Sagittal alignment and complications following lumbar 3-column osteotomy: does the level of resection matter?

Emmanuelle Ferrero, MD, MSc,^{1,2} Barthelemy Liabaud, MD,² Jensen K. Henry, MD,² Christopher P. Ames, MD,³ Khaled Kebaish, MD,⁴ Gregory M. Mundis, MD,⁵ Richard Hostin, MD,⁶ Munish C. Gupta, MD,⁷ Oheneba Boachie-Adjei, MD,⁸ Justin S. Smith, MD, PhD,⁹ Robert A. Hart, MD,¹⁰ Ibrahim Obeid, MD,¹¹ Bassel G. Diebo, MD,² Frank J. Schwab, MD,² and Virginie Lafage, PhD,² on behalf of the International Spine Study Group

¹Hôpital Européen Georges-Pompidou, APHP, Paris V University, Paris, France; ²Department of Orthopaedic Surgery, Spine Division, Hospital for Special Surgery, New York, New York; ³Department of Neurosurgery, University of California, San Francisco Medical Center, San Francisco, California; ⁴Department of Orthopaedic Surgery, Johns Hopkins University, Baltimore, Maryland; ⁵San Diego Center for Spinal Disorders, La Jolla, California; ⁶Baylor Scoliosis Center, Plano, Texas; ⁷Department of Orthopaedic Surgery, University of California, Davis, Sacramento, California; ⁸Department of Orthopaedic Surgery, Hospital for Special Surgery, New York, New York; ⁹Department of Neurosurgery, University of Virginia Health System, Charlottesville, Virginia; ¹⁰Department of Orthopaedic Surgery, University of Oregon Health Sciences Center, Portland, Oregon; and ¹¹Centre Hospitalier Universitaire de Bordeaux, France

OBJECTIVE Three-column osteotomy (3CO) is a demanding technique that is performed to correct sagittal spinal malalignment. However, the impact of the 3CO level on pelvic or truncal sagittal correction remains unclear. In this study, the authors assessed the impact of 3CO level and postoperative apex of lumbar lordosis on sagittal alignment correction, complications, and revisions.

METHODS In this retrospective study of a multicenter spinal deformity database, radiographic data were analyzed at baseline and at 1- and 2-year follow-up to quantify spinopelvic alignment, apex of lordosis, and resection angle. The impact of 3CO level and apex level of lumbar lordosis on the sagittal correction was assessed. Logistic regression analyses were performed, controlling for cofounders, to investigate the effects of 3CO level and apex level on intraoperative and postoperative complications as well as on the need for subsequent revision surgery.

RESULTS A total of 468 patients were included (mean age 60.8 years, mean body mass index 28.1 kg/m²); 70% of patients were female. The average 3CO resection angle was 25.1° and did not significantly differ with regard to 3CO level. There were no significant correlations between the 3CO level and amount of sagittal vertical axis or pelvic tilt correction. The postoperative apex level significantly correlated with greater correction of pelvic tilt (2° per more caudal level, $R = -0.2$, $p = 0.006$). Lower-level 3CO significantly correlated with revisions for pseudarthrosis ($OR = 3.88$, $p = 0.001$) and postoperative motor deficits ($OR = 2.02$, $p = 0.026$).

CONCLUSIONS In this study, a more caudal lumbar 3CO level did not lead to greater sagittal vertical axis correction. The postoperative apex of lumbar lordosis significantly impacted pelvic tilt. 3CO levels that were more caudal were associated with more postoperative motor deficits and revisions.

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KEY WORDS 3-column osteotomy; adult spinal deformity; lumbar lordosis; sagittal alignment; complications

ADULT spinal deformity (ASD) is a debilitating disorder that is increasingly prevalent, especially in the elderly.^{1–4,10} ASD is often manifested by a loss of lumbar lordosis (LL) with anterior global malalignment, pelvic retroversion, and multiple attempts at com-

pensation.^{1,14,20,31,33,38} Because of the complexity of structural pathologies and clinical presentations, ASD correction remains challenging, thus underscoring the need for better evidence-based treatment.^{19,38}

Surgical treatment of ASD requires sufficient resto-

ABBREVIATIONS ASD = adult spinal deformity; BMI = body mass index; EBL = estimated blood loss; LL = lumbar lordosis; PI = pelvic incidence; PT = pelvic tilt; SVA = sagittal vertical axis; TK = thoracic kyphosis; T1SPi = T-1 spinopelvic inclination; 3CO = 3-column osteotomy.

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ration of sagittal alignment to reset the compensatory mechanisms and improve the patient's functional status. The Scoliosis Research Society–Schwab deformity classification established key radiographic sagittal parameters with ideal thresholds for realignment in terms of sagittal vertical axis (SVA), pelvic incidence (PI) minus LL (i.e., PI-LL mismatch), and pelvic tilt (PT).^{13,22,39} The 3-column osteotomy (3CO) is a powerful method to correct fixed spinal deformity.^{2,4,9,12,27,30,37,40,42,43}

Several studies have emphasized the importance of preoperative planning for sagittal realignment procedures.^{13,41} However, anticipating the postoperative alignment after 3CO remains challenging.^{13,25,32} Although the relationship between resection angle and sagittal correction is obvious, the relationship between the osteotomy level and sagittal correction remains controversial, with a belief that osteotomies that are more caudal lead to greater correction.^{15,24} Lafage et al. reported that more caudal 3CO correlated with higher PT correction.²⁴ Nevertheless, the impact of the level of osteotomy on the distribution of truncal versus pelvic correction remains unclear.^{8,24,44,45} To our knowledge, no reports exist regarding the relationship between the apex of LL and the degree of sagittal plane correction. In addition, while studies have reported complication rates after 3CO of up to 50% and revision surgery rates of up to 44%,^{2,5,11,16,28} little is known regarding the impact of osteotomy level on complications and revisions.

The purpose of the present study was to investigate the impact of the osteotomy level and postoperative lordosis apex on sagittal correction and to assess for potential associations between the level of 3CO and complication and revision rates. It was hypothesized that the apex of LL plays a significant role in sagittal plane correction following 3CO and that caudal osteotomies will be associated with a higher risk of complications.

Methods

Patient Selection

This is a retrospective multicenter database of patients who underwent 3CO for sagittal plane malalignment. The institutional review board at each contributing site provided approval prior to study initiation. The study included patients older than 18 years who underwent a single lumbar 3CO for lumbar deformity and an upper instrumented vertebral level above L-1. Exclusion criteria were spinal deformity due to neuromuscular etiology, thoracic 3CO, and more than one 3CO.

Data Collection

Demographic parameters included age, sex, and body mass index (BMI). Full-spine radiographs were obtained at baseline and at 1 and 2 years postoperatively. Surgical parameters included 3CO level, operating room time, and estimated blood loss (EBL). Intraoperative and postoperative complications were recorded, along with incidence and timing of revision surgery (up to 2 years postoperatively).

Radiographic Measurement

Radiographs were analyzed using validated software

FIG. 1. Sagittal radiographic parameters, including SVA, LL, PI, PT, T1SPi, and TK. TPA = T-1 pelvic angle.

(Spineview, ENSAM Paris-Tech).³⁴ Sagittal spinopelvic radiographic parameters included cervical lordosis, T2–T12 thoracic kyphosis (TK), LL, PI-LL mismatch, and pelvic parameters (PI, PT, and sacral slope).⁴⁶ Global sagittal alignment parameters included SVA and T-1 spinopelvic inclination (T1SPi) (Fig. 1). The 3CO resection angle was defined as the change in the angle formed by the upper endplate of the vertebra below the 3CO and the lower endplate of the vertebra above the 3CO. Change in LL outside the osteotomy site (LL outside 3CO) was calculated as the difference between LL and the 3CO resection angle. The apex of the postoperative lordosis (apex level) was defined as the lumbar vertebra that was most anteriorly displaced from the L1–S1 line (midpoint of L-1 upper endplate to midpoint of S-1 upper endplate) (Fig. 2).

FIG. 2. Illustration of the apex of LL. A line is drawn between the midpoint of the upper endplate of L-1 and the midpoint of the upper endplate of S-1. The orthogonal distance (d) between this line and the center of each lumbar vertebral body was calculated; the vertebra with the largest distance was considered the apex of LL. Figure is available in color online only.

Statistical Analysis

Normality of distribution was confirmed using the Shapiro-Wilk test. Descriptive statistics were used to show demographic and surgical characteristics. Baseline and postoperative radiographic parameters were compared using paired t -tests. Pearson tests were used to correlate the 3CO resection angle and changes in radiographic parameters. Spearman tests assessed relationships between 3CO level, LL apex level, and sagittal correction. Multivariate regression was used to analyze the relationship between 3CO level and LL apex level on changes in radiographic parameters, using the potential confounders of baseline PT, TK, LL, and SVA. Complications and revisions were compared between 3CO levels using the chi-square test. Multivariate regression was performed to assess the impact of 3CO level on complications and revisions, adjusting for age, BMI, and resection angle. Patients who underwent revision surgery before 1 year were excluded from

radiographic analysis to avoid potential effects of revision surgery on sagittal alignment. Statistical analysis was performed using Stata software (version 13.0, StataCorp). A p value < 0.05 was considered significant.

Results

This study included 468 patients (70% of whom were female) with a mean age of 60.8 ± 11.0 years and a mean BMI of 28.1 ± 7.1 kg/m². At baseline, 393 (84%) of the patients had a history of previous spine surgery.

Radiographic Alignment

A total of 345 patients had at least 1 year of follow-up and were included in the radiographic cohort. The most common 3CO levels were L-3 (47%) and L-4 (25%). The mean resection angle was $25.1^\circ \pm 12.7^\circ$, with no significant differences across 3CO levels ($p = 0.45$; Table 1). All sagit-

TABLE 1. 3CO levels and amount of focal correction in the radiographic cohort

3CO Level	No. of Patients (%)	Mean Resection Angle (°)*
L-1	23 (7)	28.9 ± 12.9
L-2	62 (18)	23.0 ± 13.9
L-3	163 (47)	25.6 ± 12.1
L-4	86 (25)	25.4 ± 13.2
L-5	11 (3)	20.3 ± 11.8

* The mean resection angle was not significantly associated with 3CO level.

tal parameters, aside from cervical lordosis, demonstrated significant improvement postoperatively (Table 2). There were significant improvements in LL (29.3°), PT (−7.5°), PI-LL (−29.4°), and SVA (−99.1 mm). The mean change in LL outside the 3CO was 5.9° ± 14.2°.

For patients treated with 3CO at L-1, L-2, L-4, or L-5, the most common postoperative apex level was L-4 (70%, 50%, 50%, and 53%, respectively). For L-3 3CO, the most common postoperative apex level was L-3 (76%) (see Fig. 3 for the distribution of 3CO and apex levels). Figure 4 illustrates the differences between LL apex and 3CO level pre- and postoperatively. The postoperative LL apex was closer to the 3CO level than the preoperative LL apex. Correlation analysis (Table 3) revealed that the 3CO resection angle correlated with changes in LL, TK, PT, and SVA. Change in LL outside of the 3CO correlated with change in PT and change in global alignment. Apex level correlated with change in PT ($R = -0.175$, $p < 0.05$). Of patients with 3CO resection $\geq 15^\circ$, the correlation between apex level and change in PT was $R = 0.228$. Of patients with 3CO resection $\geq 25^\circ$, the correlation increased to $R = 0.238$.

Multivariate analysis demonstrated that PT correction increased with a more caudal lordosis apex (−2.03° of additional PT correction per each level below L-1; $p = 0.004$). No similar relationship was found based on 3CO level (Table 4). LL correction and baseline sagittal parameters were significant parameters involved in the change in PT and SVA, suggesting that patients with more severe preoperative deformity severity experienced greater corrections in PT and SVA. Only LL correction and baseline SVA were significant parameters influencing change in the T1SPi.

Complications

Overall, 40% of patients had major complications (either intra- or early postoperative) (Table 5). The intraoperative complication rate was 20% ($n = 93$). Intraoperative EBL of more than 4 L was the most common intraoperative complication, occurring in 18% of cases ($n = 83$). Less common intraoperative complications were intraoperative cord deficit ($n = 3$; 1%), intraoperative nerve root injury ($n = 4$; 1%), and unplanned staged surgery ($n = 3$; 1%). Intraoperative complication rates did not differ significantly based on 3CO level.

The overall 6-week postoperative complication rate was 27% ($n = 128$). Complications differed significantly based on 3CO level. Postoperative complications were

TABLE 2. Mean baseline and 1-year postoperative sagittal radiographic parameters

Parameter	Preop	Postop	Change	p Value
PI	59.5 ± 15.3			
PT	31.5 ± 10.8	24.5 ± 10.4	−7.5 ± 8.6	<0.001
PI-LL	33.7 ± 20.5	5.2 ± 16.3	−29.4 ± 18.2	<0.001
LL	25.3 ± 20.6	54.6 ± 14.3	+29.3 ± 18.1	<0.001
TK	31.8 ± 21.3	47.7 ± 17.4	+16.2 ± 15.9	<0.001
SVA (mm)	138.7 ± 78.2	42.2 ± 56.3	−99.1 ± 70.6	<0.001
T1SPi	4.2 ± 7.4	−3.5 ± 5.2	−7.7 ± 7.0	<0.001
Cervical lordosis*	18.1 ± 18.9	16.8 ± 16.8	−2.9 ± 14.5	NS

NS = not significant.

All measurements are in degrees unless otherwise noted. Boldface type indicates statistical significance from preoperative to postoperative.

* C2–7.

most common after L-5 osteotomies (47% of 3CO at L-5, $p = 0.047$). However, regression analysis did not reveal a significant impact between caudal 3CO and postoperative complications. In terms of specific complication rates, bowel/bladder deficit occurred in 3% ($n = 16$) of patients, postoperative cauda equina deficit in 0.6% ($n = 3$), postoperative deep infection in 4% ($n = 20$), and postoperative unplanned return to the operating room in 10% ($n = 48$). There were no significant differences in these complication rates based on osteotomy level ($p > 0.05$). Postoperative motor deficits occurred in 8% ($n = 39$) of patients, with significantly different rates based on 3CO level ($p = 0.03$). Regression analysis showed a significantly greater risk of motor deficits with more caudal 3CO (OR = 2.02, $p = 0.026$).

Revisions

Within 1 year, 18% of patients ($n = 84$) underwent revision surgery; 8 of these 84 patients had 2 revision surgeries (Table 5). Logistic regression analysis demonstrated a significantly greater risk of revision in the 1st year when the 3CO was performed at a more caudal level (OR = 1.67, $p = 0.009$). Revision was indicated for instrumentation failure in 6% of patients ($n = 26$), for proximal junctional kyphosis in 3% ($n = 13$), for sagittal malalignment in 2% ($n = 7$), and for neurological deficit in 3% ($n = 14$). There were no significant differences in these complication rates based on osteotomy level ($p > 0.05$). Pseudarthrosis occurred within the 1st year in 3% of patients ($n = 16$) and occurred in patients with a 3CO at L-3, L-4, or L-5. Regression analysis demonstrated a significantly greater risk of pseudarthrosis with a more caudal 3CO level (OR = 3.88, $p = 0.001$).

Discussion

In this study, more caudal lumbar 3CO did not lead to greater SVA or PT correction, although a more caudal postoperative apex of LL was associated with greater PT correction. However, 3CO levels that were more caudal were also associated with higher rates of complications and revisions. We found a mean amount of 3CO resec-

FIG. 3. Distribution of LL apex and 3CO levels for the entire cohort.

tion of 25.1°, which was similar across vertebral levels. This resection amount is comparable to that in other 3CO studies.^{7,24,35,47} Unsurprisingly, the 3CO resection directly impacted the regional LL with a mean LL correction of 29.3°. However, the indirect impact of the 3CO resection extended to the thoracic spine, with a 16.2° increase in TK. This may have been due to direct changes by instru-

mentation as well as reciprocal changes in the unfused thoracic spine, which is consistent with previous reports.^{18,22} Increase in LL led to improvement in the global alignment of the spine, characterized by decreases in SVA and pelvic retroversion (PT). This was confirmed by the correlation between angle of resection and improvement in radiographic parameters at the 1-year follow-up. This

FIG. 4. Distribution of the difference between LL apex and 3CO level pre- and postoperatively. For the values on the x-axis, “0” indicates that the LL apex and the 3CO level are located at the same level; “-1,” that the LL apex is located 1 vertebra above the 3CO level; “+1,” that the LL apex is located 1 vertebra below the 3CO level, and so on.

TABLE 3. Significant correlations between the angle of resection, 3CO level, LL apex, and change in sagittal parameters from baseline to 1 year postoperatively*

Variable	$\Delta(\text{PI-LL})$	ΔPT	ΔSVA	ΔT1SPi	ΔLL	ΔTK
3CO resection angle	-0.480	-0.230	-0.180		0.496	0.471
ΔLL outside 3CO	-0.600	-0.354	-0.509	-0.388	0.577	
3CO level						
Apex level		-0.175				

* Pearson correlation was used for 3CO resection angle and ΔLL outside 3CO. Spearman correlation was used for both 3CO and apex levels.

study illustrated that an increasing degree of 3CO resection resulted in greater changes in regional alignment as well as global sagittal alignment.²⁴ This is also consistent with previous reports demonstrating the effect of spinal osteotomies in restoring sagittal alignment of the spine in the setting of ASD (Fig. 5).^{2,4,21,30,37}

Initial studies suggested that the amount of vertebral resection needed to achieve optimal spinal realignment can be predicted based on the C-7 plumb line, PI, and 3CO level.^{13,15} However, more recent work demonstrated that the degree of wedge resection correlated more closely with spinopelvic parameter correction than 3CO level.^{24,36} The authors also established that there was no correlation between 3CO level and SVA correction.²³ The present study similarly demonstrated that there were no correlations between 3CO level and changes in spinopelvic or global sagittal parameters. This result echoes the findings of Rousseau et al., who studied 356 patients undergoing 3CO for the treatment of ASD.^{35,36} Their results demonstrated no significant impact of pedicle subtraction osteotomy level on postoperative PT or T1SPi. One specific finding of the current study relates to the correlation between change in PT and location of the postoperative apex

TABLE 5. Different types of complications, global rate, and results of ANOVA of the difference between osteotomy level

Complication	Complication Rate	p Value
Intraop complication	0.20	0.46
Cord deficit	0.01	0.05
Nerve root injury	0.01	0.88
EBL >4 L	0.18	0.65
Unplanned stage	0.01	0.89
Postop complication	0.27	0.04
Bowel/bladder deficit	0.03	0.82
Cauda equina	0.006	0.89
Deep infection	0.04	0.65
Motor deficit	0.08	0.03
Unplanned surgery	0.10	0.59
Revision	0.18	0.06
Instrumentation failure	0.06	0.10
Pseudarthrosis	0.08	0.04
PJK	0.03	0.11
Sagittal malalignment	0.015	0.19
Neurological deficit	0.03	0.56

PJK = proximal junctional kyphosis.

Boldface type indicates statistical significance.

of the lumbar curve ($R = -0.175$, $p < 0.05$). This relationship was maintained even after controlling for cofactors (preoperative PT, SVA, TK, and LL). PT decreased 2° for each level of LL apex that was more caudal. This could be explained by the change in the distribution of mass above the pelvis, which affects pelvic retroversion. Altogether, these results suggested that the extent of global spinal alignment and pelvic retroversion correction is affected by the osteotomy resection. The proportion of truncal versus PT correction has not been well described. Previous

TABLE 4. Results of the multivariate analysis demonstrating the impact of the 3CO level and postoperative LL apex on change in PT, T1SPi, and SVA

Dependent Variable	R^2	Independent Variables		Confounders*				
		3CO Level	Apex Level	ΔLL	PT	TK	LL	SVA
ΔPT	0.501							
p value		0.86	0.004	<0.001	<0.001	0.007	0.88	<0.001
Beta coefficient		-0.01	-0.14	-0.65	-0.30	0.16	-0.01	0.21
Coefficient		-0.08	-2.03	-0.32	-0.23	0.06	-0.01	0.02
ΔT1SPi	0.541							
p value		0.15	0.77	<0.001	0.027	0.12	0.11	<0.001
Beta coefficient		0.69	-0.01	-0.36	0.11	0.09	-0.12	-0.65
Coefficient		0.49	-0.15	-0.13	0.07	0.03	-0.04	-0.06
ΔSVA	0.601							
p value		0.37	0.11	<0.001	0.036	0.049	0.036	<0.001
Beta coefficient		0.04	-0.07	-0.51	0.10	0.10	-0.15	-0.59
Coefficient		3.04	-8.31	-2.06	0.62	0.33	-0.52	-0.55

Boldface type indicates statistical significance.

* Confounders were controlled.

FIG. 5. Preoperative (**A** and **C**) and 1-year postoperative (**B** and **D**) anteroposterior (**A** and **B**) and lateral (**C** and **D**) radiographs obtained in a 65-year-old patient with lumbar 3CO and major sagittal plane correction. At baseline, the patient had severe sagittal malalignment, with a PT of 26.7°, PI-LL of 54.3°, and SVA of 345.6 mm. At 1 year postoperatively, the measurements improved to a PT of 19.8°, PI-LL of -9.7°, and SVA of 1.1 mm.

studies have demonstrated varying proportions of trunk versus pelvic correction based on the spinal pathology and ankylosis.^{27,36} While there were correlations between LL correction outside the 3CO and correction of sagittal parameters, this study found no correlation between 3CO and change in radiographic parameters. This could indicate that the 3CO is not the only factor in correction surgery that leads to global realignment. Other factors such as facet resection, interbody cages, and reciprocal alignment changes in unfused segments may contribute to sagittal alignment changes. These hypotheses warrant future focused analyses.

In this study the complication rate was 41%, which is consistent with rates in other published reports. Charosky et al. and Maier et al. reported complication rates ranging from 37% to 59% in the setting of ASD surgery.^{5,28} In the current study, while the 3CO level was not associated with intraoperative complications, osteotomies that were more caudal were associated with increased early (6-week) postoperative complications and motor deficits. This could be due to the complex anatomy of the roots and lumbar plexus at the more caudal levels. Consequently, the potential risk for stretching the lumbar plexus should

be considered. The postoperative motor deficit rate of 9%, corresponding with the occurrence of a new deficit that was observed when the patient was awake after surgery but was not detected intraoperatively (with neuromonitoring or with obvious nerve root injury), was comparable to the previously reported rate of 7.5%.⁵ Of note, decompression was performed during 3CO surgery if stenosis was seen on preoperative images (CT scans and MR images) and if there was a concordance between clinical symptoms and radiological images.

In this study, the revision rate was 18% in the 1st year after 3CO. This is also consistent with previous authors' findings of reoperation rates of 14%–20% in the same time period.^{6,17,29} Regarding mechanical complications, only revisions for pseudarthrosis were related to the 3CO level, with a higher rate for the more caudal osteotomy levels (Fig. 6). However, considering the small number of 3COs performed at L-5 ($n = 11$), these significant results need to be interpreted with caution. Nevertheless, these findings suggest the need for an excellent anchor in the lumbosacral area, as well as the importance of postero-lateral bone graft.

The strengths of this study include the large number of

FIG. 6. Case example of a patient with a caudal 3CO (L-4) who developed implant failure and pseudarthrosis necessitating revision before 1 year. Baseline (A), early postoperative (3 months; B), and 1-year postoperative (C) radiographs are shown.

patients with lumbar 3CO levels and thresholds for fusion (i.e., only cases with an upper instrumented vertebra above L-1). Limitations of the study design include its retrospective nature and the consequences involved. Moreover, hip pathology and its influence on rotation of the pelvis around the hip were not studied and could potentially explain the limitations of pelvic retroversion in some cases. These issues could be addressed with hip radiographic analysis and dynamic radiography of the spine, along with soft-tissue analysis, in future studies. This study is further limited by the absence of patient-reported outcomes. Finally, assessment of additional intraoperative factors such as bone morphogenetic protein and implant type or number of rods were not assessed.

Conclusions

3CO is an effective but demanding technique to correct sagittal spinal malalignment. The current study demonstrated that resection angle and restoration of the postoperative lumbar apex to more caudal levels had a significant impact on PT correction. Restoration of the lumbar lordotic apex appears to have a great impact on spinopelvic alignment and is not necessarily equivalent to the osteotomy level. Moreover, the change in LL outside of the 3CO correlated with change in sagittal alignment. This suggests that 3CO level is not the only factor influencing truncal or pelvic correction.

In addition, the complication rate was important after 3CO surgery. The intraoperative complication rate did not differ based on 3CO level. However, the postoperative complication rate was higher with more caudal 3CO

levels, especially for complications due to pseudarthrosis and new motor deficits. Consequently, the anatomy of lumbar nerve roots and a strong distal anchor should be considered. Further work on optimal LL apex location and predictive modeling could help surgeons better plan their complex realignment operations based on individual patients' sagittal alignment.

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Author Contributions

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Correspondence

Emmanuelle Ferrero, Hôpital Européen Georges-Pompidou, 20 rue Leblanc, Paris 75015, France. email: emmanuelle.ferrero@gmail.com.