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ORIGINAL ARTICLE

Computerized preoperative planning for correction of sagittal deformity of the spine

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Abstract
Purpose Various methods of preoperative planning have been described for the correction of spinal sagittal deformities. They are reliable on condition that the thoracolumbar spine is totally fused and enable only the simulation of pedicle subtraction osteotomy (PSO). In this study, a new theoretical planning that can be used regardless of the etiology of the deformity and the type of osteotomy is described and assessed.
Methods The spino-pelvic sagittal balance can be expressed by two parameters: pelvic tilt (PT) and center of both acoustic meati (CAM) overhang. These two parameters vary according to the type, number, level, and angulation of osteotomies. The general principle of the planning is to define the surgical program in order to obtain PT and CAM overhang as close as possible to the normal values. The theoretical planning is based on a trigonometric construction which depends on numerous factors and is challenging to use in daily practice without the aid of a software tool. Modifications are proposed if the spine cannot be modeled as a solid beam due to unfused disks allowing relative motion. The SpineView software, which enables analysis and quick visualization of different correction possibilities, is presented. The planning method is assessed in a prospective cohort of 11 patients by comparing planned values of spino-pelvic parameters to postoperative values.
Results In all, 8 preoperative plans out of 11 were concordant with the postoperative results.
Conclusions The preoperative planning enables the surgeon to estimate the clinical effects of the different surgical techniques in order to choose the best procedure for a given patient.

Keywords Spine · Postural balance · Osteotomy · Software · Planning techniques

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Introduction

A kyphotic lumbar or thoracolumbar deformity of the spine leads to automatic compensatory phenomena in the adjacent spinal segments, at the pelvis, and lower limbs. Intervertebral constraints and muscular efforts are then increased, thus reducing quality of life and functional ability [8, 12].

Correction of spinal deformities must enable the patient to maintain a balanced upright posture with minimum energy expenditure. Two main techniques can be used in order to correct a fixed sagittal imbalance: the pedicle subtraction osteotomy (PSO) and the multilevel Smith-Petersen osteotomies (SPO) [2]. PSO is essentially performed if the spine is totally inflexible as in the case of ankylosing spondylitis. Various methods of preoperative planning have been described in this type of case, where there is no relative motion between vertebrae [15, 16, 19, 20, 25]. These methods are reliable because the correction is obtained with only one osteotomy and the remainder of the spine behaves as a rigid body. However, patients with a partially flexible spine may require a surgical correction with PSO or SPO. The postoperative result is then more difficult to assess. Mean improvement of lordosis is about 10° per SPO level, but there are important variations depending on the preoperative degree of intervertebral kyphosis. Further complicating the procedure, the spontaneous movements of the flexible adjacent segments are difficult to predict. In such cases, a reliable preoperative technique has not been described yet.

In this study, a preoperative theoretical planning for treating different varieties of sagittal deformities, regardless of surgical correction technique, is described. The specific computer software that enables this planning in daily practice is presented and the effectiveness of the method is assessed in a prospective cohort study.

Materials and methods

Biomechanical analysis

Spino-pelvic parameters

In the frontal plane, ideal balance is obtained by alignment of the spine, so that the vertical line passing through the center of C7 crosses the center of S1. In the sagittal plane, the problem is more complex because of the considerable morphological variability between individuals.

The works of Delmas [4] and the Duval-Beaupère group [5, 13] are fundamental references to understand the ideal spinal sagittal balance for a given patient. They have revealed the close relationship between the sagittal spinal curvatures, the spatial position of the pelvis, and its morphology. Some other authors have confirmed that spinal sagittal parameters are highly correlated with pelvic parameters [1, 7, 10, 14, 22, 23].

In our analysis, the spino-pelvic sagittal balance is characterized by the following parameters (Fig. 1).

Center of both acoustic meati (CAM) overhang It is the distance in millimeters between the vertical line passing through the CAM projection in the sagittal plane and the projection of the center of femoral heads (hip axis: HA). This value is positive if CAM projects forwards from the HA and negative if they project backwards from the HA. According to Vital and Sénégas [24], the center of mass (COM) of the head is located slightly above and in front of the CAM projection in the sagittal plane. Thus, the CAM overhang enables characterization of the position of the COM of the head with respect to the HA. Gangnet et al. [6] showed that in asymptomatic subjects, the CAM overhang is between −2 cm and 2 cm. The whole spine is globally balanced if the CAM overhang is less than or equal to 2 cm.

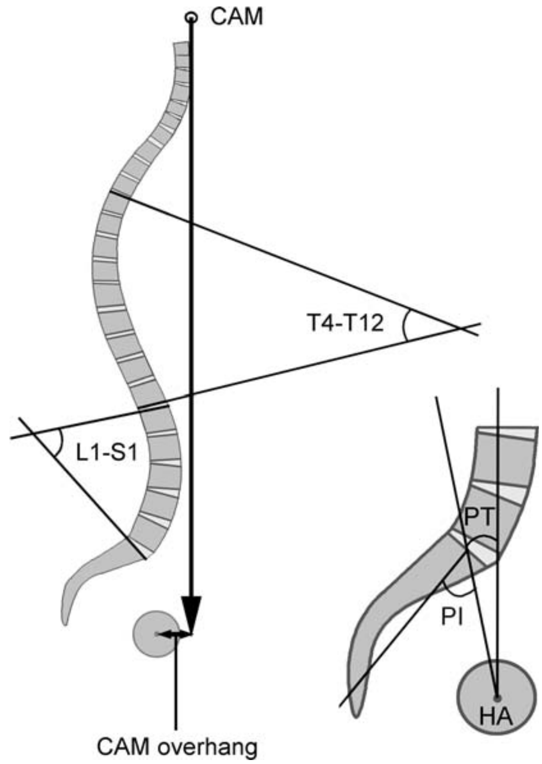

Fig. 1 Pelvic and spinal parameters. *CAM* center of both acoustic meati, *PT* pelvic tilt, *PI* pelvic incidence, *T4–T12* T4–T12 thoracic kyphosis, *L1–S1* L1–S1 lumbar lordosis, *HA* hip axis

Pelvic incidence (PI) Angle in degrees between the line perpendicular to the sacral endplate at its midpoint and the line joining the middle of the sacral endplate to the HA. The PI is a morphological parameter which represents the pelvic shape, and has a mean value of 55 ± 11° [23]. In asymptomatic subjects, the PI is strongly correlated with other spino-pelvic parameters, such as pelvic tilt, sacral slope, lumbar lordosis, and thoracic kyphosis. Subjects with a high PI have marked sagittal spinal curvatures, i.e., high lumbar lordosis and thoracic kyphosis, with high pelvic tilt and sacral slope.

Pelvic tilt (PT) Angle in degrees between the vertical line passing through the HA and the line joining the HA to the center of the sacral endplate. The PT is positive when the center of the sacral endplate projects backwards from the HA and is negative when the center of the sacral endplate projects forwards from the HA. Its mean value is 13 ± 6° [23]. This parameter represents the spatial position of the pelvis and particularly its rotation around the femoral heads. An increase in PT in an upright position represents a pelvic retroversion, which allows the subject to compensate a sagittal kyphotic deformity of the spine in order to preserve the trunk sagittal balance. PT is closely correlated to the value of PI. Vialle et al. [23] showed that the theoretical normal value can be estimated using the following equation:

$tPT = 0.37PI - 7$ (tPT = theoretical normal pelvic tilt)

Lumbar L1–S1 lordosis Angle in degrees measured using the Cobb technique between the L1 superior endplate and the sacral endplate. This angle is negative when the segment is in lordosis and positive in case of kyphosis. The mean value is $-62 \pm 10°$. L1–S1 lordosis is closely correlated to the value of PI. Its theoretical normal value can be estimated using the following equation (Gille O, PhD Thesis, Ecole Nationale Supérieure des Arts et Métiers, Paris, 2006):

$$tL1S1 = 0.54PI + 32.56$$

($tL1S1$ = theoretical normal L1-S1 lumbar lordosis)

Thoracic T4–T12 kyphosis Angle in degrees measured using Cobb's technique between T4 superior endplate and the T12 inferior endplate. This angle is positive when the segment is in kyphosis and negative in the case of lordosis. The mean value is $39 \pm 10°$ [23].

Natural history of the sagittal imbalance

A subject in an upright position can maintain balance provided that the COM of the body projects onto the polygon of support. Spinal kyphotic deformity induces a forward translation of the COM of the trunk that can be countered by several compensating mechanisms. If the whole spine is fixed, as in ankylosing spondylitis, the compensating mechanisms are located at the level of the pelvis and lower limbs. The main compensating mechanism is the pelvic retroversion, which is demonstrated by increased PT. However, the spontaneous pelvic retroversion can be insufficient to maintain balance if the deformity is too great. The last means to shift the COM of the trunk backward is to flex the knees and the ankles. In this situation, the hips appear flexed, but they are actually hyperextended (Fig. 2).

If a spinal segment adjacent to the deformity is flexible, it can be involved in the compensating mechanisms. The most typical example is the lumbar degenerative kyphosis (Fig. 2b), where the thoracic spine is usually hypokyphotic (at least at the beginning of the disease). The lumbar spine is stiffened by arthritis and the thoracic spine is flexible, so that the surgical correction of the lumbar deformity is accompanied by a spontaneous restoration of the thoracic kyphosis [11], which is necessary to consider at the time of the preoperative planning.

Four types of sagittal spinal profile

Sagittal spinal profile can be described according to four types of progressively greater deformity.

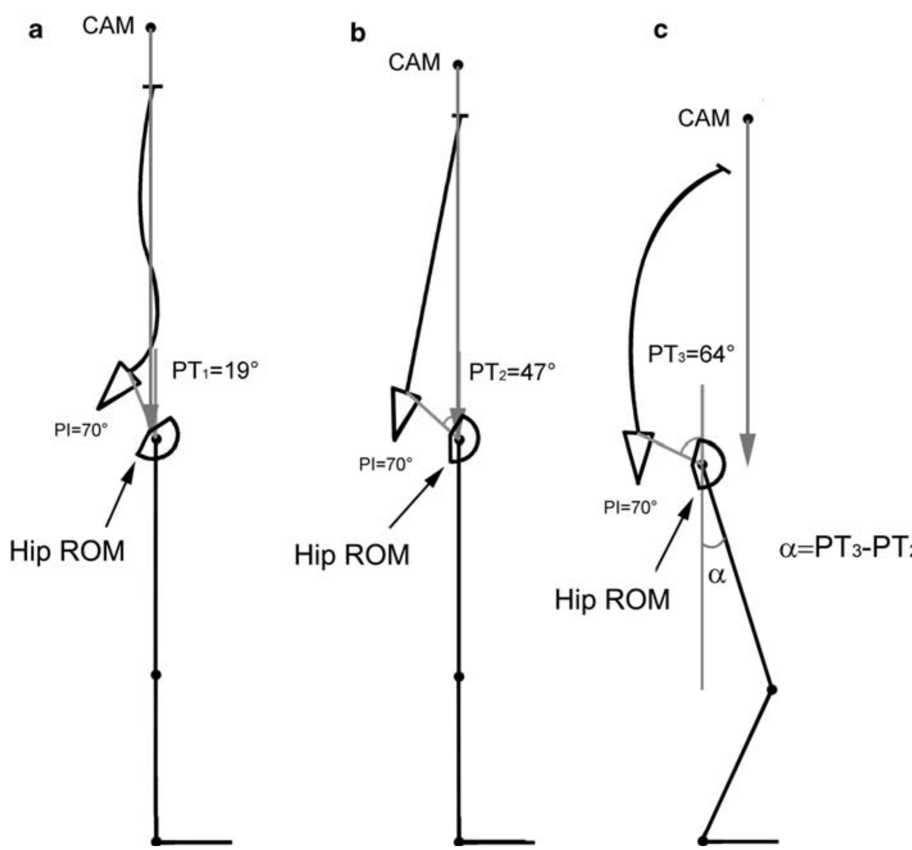

Fig. 2 Compensating mechanisms of thoracolumbar kyphotic deformities. **a** Ideal sagittal balance, **b** loss of lumbar lordosis compensated by thoracic hypokyphosis and pelvic retroversion, allowing the subject to maintain a normal CAM overhang. The pelvic retroversion induces the rotation of the hip range of motion (ROM). In this case, the upright subject has no "hip extension reserve," but his/her lower limbs are still extended. **c** Severe thoracolumbar kyphosis with sagittal trunk imbalance. The major pelvic retroversion is associated with hip hyperextension and knee and ankle flexion. If "hip extension reserve" is exhausted, the increase of PT is equal to the deviation of the femoral axis from the vertical (α). As a result, the measurement of the PT allows us to take into account the lower limb position. *Hip ROM* hip range of motion in flexion–extension, *PT* pelvic tilt, *PI* pelvic incidence

The ideal sagittal balance It is the normal profile. All the spino-pelvic parameters are normal, which means that angulations of spine curvatures and PT are in accordance with the value of the PI.

The compensated sagittal balance It is a local or regional disturbance of the sagittal spinal profile, but trunk balance is maintained (CAM overhang less than 2 cm) due to compensating mechanisms (thoracic hypokyphosis, pelvic retroversion and flexion of the knees).

The sagittal trunk imbalance It is a global disturbance of the sagittal spinal profile, which means an increase in the CAM overhang (greater than 2 cm).

The global sagittal imbalance It is a mechanical imbalance, where the subject is unable to stand without the aid of a crutch.

Surgical correction techniques

To correct a fixed sagittal imbalance there are two main alternative techniques: pedicle subtraction osteotomy (PSO) and Smith-Petersen osteotomy (SPO) (Fig. 3).

The principle of the PSO is based on resecting a posterior wedge through the pedicle and part of the vertebral body. This is accompanied by a shortening of the three columns. Closure of the osteotomy enables a mean correction of 35° in the lumbar spine and 25° in the thoracic spine [2]. However, there are variations related to the morphology of each vertebra. In particular, vertebral shape

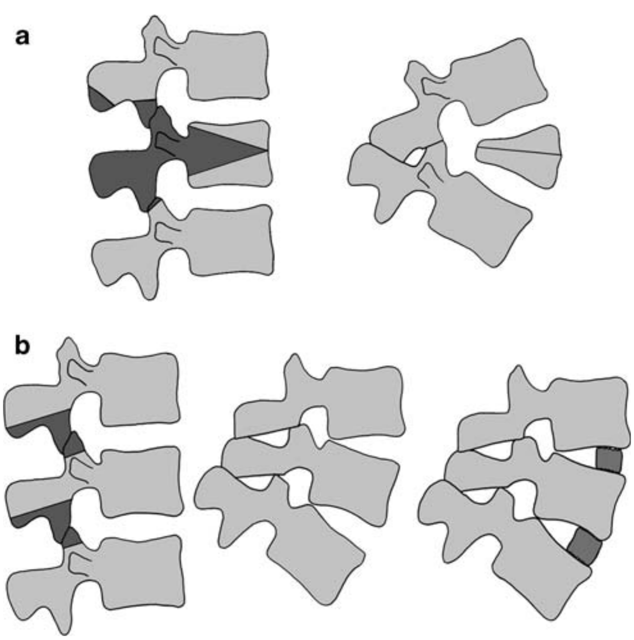

Fig. 3 Surgical correction techniques: **a** pedicle subtraction osteotomy, **b** multilevel Smith Petersen osteotomies with transforaminal lumbar interbody fusion

and height variations require a personalized analysis based on lateral X-rays to predict the postoperative result.

In most cases, a PSO can only be performed at a single vertebral level because of the risk of blood loss. In very exceptional cases, the PSO can be envisaged at two levels.

SPO, also called Chevron osteotomies, are posterior osteotomies that result in increased height of the anterior column. They consist in resecting the upper and lower articular processes at one or multiple levels. The space thus created is closed by pressing the adjacent bones together. The disk opening resulting from this type of osteotomy exposes to the risk of pseudarthrosis, which is why we systematically carry out intersomatic arthrodesis by transforaminal lumbar interbody fusion (TLIF).

Mean improvement of lordosis is 10° per level, but there are variations depending on the preoperative degree of intervertebral kyphosis. In a previous unpublished study, we established quantitative relationships between preoperative intervertebral lordosis and the potential for correction (Table 1).

In practice, it is difficult to carry out more than four levels of SPO + TLIF during the same procedure due to the risk of blood loss.

Theoretical technique of planning

Normal parameters

The first step of the planning is the definition of the normal theoretical parameters for a given subject:

- *tCAM overhang* has to be between −2 cm and 2 cm [6].
- *Pelvic tilt* depends on PI according to the following equation [23]: $tPT = 0.37PI - 7$.
- *L1–S1 lumbar lordosis* depends on PI according to the following equation (Gille O, PhD Thesis, ENSAM, Paris, 2006): $tL1S1 = 0.54PI + 32.56$.

These theoretical normal parameters are distinguished from the simulated parameters, i.e., sCAM overhang, sPT and sL1S1 which represent the values that result from the planning. In other words, the normal theoretical parameters are the targets of the planning, but they cannot always be

Table 1 Values for increasing lumbar lordosis according to preoperative intervertebral angle used for planning SPO + TLIF

Preop intervertebral angle	Potential for correction with SPO + TLIF
<−10°	−5°
[−10°–0[	−10°
≥0	−15°

reached, so that the simulated parameters represent the best compromise between the ideal solution and the technical possibilities.

Hip hyperextension, knee flexion, and ankle flexion are not directly considered in the planning, since the normalization of the PT induces an automatic correction of these clinical manifestations (Fig. 2).

Choice of surgical technique

The second step is the choice of the surgical technique depending on the deformity etiology and the state of the anterior spinal column.

If disk spaces seem to be mobile after posterior release, we carry out multilevel SPO + TLIF, since they enable a more harmonious correction of the deformity. However, in patients who have already been operated on and present a very large posterior bone callus, we prefer to do a PSO so that the spinal canal only has to be reached once.

If the spine is in circumferential fusion, as in the case of ankylosing spondylitis or in some cases of postoperative flat back, we perform a PSO.

Regardless of the correction technique chosen, if a fusion of L5–S1 disk is necessary, we carry out a circumferential arthrodesis with SPO + TLIF at this level to limit the risk of lumbosacral pseudarthrosis.

General principles of the planning

The preoperative planning is based on an elementary trigonometric construction (Fig. 4). The spine is modeled as a rigid beam and different osteotomies are simulated in order to normalize the spino-pelvic parameters (PT and CAM overhang). First, the compensated balance is reproduced by normalizing the CAM overhang up to the target of −2 cm. Second, if it is surgically feasible, either the PSO angle or the number of SPO + TLIF is increased until the PT angulation is normalized.

Adjustments of the method

In case of ankylosis spondylitis or flat-back after extensive arthrodesis, the spine can be considered a solid beam and the trigonometric construction is a model which is theoretically close to reality. If the thoracic spine is flexible, like in lumbar degenerative kyphosis, this model requires some modifications. The spontaneous increase of thoracic kyphosis, which is induced by the correction of lumbar lordosis, has to be considered [11]. Figure 5 shows that if the thoracic spine is flexible, PT is underestimated by the trigonometric construction, thus exposing the risk of undercorrection. In other words, simulated PT (sPT) is an underestimation of postop PT. For this reason, in this case, the correction targets of the planning are not only the

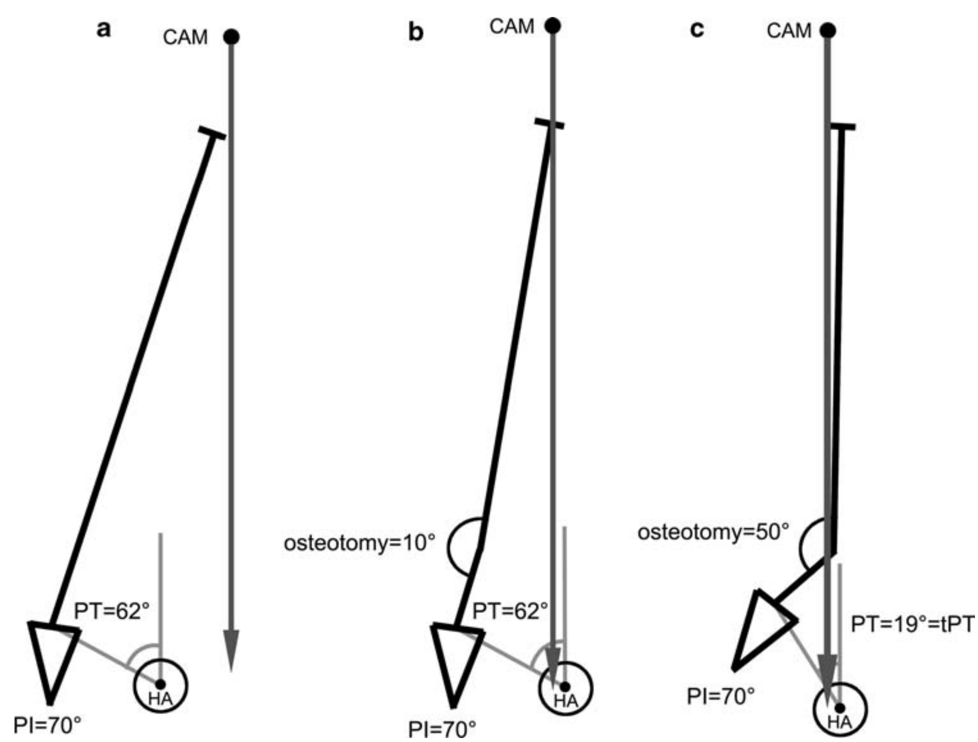

Fig. 4 General principles of the planning are based on a trigonometric construction. **a** Sagittal trunk imbalance. The PI is equal to 70° and the PT is equal to 62°. According to the PI angle, the PT should be equal to 19° (tPT = 0.37PI − 7). **b** Normalization of the CAM overhang due to a 10° osteotomy at a given level. **c** At the same level, a correction angle equal to 50° would be required to normalize the PT. *CAM* center of both acoustic meati, *PT* pelvic tilt, *PI* pelvic incidence, *HA* hip axis

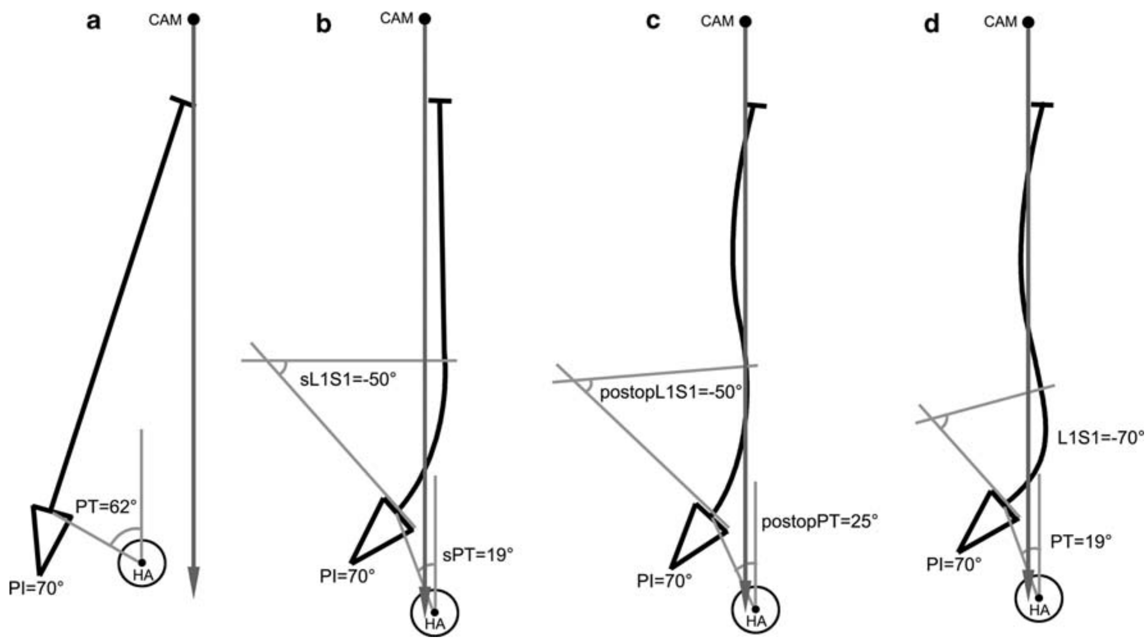

Fig. 5 Preoperative planning if the thoracic spine is flexible. **a** Flat back deformity with sagittal trunk imbalance. IP = 70° → tPT = 19°, tL1S1 = 70°. **b** Preoperative planning according to the trigonometric construction: spino-pelvic balance could be restored by increasing the L1–S1 lordosis to 50° (sL1S1 = 50°). However, this plan is reliable only if the thoracic spine is fused. **c** Postoperative results if the thoracic spine is flexible: the thoracic kyphosis increases and the PT is greater than the planned value, leading to a compensated balance (postop PT > sPT). **d** Ideal sagittal balance is restored by increasing L1–S1 lordosis to its normal theoretical value. *CAM* center of both acoustic meati, *PT* pelvic tilt, *PI* pelvic incidence, *L1S1* L1–S1 lumbar lordosis, *HA* hip axis

normalization of the CAM overhang and the PT, but also the normalization of the L1–S1 lordosis.

Computerized planning technique

The theoretical planning we have described considers numerous parameters: the surgical parameters, i.e., osteotomy number, osteotomy level(s), osteotomy angulation(s), and the morphological parameters, i.e., CAM overhang, PT, and L1–S1 lumbar lordosis. In clinical practice, the use of dedicated computer software is the only means to assess the variations of all morphological parameters according to the modifications of surgical parameters.

The osteotomy version of the SpineView 2.0 software (Surgiview, Paris, France) [3, 17] is based on the quantification of the vertebral body position and calculation of parameters from a full-spine lateral radiograph that includes the CAM and proximal femurs. This software enables simulations of various configurations by varying the level of the envisaged osteotomies, the angle of the envisaged osteotomies, and the PT. The variations of the other parameters including CAM overhang and L1–S1 lumbar lordosis can be visualized in real time.

Each analysis requires different steps (Figs. 6, 7):

1. *anatomic landmarks identification on a digital X-ray film and calibration of the distances,*
2. *automatic edge detection of the vertebra*,
3. *validation of the edge detection after visual control and manual correction*,
4. *calculation of parameters* with regard to the identified contours,
5. *normalization of the PT,*
6. *simulation of osteotomies in order to normalize the CAM overhang*: PSO is simulated by choosing the vertebral level and by modifying the osteotomy angle in real time with a cursor. The maximum angle of the osteotomy can be visualized on the 2D-reconstruction according to the shape and the height of the chosen vertebra. Multilevel SPO + TLIF are simulated by choosing up to four intervertebral levels. Step 4 enables the user to easily obtain the preoperative intervertebral angle at each level and to estimate correction angles, which are inferred from Table 1,
7. *simulation of the final balance:* After testing different alternatives, the solution that gives the closest balance to the ideal balance is chosen for the surgical procedure. If ideal balance is impossible despite the optimal correction, the PT is increased in order to restore the trunk balance by putting the CAM overhang at −2 cm.

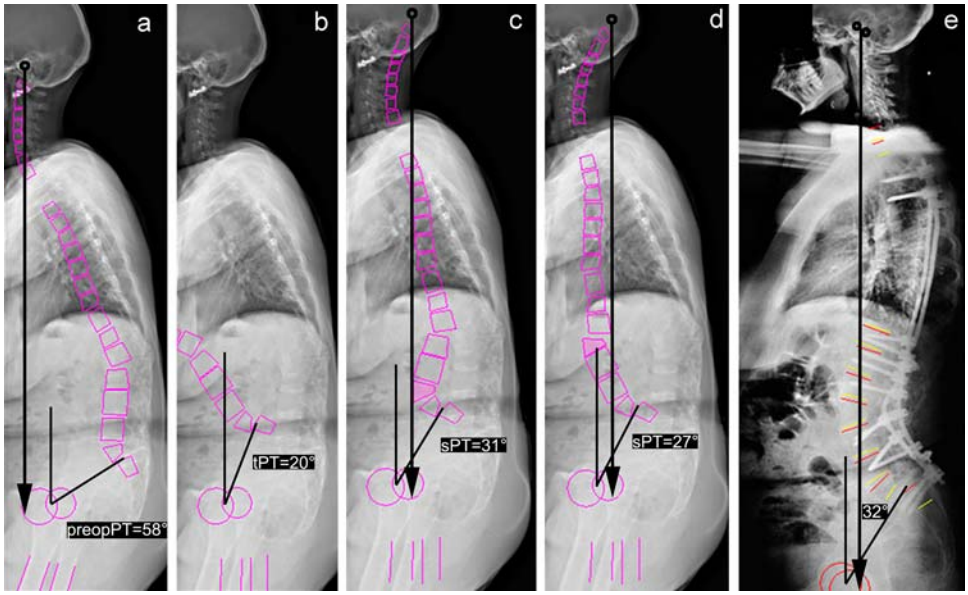

Fig. 6 Computerized planning in flat back deformity after T3–S1 arthrodesis (patient no. 11). The spine is considered as a rigid beam. PI = 72° → tPT = 20°. **a** Preoperative sagittal trunk imbalance (CAM overhang = 38 mm). **b** Normalization of PT (sPT = tPT = 20°): the sagittal trunk imbalance is virtually increased. **c** Simulation of a PSO of −40° in L4: CAM overhang can be normalized if PT is increased to 31° (sPT = 31°). **d** Simulation of a PSO of 35° in L2, widened to disk L1–L2 which is in kyphosis of 15° (correction of 50° in total): CAM overhang can be normalized if PT is increased to 27° (sPT = 27°). This simulation was retained for the surgery since the PT is the closest to the theoretical normal value. **e** Postoperative result. *PT* pelvic tilt, *tPT* theoretical normal pelvic tilt, *sPT* simulated pelvic tilt

If the thoracic spine is flexible, the value of the sPT is an underestimation of the postop PT. As a result, if the CAM overhang is at −2 cm and the PT is normalized, the correction is still insufficient. The lumbar lordosis has to be increased as close as possible to its theoretical value.

Figure 6 shows an example of PSO planning if the thoracolumbar spine is fused.

Figure 7 shows an example of Multilevel SPO + TLIF planning if the thoracic spine is flexible.

Planning method assessment

In order to assess if the preoperative planning enables prediction of the postoperative radiological result, a prospective study of 11 patients was carried out. All patients in our department with surgery for correction of disturbances of sagittal balance, including imbalance and compensated balance, between October 2006 and March 2008 were included. The patients who presented an associated frontal imbalance and those with a neuromuscular disease such as Parkinson's disease were excluded.

For each patient, the preoperative planning of the procedure was carried out on the eve of the surgery according to the method described above.

All the full spine lateral radiographs were performed under the same conditions: patient standing in a comfortable position, feet together, with upper limb on a vertical support to maintain the shoulders forward, and clear exposure of the thoracic spine. Patients were systematically instructed not to exert any force with the upper limb. No instruction was given concerning hip and knee position.

The X-rays were digitized with a Vidar™ type drum scanner—model VXR12—at a resolution of 150 dpi, using a 12-bit depth of gray level. 2D treatment of the image was carried out using SpineView 2.0 software (Surgiview, Paris, France). The lateral postoperative X-rays were analyzed at a minimum follow-up of 3 months using the same protocol. Postoperative data were compared with planned data.

As described above, the planning method is slightly modified if the thoracic spine is flexible. In this case, the sPT is an underestimation of the postop PT and the normal theoretical L1–S1 lordosis is introduced as a planning parameter. As a result, the assessment of the technique requires two separate groups:

Group 1 included patients in which the spine could be considered a solid beam. In this group, the postoperative results were in accordance with the preoperative planning if the following two criteria were present:

- Postop CAM overhang less than or equal to 2 cm
- Difference between postop PT and sPT less than or equal to 5°.

Group 2 included patients in which the thoracic spine was flexible (no fusion above T10). In this group, the

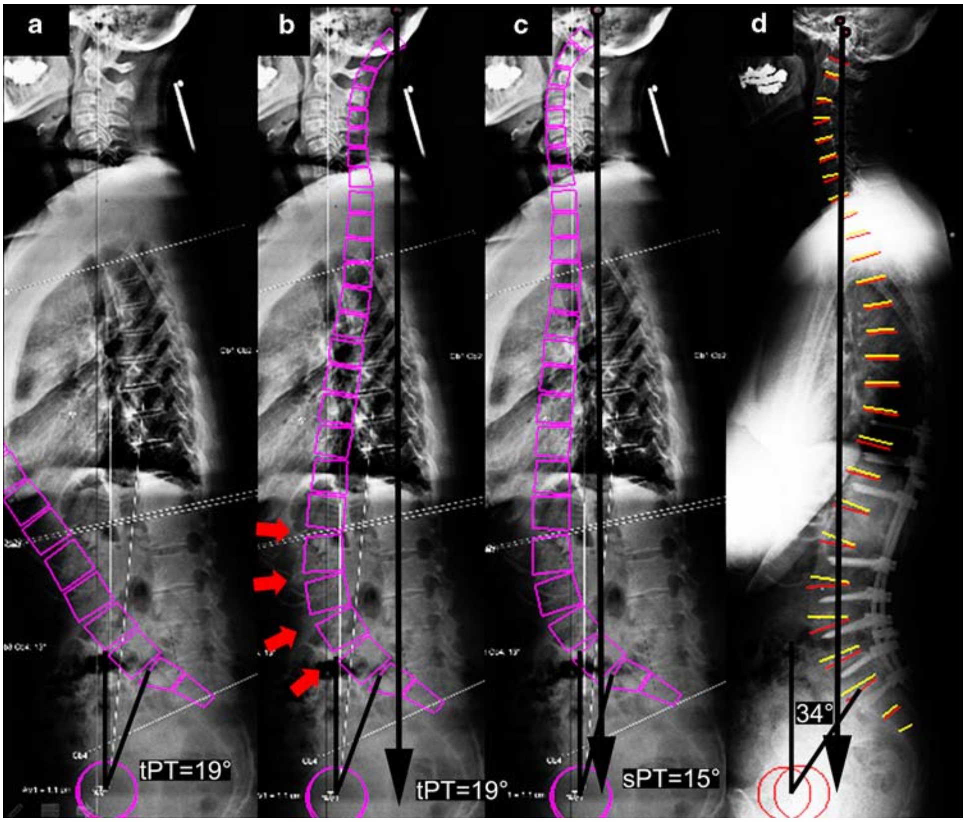

Fig. 7 Computerized planning in lumbar degenerative kyphosis (patient no. 5). The thoracic spine is flexible. PI = 71° → tPT = 19°, tL1–S1 = −70°. **a** Normalization of PT (sPT = tPT = 19°): the sagittal trunk imbalance is virtually increased. **b** Simulation of multilevel SPO + TLIF. L5–S1 is sacralized and the preoperative intervertebral lordosis are −3° in L4–L5, −4° in L3–L4, +2° in L2–L3 and −3° in L1–L2. According to Table 1, the correction angles can be estimated as follows: −10° in L4–L5, −10° in L3–L4, −15° in L2–L3 and −10° in L1–L2. With these values, sL1–S1 is equal to −58°, which is still less than tL1S1 but we usually do not perform more than 4 levels of SPO + TLIF. **c** sPT is reduced to 15° in order to normalize the CAM overhang. sPT is then an underestimation of the postop PT because of the potential increase in thoracic kyphosis. (**d**) Postoperative result. *tPT* theoretical normal pelvic tilt, *sPT* simulated pelvic tilt, tL1–S1 theoretical normal L1–S1 lordosis, *sL1–S1* simulated L1–S1 lordosis

postoperative results were in accordance with the preoperative planning if the following three criteria were present:

- Postop CAM overhang less than or equal to 2 cm.
- Postop PT greater than or equal to sPT.
- Difference between postoperative lumbar lordosis (postop L1–S1) and simulated lumbar L1–S1 lordosis (sL1–S1) less than or equal to 10°.

Results

Eleven patients were included in our study: 9 women and 2 men with a mean age of 53.8 years (36–73). In all cases, the surgical procedure was performed in accordance with the planned number and level of the osteotomies.

Five of the 11 patients belonged to Group 1: 1 patient presented an ankylosing spondylitis and 4 patients presented a prior history of extensive thoraco-lumbar arthrodesis. The results of the plan for this group are summarized in Table 2. In all, 5 SPO + TLIF were carried out in two patients and 4 PSO in three patients (T10, L2, L3, and L4). The mean decrease of CAM overhang was 38 ± 20 mm and the mean decrease of PT was 18.6 ± 7.2°. On average, the difference between postop CAM overhang and sCAM overhang was 38 ± 54 mm, and the difference between postop PT and sPT was 3.2 ± 1.6°. Individually, postoperative results were in accordance with the preoperative planning in four cases and were conflicting with the planning in one case. In this case (patient no. 6), the CAM overhang was still much greater than 2 cm even though two PSOs were carried out (one in L3 and the other in T10). We noticed that the angulation of each osteotomy was less than the value predicted by the planning. In Group 1 (with the exception of patient no. 6, for whom a T10 PSO was carried out), thoracic T4T12 kyphosis had slight variation, if any at all. The maximum variation reached 12° for patient no. 1 who had a prior history of T6–L4 arthrodesis.

The other six patients belonged to Group 2. Three patients had lumbar degenerative kyphosis without prior history of spinal surgery and three patients presented a prior history of localized lumbar arthrodesis. The results of the plan for this group are summarized in Table 3. In all, 20 SPO + TLIF and 1 PSO (L3) were carried out. The mean decrease in CAM overhang was 26 ± 49 mm. The mean decrease in PT was 17.8 ± 5.8° and the mean increase in L1–S1 lumbar lordosis was 46.5 ± 6.5°. On average, the difference between postop CAM overhang and sCAM overhang was 27 ± 21 mm; the difference between postop PT and sPT was 10.2 ± 7.9°; and the difference between postop L1S1 lordosis and sL1S1 lordosis was 9.2 ± 5.7°. Individually, two of the postoperative results were conflicting with the preoperative planning (patient nos. 3 and 4). For these two cases, the postoperative L1S1 lordoses were greater than the simulated lordoses by 11° in one case and 19° in the other. For patient no. 3, the CAM overhang was still greater than 2 cm and the PT was paradoxically negative (−7°). For patient no. 4, the postop PT was greater than the sPT. In group 2, the T4–T12 kyphosis increased in all cases, with a mean value of 23° (10–35°).

In all, 8 of the 11 preoperative plans were concordant with the postoperative results according to the criteria defined above. Considering the 11 patients, the mean correction of CAM overhang was 31 ± 38 mm and the mean decrease of PT was 18 ± 6°. On average, the difference between postop CAM overhang and sCAM overhang was 32 ± 38 mm, and the difference between postop PT and sPT was 7 ± 7°.

Discussion

Anterior imbalance of the trunk corresponds to an advanced spinal deformity. Surgical treatment implies significant correction, the repercussions of which are difficult to determine without detailed planning. A number of planning techniques has been described, but apart from the restricted case of ankylosing spondylitis their precision is poor. The trigonometric formula proposed by Ondra et al. [15] is based solely on normalizing the C7 plumb line and does not enable planning for global spino-pelvic sagittal balance. Furthermore, some patients presented a non-fused thoracic spine, which could not be exactly considered a solid beam. We therefore chose to distinguish two groups of patients according to flexibility of the thoracic spine and the results of our review reinforce this: the patients in group 2 presented a spontaneous increase in kyphosis of 23° on average.

Cervical lordosis can also vary spontaneously with correction of the posture deformity, but the effect on the CAM overhang is much less significant. In most cases, we therefore do not take this parameter into account in our planning method. However, it should be considered in patients who present a major anterior imbalance and whose cervical spine is flexible. In this case, the C7 plumb line or the sagittal vertical axis (SVA) can be taken as reference. The use of computer software enables us to work easily with a large number of different parameters, each of which can be of particular interest. We usually analyze the global sagittal balance of the spine on the CAM overhang, because this parameter takes into account the whole spine and the pelvis position. It is disturbed when all spino-pelvic compensating mechanisms are overstepped. Moreover, in clinical practice CAM are easily identifiable on X-rays, whereas C7 is hidden by the shoulders in 23–32% of the cases depending on arm position [9].

The SpineView program was inspired by the tracing technique described by Mangione (Vital JM, Mangione P, Pedram M, Senegas J, Oral communication, Meeting of the GRECO, Paris, 1999). This method only allowed one or two simulations per patient since a new cut out had to be made for each PSO level. Using computer software, simulation at several different levels is very quick, and it is possible to combine several corporeal or posterior

Table 2 Results of planning for Group 1 patients

Case no.	PI	Preop data		Theoretical normal values		Planned data		Postoperative data		Comparison planning versus postop results		
		Preop CAM (mm)	Preop PT	tCAM (mm)	tPT	sCAM (mm)	sPT	Postop CAM (mm)	Postop PT	Postop CAM–sCAM	Postop PT–sPT	Concordance
1	55	44	24	<20	13	−20	17	**20**	12	40	**−5**	**G**
2	46	29	36	<20	10	−20	14	**−21**	12	−1	**−2**	**G**
6	56	121	42	<20	14	−20	19	**111**	21	131	**2**	**P**
10	48	45	23	<20	11	−20	11	**−10**	13	10	**2**	**G**
11	72	38	58	<20	20	−20	27	**−14**	32	6	**5**	**G**

The concordance between the postoperative results and the preoperative planning was good (G) if the postop CAM overhang was less than or equal to 2 cm and the difference between postop PT and sPT was less than or equal to 5°

PI pelvic incidence; *tCAM* theoretical normal CAM overhang; *tPT* theoretical normal pelvic tilt; *sCAM* simulated CAM overhang; *sPT* simulated pelvic tilt; *G* good; *P* poor

Table 3 Results of planning for Group 2 patients

Case no.	PI	Preop data			Theoretical normal values			Planned data			Postoperative data			Comparison planning versus postop results			
		Preop CAM (mm)	Preop PT	Preop L1S1	tCAM (mm)	tPT	tL1S1	sCAM (mm)	sPT	sL1S1	Postop CAM (mm)	Postop PT	Postop L1S1	Postop CAM–sCAM	Postop PT–sPT	Postop L1S1–sL1S1	Concordance
3	36	−3	17	−3	<20	6	−50	−20	0	−43	**43**	−7	−54	63	**−7**	**−11**	**P**
4	64	43	47	−7	<20	17	−66	−20	26	−42	**−52**	24	−61	−32	**−2**	**−19**	**P**
5	71	5	45	−13	<20	19	−70	−20	15	−58	**−44**	34	−52	−24	**19**	**6**	**G**
7	61	0	36	−16	<20	16	−67	−20	8	−66	**−18**	15	−58	−2	**7**	**8**	**G**
8	45	0	23	−4	<20	10	−58	−20	1	−54	**8**	6	−56	28	**5**	**−2**	**G**
9	62	40	36	−9	<20	16	−66	−20	4	−59	**−7**	25	−50	13	**21**	**9**	**G**

The concordance between the postoperative results and the preoperative planning was good (G) if postop CAM overhang was less than or equal to 2 cm and postop PT was greater than sPT and the difference between postop L1–S1 lordosis and sL1–S1 lordosis was less than or equal to 10°

PI pelvic incidence; *tCAM* theoretical normal CAM overhang; *tPT* theoretical normal pelvic tilt; *tL1S1* theoretical normal L1S1 Lordosis; *sCAM simulated CAM overhang; sPT* simulated pelvic tilt; *sL1S1* simulated L1–S1 lordosis; *G* good; *P* poor

osteotomies at the same time. To our knowledge, this technique is the only one that enables planning of multi-level SPO, in a way which is extremely rapid and intuitive, making it useable in everyday clinical practice. Van Royen et al. [19, 20] described a method similar to the tracing technique, based on trigonometric calculations, which was integrated into a software program (ASKyphoplan). Spinal sagittal balance is assessed by the SVA and pelvic balance is taken into account by normalizing the sacral slope to a target mean value of 40°. These authors, who only apply their planning technique to ankylosing spondylitis also take into account maintenance of horizontality of sight level. It is a criterion that we have not mentioned in our review because only one of our patients had ankylosing spondylitis, but in this particular case where the cervical spine may be inflexible, we systematically look at the position of sight level.

The originality of our planning method is also based on the personalization of goals. Because of the considerable variations in pelvic and spinal parameters between individuals, we propose to restore a balance which is in keeping with the morphology of each patient. Several studies have shown the existence of correlations between these different parameters [1, 7, 10, 14, 22, 23]. Measuring the PI enables an estimation of the ideal values of L1–S1 lumbar lordosis and PT, even if the regression equations described, were established from healthy subjects, whose mean age was lower than the population of patients generally referred for spinal imbalance.

In our planning method, sagittal balance is defined from two parameters: CAM overhang and PT. Van Royen et al. [21] showed that slightly different instructions for posture at the time of X-ray acquisition can lead to important translation of SVA in patients with ankylosing spondylitis. Therefore, a sagittal vertical plumbline cannot individually be used to assess the sagittal balance, unless very strict procedures are used in order to control the position of the lower limb. In practice, however, these procedures are very challenging to apply and to reliably reproduce. Subjects with a severe sagittal imbalance are generally unable to stay upright without external support if their lower limbs are fully extended. By simultaneously considering PT or sacral slope and a sagittal vertical plumbline, the sagittal balance can be assessed regardless of the position of the lower limb (Fig. 2). The spinal balance cannot be reliably analyzed independently of the pelvic balance.

For most patients in our study, the simulated parameters were close to the postoperative parameters, thus demonstrating that the method is fairly reliable. The mean results are less satisfactory, but the cohort is very small and the statistical analysis has to be interpreted carefully. In Group 1, the planning conflicted with the postoperative results in one case (patient no. 6) due to a deficient surgical technique. The global sagittal balance was not restored because the angles of the 2 PSOs carried out were less than the simulated values. The postoperative CAM overhang value was still very large (111 mm), which influenced much the average values. Despite these results, planning a PSO on a globally inflexible spine is the situation where the method is the most reliable because there are few sources of error. In this scenario, the thoraco-lumbar spine behaves like a rigid beam on either side of the PSO. In the future, the development of navigation techniques for spinal surgery could be a means of performing the procedure exactly as planned [18]. In Group 2, there were more sources of planning errors because the spontaneous variation of thoracic kyphosis is difficult to predict. In the two cases where the planning was conflicting with postoperative results, the postoperative L1–S1 lordosis was much greater than the simulated lordosis, but was close to the theoretical normal value. Patient no. 4 had a postoperative sagittal balance close to the ideal value. For patient no. 3, there remained postoperative trunk sagittal imbalance with a CAM overhang of 43 mm, whereas PT was negative (−7°). Paradoxically, the pelvis was anteverted despite trunk anterior imbalance, which conflicts with our theoretical reasoning. This may be linked to poor posture at the time of the postoperative X-ray potentially caused by the patient leaning on his/her arms despite recommendations. Since this study, we have changed our acquisition protocol using the "clavicle position," which does not require external support and results in more accurate radiographic measures [9]. This can also be explained by deficiencies of the gluteal muscles, which are no longer able to retrovert the pelvis, and therefore reduce the CAM overhang. This case emphasizes that our planning does not consider muscular elements, which is nevertheless essential in the sagittal balance. The preoperative muscular assessment should also be taken into account in the preoperative planning, but methods for this remain to be defined.

Conclusion

In most cases, the theoretical planning presented in this study enables the surgeon to estimate the results of the surgical correction of sagittal deformities of the spine. As long as the limitations of the technique are well understood, all situations can be considered regardless of the etiology of the deformity or the correction technique. The best surgical procedure for a given patient can be determined, considering the global spino-pelvic sagittal balance and the individual morphological variations. In clinical practice, the SpineView software offers valuable assistance to this planning, since numerous parameters can be taken into account in a very short time.

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