Use of Surgimap Spine in Sagittal Plane Analysis, Osteotomy Planning, and Correction Calculation

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KEYWORDS

• Sagittal deformity • Sagittal balance • Osteotomy • Surgimap

KEY POINTS

- Poor sagittal alignment has been shown to correlate highly with poor preoperative and postoperative patient-reported outcomes.
- Surgical techniques exist to correct sagittal alignment, including osteotomies; however, there is a lack of a clear standardized methodology for planning and executing surgical corrections.
- New digital tools can make surgical planning, in particular osteotomy planning, more effective and accurate.
- This article offers a logical and thoughtful process in surgical planning with regard to the use of corrective osteotomy in the adult patient with spinal deformity.

INTRODUCTION

Sagittal Plane Deformity: A Growing Problem

Over the past 3 decades the scientific community and spine surgeons have shown an increased interest in sagittal-plane deformity, ultimately acknowledging the complexity of this problem. The term, initially restricted to abnormalities such as "flat back syndrome" or "failed back," is gaining applicability as it now refers to any condition with an abnormal spinopelvic alignment in the sagittal plane: from degenerative conditions,[1,2] to pediatric abnormalities such as adolescent idiopathic scoliosis[3–5] or spondylolisthesis,[6,7] and including a broad range of deformity in the adult spine.[8–10] The general principles of realignment procedures are well accepted,[11] although the systematic analysis of patients remains challenging and poorly implemented. The lack of implementation can be easily explained by the limited availability of formal training in the relevance of sagittal parameters and by the historical emphasis given to the coronal Cobb angle. However, a shift in perspective is necessary, as coronal Cobb angle has been proved to poorly correlate with patient-reported outcomes in the adult population.[12]

Why Should We Plan?

Identification of the sagittal plane as a major driver of poor clinical outcomes has given way for science to delve deeper into the concept and, ultimately, offer better clinical approaches to sagittal

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malalignment and associated methods of compensation. Acknowledging the influence of sagittal alignment on health-related quality of life (HRQoL) forces a clear change in surgeons' perspectives; to improve clinical outcomes, we must correct sagittal malalignment. Several studies have proved that proper restoration of the sagittal profile is critical to postoperative patient-perceived improvement as quantified through HRQoL scores.[13,14]

Acknowledging the impact of sagittal alignment on patient outcomes is critical; however, a systematic approach to quantifying sagittal parameters and planning optimal correction is lacking. Through multicenter studies it is emerging that a reasonably sizable number of patients are ultimately undercorrected after surgery. In one such study examining patients who underwent lumbar pedicle subtraction osteotomy (PSO), it was determined that 23% of realignment procedures failed.[15] Similarly, 22% of thoracic PSO patients were found to have poor postoperative spinopelvic alignment.[16] Realignment failure has been associated with not only poor functional outcome but also major complications, such as pseudarthrosis and rod breakage, which often ultimately result in addition surgical procedures. Smith and colleagues[17] evaluated symptomatic rod fracture after posterior instrumented fusion for adult spinal deformity, and found rod breakage in up to 8.6% of adult patients with deformity and 15.6% of PSO patients. The investigators concluded that remaining sagittal malalignment may increase the risk for rod breakage. It is clear that this issue must be addressed, and a method for determining the ideal amount of sagittal correction on a patient-by-patient basis is essential to attaining favorable postoperative outcomes.

How Much Correction is Necessary to Achieve Good Postoperative Results?

The question of the required amount of correction in the setting of deformity is not simple. A proper response requires measuring key spinopelvic parameters, and classifying the extent of compensation. It is necessary to accept that surgical planning starts with measurement of the spinopelvic parameter.[18] The objective of this article is to propose a systematic clinical approach for surgeons through a step-by-step analysis based on a patient presenting with sagittal-plane deformity. For each key radiographic parameter, the clinical relevance of the measurements are discussed in light of the recent literature, and a new method for surgical planning using Surgimap Spine software (Nemaris Inc, New York, NY) is offered as a tool. This case presentation aims to illustrate how a complex spinopelvic alignment can be broken down into simple key numbers to differentiate the primary drivers of the deformity from the compensatory mechanisms.

STEP-BY-STEP ANALYSIS

Case Presentation

The patient is a 73-year-old man complaining of low back pain for about 7 years. The patient feels he also has marked truncal shift anteriorly. He underwent spine surgery with an interspinous device in 2008 and experienced mild relief of some leg pain, but over time, particularly the last 4 years, he has noted increasing low back pain (7 out of 10 on a visual analog scale), with fatigue to the lower extremities and loss of standing and ambulatory endurance. The patient denies any neurologic deficits such as leg numbness, weakness, or paresthesias. Past treatment included pharmacologic management, physical therapy, and steroid injections.

On physical examination the patient's standing posture is with marked positive truncal inclination and an ability to stand fully erect. The patient demonstrates paravertebral lumbar tenderness, and discomfort with range of motion of the lumbar spine. Neurologic examination of the lower extremities reveals no deficits.

Evaluation of the Coronal Plane

Historically, evaluation of the coronal plane has been extrapolated from the Lenke classification of adolescent idiopathic scoliosis (AIS)[19,20]; however, recent studies have demonstrated that adult spinal deformity should not be considered an "adult version" of AIS. One of the first studies to closely examine the clinical impact of coronal deformity demonstrated that the obliquity of lumbar vertebrae (but not Cobb angle) correlate with pain scores.[21] Subsequently, multicenter studies[12,22] have revealed that apical level of a scoliotic deformity,[12] intervertebral subluxation, and coronal imbalance are also correlated with outcomes scores.[23] In light of these findings, a systematic evaluation of the coronal plane in the setting of adult spinal deformity should include the quantification of local (ie, intervertebral subluxation), regional (ie, identification of the apex), and global deformities (ie, global coronal malalignment). It appears that coronal C7 to center of the sacrum (central sacral vertical line) offset up to 4 to 5 cm is well tolerated, and that rotatory subluxations become mostly significant above 7 mm.[12]

As illustrated **Fig. 1** (left), preoperatively the patient did not present any coronal deformity (local, regional, or global).

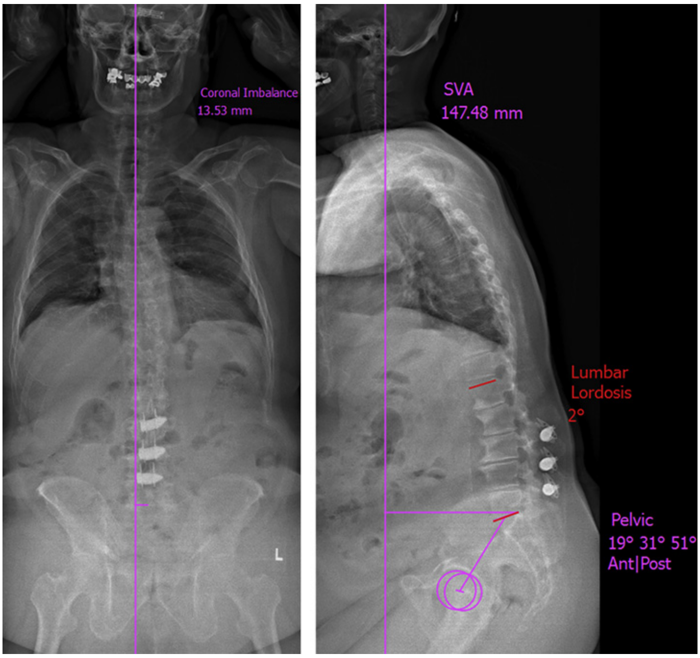

Fig. 1. Preoperative coronal and sagittal radiographs demonstrating a severe sagittal-plane deformity in association with previously placed interspinous devices (sagittal vertical axis [SVA] = 14.7 cm, PT = 31°, and PI-LL mismatch = 49°).

Evaluation of the Sagittal Plane

Global spinopelvic alignment

One of the most commonly used radiographic parameters in the setting of sagittal-plane evaluation is the sagittal vertical axis (SVA). This global parameter is defined as the linear offset between a plumb line dropped from C7 and the posterosuperior corner of S1. A possible substitution of the SVA is the T1 spinopelvic inclination (T1SPI), defined as the angle between a vertical and the line from T1 to the center of the bicoxofemoral axis.[8] T1SPI demonstrates almost perfect correlation with SVA and carries the advantage of being an angular measurement, which avoids the error inherent in measuring offsets in noncalibrated radiographs.[8] Global spinal realignment should attempt to obtain a postoperative SVA of less than 50 mm, or T1SPI of less than 0°.[8] Restoration of global alignment facilitates level gaze and achievement of a physiologic standing posture. From a clinical point of view, both parameters correlate with HRQoL (pain and disability),[8] and restoration of these parameters within normative values correlates with an increased likelihood of reaching a minimal clinically important difference.[13,14]

As illustrated in **Fig. 1** (right), preoperatively the patient had an SVA measured at 14.7 cm. According to the Scoliosis Research Society Schwab classification of adult spinal deformity,[24] this level of SVA identifies the patient as "severe sagittal deformity" with an SVA grade of ++.

Compensatory mechanisms

In addition to the evaluation of global spinopelvic alignment, it is of primary importance to also identify and quantify the use of compensatory mechanisms used in an effort to maintain the trunk as vertical as possible.[18] From a physiologic point of view several mechanisms have been reported in the literature,[1] such as changes of spinal curvatures (eg, hyphokyphosis of the thoracic spine, flexion of the knee, or retroversion of the pelvis). Changes in spinal curvatures are very common across the spectrum of spinal pathology (eg, increase of segmental lumbar lordosis above spondylolisthesis); they require not only a flexible spine but also the muscular ability to maintain those changes. Because of the nature of standard scoliosis films, knee flexion is difficult to evaluate on radiographs; a surrogate measurement can be the quantification of the femoral angulation with the vertical.[25,26]

Among the possible compensatory mechanisms to sagittal-plane malalignment, pelvic retroversion is probably the most commonly measured parameter. Pelvic retroversion is defined as a backward rotation of the pelvis; it is quantified by an elevated pelvic tilt (PT): the angle between the vertical and the line from the center of the bicoxofemoral axis to the middle of the superior endplate of S1. Jean Dubbouset[27] introduced the concept of “pelvic vertebra,” considering the pelvis as the pedestal[28] of the spine where pelvic retroversion aims at “bringing back” the spine into a vertical position. From a physiologic point of view, an increase in PT is not energy efficient, and correlates with increased pain and disability.[8,18]

As illustrated in **Fig. 2**A, preoperatively the patient had a PT of 31°, illustrating a pelvic retroversion in an effort to compensate for the sagittal deformity. From a hypothetical point of view, if the patient was able to further increase his pelvic retroversion (physiologic limit of pelvic retroversion = horizontal sacral endplate), the SVA would be within normative values (**Fig. 2**B; PT = 48°, SVA = 2.5 cm). From a pragmatic point of view, this illustrates that measurement of SVA alone does not permit accurate quantification of the sagittal plane, as it does not integrate how much of the “true SVA” is compensated for by increased retroversion. Using the same analogy, if the patient was not using any pelvic compensation (ie, PT = normative value [~20°]), the projected SVA would be even more severe than the one measured on standing radiographs (**Fig. 2**C; PT = 20°, SVA = 22 cm).

The ability of a patient to compensate for a spinal malalignment via an increase of pelvic retroversion is of primary importance in the clinical evaluation. Nevertheless, one should keep in mind that pelvic retroversion may also be the primary cause of sagittal malalignment if a patient presents with some specific soft-tissue[8] or lower-extremity disorder (shortening of the hamstring, hip-flexion contracture, hip deformity).[8] It is also interesting that a small number of patients have a mismatch between PT and SVA and do not compensate through the pelvis for their sagittal-plane malalignment. Ames and colleagues[18] reported that patients with an elevated SVA and a low PT (lack of pelvic compensation for a high SVA) represent a distinct subgroup in which surgical realignment procedures are at risk of postoperative failure. This relation may be seen in (1) patients with preexisting hip flexion contracture, (2) patients with degenerative flat back with primary extensor muscle abnormality, (3) globally decompensated patients with secondary extensor muscle weakness, and (4) patients leaning forward to compensate for severe lumbar stenosis.[18] All patients for whom corrective surgery is being considered should undergo clinical evaluation of the lower extremities to rule out hip-flexion contracture.[18]

Lumbar lordosis

Lumbar lordosis is probably the most commonly used sagittal radiographic parameter across all spinal abnormalities. The analysis of reported normative values[29–35] revealed an average lumbar lordosis of 60° on asymptomatic adult volunteers.

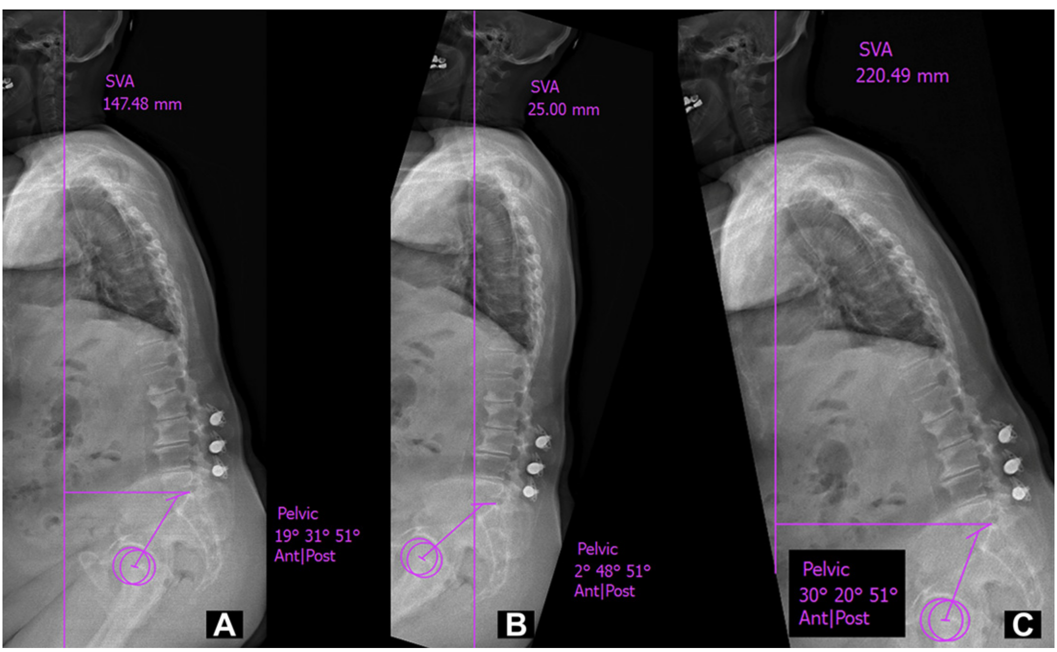

Fig. 2. The impact that pelvic version (PT) has on global alignment. Preoperatively (*A*), the patient presented with a sagittal vertical axis (SVA) of 14.7 cm and a pelvic tilt (PT) of 31°. A hypothetical further increase of pelvic retroversion (eg, PT = 48°; *B*) would drastically reduce the projected SVA. On the other hand, a reduction of pelvic tilt (PT = 20°; *C*) would increase the projected SVA.

It is important to note the extremely wide range of lumbar lordosis values contributing to that average. Vialle and colleagues,[36] in their review of 300 asymptomatic subjects, reported a lumbar lordosis ranging from 30° to 89°. These large variations reflect that each subject requires his or her own amount of lumbar lordosis. As reported by numerous investigators, the lumbar lordosis for a given subject should be proportional to the observed pelvic incidence (PI). PI is a morphologic parameter defined as the angle between the perpendicular to the sacral plate at its midpoint and a line connecting the same point to the center of the bicoxofemoral axis. The intrinsic relationship between PI and lumbar lordosis can easily be explained by the strong relationship between PI and sacral slope (ie, inclination of the sacral endplate with the horizontal).

- *Small PI* is associated with a vertical sacrum and, therefore, a horizontal sacral endplate. Because the spine originates at the sacrum, a horizontal sacral endplate is associated with an almost horizontal L5 vertebra. As a result, a small lumbar lordosis is sufficient to maintain the head over the pelvis.
- *Large PI* is associated with a more horizontal sacrum and therefore a titled sacral endplate and L5 vertebra. As a result, a large lumbar lordosis is required to maintain the head over the pelvis.

While the optimal lordosis specific for a particular subject is still a debatable question, the analysis of normative data demonstrates that 80% of subjects have a lumbar lordosis within 10° of their measured PI. Based on this finding, a new parameter has recently been introduced to evaluate the mismatch between PI and lumbar lordosis (PI minus lumbar lordosis, or PI-LL mismatch) rather than each parameter independently. The analysis of HRQoL in the setting of adult spinal deformity also demonstrates that an increase in PI-LL mismatch was associated with higher level of pain and disability. In terms of surgical realignment planning, the PI-LL mismatch can thus be a simplified way to assess the degree of realignment necessary. The caveat is that this applies only when the sagittal plane deformity is isolated to the lumbar spine and does not account for abnormal thoracic or thoracolumbar alignment. In addition, such a simplified realignment planning does not account for changes in unfused portions of the spine that can occur (eg, reciprocal increased kyphosis following lumbar realignment).

As illustrated **Fig. 1** (right), preoperatively the patient had a PI-LL mismatch of 49° (PI = 51°, LL = 2°). From a planning point of view, a 40° increase in lumbar lordosis would be necessary to reach a PI-LL of less than 10° (if LL = 40° + 2°, PI-LL = 51°–42° = 9°).

Surgical Planning

Mathematical planning

In an attempt to optimize postoperative spinopelvic alignment, several investigators have proposed mathematical formulas to assist surgical planning. These formulas[37–42] vary in their level of complexity, as some simply provide a target postoperative lumbar lordosis/thoracic kyphosis relationship, whereas others estimate the degree of osteotomy resection needed to restore an acceptable global sagittal alignment. The predictive accuracy of these formulas has recently been analyzed in a large database of 3-column osteotomies, which revealed that only formulas integrating pelvic parameters preoperatively were able to correctly predict postoperative global alignment (SVA) and pelvic version (PT).[43] Lafage and colleagues[44] reported on the formula with the highest accuracy in predicting postoperative SVA after PSO. A limitation of the aforementioned formulas are the lack of full consideration of the position of the lower extremities and the head.[43] When planning spinal reconstructive procedures, it is important to acknowledge that preoperative planning formulas that do not evaluate pelvic parameters, especially PI and PT, may be inaccurate and may increase the risk for postoperative undercorrection. Although these formulas clearly represent an advancement in predicting the postoperative outcome, they may be too complex for routine clinical use.[37–42]

Graphical planning

Existing methods In addition to published mathematical formulas, several investigators have proposed graphical methods for surgical planning of osteotomy procedures. Ondra and colleagues[39] used a trigonometric method to calculate the angle of correction needed to achieve neutral alignment for PSO procedures. One shortcoming of this method, however, is that the contribution of the pelvis to sagittal alignment is neglected; the use of this method will probably lead to undercorrection. The FBI technique[25] is a more comprehensive graphical method integrating the pelvis and the lower extremities in the geometric calculation. The technique is based on a global analysis of the full body. The amount of correction is geometrically calculated using appropriate radiographic measurements. To determine the amount of correction required, the FBI technique applies 3 distinct angle measurements. The integration of the femoral shaft to represent knee flexion on long cassette radiograph films is an important parameter for analyzing the patient's posture in the standing position, avoiding postoperative undercorrection and residual sagittal malalignment. A limitation of the FBI graphical technique is that the femoral shaft needs to be visualized and that the exact extent of pelvic retroversion (PT) is not integrated, as the investigators propose a generic solution (increase of correction by 5° in the setting of any pelvic retroversion).

Surgimap Spine Surgimap Spine, a free computer program (http://www.surgimap.com; Nemaris Inc, New York, NY) that integrates spine-related measurement and tools for surgical planning in combination with knowledge gained from the published literature, offers a pragmatic graphical method for the surgical planning of osteotomies. This method integrates not only global malalignment but also the spinopelvic parameters, and enables the user to simulate the sagittal correction and its influence on the spinopelvic parameters and global alignment. After import of preoperative digital radiographs into a Surgimap Spine customizable database, realignment planning can be executed in 4 simple phases (**Figs. 3–6**).

1. Measurement of preoperative sagittal radiographs (see **Fig. 3**). As described previously,

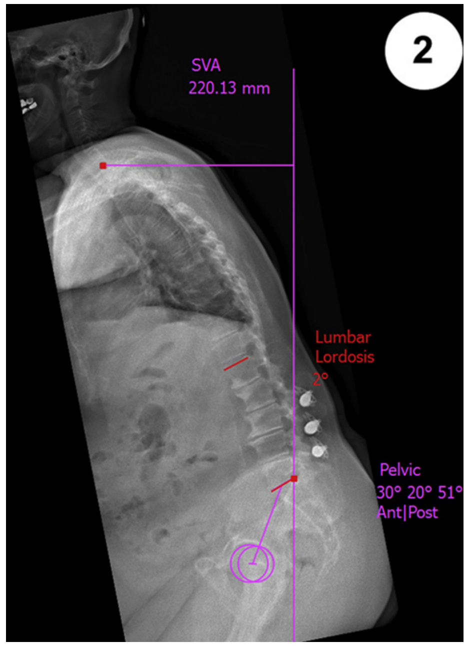

Fig. 4. The second phase of the graphical surgical planning consists in rotating (in this case counterclockwise) the sagittal radiograph until a desired planned pelvic tilt is reached (here 20°).

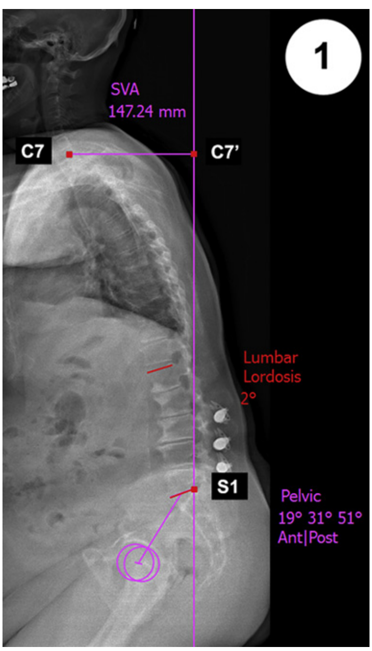

Fig. 3. The first phase of the graphical surgical planning consists in the identification of the pelvic parameters, lumbar lordosis, and global alignment. SVA, sagittal vertical axis.

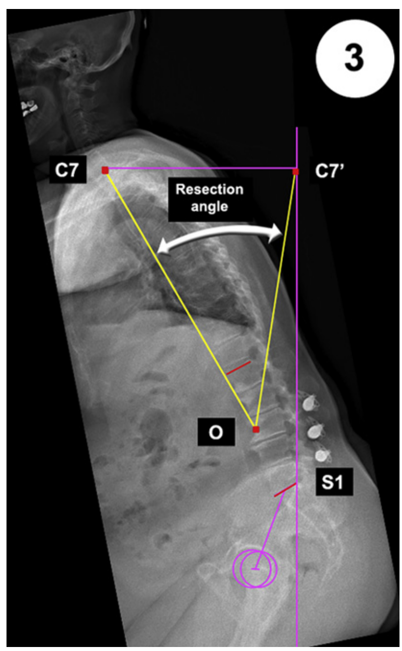

Fig. 5. The third phase of the graphical surgical planning consists in the identification of the resection angle based on the osteotomy site (O), the current location of C7, and the desired postoperative location of C7 (C7′).

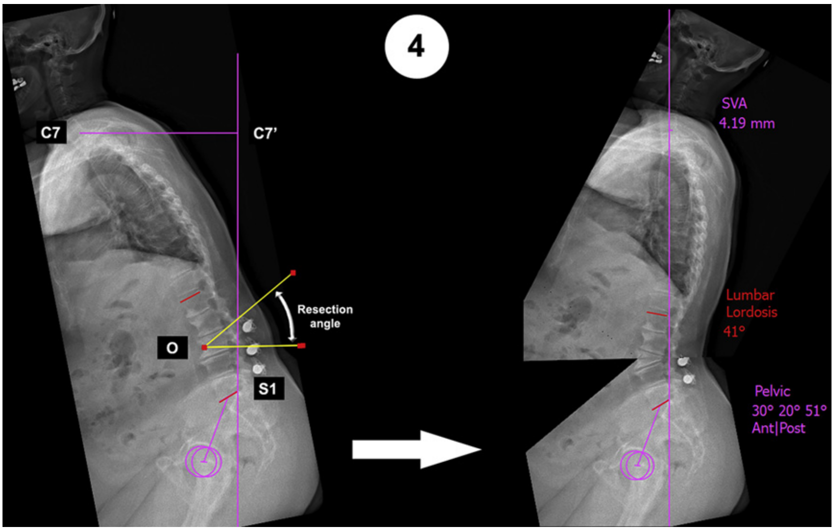

Fig. 6. The fourth and last phase of the graphical surgical planning consists in drawing the resection matched to the angle from O to C7 and C7′, followed by (wedge osteotomy) simulation of the osteotomy. On the left is the planning scheme and on the right the activated planning simulation, with transition indicated by the arrow.

the minimum set of measurements required for sagittal-plane analysis include pelvic parameters, lumbar lordosis, and global alignment (SVA or T1SPI). Surgimap Spine offers dedicated tools for each of these measurements. The pelvic parameters are automatically calculated on identification of the sacral endplate and the 2 femoral heads. The lumbar lordosis measure requires the identification of the cranial endplate of L1 in addition to the sacral endplate. Finally, in the context of the proposed method, the SVA is constructed in a reverse fashion, by dropping a plumb line from the posterosuperior corner of S1 and by the identification of C7. Using this specific construction of the SVA, the overall objective of the method consists in “bringing C7 in line with the posterosuperior corner of S1” (ie, moving C7 over C7′ as illustrated in **Fig. 3**).

2. Rotation of the image to reach desired postoperative PT (see **Fig. 4**). Surgimap Spine offers the ability to rotate images (degree by degree) while monitoring the impact of the rotation on existing measurements (instant recalculation). In an effort to take into account the pelvic compensation, this second phase consists of turning the entire image until PT reaches the planned, or ideal postoperative PT (20° in this case presentation).
3. Quantification of the resection needed (see **Fig. 5**). After identification of the osteotomy site (point O in **Fig. 5**), the third phase consists in calculating the amount of resection needed to superimpose C7 and C7′. As for other graphical techniques of osteotomy planning, this angle is defined as the angle between OC7 and OC7′, and can be measured via Surgimap Spine using the generic “angle” tool.
4. Simulation of the osteotomy (see **Fig. 6**). The fourth and final phase consists in applying a resection angle at the intended osteotomy site using the “Wedge Osteotomy” tool and graphically tracing the osteotomy directly on the radiographic image. Of note, this tool offers the ability to adjust the ratio of rotation between the trunk and the pelvis. Surgimap depicts this ratio via a third line. In the proposed realignment approach described here, the ratio line should be shifted to directly over the lower resection line of the osteotomy (ratio set at 100%). In other methods, if the PT is not adjusted first through image rotation, one can use the ratio line of the osteotomy to adjust for variable correction of PT or SVA.

Of note, this graphical technique does not necessarily represent the exact amount of resection needed but rather of amount of change in lumbar lordosis needed to correct the global alignment and pelvic retroversion. One of limitations of the method is that it does not take into account the possible reciprocal changes that may occur in the unfused segments of the spine.

As illustrated in **Fig. 7**, using the proposed technique with a grade 3 osteotomy[45] applied at L3, the sagittal plane of the patient was corrected to reach an SVA of 0.9 cm, PT of 22°, and lumbar lordosis of 44°.

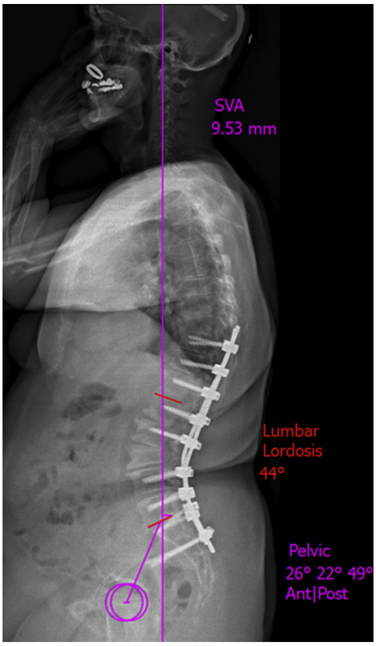

Fig. 7. Postoperative sagittal radiograph demonstrating correction of the deformity (PT = 22°, SVA = 0.9 cm, and PI-LL mismatch = 5°) according to plan.

Surgical tools

Schwab and colleagues[45] proposed an osteotomy classification system based on 6 anatomic grades of resection (1 through 6) corresponding to the extent of bone resection and the increasing degree of destabilizing potential. The classification provides a comprehensive description of the various osteotomies performed in spinal deformity correction surgery (Surgimap tools offer openings and various methods of resections and vertebrectomy reflecting the range of osteotomies from grades 1 through 6). Its use may allow a common framework for osteotomy description and comparative analysis. Ames and colleagues[18] reported that the location of the osteotomy along the spine needs to be considered when attempting to normalize PT. PT reduction is greater when the osteotomy performed is more caudal. It is also important to consider that spinal segments not incorporated within the fusion may become more kyphotic after lumbar PSO.

SUMMARY

Surgical planning should not be simply an academic or purely theoretical exercise. It is critical that surgeons adopt planning tools to encourage better outcomes for their patients. This article offers a pragmatic and systematic approach involving measurement of the key spinopelvic parameters, evaluation if the compensatory mechanisms, identification of the amount of correction needed, and selection of surgical tools needed to achieve outlined objectives.

Depending on the severity of sagittal deformity, spinopelvic parameters, and compensatory mechanism (high preoperative PT), there is the possibility to select the most adapted type and extent of osteotomy, pursue a simulated correction, and assess its direct influence on spinopelvic parameters. The surgeon-developed surgical planning software Surgimap Spine can be a tremendously helpful tool in assessing various approaches and strategies to combat spinal deformity, with the goal of optimal treatment for patients (http://www.surgimap.com, Nemaris, New York, NY).

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