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ORIGINAL PAPER

Sagittal alignment assessment after short-segment lumbar fusion for degenerative disc disease

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Abstract

Purpose To investigate whether differences in spinopelvic parameters, and especially spinopelvic alignment, could be associated with adjacent segment disease (ASD) or pseudarthrosis after short-segment lumbar fusion.

Methods Retrospective study of patients offered mono- or bisegmental transforaminal lumbar interbody fusion (TLIF) with polyetheretherketone (PEEK) or titanium cages, due to degenerative disease. Of 419 patients, 32 (7.6%) presented pseudarthrosis (nonunion group), 29 (6.9%) developed symptomatic ASD (ASD group), and 358 patients (85.5%) showed evidence of uncomplicated fusion (control group). Standard spinopelvic parameters were measured in all patients before and after surgery. The differences of the values within the parameters (Δ values) were also calculated. A comparative analysis within and among groups was performed. Patients were also analyzed by cage characteristics (large vs small, titanium vs PEEK).

Results All studied parameters changed significantly after surgery both in the control and ASD group, while in the nonunion group, only LL and PI-LL changed significantly (PI-LL increased from 10 ± 11° to 14 ± 10°, $p = 0.008$). Patients in the nonunion group presented greater SS before and after surgery, greater PI-LL after surgery, and higher PI, while ASD patients presented greater absolute mean ΔPT value. Age, size, and type of cage were not related to fusion, nonunion, or ASD.

Conclusions Greater SS, greater PI, and a PI-LL mismatch greater than 10° are associated with failed bony fusion, while ASD is related to a greater difference between the pre-operative and post-operative values of PT. Neither the type nor the size of cage seem to have a significant impact on either solid bony fusion, nonunion, or ASD rates. Thus, we recommend on the study of patients' sagittal alignment in the pre-operative setting even when treating patients with short-segment lumbar interbody fusion.

Keywords Lumbar interbody fusion · PEEK · Titanium · Degenerative disc disease · Disc herniation · Sagittal alignment

Introduction

Lumbar disc herniation and degeneration are common spine pathology, leading frequently to disability, and treatment options include conservative care, i.e., with steroid injections and prescribed opiates, and surgery [1, 2]. Surgical interbody fusion of degenerative levels is an effective treatment option to stabilize the painful motion segment, which may adequately provide indirect decompression of the neural elements, restore lordosis, and correct deformity [3, 4]. The development of pseudarthrosis, however, represents a well-known complication of lumbar spine surgery, with the reported rates ranging between 5 and 35%, and the factors influencing the risk of nonunion being highly variable [5]. On the other hand, fusion of lumbar vertebrae has been deemed to increase biomechanical stresses at levels adjacent to the fusion, rendering these unfused vertebral segments susceptible to degenerative changes, a well-recognized condition described as adjacent segment disease (ASD) [6–8]. The incidence of symptomatic ASD after lumbar spinal fusion has been reported ranging between 0 and 24%, with a mean annual incidence of 1.2–3.9%, while radiographic findings indicative of ASD are even more common with reported rates ranging between 36 and 84% [6, 9, 10].

Even Hippocrates recognized that the function of the spine is to maintain the upright position of the human body and form

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the shape of the human trunk [11], which is facilitated, from what we know in modern medicine, via maintaining proper alignment. Over the past years, sagittal balance analysis has gained importance in reconstructive surgery of the spine, and there is growing interest in the use of spinopelvic parameters to predict outcomes in patients with degenerative spinal disease [12]. In fact, sagittal imbalance has been associated with various spinal conditions, but its impact on outcomes after posterior lumbar fusion for degenerative disease has not been investigated until recently. There has been only some evidence implying that sagittal malalignment may lead to ASD [9, 13, 14]; nevertheless, little is known regarding possible relations between variances in sagittal contours and the development of pseudarthrosis or successful union after short-segment lumbar instrumentation.

We hypothesized that different sagittal patterns could be related to the development of either ASD or pseudarthrosis; therefore; the purpose of the present study was to investigate whether differences in spinopelvic parameters, and especially spinopelvic alignment, could be associated with either of these common conditions following lumbar spine surgery.

Materials and methods

We retrospectively studied patients, who underwent posterior lumbar fusion in transforaminal lumbar interbody fusion technique (TLIF) with polyetheretherketone (PEEK) or titanium cages, due to degenerative disc disease, recurrent disc herniation, facet joint arthritis, and spinal stenosis. The surgical technique included the application of multiaxial pedicle screws in one or two segments (mono- or bisegmental) between L3 and S1 levels. Cases with spondylolysis, congenital vertebral anomalies, infections, fractures, and scoliosis greater than 20° were excluded. Patients were followed averagely for 50 months (range, 36–84 months), and the presence of fusion, pseudarthrosis, or ASD was documented in their files after clinical and radiological evaluation. If pseudarthrosis was suspected each patient was examined by thin-cut CT. Finally, 419 patients (252 women and 167 men; mean age, 71 ± 11 years) were included in our study; 32 patients (7.6%) presented pseudarthrosis (nonunion group); 29 patients (6.9%) developed symptomatic ASD (ASD group); and evidence of uncomplicated fusion was present in 358 patients (85.5%) (control group) (Figs. 1 and 2). A radiographic spinal evaluation in the free-standing position was performed in all patients before and after surgery. Standard spinopelvic parameters, namely pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS), L1-S1 lumbar lordosis (LL), L4-S1 lordosis (L4S1), and the lumbopelvic mismatch (PI-LL; PI minus LL modifier is considered an assessment tool for sagittal alignment) were measured in all patients, before and after surgery (Fig. 3). The differences of the values within the parameters were also calculated: ΔPT = preopPT − postopPT, ΔSS = preopSS − postopSS, ΔLL = preopLL − postopLL, ΔL4S1 = preopL4S1 − postopL4S1, and Δ (PI-LL) = preop (PI-LL) − postop (PI-LL).

Radiographic films were downloaded from Cerner ProVision™ PACS (picture archiving and communication system) and sagittal spinopelvic parameters were evaluated using computer software that enables quantitative measurements of the spine and pelvis. Data were tabulated in a Microsoft Excel® sheet (Microsoft Corporation, Redmond, Washington, USA). A paired sample analysis of the parameters was performed within groups. The independent *t* test was used for the comparison of the measurements among groups. A comparative analysis among groups with respect to size and

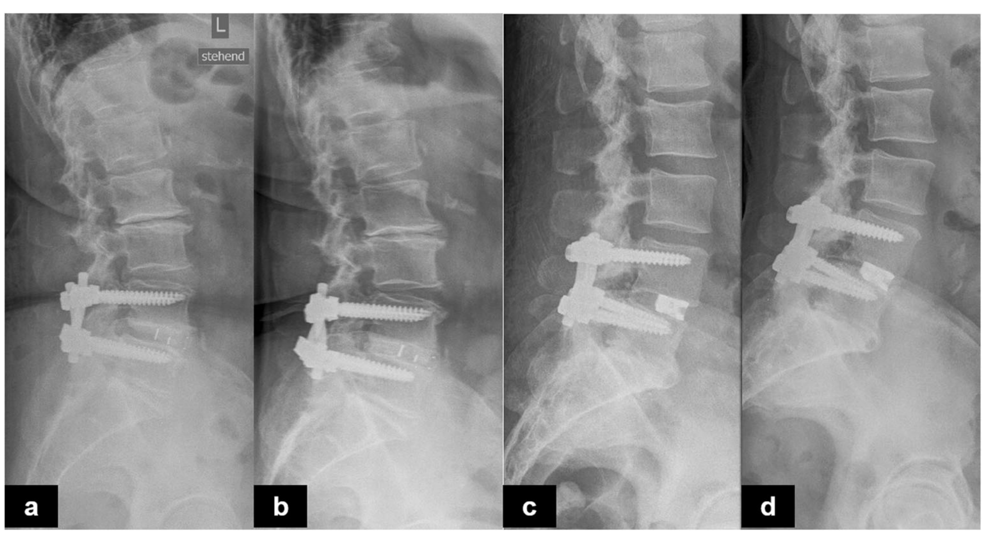

Fig. 1 Lateral standing radiographs of the lumbar spine after TLIF with PEEK cages **a** immediately and **b** 60 months after surgery, and titanium cages **c** immediately and **d** 48 months after surgery, show uneventful fusion

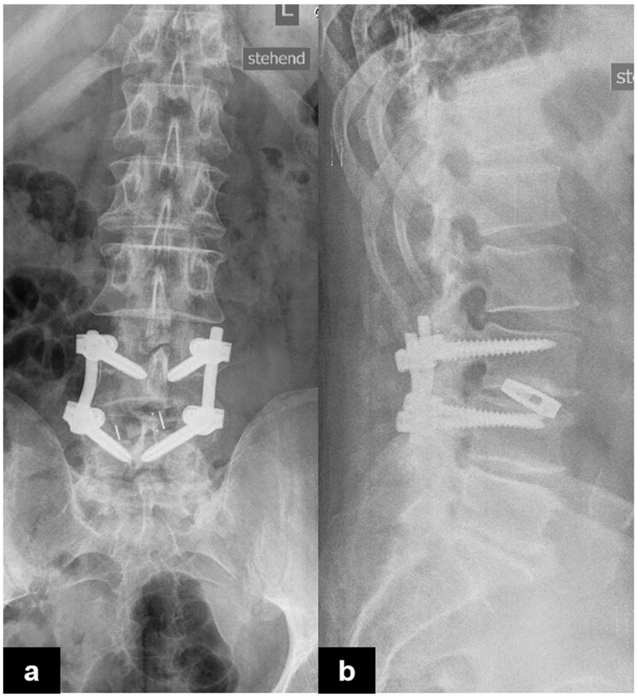

Fig. 2 Standing radiographs of the lumbar spine after TLIF with **a** PEEK cage (AP view) and **b** titanium cage (lateral view), show cage subsidence in the setting of failed union, 12 and 16 months after surgery, respectively

type of cage (34 mm vs 29 mm cages; PEEK vs titanium cages) was also performed using the chi-square test. Data were analyzed using the SPSS v.18.0 (SPSS Inc. Chicago, IL, USA) statistical package for personal computers. The level of significance was set to 0.05.

Results

Comparison of the parameters within groups

All studied parameters changed significantly after surgery both in the control and ASD group. More precisely LL, L4S1, and SS decreased, while PT and PI-LL increased (Table 1). In the nonunion group, however, only LL and PI-LL changed significantly (Table 1). In fact, the mean PI-LL in these patients was greater than 10° after surgery (10 ± 11° preoperatively vs 14 ± 10° postoperatively, $p = 0.008$), while in patients with uncomplicated fusion and those presenting ASD, the PI-LL modifier may have increased but remained nevertheless below 10° (Table 1).

Comparison of the parameters between groups

The analysis among groups revealed significant differences between the nonunion and the control group, and although patients presenting symptomatic ASD did not differ significantly from controls, significant differences were found among patients presenting ASD and pseudarthrosis (Table 2). More precisely, patients in the nonunion group presented greater SS before and after surgery as compared to the control and ASD group patients; pre-operative SS in the nonunion group was approximately 38 ± 6° vs 34 ± 9° (control group, $p = 0.034$) vs 34 ± 7° (ASD group, $p = 0.019$); post-operative SS was 36 ± 7° in the nonunion group vs 33 ± 8° (control group, $p = 0.033$)

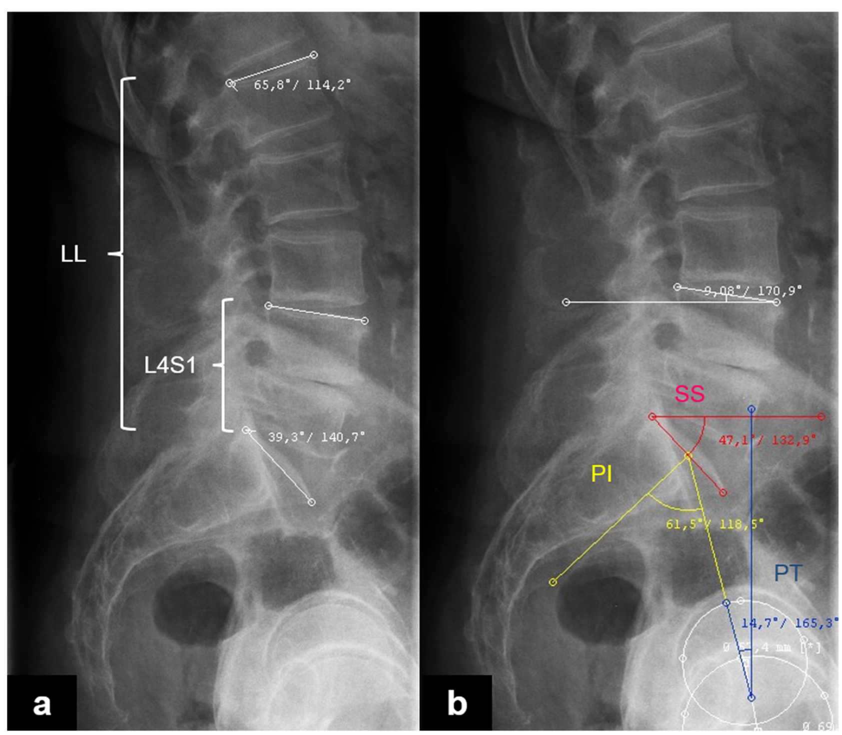

Fig. 3 Measurement of spinopelvic parameters in a lateral standing radiograph of the lumbar spine. **a** Lumbar lordosis (LL) and L4S1 lordosis (L4S1). **b** Pelvic incidence (PI, yellow) was regarded as the angle between the line connecting the hip axis and the midpoint of the superior endplate of S1 and the line perpendicular to it; pelvic tilt (PT, blue) was regarded as the angle between the line connecting the midpoint of the superior endplate of S1 and the hip axis, and the vertical line; sacral slope (SS, red) was regarded as the angle between the superior endplate of S1 and the horizontal plane

Table 1 Comparison of spinopelvic parameters before and after surgery within the three groups of patients

	Control		Nonunion		ASD	
	Mean ± SD	*p*	Mean ± SD	*p*	Mean ± SD	*p*
Pre-operative PT	20.9 ± 8.8	*0.019*	21.8 ± 8.7	0.398	19.5 ± 8.7	*< 0.001*
Post-operative PT	21.5 ± 8.1		22.4 ± 7.9		22.1 ± 7.9	
Pre-operative SS	34.4 ± 8.5	*< 0.001*	37.6 ± 6.1	0.163	33.5 ± 7.2	*< 0.001*
Post-operative SS	33 ± 8.4		36.3 ± 7.1		30.5 ± 7.4	
Pre-operative LL	47 ± 12.9	*< 0.001*	48.4 ± 11.4	*< 0.001*	47.9 ± 11.6	*0.001*
Post-operative LL	45 ± 13.1		44.4 ± 12.1		44.1 ± 9.7	
Pre-operative L4S1	28.5 ± 9.1	*< 0.001*	30 ± 7.2	0.155	27.5 ± 7.5	*0.007*
Post-operative L4S1	27.1 ± 9.2		28.6 ± 8.3		25.1 ± 8.2	
Pre-operative PI-LL	7.2 ± 11.7	*< 0.001*	10.3 ± 11.4	0.008	4.5 ± 11.8	*0.001*
Post-operative PI-LL	9.3 ± 11.5		14.2 ± 10.4		8.3 ± 11.4	

Mean values of parameters in degrees. *SD* standard deviation. Paired samples analysis. Significant differences in italics

vs 31 ± 7° (ASD group, $p = 0.002$). PI-LL after surgery was also found significantly greater in patients with pseudarthrosis; 14 ± 10° vs 9 ± 12° in the control group ($p = 0.02$) vs 8 ± 11° in the ASD group ($p = 0.037$). Similarly, PI was greater in the nonunion group (59 ± 10°) as compared to controls (54 ± 11°, $p = 0.032$) and patients with ASD (52 ± 8°, $p = 0.011$). Lastly, patients with ASD presented greater absolute ΔPT values compared to nonunion and control groups. The analysis between groups did not reveal any other significant differences with respect to the rest of the parameters studied (Table 2).

Age, cage size, and cage type

Patients in the control group were slightly younger (70.9 ± 11.3 years) than pseudarthrosis (72.3 ± 6.7 years) and ASD (72.9 ± 7.8 years) patients without any statistical significance whatsoever (Table 3). Regarding cage size, of 223 patients receiving a large cage (34 mm), 16 patients developed pseudarthrosis (7.2%) and 15 developed ASD (6.7%), while of 196 patients receiving a small cage (29 mm), 16 developed pseudarthrosis (8.2%) and 14 developed ASD (7.1%). The analysis showed no association between cage size and the occurrence of pseudarthrosis or ASD. Similar were the

Table 2 Comparison of spinopelvic parameters and age among the three groups of patients

	Nonunion Mean ± SD	Control Mean ± SD	*p*	Nonunion Mean ± SD	ASD Mean ± SD	*p*	Control Mean ± SD	ASD Mean ± SD	*p*
Pre-operative PT	21.8 ± 8.7	20.9 ± 8.8	0.57	21.8 ± 8.7	19.5 ± 8.7	0.292	20.9 ± 8.8	19.5 ± 8.7	0.393
Post-operative PT	22.4 ± 7.9	21.5 ± 8.1	0.578	22.4 ± 7.9	22.1 ± 7.9	0.879	21.5 ± 8.1	22.1 ± 7.9	0.733
Pre-operative SS	37.6 ± 6.1	34.4 ± 8.5	*0.034*	37.6 ± 6.1	33.5 ± 7.2	*0.019*	34.4 ± 8.5	33.5 ± 7.2	0.601
Post-operative SS	36.3 ± 7.1	33 ± 8.4	*0.033*	36.3 ± 7.1	30.5 ± 7.4	*0.002*	33 ± 8.4	30.5 ± 7.4	0.103
Pre-operative LL	48.4 ± 11.4	47 ± 12.9	0.565	48.4 ± 11.4	47.9 ± 11.6	0.88	47 ± 12.9	47.9 ± 11.6	0.707
Post-operative LL	44.4 ± 12.1	45 ± 13.1	0.827	44.4 ± 12.1	44.1 ± 9.7	0.914	45 ± 13.1	44.1 ± 9.7	0.734
Pre-operative L4S1	30 ± 7.2	28.5 ± 9.1	0.359	30 ± 7.2	27.5 ± 7.5	0.182	28.5 ± 9.1	27.5 ± 7.5	0.553
Post-operative L4S1	28.6 ± 8.3	27.1 ± 9.2	0.397	28.6 ± 8.3	25.1 ± 8.2	0.101	27.1 ± 9.2	25.1 ± 8.2	0.233
Pre-operative PI-LL	10.3 ± 11.4	7.2 ± 11.7	0.159	10.3 ± 11.4	4.5 ± 11.8	0.054	7.2 ± 11.7	4.5 ± 11.8	0.218
Post-operative PI-LL	14.2 ± 10.4	9.3 ± 11.5	*0.02*	14.2 ± 10.4	8.3 ± 11.4	*0.037*	9.3 ± 11.5	8.3 ± 11.4	0.645
PI	58.6 ± 10.1	54.2 ± 11.2	*0.032*	58.6 ± 10.1	52.4 ± 8.3	*0.011*	54.2 ± 11.2	52.4 ± 8.3	0.38
ΔPILL	− 4.2 ± 7.9	− 2.02 ± 7.1	0.349	− 4.2 ± 7.9	− 3.9 ± 5.7	0.304	− 2.02 ± 7.1	− 3.9 ± 5.7	0.68
ΔPT	− 0.6 ± 3.7	− 0.6 ± 5.3	0.928	− 0.6 ± 3.7	− 2.6 ± 3.2	*0.02*	− 0.6 ± 5.3	− 2.6 ± 3.2	*0.044*
ΔSS	1.3 ± 5.2	1.3 ± 5.4	0.991	1.3 ± 5.2	3.1 ± 3.8	0.172	1.3 ± 5.4	3.1 ± 3.8	0.138
ΔLL	3.9 ± 7.9	2.1 ± 7	0.15	3.9 ± 7.9	3.8 ± 5.6	0.966	2.1 ± 7	3.8 ± 5.6	0.179
ΔL4S1	1.4 ± 5.6	1.3 ± 5.9	0.932	1.4 ± 5.6	2.4 ± 4.5	0.526	1.3 ± 5.9	2.4 ± 4.5	0.436
Age (years)	72.3 ± 6.7	70.9 ± 11.3	0.504	72.3 ± 6.7	72.9 ± 7.8	0.718	70.9 ± 11.3	72.9 ± 7.8	0.342

Mean values of parameters in degrees. *SD* standard deviation. Independent *t* test. Significant differences in italics findings regarding the type of cage; 323 patients received a PEEK cage (77.1%) and 96 patients a titanium cage (22.9%). From the PEEK group, 27 patients (8.4%) developed pseudarthrosis and 19 patients (5.9%) ASD, while 5 (5.2%) and 10 patients (10.4%) from the titanium group developed pseudarthrosis and ASD, respectively. Although titanium cages seem to be related to ASD while PEEK cages to pseudarthrosis, analysis revealed no significant differences between groups (Table 3).

Discussion

The study of sagittal balance has shown that malalignment after adult spinal deformity procedures may lead to poor outcomes in both lumbar and cervical regions [12, 15–18]. In order to prevent instrumentation and/or surgery related complications to occur, patients with apparent sagittal imbalance, regardless the coronal imbalance, should be offered proper correction of the spinal alignment [19]. Pseudarthrosis represents a common complication of spine surgery that most of the times needs to be surgically addressed, while various risk factors have been identified that may lead to unsuccessful arthrodesis, such as osteoporosis, older age, excessive alcohol consumption, smoking, malnutrition, and excessive motion at the thoracolumbar junction [5, 20]. A relationship between hypolordosis and elevated PI, and the risk of pseudarthrosis has been suggested for patients who undergo long posterior lumbar instrumentation and fusion [21]. To the best of our knowledge, the relation between sagittal alignment parameters and pseudarthrosis, in patients treated with short-segment fusion for non-deformity spinal conditions, has not been previously investigated. The most important finding was that patients with unsuccessful fusion presented significantly greater mean PI and mean difference between PI and LL than patients with uneventful arthrodesis. Additionally, in these patients the PI-LL mismatch increased after surgery to approximately 14°. PI is of primary importance in regulating sagittal spinal alignment, and the relationship between LL and PI has been already investigated and considered as a significant assessment tool for sagittal alignment [22–24]. The non-pathological cut-off value of PI-LL has been speculated to be within 10° [14, 25]. As a matter of fact, patients in this series with successful spinal fusion presented a mean value of PI-LL of approximately 9°, which was not the case in patients with pseudarthrosis. The reason that PI-LL modifier has been generally considered as an important index of sagittal balance is due to findings showing that a great PI-LL mismatch (> 10°) has the strongest correlation with disability and lower quality of life scores in adult patients with spinal deformity [6, 26], associated at the same time with surgery-related complications like screw loosening and ASD [14, 27]. Should be noted that the sum of SS and PT equals to PI, which is regarded as a constant and unique anatomical parameter in individuals regardless of the pelvic position and age [23, 28]. Since PT was approximately the same between groups before and after surgery (less than 1° differences), patients in the nonunion group presenting greater PI would consequently have greater SS, which was the case here, indeed. If, theoretically, SS values were to be decreased in these patients to values more closely to the control group, then PT would be equally and significantly increased, for the sum (PI = PT + SS) to remain the same. This would rather complicate restoration of spinal alignment in these patients, as an increased pelvic retroversion (increased PT) is related to suboptimal outcomes after surgery and sagittal imbalance [26, 29]. Thus, it can be implied that patients with greater PI and SS may be inherently subjected to greater forces, and subsequently to instability and pseudarthrosis; therefore, we agree with Le Huec et al. [12], that with respect to sagittal alignment in the treatment of lumbar degenerative disc disease what is mainly essential is restoring lordosis proportional to the PI value.

Patients presenting ASD in this series had similar alignment patterns to patients with uncomplicated fusion. The only significant difference between these patients and the other groups was ΔPT value. More precisely, PT increased after surgery in these patients not only significantly, but also at a greater degree compared to the other patients. Matsumoto et al. [6], in their retrospective matched case-control study showed that 20 patients developing ASD after single-segment posterior lumbar interbody fusion presented higher PT than the control group ($n = 100$). In the same study, it was shown, nonetheless, that the PI-LL mismatch was associated with ASD (75% presented PI-LL greater than 10° vs 40% in

Table 3 Between group analysis (Chi-square test) with respect to size and type of cage

	Control (%)	Nonunion (%)	ASD (%)	p Control vs ASD	p Control vs Nonunion
Large cage	86.1	7.2	6.7	0.849	0.854
Small cage	84.7	8.2	7.1		
PEEK cage	85.7	8.4	5.9	0.172	0.504
Titanium cage	84.4	5.2	10.4		

Large = 34 mm vs small = 29 mm; and PEEK vs titanium cages. The ASD vs nonunion group analysis was performed but did not show statistical significant differences the control group), which was not the case in the present study. Rothenfluh et al. [14], in another retrospective study with 84 patients, showed also that ASD patients ($n = 45$) had greater PI-LL values than the control group patients ($n = 39$). On the other hand, Alentado et al. [9], retrospectively studied 137 patients, of whom 13 developed ASD, and found that these patients presented rather lower PI and SS than controls, while PI-LL and PT were not found to be significantly different among groups. It can be hereby suggested that differences in the spinopelvic parameters between patients with ASD and uneventful fusion seem to exist; nonetheless, a safe conclusion is yet to be drawn, as the complex biomechanical interactions and the compensatory mechanisms that apply in the setting of spinal sagittal malalignment are still not fully understood and studied.

In an attempt to investigate whether different cage properties play a key role in the fusion process, groups were analyzed according to type and size of interbody cage implanted. It was shown that neither type (PEEK vs titanium) nor size (large vs small) were associated to pseudarthrosis and ASD after short-segment lumbar fusion. Titanium presented higher ASD and lower nonunion rates, and conversely PEEK cages presented higher nonunion and lower ASD rates. However, these differences were not significant among groups. Data from literature are quite controversial on the subject. Nemoto et al. [30] found that fusion rates in patients undergoing single level TLIF were higher in the titanium group two years after surgery (100% vs 76% in the PEEK group, $p = 0.016$), while in another study, Tanida et al. [31] showed that the union rate at two years after TLIF was approximately the same between titanium and PEEK cages [82.8% vs 80.4%, respectively ($p = 0.72$)]. More recently, investigators analyzed fusion rates in patients, who underwent mono- or bisegmental PLIF with either titanium or PEEK cages, but without additional bone grafting [32]. It was shown that fusion rates were higher in the titanium group (53% vs 32% in the PEEK group), while ASD rates were almost the same among groups (7% and 8% in the titanium and PEEK groups, respectively); nevertheless, an analysis confirming the significance of these results was not performed [32]. Lastly, in a recent meta-analysis, the fusion rates of titanium and PEEK cages, used in both lumbar and cervical procedures, were studied; overall, there was no statistically significant difference in the fusion rates between groups [33].

We acknowledge the fact that the retrospective design of our study represents a major limitation when interpreting the results. However, the size of our sample, which is of the largest published regarding the subject analyzed, in addition to the fact that it is a single-centre study, where all patients were treated by the same group of surgeons in the same manner, may limit the bias created by the study design. Another limitation is that the sagittal vertical axis (SVA), a basic tool when estimating sagittal alignment, was not included in our analysis. This was due to the fact that data regarding SVA were available only for a limited number of patients, as we do not routinely perform lateral radiographs of the entire spine before and after surgery in all patients. Nonetheless, the PI-LL modifier analyzed in this study has been proven a significant measure in the assessment of spinopelvic balance, allowing for conclusions to be drawn.

Conclusions

In summary, spinopelvic parameters and sagittal alignment seem to play a significant role in the success of short-segment TLIF procedures for disc degeneration or herniation. Patients in this series with failed bony fusion presented greater SS before and after surgery, and greater PI as compared to patients with arthrodesis. Additionally, pseudarthrosis was related to suboptimal sagittal alignment, since these patients presented not only greater PI-LL mismatch after surgery, but also a mean mismatch that was greater than 10°. The occurrence of ASD was not related to the aforementioned parameters; nevertheless, a greater difference between the pre-operative and post-operative values of PT was observed in these patients. Lastly, neither the type nor size of interbody cage were found to have a significant impact on either solid bony fusion, nonunion, or ASD rates. Thus, it can be further implied that spinopelvic sagittal malalignment may contribute in the development of surgery related complications, and we recommend on the study of patients' sagittal alignment in the pre-operative setting even when treating patients with short-segment lumbar interbody fusion.

Compliance with ethical standards

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

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

References

1. Tao S, Jin L, Hou Z, Zhang W, Chen T, Zhang Y (2018) A new radiographic feature of lower lumbar disc herniation in young patients. Int Orthop 42(3):583–586. https://doi.org/10.1007/s00264-017-3723-8
2. Pettine KA, Suzuki RK, Sand TT, Murphy MB (2017) Autologous bone marrow concentrate intradiscal injection for the treatment of degenerative disc disease with three-year follow-up. Int Orthop 41(10):2097–2103. https://doi.org/10.1007/s00264-017-3560-9
3. Mobbs RJ, Phan K, Malham G, Seex K, Rao PJ (2015) Lumbar interbody fusion: techniques, indications and comparison of interbody fusion options including PLIF, TLIF, MI-TLIF,

OLIF/ATP, LLIF and ALIF. J Spine Surg 1(1):2–18. https://doi.org/10.3978/j.issn.2414-469X.2015.10.05

4. Zhang D, Gao X, Jiang J, Shen Y, Ding W, Cui H (2018) Safe placement of pedicle screw in lumbar spine with minimum three year follow-up: a case series and technical note. Int Orthop 42(3):567–573. https://doi.org/10.1007/s00264-018-3806-1
5. Chun DS, Baker KC, Hsu WK (2015) Lumbar pseudarthrosis: a review of current diagnosis and treatment. Neurosurg Focus 39(4):E10. https://doi.org/10.3171/2015.7.FOCUS15292
6. Matsumoto T, Okuda S, Maeno T, Yamashita T, Yamasaki R, Sugiura T, Iwasaki M (2017) Spinopelvic sagittal imbalance as a risk factor for adjacent-segment disease after single-segment posterior lumbar interbody fusion. J Neurosurg Spine 26(4):435–440. https://doi.org/10.3171/2016.9.SPINE16232
7. Virk SS, Niedermeier S, Yu E, Khan SN (2014) Adjacent segment disease. Orthopedics 37(8):547–555. https://doi.org/10.3928/01477447-20140728-08
8. Chen XL, Guan L, Liu YZ, Yang JC, Wang WL, Hai Y (2016) Interspinous dynamic stabilization adjacent to fusion versus double-segment fusion for treatment of lumbar degenerative disease with a minimum follow-up of three years. Int Orthop 40(6):1275–1283. https://doi.org/10.1007/s00264-016-3199-y
9. Alentado VJ, Lubelski D, Healy AT, Orr RD, Steinmetz MP, Benzel EC, Mroz TE (2016) Predisposing characteristics of adjacent segment disease after lumbar fusion. Spine (Phila Pa 1976) 41(14):1167–1172. https://doi.org/10.1097/BRS.0000000000001493
10. Lee JC, Kim Y, Soh JW, Shin BJ (2014) Risk factors of adjacent segment disease requiring surgery after lumbar spinal fusion: comparison of posterior lumbar interbody fusion and posterolateral fusion. Spine (Phila Pa 1976) 39(5):E339–E345. https://doi.org/10.1097/BRS.0000000000000164
11. Korres D, Markatos K, Chytas D, Andreakos A, Mavrogenis A (2017) Injuries of the spine and of the spinal cord in the Hippocratic Corpus of medicine. Int Orthop 41(12):2627–2629. https://doi.org/10.1007/s00264-017-3527-x
12. Le Huec JC, Faundez A, Dominguez D, Hoffmeyer P, Aunoble S (2015) Evidence showing the relationship between sagittal balance and clinical outcomes in surgical treatment of degenerative spinal diseases: a literature review. Int Orthop 39(1):87–95. https://doi.org/10.1007/s00264-014-2516-6
13. Djurasovic MO, Carreon LY, Glassman SD, Dimar JR II, Puno RM, Johnson JR (2008) Sagittal alignment as a risk factor for adjacent level degeneration: a case-control study. Orthopedics 31(6):546
14. Rothenfluh DA, Mueller DA, Rothenfluh E, Min K (2015) Pelvic incidence-lumbar lordosis mismatch predisposes to adjacent segment disease after lumbar spinal fusion. Eur Spine J 24(6):1251–1258. https://doi.org/10.1007/s00586-014-3454-0
15. Hyun SJ, Kim KJ, Jahng TA, Kim HJ (2017) Clinical impact of T1 slope minus cervical lordosis after multilevel posterior cervical fusion surgery: a minimum 2-year follow up data. Spine (Phila Pa 1976) 42(24):1859–1864. https://doi.org/10.1097/BRS.0000000000002250
16. Lafage V, Ames C, Schwab F, Klineberg E, Akbarnia B, Smith J, Boachie-Adjei O, Burton D, Hart R, Hostin R, Shaffrey C, Wood K, Bess S, International Spine Study G (2012) Changes in thoracic kyphosis negatively impact sagittal alignment after lumbar pedicle subtraction osteotomy: a comprehensive radiographic analysis. Spine (Phila Pa 1976) 37(3):E180–E187. https://doi.org/10.1097/BRS.0b013e318225b926
17. Baek SW, Park YS, Ha KY, Suh SW, Kim C (2013) The analysis of spinopelvic parameters and stability following long fusions with S1, S2 or iliac fixation. Int Orthop 37(10):1973–1980. https://doi.org/10.1007/s00264-013-2000-8
18. Geiger EV, Muller O, Niemeyer T, Kluba T (2007) Adjustment of pelvispinal parameters preserves the constant gravity line position. Int Orthop 31(2):253–258. https://doi.org/10.1007/s00264-006-0157-0
19. Hara M, Nishimura Y, Nakajima Y, Umebayashi D, Takemoto M, Yamamoto Y, Haimoto S (2015) Transforaminal lumbar interbody fusion for lumbar degenerative disorders: mini-open TLIF and corrective TLIF. Neurol Med Chir (Tokyo) 55(7):547–556. https://doi.org/10.2176/nmc.oa.2014-0402
20. Bouloussa H, Alzakri A, Ghailane S, Vergari C, Mazas S, Vital JM, Coudert P, Gille O (2017) Is it safe to perform lumbar spine surgery on patients over eighty five? Int Orthop 41(10):2091–2096. https://doi.org/10.1007/s00264-017-3555-6
21. Cho KJ, Suk SI, Park SR, Kim JH, Kang SB, Kim HS, Oh SJ (2010) Risk factors of sagittal decompensation after long posterior instrumentation and fusion for degenerative lumbar scoliosis. Spine (Phila Pa 1976) 35(17):1595–1601. https://doi.org/10.1097/BRS.0b013e3181bdad89
22. Boulay C, Tardieu C, Hecquet J, Benaim C, Mouilleseaux B, Marty C, Prat-Pradal D, Legaye J, Duval-Beaupere G, Pelissier J (2006) Sagittal alignment of spine and pelvis regulated by pelvic incidence: standard values and prediction of lordosis. Eur Spine J 15(4):415–422. https://doi.org/10.1007/s00586-005-0984-5
23. Duval-Beaupere G, Schmidt C, Cosson P (1992) A Barycentremetric study of the sagittal shape of spine and pelvis: the conditions required for an economic standing position. Ann Biomed Eng 20(4):451–462
24. Legaye J, Duval-Beaupere G, Hecquet J, Marty C (1998) Pelvic incidence: a fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves. Eur Spine J 7(2):99–103
25. Cho W, Mason JR, Smith JS, Shimer AL, Wilson AS, Shaffrey CI, Shen FH, Novicoff WM, Fu KM, Heller JE, Arlet V (2013) Failure of lumbopelvic fixation after long construct fusions in patients with adult spinal deformity: clinical and radiographic risk factors: clinical article. J Neurosurg Spine 19(4):445–453. https://doi.org/10.3171/2013.6.SPINE121129
26. Schwab FJ, Blondel B, Bess S, Hostin R, Shaffrey CI, Smith JS, Boachie-Adjei O, Burton DC, Akbarnia BA, Mundis GM, Ames CP, Kebaish K, Hart RA, Farcy JP, Lafage V, International Spine Study G (2013) Radiographical spinopelvic parameters and disability in the setting of adult spinal deformity: a prospective multicenter analysis. Spine (Phila Pa 1976) 38(13):E803–E812. https://doi.org/10.1097/BRS.0b013e318292b7b9
27. Banno T, Hasegawa T, Yamato Y, Kobayashi S, Togawa D, Oe S, Mihara Y, Matsuyama Y (2017) Prevalence and risk factors of iliac screw loosening after adult spinal deformity surgery. Spine (Phila Pa 1976) 42(17):E1024–E1030. https://doi.org/10.1097/BRS.0000000000002047
28. Lee CS, Chung SS, Park SJ, Kim DM, Shin SK (2014) Simple prediction method of lumbar lordosis for planning of lumbar corrective surgery: radiological analysis in a Korean population. Eur Spine J 23(1):192–197. https://doi.org/10.1007/s00586-013-2895-1
29. Mehta VA, Amin A, Omeis I, Gokaslan ZL, Gottfried ON (2015) Implications of spinopelvic alignment for the spine surgeon. Neurosurgery 76(Suppl 1):S42–S56; discussion S56. https://doi.org/10.1227/01.neu.0000462077.50830.1a
30. Nemoto O, Asazuma T, Yato Y, Imabayashi H, Yasuoka H, Fujikawa A (2014) Comparison of fusion rates following transforaminal lumbar interbody fusion using polyetheretherketone cages or titanium cages with transpedicular instrumentation. Eur Spine J 23(10):2150–2155. https://doi.org/10.1007/s00586-014-3466-9
31. Tanida S, Fujibayashi S, Otsuki B, Masamoto K, Takahashi Y, Nakayama T, Matsuda S (2016) Vertebral endplate cyst as a predictor of nonunion after lumbar interbody fusion: comparison of titanium and polyetheretherketone cages. Spine (Phila Pa 1976) 41(20):E1216–E1222. https://doi.org/10.1097/BRS.0000000000001605

32. Wrangel CV, Karakoyun A, Buchholz KM, Suss O, Kombos T, Woitzik J, Vajkoczy P, Czabanka M (2017) Fusion rates of intervertebral Polyetheretherketone and titanium cages without bone grafting in posterior interbody lumbar fusion surgery for degenerative lumbar instability. J Neurol Surg A Cent Eur Neurosurg 78(6): 556–560. https://doi.org/10.1055/s-0037-1604284

33. Seaman S, Kerezoudis P, Bydon M, Torner JC, Hitchon PW (2017) Titanium vs. polyetheretherketone (PEEK) interbody fusion: meta-analysis and review of the literature. J Clin Neurosci 44:23–29. https://doi.org/10.1016/j.jocn.2017.06.062