Eur Spine J (2015) 24:1191–1198
DOI 10.1007/s00586-014-3738-4

CrossMark

ORIGINAL ARTICLE

Cervical spine alignment following lumbar pedicle subtraction osteotomy for sagittal imbalance

Ibrahim Obeid · Anthony Boniello · Louis Boissiere · Anouar Bourghli · Vincent Pointillart · Olivier Gille · Virginie Lafage · Jean-Marc Vital

Received: 7 July 2014 / Revised: 19 December 2014 / Accepted: 21 December 2014 / Published online: 9 January 2015

Abstract
Purpose The alignment of the cervical spine is of primary importance to maintain horizontal gaze and contributes to the functional outcome of patients. Cervical spine alignment after correction of major sagittal imbalance has rarely been reported in the literature.
Methods Retrospective review of 31 consecutive patients with sagittal plane deformities operated by lumbar pedicle subtraction osteotomy. Pre-operative and 3 months post-operative full-length radiographies were analyzed for spinopelvic and cervical-specific parameters.
Results There was a significant increase in lumbar lordosis (LL), thoracic kyphosis, and sacral slope. There was also a significant decrease in pelvic tilt, pelvic incidence minus LL, knee flexion and sagittal vertical axis. The cervical analysis revealed that there was no significant difference between pre- and post-operative global cervical lordosis (CL) angle and external auditory meatus (EAM) tilt. There was a significant decrease of C7 slope and distal CL, while a significant increase in occipito-C2 (OC2) angle was observed.
Conclusion LL restoration decreased the need of compensation at the pelvis and thoracic spine. The distal CL and C7 slope decreased because there was no need for compensation at this level after the surgery, but the proximal cervical spine takes a slightly flexed position to maintain horizontal sight. EAM tilt measures the head position toward C7, and is close to 0° even in severe cases. Changes of this parameter after surgery are insignificant, probably due to the balance between upper and lower cervical segments; when one of these segments shifts backward the other shifts forward and the result is a balanced head over C7.

Keywords Cervical alignment · Pedicle subtraction osteotomy · Sagittal alignment · Adult spinal deformity · Lumbar

Introduction

The cervical region is of particular importance as it allows for the widest range of motion relative to the rest of the spine while simultaneously providing support for the mass of the head. The high degree of mobility and dynamic nature of the region lends itself to compensation that is associated with changes in global spinal alignment [1]. Perhaps the most dramatic example of these compensatory changes occurs following adult spinal deformity surgery [2, 3]. Although the greatest improvement in alignment occurs within the instrumented and fused spinal segments, alterations can occur beyond the fused segments. These reciprocal changes may generate a more homeostatic and natural alignment. However, unintended overcorrection or unforeseen alterations outside of the surgical region may compromise sagittal alignment with a substantial negative impact on pain and quality-of-life scores [4–6].

Reciprocal changes outside of the fused segments have previously been reported for the thoracic, lumbar and

I. Obeid (✉) · L. Boissiere · A. Bourghli · V. Pointillart · O. Gille · J.-M. Vital
Bordeaux University Hospital, Spine Unit 1, Bordeaux, France
e-mail: ibrahim.obeid@gmail.com

A. Boniello · V. Lafage (✉)
Division of Spinal Surgery, Department of Orthopaedic Surgery, NYU Medical Center Hospital for Joint Diseases, NYU School of Medicine, New York, USA
e-mail: virginie.lafage@gmail.com

pelvic regions [7–11]. It has also been noted that changes in global spinal alignment following surgery affect the alignment of the cervical region [12–15]. Multiple studies have demonstrated that a compensatory decrease in cervical lordosis occurs in adult spinal deformity patients following lumbar pedicle subtraction osteotomy [12, 14]. It is theorized that these compensatory changes occur in the cervical region in an effort to maintain horizontal gaze. Maintaining functional alignment is a key component in minimizing overall energy expenditure [13, 14].

There remains a paucity of literature on how different segments within the cervical spine achieve this new conformation. Previous studies that identify a decrease in cervical lordosis following lumbar pedicle osteotomy do not report on occipito-cervical radiographic parameters [12, 14]. Of particular interest is determining whether compensation to maintain horizontal gaze occurs primarily in the upper or lower segments. Such analysis would help surgeons predict which cervical segments contribute most to functional alignment following lumbar pedicle subtraction osteotomy. This study aims to explore these compensatory changes in occipito-cervical radiographic parameters.

Materials and methods

Study design and inclusion criteria

The medical records and radiographs of 31 consecutive patients treated at a single institution from April, 2010 to June, 2012 with pedicle subtraction osteotomy for lumbar hypolordosis were retrospectively examined. Database inclusion criteria included patients over the age of 40 with thoracic kyphosis (TK) less than 60°. Exclusion criteria included neuromuscular, neoplastic, rheumatologic, and/or infectious etiologies of sagittal imbalance.

Radiographic measurements

Pre-operative and post-operative full-length EOS radiographs (EOS Imaging®) were obtained with patients in both bent and straightened knee posture, with elbows flexed at approximately 45°, and fingertips on the clavicles (Fig. 1) [16]. Sagittal radiographic spinal measurements were performed using validated SterEOS software (EOS imaging, Paris, France, Fig. 2) [17, 18]. The following spinopelvic parameters were measured (Fig. 3): L1-S1 lumbar lordosis (LL); T4-T12 thoracic kyphosis (TK); C7-S1 sagittal vertical axis (SVA); knee flexion angle; pelvic incidence (PI); sacral slope (SS); and pelvic tilt (PT). In addition the PI minus the absolute value of LL (PI − LL), a sagittal modifier described by the SRS-Schwab

Fig. 1 Standing full-length EOS (EOS Imaging®) lateral and coronal radiographs of a 42-year-old female, 2 years following an L4 pedicle subtraction osteotomy with T10-ilium instrumentation

Classification system, was reported [19]. PI − LL emphasizes the mismatch between lumbar lordosis and pelvic morphology and reaches deformity threshold when greater than 10° [20]. The following occipito-cervical parameters were measured: C1–C7 cervical lordosis (global CL); C1–C2 cervical lordosis (proximal CL); C2–C7 cervical lordosis (distal CL); and C7 slope. Additionally, the occipito-C2 angle (OC2), a measure of the occipito-

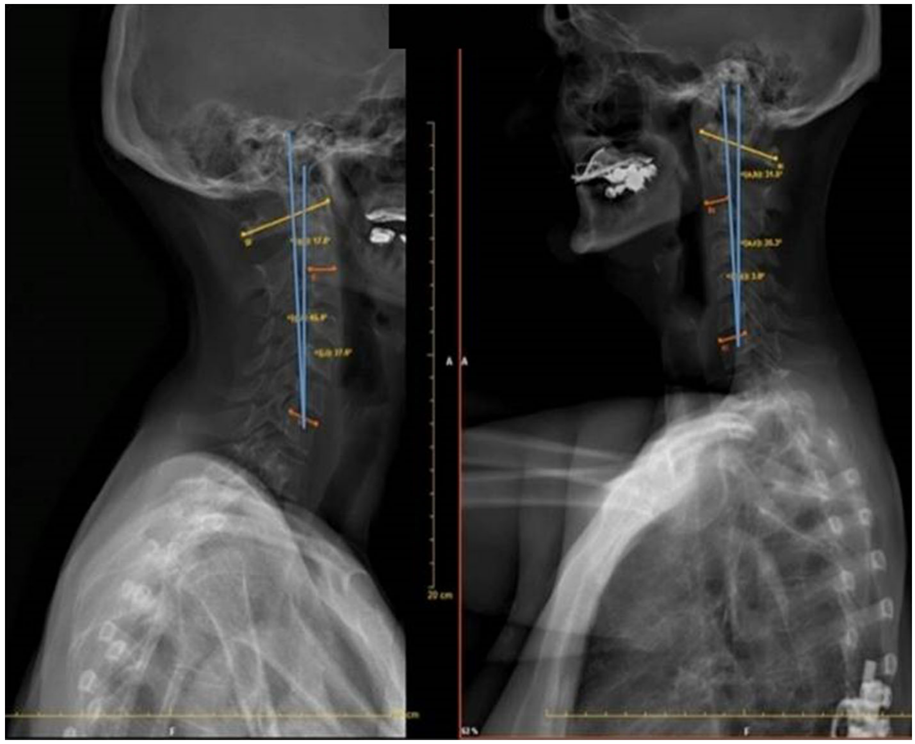

Fig. 2 Pre-operative (*left*) and post-operative (*right*) measurements of cervical parameters utilizing Surgimap^{TM}. External auditory meatus tilt remains close to 0 degrees; *Upper* and *distal* cervical curvatures demonstrated significant changes

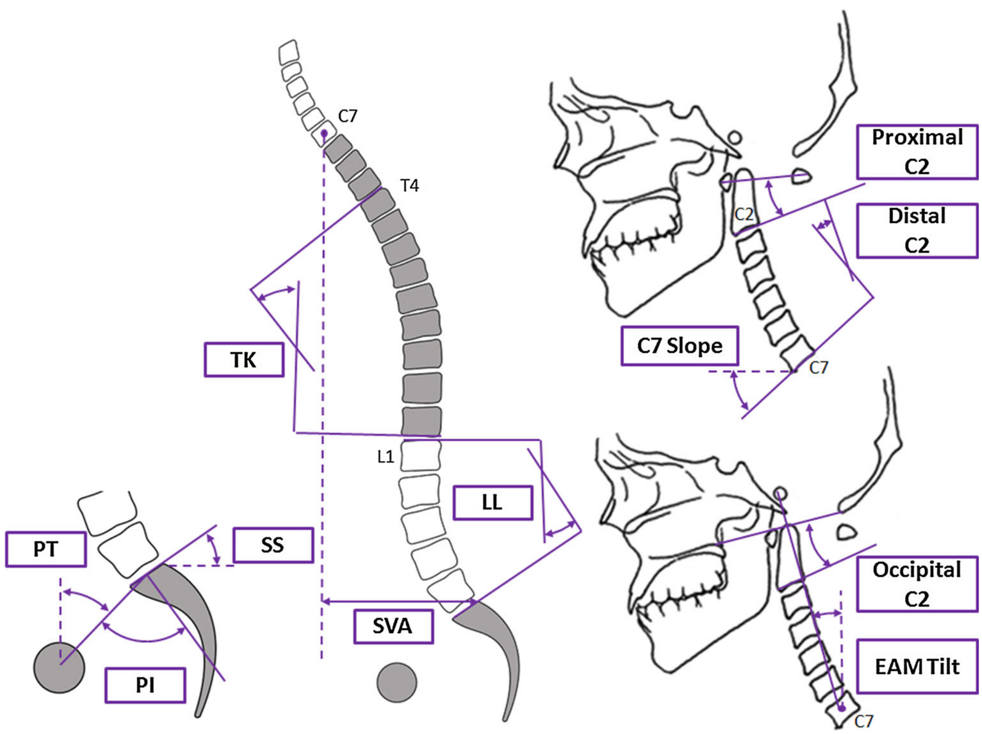

Fig. 3 Spinopelvic parameters: lumbar lordosis (LL), thoracic kyphosis (TK), pelvic incidence (PI), sacral slope (SS), pelvic tilt (PT), sagittal vertical axis (SVA), occipito C2 angle, proximal cervical lordosis, distal cervical lordosis, C7 slope, external auditory meatus (EAM) tilt

cervical alignment, was defined as the angle between the McGregor line and the inferior endplate of C2. The external auditory meatus (EAM) tilt, a global parameter of the head position in relation to C7, was defined as the angle between the vertical and the line joining the center of C7 and EAM. For all sagittal measurements, the angle was considered negative if the curve were lordotic and positive if the curve were kyphotic. When discussing an "increase" in lordosis or kyphosis, the angle becomes more negative and positive in value, respectively. A change in lordosis or kyphosis was reported as an absolute value, designated by [Δ].

Statistical analysis

The mean value and standard deviations of pre- and post-operative spinopelvic parameters were determined and changes were evaluated using a paired Student's *t* test. The normality of data was evaluated using the Shapiro–Wilk test. A p value of less than 0.05 was considered statistically significant. All statistical analyses for radiographic data were performed using the Statistical Package for the Social Sciences (SPSS) for Windows 17.0 (SPSS Inc., Chicago, IL). For the purpose of this paper, the study mean was compared to normative values in subjects with normal alignment. Reference normal values for spinopelvic parameters were obtained from a cross-sectional study by Vialle et al. [21] of 300 asymptomatic volunteers. Reference normal values for cervical parameters were obtained from Ames et al. [2], which was adapted from a study by Hardacker et al. [22], in addition to a cross-sectional study of 106 healthy volunteers by Le Huec et al. [23]. A value was considered "normative" if within one standard deviation from the mean of reference normative values.

Results

Baseline characteristics

Included in this study were 23 females and eight males with an average age of 63 years (range 42–79) at time of surgery. Etiologies for lumbar hypolordosis included degenerative ($n = 12$), post-traumatic ($n = 4$) and iatrogenic ($n = 15$). Radiographic measures are summarized in Table 1. Pre-operatively, the sample showed global spinal malalignment, as reflected by a high mean value of SVA (11.1 ± 5.5 cm) and PI − LL mismatch (38.5 ± 17.1°) greater than 20° [20]. Patients compensated for this malalignment via thoracic hypokyphosis (26.2 ± 17.2°) that is less than the reference normal values (39 ± 10°) [21]. Additional compensation occurred via knee flexion (13.4 ± 8.4°) and pelvic retroversion. The mean PT (32.4 ± 11.8°) was higher than the mean reported values in asymptomatic subjects (13.6 ± 6°).

Mean OC2 (11.9 ± 8.5°) and EAM tilt (1.4 ± 8.3°) were within reference normal values (15.81 ± 7.15° and 0°, respectively) [23], indicating patients maintained horizontal gaze. Similarly, mean global CL (−43.9 ± 13.4°) was similar to the reference normal values (−41.8°) [2]. Interestingly, analysis of proximal versus distal cervical lordosis revealed mean proximal CL (−27.3 ± 6.9°) was hypolordotic, whereas distal CL (−16.5 ± 14.7°) was hyperlordotic compared to reference normal values (−32.2 ± 7.0° and −9.6°, respectively) [2]. These segmental cervical parameters suggest there are different compensation mechanisms between the different segments of the cervical spine.

Post-operative characteristics

Post-operative radiographs were obtained between 0.2 and 37 months after surgery (mean 9 months). Level of pedicle subtraction osteotomy was L3 (19 %), L4 (71 %), L5 (6 %), and S1 (3 %). The mean levels of instrumentation were 8.8 ± 2.9. Lumbar pedicle subtraction osteotomy significantly increased the LL by 37.7° ($p < 0.001$), resulting in a mean PI − LL mismatch of −0.8° ± 14.2°. The increase in LL resulted in a significant increase in thoracic kyphosis (Δ17.8°, $p < 0.001$), decrease in pelvic retroversion (Δ−15°, $p < 0.001$), and increase in SS (Δ13.3°, $p < 0.001$). These compensatory changes brought TK, PT, and SS spinal parameters within reference normal values (Table 1). All together, these regional spinal changes improved global alignment. SVA decreased (Δ−8.5 cm, $p < 0.001$) to a post-operative mean (2.6 ± 4 cm) within reference normal values. Similarly, the amount of compensation via knee flexion decreased (Δ−8.3°, $p < 0.001$), resulting in negligible post-operative knee flexion (5.1 ± 5.2°).

The analysis of occipito-cervical parameters revealed no significant increase in global CL (Δ3.6°, $p = 0.074$), proximal CL (Δ−0.9°, $p = 0.357$), and EAM tilt (Δ1.4°, $p = 0.195$). However, significant increases were noted in distal CL (Δ5.6°, $p = 0.010$) and OC2 (Δ2.2°, $p = 0.008$) with significant decrease in C7 slope (Δ−3.6°, $p = 0.028$).

Discussion

Reciprocal changes have been reported previously for the thoracic, lumbar and pelvic regions [12, 24–35]. For example, reciprocal decrease in lordosis within the unfused lumbar spine has been demonstrated after thoracic osteotomy with limited fusion for correction of kyphosis [7]. Similarly, a lumbar osteotomy with restoration of LL also generates a spontaneous increase in kyphosis within the unfused thoracic spine [7]. These unanticipated reciprocal changes can bring the global spine into malalignment. For example, hyperkyphosis following lumbar pedicle subtraction osteotomy can negatively impact SVA, potentially countering the improvement in alignment for which surgery is typically performed [8].

Table 1 Pre-operative, post-operative, and change in mean radiographic values

Region	Parameters	Mean	SD	Mean	SD	Difference	p
Thoracolumbar	Lumbar lordosis (°)	−19.9	19.5	−57.6	12.8	−37.7	<0.001
	Thoracic kyphosis (°)	26.2	17.2	44.0	10.5	17.8	<0.001
Pelvic	Pelvic tilt (°)	32.4	11.8	17.4	10.2	−15.0	<0.001
	Sacral slope (°)	26.0	14.1	39.3	9.8	13.3	<0.001
	Pelvic incidence (°)	58.4	16.4	56.7	14.3	−1.7	0.054
	Pelvic incidence minus lumbar lordosis (°)	38.5	17.1	−0.8	14.2	−39.4	<0.001
Cervical	Occipito C2 angle (°)	11.9	8.5	14.1	8.4	2.2	0.008
	Global cervical lordosis (°)	−43.9	13.4	−40.3	11.6	3.6	0.074
	Proximal cervical lordosis (°)	−27.3	6.9	−28.2	8.6	−0.9	0.357
	Distal cervical lordosis (°)	−16.5	14.7	−10.9	11.9	5.6	0.010
	C7 slope (°)	28.3	10.3	24.7	9.0	−3.6	0.028
	EAM tilt (°)	1.4	8.3	2.9	5.3	1.4	0.195
Global	Knee flexion (°)	13.4	8.4	5.1	5.2	−8.3	<0.001
	Sagittal vertical alignment (cm)	11.1	5.5	2.6	4.0	−8.5	<0.001

The present study agrees with the assessment of global spinopelvic alignment by Blondel et al. [12]. Their assessment concluded that a larger PI requires a larger LL to achieve anatomical spinopelvic harmony. This correlates with increased TK, which in turn correlates with increased CL [12]. As expected, improvement of lumbar hypolordosis eliminated compensation through thoracic hypokyphosis. This study also noted predictable improvements in pelvic parameters. A mild loss of LL is correlated with a hypokyphosis or a lordosis of the thoracic region, whereas a more significant loss of LL is correlated with pelvic retroversion (increased PT) as a compensatory mechanism [2]. This study found a decrease in pelvic retroversion to within the reference normal pelvic values following improvement in lumbar alignment.

These regional changes resulted in improvement of global alignment, as indicated by the return of mean SVA to reference normal values. This is of particular clinical significance, as major sagittal malalignment (defined as SVA > 5 cm) is recognized as a cause of pain and disability [24, 36–38] and requires increased energy expenditure [36, 37, 39]. Likewise, Schwab et al. have shown that patients with PI − LL mismatch (PI − LL > 11°) are more likely to have pelvic retroversion or global malalignment [40]. Additionally, patients with PI − LL mismatch compared to patients with PI − LL harmony have a 4.2-fold greater risk of pelvic retroversion, 10.9-fold greater risk of positive sagittal malalignment (SVA), and 3.9-fold greater risk of severe disability [40].

Compensatory mechanisms of the cervical spine following spinal deformity surgery have only recently been considered. Smith et al. [14] demonstrated that adults with positive sagittal spinopelvic malalignment compensate with abnormally increased CL in an effort to maintain horizontal gaze. Blondel et al. [12] similarly demonstrated a compensatory loss of cervical lordosis to maintain horizontal gaze in patients with sagittal malalignment following lumbar pedicle subtraction osteotomy. The present study found no significant post-operative changes in global CL and proximal CL. There was, however, significant decrease in distal CL and OC2 angles. This is probably due to the balance between upper and lower cervical segments. When one of these segments shifts backward, the other segment shifts forward, resulting in a repositioning of the head balanced over C7.

The decrease in distal CL and C7 slope seen in the present study represents a decreased need for compensation at these levels after the surgery. There is a strong correlation between the C7 slope and the cranio-cervical system, with high values of C7 slope corresponding to high values of cervical lordosis, and vice versa [23]. Additionally, the proximal cervical spine will take a slightly flexed position to maintain horizontal gaze. This is evident in the slight increase in kyphosis in the proximal CL and the OC2 angle within reference normal values.

The most clinically important finding of this study was that there was no significant decrease in EAM tilt. The EAM tilt evaluates the global position of the head and remains unchanged following surgery, thanks to the balance and harmony between the upper and lower cervical segments (Fig. 4). The tendency of the pelvic, thoracolumbar and cervical parameters to normalize following pedicle subtraction osteotomy in the setting of a maintained EAM tilt represents a more natural posture with less compensation.

One strength of this study is the inclusion of a homogenous population of consecutive patients undergoing pedicle subtraction osteotomy surgeries. It is limited by its

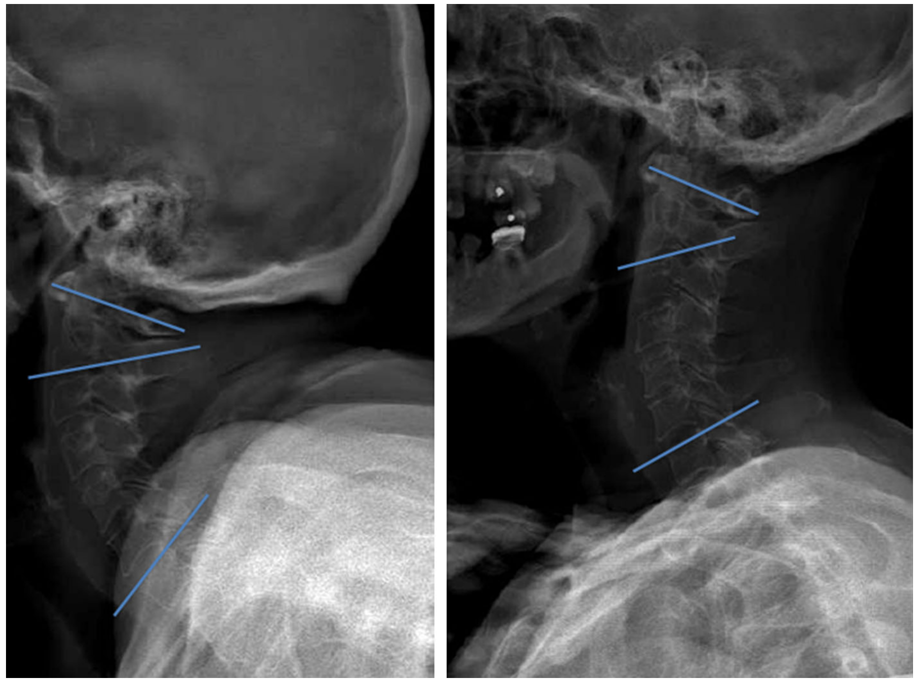

Fig. 4 Pre-operative (*left*) and post-operative (*right*) measurements of cervical parameters. EAM tilt remains close to 0 degrees; *Upper* and *distal* cervical curvatures demonstrated significant changes

small sample size though. The inclusion of relatively few surgical and patient factors may have skewed outcomes like curve type, BMI, sex, and health-related quality-of-life surveys. Conclusions on thoracic compensatory mechanisms are difficult to interpret as patients with high values of thoracic kyphosis (TK < 60°) was an exclusion criterion, perhaps partially accounting for the thoracic hypokyphosis noted at baseline. According to Lamartina–Berjano [1] sagittal deformity classification, such globally kyphotic patients should be fused up to T2, likely modifying the position of C7 and having an effect on the cervical parameters addressed. Future studies are needed from a larger population of patients including the aforementioned variables to further investigate the relationship between cervical and thoracic compensatory mechanisms.

This manuscript compared the results and the sagittal parameters to "normative" reference values [2, 21–23]. It is important to note that these values are not absolute definitions of deformity. Defining ideal sagittal parameters is currently the subject of ongoing research. The reference normal values are therefore presented as a vehicle for rough comparison with asymptomatic adults, and does not intend to include the specificity of the chains of correlations established in the literature [19, 20, 38, 41].

Conclusion

This study expanded upon previous research that identified a decrease in global CL following lumbar pedicle osteotomy [12, 14]. By analyzing occipito-cervical radiographic parameters, this study attempts to determine the most influential and important region utilized for cervical compensation. The present study found no post-operative changes in global CL, proximal CL, and EAM tilt in the setting of a normal post-operative OC2 angle. Increased post-operative distal CL represents a decreased need for compensation within the distal cervical spine to maintain horizontal gaze. These findings indicate that cervical compensatory mechanisms are not singularly captured by analysis of global CL.

These findings highlight how the different regions of the spine influence and are influenced by each other. Specifically, the cervical region resumes a more natural and efficient alignment following lumbar pedicle subtraction osteotomy in the setting of lumbar hypolordosis. Surgeons who perform lumbar pedicle subtraction osteotomies in this patient population should give consideration to these compensatory mechanisms in their pre-operative planning.

References

1. Lamartina C, Berjano P (2014) Classification of sagittal imbalance based on spinal alignment and compensatory mechanisms. Eur Spine J 23:1177–1189. doi:10.1007/s00586-014-3227-9
2. Ames CP, Blondel B, Scheer JK et al (2013) Cervical radiographical alignment: comprehensive assessment techniques and potential importance in cervical myelopathy. Spine (Phila Pa 1976) 38:S149–S160. doi:10.1097/BRS.0b013e3182a7f449
3. Canavese F, Turcot K, De Rosa V et al (2011) Cervical spine sagittal alignment variations following posterior spinal fusion and instrumentation for adolescent idiopathic scoliosis. Eur Spine J 20:1141–1148. doi:10.1007/s00586-011-1837-z

4. Glassman SD, Bridwell K, Dimar JR et al (2005) The impact of positive sagittal balance in adult spinal deformity. Spine (Phila Pa 1976) 30:2024–2029
5. Wu W-J, Jiang L-S, Liang Y, Dai L-Y (2012) Cage subsidence does not, but cervical lordosis improvement does affect the long-term results of anterior cervical fusion with stand-alone cage for degenerative cervical disc disease: a retrospective study. Eur Spine J 21:1374–1382. doi:10.1007/s00586-011-2131-9
6. Lee JS, Youn MS, Shin JK et al (2014) Relationship between cervical sagittal alignment and quality of life in ankylosing spondylitis. Eur Spine J. doi:10.1007/s00586-014-3491-8
7. Klineberg E, Schwab F, Ames CP et al (2011) Acute reciprocal changes distant from the site of spinal osteotomies affect global postoperative alignment. Adv Orthop 2011:415946. doi:10.4061/2011/415946
8. Lafage V, Ames C, Schwab F et al (2012) Changes in thoracic kyphosis negatively impact sagittal alignment after lumbar pedicle subtraction osteotomy: a comprehensive radiographic analysis. Spine (Phila Pa 1976) 37:E180–E187. doi:10.1097/BRS.0b013e318225b926
9. Lafage V, Schwab F, Vira S et al (2011) Spino-pelvic parameters after surgery can be predicted: a preliminary formula and validation of standing alignment. Spine (Phila Pa 1976) 36:1037–1045. doi:10.1097/BRS.0b013e3181eb9469
10. Lafage V, Smith JS, Bess S et al (2012) Sagittal spino-pelvic alignment failures following three column thoracic osteotomy for adult spinal deformity. Eur Spine J 21:698–704. doi:10.1007/s00586-011-1967-3
11. Yu M, Silvestre C, Mouton T et al (2013) Analysis of the cervical spine sagittal alignment in young idiopathic scoliosis: a morphological classification of 120 cases. Eur Spine J 22:2372–2381. doi:10.1007/s00586-013-2753-1
12. Blondel B, Schwab F, Bess S et al (2013) Posterior global malalignment after osteotomy for sagittal plane deformity: it happens and here is why. Spine (Phila Pa 1976) 38:E394–E401. doi:10.1097/BRS.0b013e3182872415
13. Ha Y, Schwab F, Lafage V et al (2014) Reciprocal changes in cervical spine alignment after corrective thoracolumbar deformity surgery. Eur Spine J 23:552–559. doi:10.1007/s00586-013-2953-8
14. Smith JS, Shaffrey CI, Lafage V et al (2012) Spontaneous improvement of cervical alignment after correction of global sagittal balance following pedicle subtraction osteotomy. J Neurosurg Spine 17:300–307. doi:10.3171/2012.6.SPINE1250
15. Roussouly P, Labelle H, Rouissi J, Bodin A (2013) Pre- and post-operative sagittal balance in idiopathic scoliosis: a comparison over the ages of two cohorts of 132 adolescents and 52 adults. Eur Spine J 22(Suppl 2):S203–S215. doi:10.1007/s00586-012-2571-x
16. Dubousset J, Charpak G, Dorion I et al (2005) A new 2D and 3D imaging approach to musculoskeletal physiology and pathology with low-dose radiation and the standing position: the EOS system. Bull Acad Natl Med 189:287–297 Discussion 297–300
17. Humbert L, De Guise J, Aubert AB et al (2009) 3D reconstruction of the spine from biplanar X-rays using parametric models based on transversal and longitudinal inferences. Med Eng Phys 31:681–687. doi:10.1016/j.medengphy.2009.01.003
18. Gille O, Champain N, Benchikh-El-Fegoun A et al (2007) Reliability of 3D reconstruction of the spine of mild scoliotic patients. Spine (Phila Pa 1976) 32:568–573. doi:10.1097/01.brs.0000256866.25747.b3
19. Schwab F, Ungar B, Blondel B et al (2012) Scoliosis Research Society-Schwab adult spinal deformity classification: a validation study. Spine (Phila Pa 1976) 37:1077–1082. doi:10.1097/BRS.0b013e31823e15e2
20. Bess S, Schwab F, Lafage V et al (2013) Classifications for adult spinal deformity and use of the Scoliosis Research Society-Schwab adult spinal deformity classification. Neurosurg Clin N Am 24:185–193. doi:10.1016/j.nec.2012.12.008
21. Vialle R (2005) Radiographic analysis of the sagittal alignment and balance of the spine in asymptomatic subjects. J Bone Joint Surg Am 87(2):260–267
22. Hardacker JW, Shuford RF, Capicotto PN, Pryor PW (1997) Radiographic standing cervical segmental alignment in adult volunteers without neck symptoms. Spine (Phila Pa 1976) 22:1472–1480 Discussion 1480
23. Le Huec JC, Demezon H, Aunoble S (2013) L'équilibre sagittal du rachis cervical sur une population asymptomatique: nouveaux paramètres et valeurs standards Sagittal parameters of cervical global balance. Normative values from a prospective cohort of asymptomatic volunteers. e-mémoires l'Académie Natl Chir 12:18–24
24. Glassman SD, Berven S, Bridwell K et al (2005) Correlation of radiographic parameters and clinical symptoms in adult scoliosis. Spine (Phila Pa 1976) 30:682–688
25. Berven S, Deviren V, Smith JA et al (2001) Management of fixed sagittal plane deformity: results of the transpedicular wedge resection osteotomy. Spine (Phila Pa 1976) 26:2036–2043
26. Bridwell KH (2006) Decision making regarding Smith-Petersen vs. pedicle subtraction osteotomy vs. vertebral column resection for spinal deformity. Spine (Phila Pa 1976) 31:S171–S178. doi:10.1097/01.brs.0000231963.72810.38
27. Bridwell KH, Lewis SJ, Edwards C et al (2003) Complications and outcomes of pedicle subtraction osteotomies for fixed sagittal imbalance. Spine (Phila Pa 1976) 28:2093–2101. doi:10.1097/01.BRS.0000090891.60232.70
28. Bridwell KH, Lewis SJ, Lenke LG et al (2003) Pedicle subtraction osteotomy for the treatment of fixed sagittal imbalance. J Bone Joint Surg Am 85-A:454–463
29. Cho K-J, Bridwell KH et al (2005) Comparison of Smith-Petersen versus pedicle subtraction osteotomy for the correction of fixed sagittal imbalance. Spine (Phila Pa 1976) 30:2030–2037 Discussion 2038
30. Johnson RD, Valore A, Villaminar A et al (2013) Sagittal balance and pelvic parameters-a paradigm shift in spinal surgery. J Clin Neurosci 20:191–196. doi:10.1016/j.jocn.2012.05.023
31. Kim YJ, Bridwell KH, Lenke LG et al (2007) Results of lumbar pedicle subtraction osteotomies for fixed sagittal imbalance: a minimum 5-year follow-up study. Spine (Phila Pa 1976) 32:2189–2197. doi:10.1097/BRS.0b013e31814b8371
32. Lenke LG, Newton PO, Sucato DJ et al (2013) Complications after 147 consecutive vertebral column resections for severe pediatric spinal deformity: a multicenter analysis. Spine (Phila Pa 1976) 38:119–132. doi:10.1097/BRS.0b013e318269fab1
33. O'Shaughnessy BA, Kuklo TR, Hsieh PC et al (2009) Thoracic pedicle subtraction osteotomy for fixed sagittal spinal deformity. Spine (Phila Pa 1976) 34:2893–2899. doi:10.1097/BRS.0b013e3181c40bf2
34. Rose PS, Bridwell KH, Lenke LG et al (2009) Role of pelvic incidence, thoracic kyphosis, and patient factors on sagittal plane correction following pedicle subtraction osteotomy. Spine (Phila Pa 1976) 34:785–791. doi:10.1097/BRS.0b013e31819d0c86
35. Yang BP, Ondra SL, Chen LA et al (2006) Clinical and radiographic outcomes of thoracic and lumbar pedicle subtraction osteotomy for fixed sagittal imbalance. J Neurosurg Spine 5:9–17. doi:10.3171/spi.2006.5.1.9
36. Lafage V, Schwab F, Patel A et al (2009) Pelvic tilt and truncal inclination: two key radiographic parameters in the setting of adults with spinal deformity. Spine (Phila Pa 1976) 34:E599–E606. doi:10.1097/BRS.0b013e3181aad219
37. Schwab F, Lafage V, Patel A, Farcy J-P (2009) Sagittal plane considerations and the pelvis in the adult patient. Spine (Phila Pa 1976) 34:1828–1833. doi:10.1097/BRS.0b013e3181a13c08

38. Schwab F, Farcy J, Bridwell K et al (2006) A clinical impact classification of scoliosis in the adult. Spine (Phila Pa 1976) 31:2109–2114. doi:10.1097/01.brs.0000231725.38943.ab
39. Schwab F, Patel A, Ungar B et al (2010) Adult spinal deformity—postoperative standing imbalance assessing alignment and planning corrective surgery. Spine (Phila Pa 1976) 35:2224–2231. doi:10.1097/BRS.0b013e3181ee6bd4
40. Schwab FJ, Blondel B, Bess S et al (2013) Radiographical spinopelvic parameters and disability in the setting of adult spinal deformity: a prospective multicenter analysis. Spine (Phila Pa 1976) 38:E803–E812. doi:10.1097/BRS.0b013e318292b7b9
41. Smith JS, Klineberg E, Schwab F et al (2013) Change in classification grade by the SRS-Schwab adult spinal deformity classification predicts impact on health-related quality of life measures: prospective analysis of operative and non-operative treatment. Spine (Phila Pa 1976) 38:1663–1671. doi:10.1097/BRS.0b013e31829ec563