective of this retrospective study is to identify the best immediate postoperative radiological predictors for the occurrence of proximal junctional kyphosis (PJK). Four proposed methods will be explored.
Methods A homogeneous database of adult scoliosis from multiple centers was used. Patients with whole spine X-rays at the required follow-up (FU) periods were included. Spinal and pelvic parameters were measured and calculated to compare four predictive methods: Method 1: assessment of the global sagittal alignment (GSA); Method 2: restoration of the theoretical values of lumbar lordosis (LL) and thoracic kyphosis (TK) according to pelvic incidence (PI); Method 3: evaluation of TK + LL, and Method 4: restoration of the apex of sagittal LL to its theoretical values according to various spine shapes in Roussouly Classification. PJK occurrence was assessed at the last FU radiograph.
Results 250 patients were included; mean age was 56.67 years and mean FU was 2.5 years. PJK occurred in 25.6% of cases. PJK occurred in 19.9% in patients with a GSA <45° and in 29.9% where GSA >45° ($p = 0.04$, OR = 1.71). Restoring the sagittal apex of the LL to its theoretical values according to PI deceased PJK to 13.5% compared to 38.9% in the other cases ($p = 0.01$, OR = 4.6). The two other described methods (2 and 3) were not significant predictors.
Discussion The comparison between the four predictive methods showed that a GSA >45° and restoration of sagittal apex of lordosis according to PI, were the most predictive methods for PJK in ASD. The latter had a higher predictive value. Our findings could prove useful in effective preoperative planning in ASD surgery to reduce PJK rates.
Level of evidence Level IV.

Keywords Proximal junctional kyphosis · Adult spinal deformity · Roussouly classification · Global sagittal alignment

Introduction

Adult spinal deformity (ASD) incidence is increasing with the high incidence of adult scoliosis and with the population aging phenomenon [1]. This surgery is associated with 20% of mechanical complications (pseudarthrosis, proximal junctional kyphosis (PJK)…) [2]. PJK was first described in Scheuermann's kyphosis [3] and adolescent idiopathic scoliosis [4]. This mechanical complication is a radiological finding that could lead in frequent cases to multiple surgical revisions [5]. The most used PJK definition is the one defined by Glattes et al. [6]: PJK angle is determined by the angle between the lower endplate of the last instrumented vertebra and the upper endplate of the

✉ Amer Sebaaly
amersebaaly@hotmail.com

1 Department of Orthopedic Surgery, Clinique médico-chirurgicale des Massues, 92 rue Edmond Locard, 65005 Lyon, France

2 Saint Joseph University, Faculty of Medicine, Beirut, Lebanon

3 Department of Orthopedic Surgery, Groupe Hospitalier Paris Saint Joseph, Paris, France

4 Spinal Unit 1, Department of Orthopaedic Surgery, University Hospital of Bordeaux, Bordeaux, France

5 Spine Surgery Unit, Hôpitaux Universitaires de Strasbourg, Université de Strasbourg, Strasbourg, France

two supra-adjacent vertebrae. PJK is considered present when the angle is superior to 10° and at least 10° greater compared its preoperative value [6]. Radiological incidence of PJK in ASD is variable and ranges between 6 and 50% [7–9]. Furthermore, there is lack of consensus on risk factors for PJK. For instance, increased age, preoperative comorbidities, obesity, osteoporosis, posterior elements disruption, proximal anchor types, sagittal imbalance, long constructs, female sex, higher preoperative lumbar lordosis (LL), long thoracic kyphosis (TK) have all been incriminated as potential risk factors for the occurrence of PJK [10]. Moreover, PJK was found to have a serious clinical impact on quality of life score like the SRS-22 or the ODI scores [9, 11].

There is no consensus on the immediate postoperative radiological predictive parameters for PJK that warrant closer follow-up for patients. In fact, Yagi et al. suggested that correction of the spinal deformity with Global Sagittal Alignment (GSA) greater than 45° would result in higher PJK incidence [12]. GSA was first described by Rose et al. and is the sum of TK, LL and PI [13] (PI: pelvic incidence) (Method 1). On the other hand, Vialle et al. [14] proposed to restore LL and TK to the theoretical values based on PI (Method 2); Correction methods (osteotomies, cages insertion…) should aim to achieve these calculated values. Mendoza-lattes et al. suggested that the positive sum of LL and TK was associated with an increased incidence of PJK [15] (Method 3). Surgeons were encouraged to have a LL greater than TK. Roussouly et al., proposed a classification of 4 types of normal spine and claim that the sagittal apex of the LL is to be placed at L4 in low pelvic incidence (PI) types (type 1 and 2), whereas it is at L3 or L3-L4 disc in higher PI types (Types 3 and 4) [16]. According to this author, restoration of the sagittal LL apex to its theoretical value could be a radiological predicting factor for incidence of rod breakage and PJK [17] (Method 4).

The objective of this study is to evaluate the most reliable immediate postoperative radiological predictors for the occurrence of PJK among four proposed methods, using a large multicentric database of a homogeneous population of adult scoliosis.

Materials and methods

A multicentric database was used for this study with more than 900 cases of scoliosis. Adult scoliosis patients (de novo and aged idiopathic) constituted this database with uniform treatment (posterior reduction and fusion). A spine fellow, who was not involved in the surgical treatment of the patients, collected and measured retrospectively all radiographic data. Full spine radiographs were analyzed using semi-manual computerized software for sagittal spinopelvic and scoliosis curvature radiologic measurements, such as KEOPS® (SMAIO, Lyon, France) which has shown excellent reliability in measuring sagittal and coronal parameters [18]. Inclusion criteria were: presence of scoliosis (Cobb angle >20°) on the AP radiography, age ≥20 years old, lower instrumented vertebra to be at or below L4, and patients with whole spine X-rays (AP and lateral) at a minimum of three time points (preoperatively, immediate postoperative time, and last follow-up). Exclusion criteria were: history of instrumented spinal surgery, scoliosis with tumoral or traumatic etiology, and patients with less than a 6 months follow-up. Records with missing data were excluded.

Full spinal X-rays were collected from patients *preoperatively* and *immediately following surgery*. They included PI, pelvic tilt (PT), sacral slope (SS), LL, TK, as well as the sagittal apex of lumbar lordosis.

To compare the different predictive methods, several values were calculated:

1. Method 1: Postoperative GSA (LL + PI + TK) was calculated for the analysis according to the method of Yagi et al. [12].
2. Method 2: Theoretical values of TK and LL were calculated according to Vialle et al. using the formulas depending on PI: $LL = 0.67\ PI + 23.7$ and $TK = 0.15\ PI + 43$ [14].
3. Method 3: Postoperative LL + TK were calculated according to the predictor method of Mendoza-Lattes [15].
4. Method 4: The sagittal apex of the LL was noted from immediate postoperative imaging. The theoretical apex of the lumbar lordosis was considered L4 when PI <55° and L3 when PI ≥55° as described by Roussouly et al. [16].

PJK was defined *at the last follow-up radiograph* as described by Glattes [6].

IBM SPSS (version 20.0) software was used for statistical analysis. A Fisher exact test was used for continuous variables and a Chi-squared test was performed for non-continuous variables. Odds ratios (OR) for predictive factors were then calculated. *p* values below 0.05 were considered statistically significant.

Results

250 patients met the inclusion criteria, had a whole spine AP and lateral views at the three time points, with complete records measurement, and were kept for final analysis (Fig. 1). The mean age was 57.67 years (22–82). The mean follow-up was 2.5 years (1.4–5.3) with a female to male ratio of 8.3/1. Mean time gap between surgery and

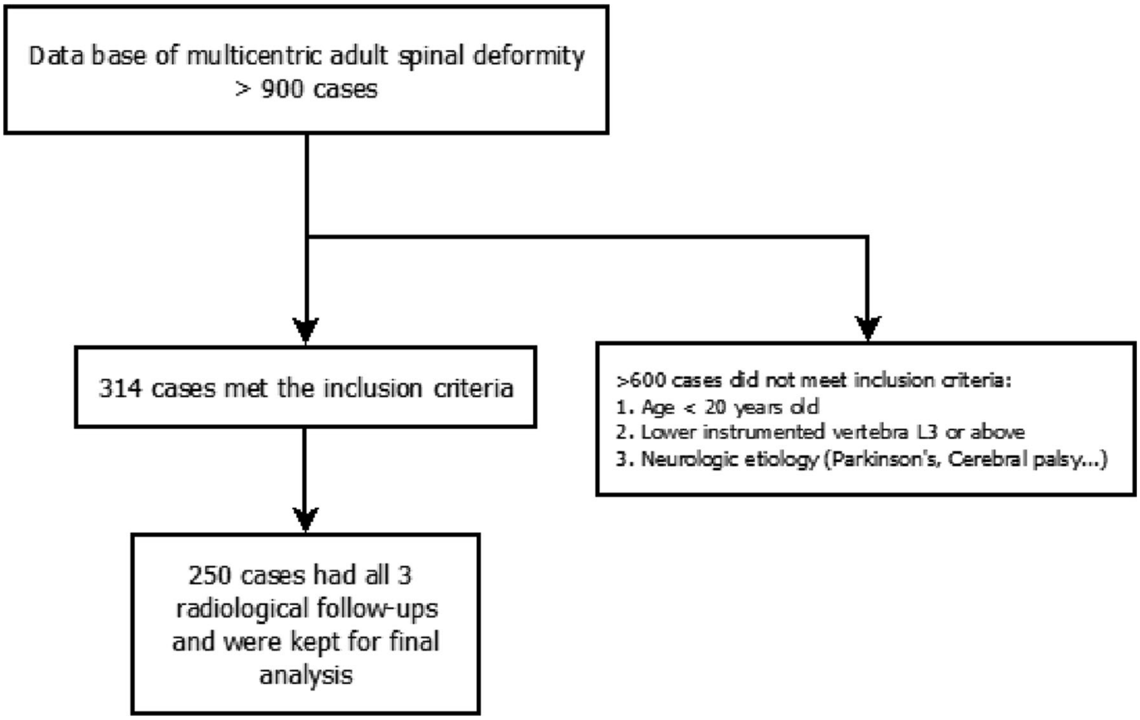

Fig. 1 Flow chart showing the inclusion criteria, exclusion criteria, and final analysis

diagnosis of PJK was 5.6 months (0.72–13.2), with more than 80% of the cases occurring before the first year. Table 1 shows the measured radiographic parameters. The average PI was 56.2° (24.3–98.9). There were 64 cases of PJK with an incidence of 25.6%. Mean age was 57.1 for patients without PJK and 59.2 for patients with PJK ($p > 0.05$). The average preoperative PT was 24.4°, which decreased to 21.0° in the immediate postoperative period ($p < 0.01$). Mean LL increased from 46.8° to 52.2° ($p < 0.01$), whereas mean TK increased from 41.2° (0.3–93.4) to 44.0° ($p = 0.02$). UIV was in the upper thoracic area (T1–T4) in 66.8% of cases, in the middle thoracic area (T5–T9) in 28.4%, and in the thoracolumbar area (T10–L2) in only 4.8%. There was no difference in PJK incidence (respectively, 25.8, 28.2 and 16.6%; $p > 0.05$). The proximal anchor type did not influence occurrence of PJK (Hooks 28.8%; pedicle screws 30.4%; $p = 0.85$). The postoperative sagittal lordosis apex was L1 in 1.2% of cases, L2 in 8.1%, L3 in 55.6%, L4 in 32.5%, and L5 in 2.5%. Finally, the rate of revision surgery for PJK was very low in this cohort. Only 6 out of 250 patients (2.4%) were revised for symptomatic PJK. Mean PJK angle was 13.86. There was no difference in PJK angle between cases requiring revision and cases not requiring revision (13.9 vs. 13.56; $p > 0.05$). This low rate of revision prevented statistical analysis of predictive method for revision per se.

Theoretical parameters were calculated and compared to the actual immediate postoperative values:

1. Method 1: The average GSA was 48.0°. 42.4% of this cohort had GSA <45°, whereas for the rest (57.6%), it

Table 1 Preoperative and postoperative spinal and pelvic parameters

	Preoperative				Postoperative				*p* value
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	
Pelvic incidence	56.23	13.43	24.30	98.88					
Pelvic tilt	24.42	10.56	1.31	52.50	21.06	8.98	0.09	48.41	<0.01
Sacral slope	31.73	12.20	1.75	68.99	34.54	9.65	5.63	59.74	<0.01
Lumbar lordosis	46.85	18.97	0.78	86.80	52.15	11.26	22.98	81.53	<0.01
Thoracic kyphosis	41.23	19.44	0.29	93.37	43.98	16.57	2.23	118.30	0.02

SD standard deviation

was greater than 45°. PJK occurred in 19.8% in the first group and it occurred in 29.9% in the second group ($p = 0.04$) with an OR = 1.71 (1.06–2.9) (Fig. 2).

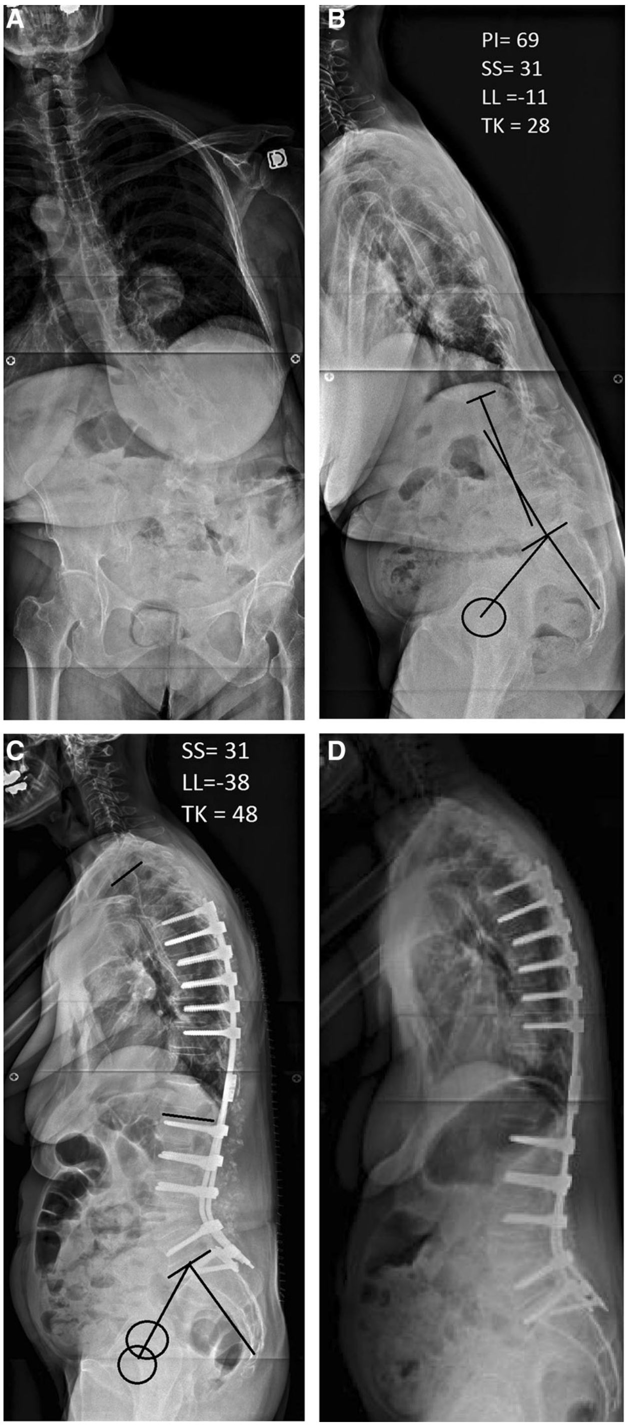

Fig. 2 68 year old woman presented with lumbar scoliosis and major sagittal imbalance (**a**, **b**). She was operated on with posterior fusion with L4 pedicle substraction osteotomy. Postoperative GSA was 58°, while the apex of the lordosis was L3 for a PI of 69° (**c**). 6 months postoperatively she presented with a PJK at the upper thoracic area with no clinical implication (**d**)

2. Method 2: The average theoretical LL, as proposed by Vialle, was 61.4° (40°–90°) with a significant difference compared to the observed postoperative LL. Theoretical TK was 52.0° (46.9°–58.8°) and was found significantly different than the observed postoperative value of 44.0°. PJK occurred in 25% of the cases when postoperative values were equal to theoretical values, and in 26% of cases when LL did not correspond to TK ($p = 0.80$) with an OR = 1.006 (0.57–1.8).
3. Method 3: The average LL + TK was 8.2°. PJK occurred in 27% when LL + TK was positive, yet occurred in 23% when it was not ($p = 0.24$) with an OR = 0.64 (0.36–1.2).
4. Method 4: The theoretical sagittal lordosis apex was L3 in 54% of the cases and L4 in the remaining 46% of cases. When the postoperative sagittal apex of the lumbar curve was identical to the theoretical apex (127 cases), PJK occurred in 13.5% of cases. On the other hand, it occurred in 38.9% of cases where the theoretical and actual apex were different (123 cases) ($p = 0.01$) with an OR = 4.6 (2–9.3). In addition, cases were divided according to the distance of the postoperative apex compared to theoretical apex. PJK occurred in 39.6% when the postoperative lordotic apex was one level above or below the theoretical apex, in 75% when it is located two levels above, and in 50% when it was two levels below (only 12 cases in this subgroup) (Fig. 3).

The series was splat between two groups according to minimum follow-up (FU <24 months and FU ≥24 months). 171 cases had a minimum FU of 24 months. Mean age was 51.6 years and PJK occurred in 25% of cases. The comparison of the four predictive methods showed similar results to the overall series. PJK occurred in 18% in patients with a GSA <45° and in 28% where GSA was >45° ($p = 0.039$) with an OR = 1.88. Restoring the sagittal apex of LL according to the theoretical value of PI deceased the risk for PJK to 14.8% compared to 35.09% in cases where LL and PI were not concordant ($p = 0.01$, OR = 3.5). The two other methods (restoring theoretical values of LL and TK, and LL + TK) were not significant predictors. There was no statistical difference between the values in the overall series and in the minimum 2 years follow-up group.

Discussion

This is the first study that compares, using a large cohort, four methods to predict the occurrence of PJK based on immediate postoperative radiographs. We found that two methods could statistically predict the

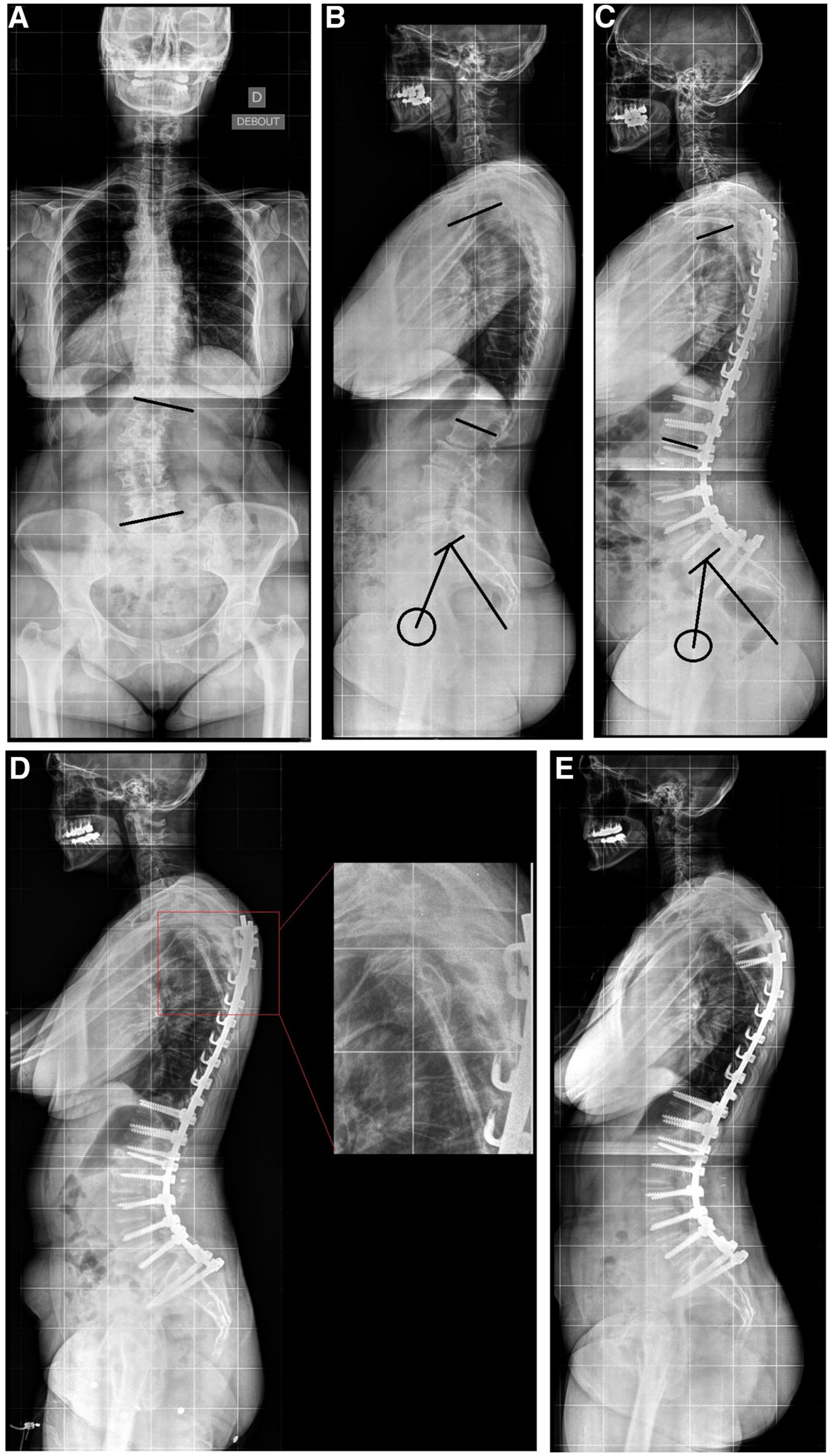

Fig. 3 61 year old woman presenting with degenerative lumbar scoliosis (Cobb angle 32°) (**a**). Pelvic incidence was 53° with a theoretical apex at the upper L4 plateau (**b**). She was operated on with a T3-iliac fusion. She had a long lordosis (LL = 65°, NVL = 7), with a lordosis apex at L2 giving rise to an anteverted pelvis (SS = 48°, PT = 5°) (**c**). 4 months later, she presented with a progressive kyphotic deformity (PJK angle 22.3°) (**d**). Revision surgery was done with an extension to T2 with pedicle screws, in order to follow the shape of proximal kyphosis (**e**)

occurrence of PJK: the first was GSA (PI + LL + TK) that should be less than 45° (Method 1) as described by Yagi et al. [12]. The second method is using the sagittal apex of lordosis (Method 4). Between these two methods, the sagittal apex of lordosis had a higher predictive value, with an OR of 4.6.

PJK is a common complication of corrective surgery for ASD with an incidence ranging between 6–50% [8, 9]. We found an incidence of 25.6% in this cohort, which was similar to the incidence described by Liu el al in their recent metaanalysis of the literature [10]. These authors outlined several risk factors for the development of PJK such as increased age, postoperative imbalance, and fusion to the sacrum and low body mass index. Nonetheless, there is no consensus as to which postoperative indicator is best suited to predict the occurrence of this complication and to closely monitor patients at risk in clinical practice. Several authors proposed postoperative scores and predictors to evaluate the occurrence of PJK. Lee et al. made the first description of PJK in adolescent scoliosis and suggested that PJK occurrence could be predicted from preoperative radiographs [4].

In 2011, Yagi et al. reviewed 157 patients with ASD that underwent posterior fusion and found an incidence of PJK of 25% [12]. They also found that PJK did not affect the final clinical outcome, but only significantly affected the self-image subscale in the SRS-30 questionnaire. They also found that 84% of the PJK group was associated with non-ideal global sagittal alignment (GSA >45°) preoperatively, as well as in the immediate postoperative period. This figure decreases to 6.4% in the non PJK group [8]. The calculated OR for occurrence of PJK in GSA >45 was 29. However, this study on a larger cohort was able to demonstrate that even a GSA >45° remains a significant predictor of PJK. Furthermore, its OR is less than the one described by Yagi et al. [12], which was approximately 1.7.

In 2005, Berthonnaud et al. introduced the "inflexion point" where lordosis curvature switched into kyphosis [19]. They described the shape of LL that is characterized by two arches: the lower arch, which is equal to SS, and a quasi-constant upper arch. Based on this theory of inflexion point, and constitution of lordosis, Roussouly et al. proposed a classification of normal spinal sagittal balance and classified spinal shapes in four types based on inflexion points [16]. Types 1 and 2 have a low PI and a sagittal lordosis apex at L4, while types 3 and 4 have a higher PI with an apex of the lordotic curve at L3. They showed that the geometrical construction of the lordosis depends on the SS, and that TK depends largely on the LL and number of vertebra included in the LL curve. Namely, the longer and higher the lordosis, the lesser room there is for the kyphosis to be constructed [20]. One example for this theory is the cervical kyphosis in adolescent idiopathic scoliosis patients with thoracic lordosis [21]. This finding is also well shown in our series of cases where postoperative apex is two levels above the theoretical apex, where the incidence of PJK is 75% because the kyphosis has little space to be constructed (Fig. 3).

The main finding of this study is that failure to restore a correct sagittal apex in lordosis is an important risk factor for PJK. This finding could have several pathological implications for degenerative spine surgery. The first implication is the choice of the level of a pedicle substraction osteotomy (PSO) when treating adult deformity. As a matter of fact, debate still exists on the ideal level of choice for PSO. For instance, some authors found no difference in global balance correction or complication rate with level of PSO (comparing L3 and L4 osteotomy) [22]. However, other authors found better sagittal balance correction as well as PT correction with L4 osteotomy compared to L3 osteotomy [23]. The findings of this paper could help surgeons make this decision favoring a L4 osteotomy. In fact, L4 osteotomy is better placed to restore the apex of the lordosis at the desired theoretical value, even if L3 is the theoretical apex vertebra. The second implication of this paper regards the anterior correction techniques of adult scoliosis, or anterior indirect decompression techniques. To elaborate, these techniques rely on anterior release of the disco-ligament complex and on insertion of lordotic cages. Nonetheless, restoring the correct sagittal apex of the lordosis is important. Thus, proper choice and placement of lordotic cages (very lordotic cages in L5–S1 and L4–L5 discs) helps avoiding very long lumbar lordosis and decreases mechanical complications in general, PJK in particular.

One should note that merely restoring the sagittal apex of the lordosis is insufficient to prevent the occurrence of PJK. We found a 13.5% incidence of PJK even when the apex of the lordosis is restored, as PJK is a multifactorial complication. Age is one of the most accepted risk factors [10]. Nonetheless, restoration of the lordosis apex is an independent protector factor regarding the patient's age. Other risk factors include long fusion to the sacrum and to the upper thoracic area [10]. This could be explained by overcorrecting the kyphosis to a point that the patient could not tolerate, or by insufficient rod bending to accompany the beginning of thoracic kyphosis. In fact, high mechanical stress on the instrumentation was found to be risk factor for developing PJK [24] (Figs. 3, 4).

Revision rates for PJK were low in our series as they concerned only 2.4% of the cases. These results are similar to other series in the literature (Yagi et al: 1.4% [5]; Hostin et al.: 2.3% [7]), while others found an increased incidence of revision [25, 26]. Revisions occurred in the first 7 months, whereas Yagi found a mean time for the revision of 10.5 months for symptomatic PJK [5]. Finally, the incidence of revision surgery for PJK was too low to study correlations of the apex of the lordosis to revision rate.

There are some limitations of this study. First, it is a retrospective study with some un-exploitable data and some missing values (such as bone density to study the

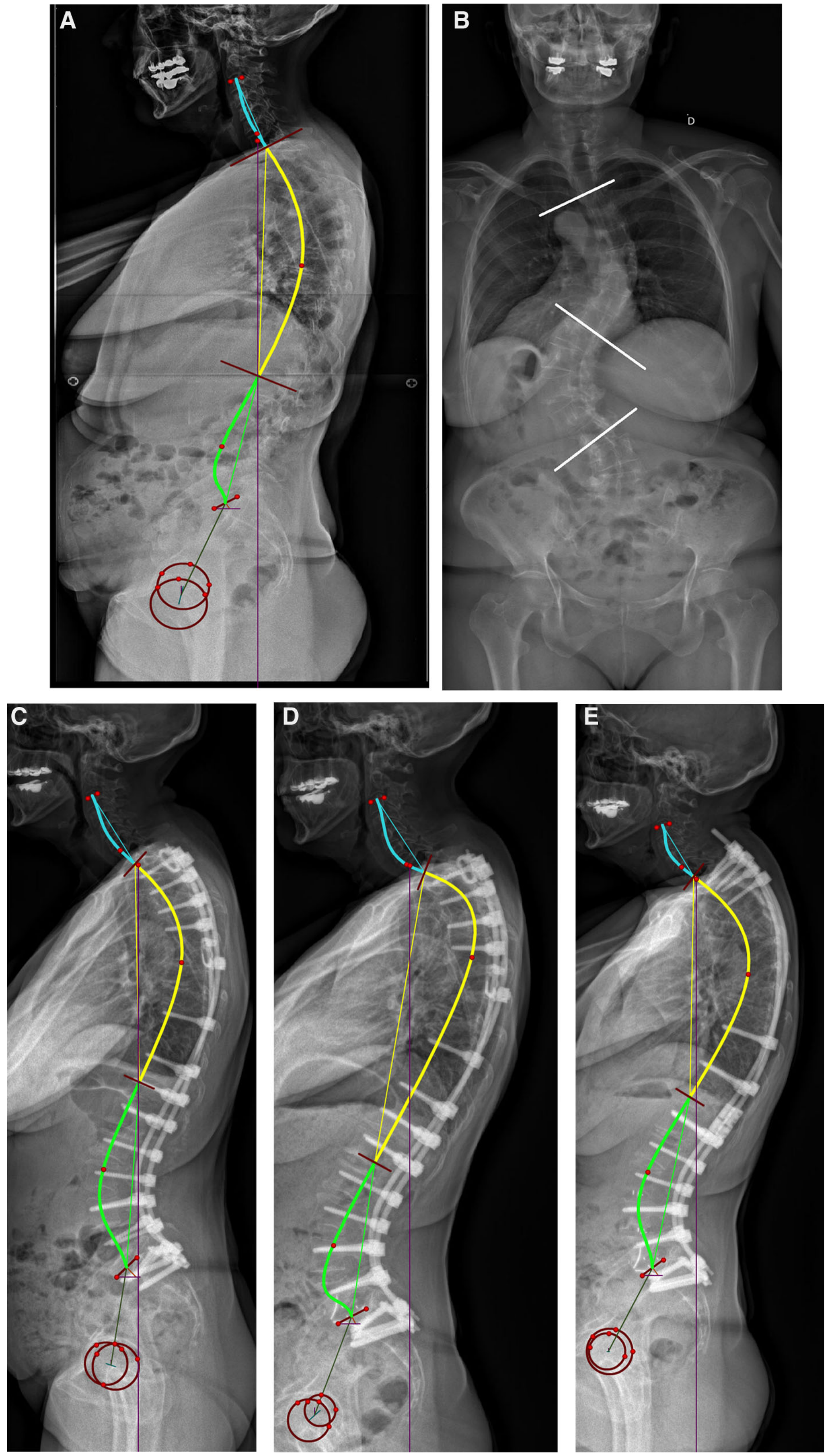

Fig. 4 56 year old woman presented with a thoracolumbar scoliosis with good overall sagittal imbalance (PI = 50°) (**a**, **b**). She was operated on with posterior fusion (T2–S1), using proximal screws as anchors. Postoperative GSA was 52°, while the apex of the lordosis was L3 for a PI of 50° (**c**). 4 months postoperatively, she presented a PJK with a PJK angle of 38° (**d**), and was subsequently operated on 3 months later with an extension to T1 using pedicle screws (**e**). The surgical strategy was to bridge the kyphotic area and follow the natural kyphosis with the rod. Fusion was noted in the upper thoracic area and several implants were removed to assist rod adaptation

effect of osteoporosis). Nevertheless, all others studies in the literature are retrospective case-series or case–control studies [10]. Second, no clinical or pain scores were studied in this cohort, partially because not all centers had a preoperative scores for all patients and partially because the database (KEOPS) was recently instituted in others.

Conclusion

Four postoperative radiological predictive parameters for PJK have been proposed. This study is the first one to compare these four parameters in a homogenous population of adult spinal deformity. Correction to the theoretical values of LL and TK according to pelvic incidence (PI) and the evaluation of TK + LL did not accurately predict the occurrence of PJK. However, only two immediate postoperative methods could accurately predict its occurrence. The first one is the method of Yagi et al. where GSA should be less than 45°, and the second one is the accurate restoration of the sagittal apex of lordosis. The second method has a higher predictive value with a significant OR of 4.6. Consequently, restoring the apex of the sagittal lumbar lordosis to its theoretical value, dictated by the value of the PI and the spinal shape according to Roussouly's classification, is recommended to decrease the incidence of PJK and offer a more harmonious spinal sagittal balance.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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