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B. J. Van Royen
A. De Gast
T. H. Smit

Deformity planning for sagittal plane corrective osteotomies of the spine in ankylosing spondylitis

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B. J. Van Royen (✉) · A. De Gast
T. H. Smit
Department of Orthopaedic Surgery,
Free University Hospital,
De Boelelaan 1117,
1081 HV Amsterdam, The Netherlands
e-mail: BJ.vanRoyen@azvu.nl,
Tel.: +31-20-4444444,
Fax: +31-20-4442357

T. H. Smit
Department of Clinical Physics
and Informatics, Free University Hospital,
Amsterdam, The Netherlands

Abstract Ankylosing spondylitis (AS) may lead to a severe fixed thoracolumbar kyphotic deformity (TLKD) of the spine. In a few patients, the TLKD is so extreme that a corrective osteotomy of the spine may be considered. Several authors have reported the results of patients treated by a lumbar osteotomy, but there is no consensus on the level of the osteotomy and on the exact degree of correction required. This can be explained by the lack of quantification of the sagittal plane deformity, since compensation mechanisms of the lower extremities have to be reckoned with for the assessment of spinal sagittal balance in AS. Therefore, there is a need for a method of deformity planning for sagittal plane corrective osteotomies of the spine in AS. In this study, a biomechanical analysis and a newly developed planning procedure are presented and illustrated with two cases of AS. Sagittal balance of the spine was defined in relation to the physiologic sacral end plate angle using trigonometric terms. Nomograms were constructed to show the relationship between the correction angle, horizontal position of the C7 plumb line and the level of the spinal osteotomy. The surgical results of two patients were retrospectively analyzed with our method. It showed that the effect of a spinal osteotomy on the horizontal position of the C7 plumb line depends on the combination of correction angle and the level of osteotomy. In one patient, the achieved correction of the deformity proved to correct the sagittal spinal balance and the pelvic sacral endplate angle. In the other patient, the achieved correction was not sufficient. It is concluded that adequate deformity planning for sagittal plane corrective osteotomies of the spine in AS is essential for reliable prediction of the effect of a lumbar osteotomy on the correction of the spine.

Key words Ankylosing spondylitis · Osteotomy · Spine · Methods

Introduction

In ankylosing spondylitis (AS), the spine becomes a rigid beam of bone from the occiput down to the sacrum. With few exceptions, AS also leads to a rigid thoracolumbar kyphotic deformity (TLKD). Consequently, the patient stands in a stooped position and is not able to see the horizon (Fig. 1 A). Due to the downward view, the face makes an angle with the vertical, the 'chin-brow to vertical angle' [13]. In order to reduce the chin-brow to vertical angle (CBVA) and to maintain sagittal balance during standing, the patient rotates their pelvis backward, extends their hips, and flexes their knees and ankles [3]. This results in a fatiguing standing position (Fig. 1 B).

Surgical correction of the TLKD by an extending osteotomy of the spine may be considered. The goal of such a surgical procedure is to restore both the patients' capac-

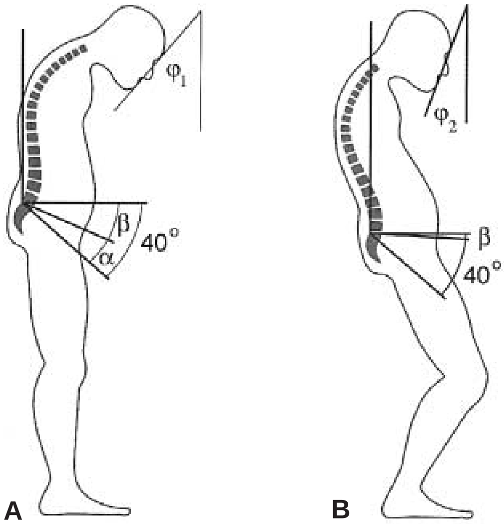

Fig. 1A, B Method of measurement of the chin-brow to vertical angle (CBVA) and the sacral endplate angle (SEA) in a patient with ankylosing spondylitis (AS). CBVA-correction = ($\varphi_1 - \varphi_2$); SEA = $\beta = 40° - \alpha$. The overall correction φ needed to correct thoracolumbar kyphotic deformity (TLKD) in a patient is determined by the sum of the CBVA correction and the deviation of the SEA from 40°: $\varphi = (\varphi_1 - \varphi_2) + \alpha$. Note that in the position with corrected CBVA (**B**), the overall correction φ can be measured by $\varphi = 40° - \beta = \alpha$, where β has a negative angle above, and a positive angle below the horizontal

ity to see the horizon, as well as the sagittal balance of the ankylosed spine, so the legs can remain straight in normal standing and little muscular effort is needed to balance the spine. Although a correction osteotomy is possible at different levels of the spine, the procedure is most often performed in the lumbar spine [16]. Several authors have reported the results of numerous patients treated by a lumbar osteotomy, but there is no consensus on the appropriate level of the osteotomy nor on the exact degree of correction required [16]. This is not surprising, since a reliable predictor of the effect of such a surgical correction on the CBVA and on the sagittal balance of the spine does not exist.

Since in AS the spine is a rigid beam of bone, an osteotomy can be planned with elementary trigonometric equations. In this study, a biomechanical analysis is presented, which forms the basis for a new concept of deformity planning for sagittal plane corrective osteotomies of the spine. We also present a method to construct nomograms for individual patients to predict the effects of the level of the osteotomy and of the surgical correction angle on the sagittal balance of the spine. We retrospectively tested the model in two patients who were treated by a lumbar osteotomy at L4, with follow-ups of 4 and 6 years respectively, to determine the required correction of the spinal balance in the sagittal plane. Finally, the relationship between the achieved correction angle and sagittal spinal balance is discussed.

Biomechanical analysis

Three aspects concerning the analysis of TLKD due to AS need further explanation: the sacral endplate angle, the plumb line from the center of the body of the seventh cervical vertebra (C7), and the chin-brow to vertical angle (CBVA).

The sacral endplate angle

The spatial orientation of the sacrum relative to the lumbar spine has been the subject of many studies [4, 7, 9, 10,15]. In healthy persons, the sacral endplate (i.e., the superior surface of the sacrum) makes an average angle of approximately 40° with the horizontal on a standing lateral radiographic projection [7, 9, 12,15]. This angle is referred to as the sacral endplate angle (SEA) (Fig. 3). According to the literature, we considered this average SEA in healthy persons as normal. With the normal SEA of 40°, small movements of the pelvis in the hip joints and spine suffice to compensate for small distortions of sagittal balance. Furthermore, with a normal SEA the hip joints are not in full extension (which is their end position), thus allowing for these compensatory movements of the pelvis. Simultaneously, small compensatory movements of the spine are possible. These compensatory movements of the hips and spine are necessary not only during activities such as walking on a slope and carrying weights, but also in cases of muscular imbalance and especially in spinal sagittal plane deformities. Due to thoracic hyperkyphosis and loss of lumbar lordosis in AS, the center of mass (COM) of the trunk shifts forward. To keep the trunk balanced over the femoral heads, the pelvis has to rotate backwards, thereby reducing the SEA. This backward rotation of the pelvis forces the hip joints into a more extended position. Consequently, less hip extension is available to compensate for additional disturbances of sagittal balance.

The sagittal vertical axis

In upright position, a plumb line from the collective COM of trunk, head, upper extremities and any external weight must intersect the connective axis between the femoral heads and the supporting area of the feet. Obviously, the exact position of the COM depends on the distribution of mass, and thus on the shape of the spine, the distribution of fat, muscles and bowels, and the position of head and arms. In clinical practice, it is not feasible to determine the exact position of the COM. Moreover, it is impossible to assess the COM on a lateral photograph or on a lateral radiograph. Therefore, for practical reasons, sagittal balance has to be expressed in terms of a predetermined vertical axis. In our analysis, we use the plumb line from the center of the vertebral body of C7, which can be drawn on a standing full-length lateral radiograph of the spine. The horizontal distance between the posterior edge of the sacral endplate and the plumb line from C7 is referred to as the sagittal vertical axis (SVA) of the spine. Normally, the C7 plumb line roughly intersects the posterior edge of the sacral endplate [5, 8, 9, 12,21]. The SVA does not depend on the inclination of the sacral endplate [9], and thus is a good measure for sagittal balance of the spine in healthy persons.

The chin-brow to vertical angle

Amongst other noninvasive measurements [20], TLKD can be assessed by the chin-brow to vertical angle (CBVA) [13,17]. Functional restoration of the CBVA is of utmost importance. The CBVA correction needed is assessed by measuring the CBVA in two positions. First, in relaxed standing position with hips and knees extended (Fig. 1A). Then, it is measured again after the patient is asked to restore the CBVA to as close to normal as possible. The patient is encouraged to flex the knees and extend the hip joints (Fig. 1B).

Materials and methods

Mathematical analysis

The total amount of correction needed in the lumbar spine (referred to as the correction angle φ) is determined by the sum of the corrected CBVA and the deviation of SEA from 40° (Fig. 1). We used a Cartesian co-ordinate system to represent the ankylosed spine with SEA at 40° to the x-axis (Fig. 2). Mathematical analysis was performed using elementary trigonometric equations (Appendix). From this analysis, a nomogram was constructed to show the relationship between the level of spinal osteotomy, the angle of correction needed, and the SVA. Such nomograms can be constructed for any patient with TLKD attributable to AS.

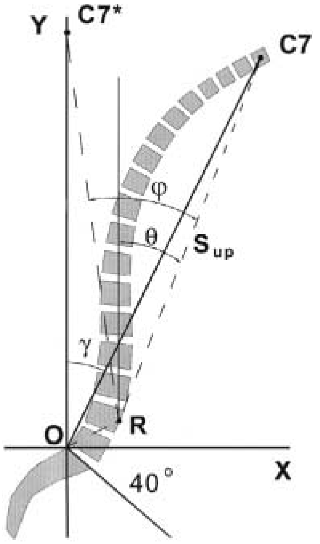

Fig. 2 Mathematical deformity planning for sagittal plane corrective osteotomy of the spine in AS. For details see Appendix. C7 denotes the position of the seventh cervical vertebra preoperatively. After correction over an angle φ around point R, this vertebra moves to C7*. Note that in this example a closing-wedge osteotomy is chosen at L4, and that SVA is planned at $x_{C7*} = 0$ mm. Angle π is defined as the angle between the part of the spine above R (S_{up}) and the vertical line through R. Angle γ is a measure of the severity of the TLKD in AS

Patients

We studied two patients with TLKD resulting from AS, who were treated by a lumbar osteotomy, i.e., a closing-wedge posterior osteotomy with partial corporectomy of L4 (Table 1). Both patients have been reported previously [18] and both had at least one standing full-length lateral radiograph of the spine taken preoperatively and one taken at 4 and 6 years follow-up respectively. The hip function was not affected. At follow-up, both patients were satisfied with the clinical result; their horizontal gaze was restored. In this study, the results were retrospectively and objectively re-assessed. For this purpose, our mathematical method was implemented on the pre- and postoperative radiographs. First, the deviation of SEA from 40° (α) was measured on the standing full-length lateral radiograph of the spine (Fig. 3A). The grid of the film was used as a reference for the vertical and the horizontal. Second, to assess the TLKD, the standing full-length lateral radiographs of the patients were digitized (Linotype-Hell flatbed scanner, Heidelberg CPS Americas, McClean Va., USA; PowerMac 7600/120, Apple Computer Inc. Cupertino, Calif., USA). These digitized images were projected onto the co-ordinate system with the origin (O) at the posterior edge of the sacral endplate, and rotated in such a way that the SEA was 40° (Fig. 3B). Measurements were calibrated with respect to the 50-mm grid of the radiograph. The resolution of the scanned radiograph proved to be less than 0.3 mm. The SVA was measured by the horizontal distance between the

Table 1 Mathematical parameters of the two patients who underwent a lumbar osteotomy at L4 for thoracolumbar kyphotic deformity (TLKD) due to ankylosing spondylitis (AS). For detailed explanations of abbreviations see Appendix and Fig. 2. (*FU* follow-up, *SEA* sacral endplate angle; *SVA* horizontal distance between the posterior edge of the sacral endplate and the plumb line from C7)

	Patient 1	Patient 2
Age at operation	46	44
Sex	M	M
Surgical correction φ L4 (°)	30	23
Loss of correction at FU (°)	0	4
SEA preop. (°)	25.2	5.3
SEA at FU (°)	37.3	10.5
SEA correction (°)	12.1	5.2
SVA preop. (mm)	264.9	358.3
SVA predicted postop. (mm)	78.6	217.7
SVA at FU (mm)	65.9	260.7
SVA difference (mm)	–12.7	43.3
Y_{C7} pre-op. (mm)	348.7	334.6
Y_{C7} follow-up (mm)	432.5	385.4
Increase of length (Y) at FU	83.8	50.8
γ preop. (°)	37.2	47.0
γ at FU (°)	8.7	34.1
X_R L4 preop.(mm)	57.5	62.8
Y_R L4 at FU (mm)	31.5	36.4
Thoracic kyphosis preop. (°)	61	74
Thoracic kyphosis at FU (°)	65	75
Length (S) upper segment (mm)	393.4	439.4

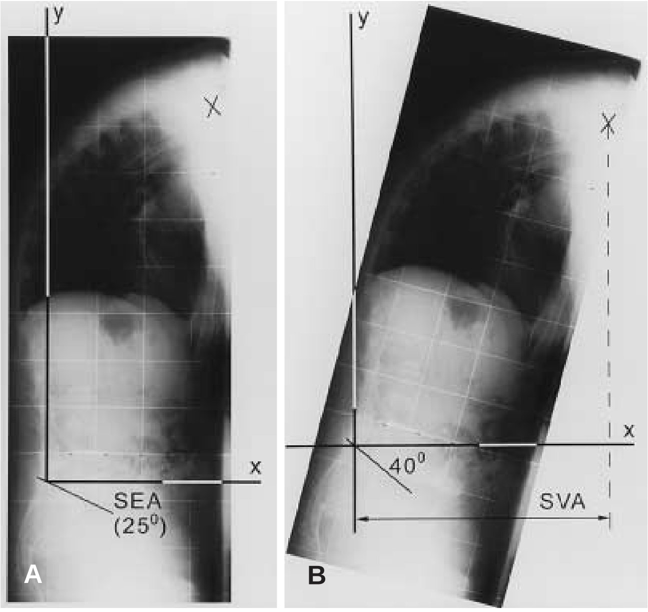

Fig. 3A, B The two basic steps involved in deformity analysis. First, the patient stands relaxed with extended knees and a standard full-length standing lateral radiograph of the whole spine with the center of C7 and SEA is made and digitized. (**A**) On this radiograph the deviation of SEA from 40° (40°–β = α) is measured with the grid of the film used as a reference for vertical (40°–25° = 15°, see Fig. 1). Second, the radiograph is projected onto the co-ordinate system with the SEA at 40° (**B**). The pre-operative SVA is measured by the horizontal distance between the posterior edge of the sacral endplate and the plumb line from C7. The SVA is expressed in millimeters on a scale with a 1-mm division. The osteotomy angle φ and the SEA are expressed in degrees, on a scale with a 1° division

posterior edge of the sacral endplate and the plumb line from C7. The same steps were performed for the deformity assessment preoperatively, postoperatively, and at final follow-up. The achieved surgical correction in the lumbar spine (φ) was determined on the direct postoperative lateral radiograph of the lumbar spine by measuring the Cobb angle between the vertebral bodies adjacent to the osteotomy. The same procedure was performed at latest follow-up. With the use of the postoperatively achieved angle φ, a nomogram was constructed and the predicted correction of SVA was calculated. The predicted correction of SVA was compared to the actual correction of SVA at follow-up. In order to quantify the consequences of deviations from the planned correction angle during surgery on the SVA, the theoretical SVA is plotted as a function of the correction angle. This provides a better understanding of the need for accuracy of the assessment and the surgical treatment of TLKD due to AS.

Results

For the mathematical equations see Appendix and Figs. 1 and Fig. 2. From the constructed nomograms, a general trend can be identified. The effect of a spinal osteotomy on the horizontal position of the SVA depends on the combination of the correction angle φ and the level of osteotomy. For example, to achieve a certain decrease in the SVA, a smaller correction angle φ is needed if the osteotomy is performed at a lower spinal level.

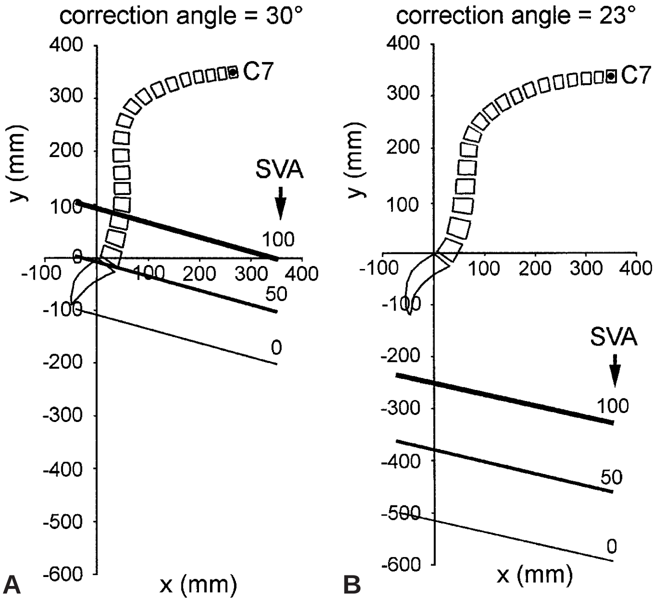

Fig. 4 Nomograms constructed from the mathematical model for case 1 (**A**) and case 2 (**B**) are shown for the sagittal spine. These nomograms illustrate the combined effects of the achieved correction angle φ and the level of osteotomy on the amount of SVA displacement. A drawing of the patient's lateral radiograph is projected onto the nomogram with the SEA at 40°. The intersection point of the line, described by Eq. 7 (Appendix), and the anterior edge of the spinal column is the theoretical optimum for a closing-wedge osteotomy. For an opening-wedge osteotomy, the intersection of this line with the posterior edge of the vertebral column is used

The preoperative, predicted and actual measurements of the mathematical parameters in two clinical cases are shown in Table 1. For the patient's nomograms see Fig. 4. These nomograms illustrate the combined effects of the achieved correction angle φ and level of the osteotomy on the amount of SVA correction. In the first case (case 1), the SEA normalized after the lumbar osteotomy. The actual decrease in the SVA was 199 mm, resulting in a final SVA of 66 mm at follow-up. In the second case (case 2), the SEA increased marginally after the extending lumbar osteotomy. The actual SVA decreased 97.6 mm, resulting in an SVA of 260.7 mm at follow-up.

The relationship between the SVA and the correction angle φ is calculated for both cases, and is shown in Fig. 5. Note that this graph is case-related and depends on the level of the osteotomy. Here, both osteotomies were performed at L4. Although the graph does not show a perfect straight line, it shows that per degree of correction (φ), the SVA decreases by approximately 6 mm.

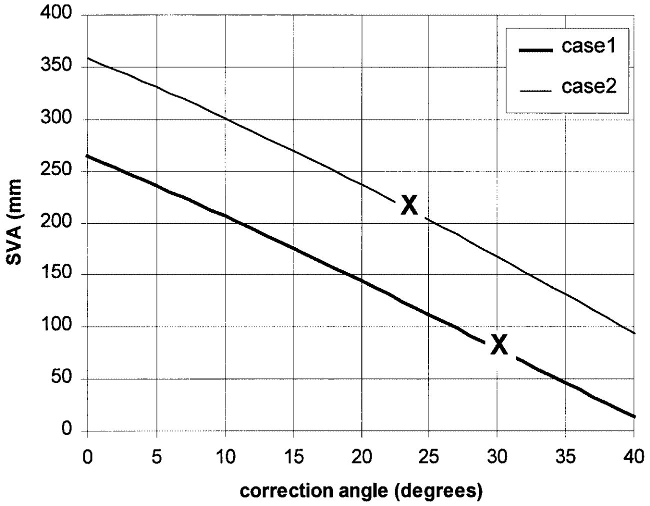

Fig. 5 The relation between the correction angle φ (degrees) and the SVA (mm) for both cases is discussed in the text. The figure is constructed for an osteotomy as performed at level L4. Correction angle φ = 0 stands for SVA preoperatively. The achieved SVA postoperatively is marked *X* for both patients

Table 2 Guidelines for preoperative deformity planning in AS

Step 1. Assessment of the correction angle (φ)

Measure clinically the chin-brow vertical angle (CBVA) in relaxed standing position with hips and knees extended (φ_1).

Repeat this measurement when the patient is asked to restore the CBVA to as close to normal as possible (φ_2). Calculate the CBVA-correction = ($\varphi_1 - \varphi_2$)

Make a standard full-length lateral radiograph of the whole spine with the patient in relaxed standing position. On this radiograph, measure the deviation of SEA from 40° (α) with the grid of the film used as a reference for vertical.

The overall correction φ needed to correct TLKD in a patient is determined by the sum of the CBVA correction and the deviation of the SEA from 40° [$\varphi = (\varphi_1 - \varphi_2) + \alpha$].

Step 2. Assessment of the sagittal plane deformity by the SVA

Digitize the standing full-length lateral radiograph.

Project the digitized image onto the co-ordinate system with the origin (O) at the posterior edge of the sacral endplate in such a way that SEA is 40°.

The horizontal distance between the posterior edge of the sacral endplate and the plumb line from C7 measures the preoperative SVA expressed in millimeters with respect to the 50-mm grid of the radiograph.

The position of the center of the vertebral body of C7 then is given by (x_{C7}, y_{C7}).

Step 3. Preoperative deformity planning

Determine point R with co-ordinates (x_R, y_R) on the lumbar vertebra, around which the upper part of the spine rotates posteriorly after a closing- or opening-wedge osteotomy.

Knowing the position of C7 and R, and having chosen the correction angle φ, Eq. 6 allows the calculation of the resulting SVA.

For every combination of x_{C7}* and φ, a series of rotation points R on a line satisfies Eq. 7, and nomograms can be constructed to determine the best level of correction for each desirable φ and SVA.

Discussion

The most important result to emerge from this study is that our method makes it possible to quantify the severity of the TLKD by assessing the disturbance of sagittal balance. New in our study is the combined use of the CBVA and the SEA as biomechanical parameters. With the use of these parameters, a mathematical method was developed for deformity planning for sagittal plane corrective osteotomies of the spine in AS (Table 2).

In the past, numerous patients with TLKD caused by AS were treated by lumbar osteotomies. As to be expected, these osteotomies alter the sagittal balance of the spine. To predict the effect of a lumbar osteotomy on the correction of the sagittal plane deformity, the clinician needs an accurate preoperative assessment of TLKD. However, methods for such an assessment do not exist [16]. Several authors have tried to quantify normal and abnormal sagittal spinal balance on standing lateral full-length radiographs of the spine [1, 5, 8, 9, 12,21]. It should be noted, however, that these studies deal with subjects with normal spinal segmental mobility. Thus, disturbances of sagittal balance can be compensated for by segmental movements within the spine. Naturally, in patients with AS, this is not possible; they rely on compensatory movements in the hip, knee, and ankle joints. It has been shown that compensatory movements in the lower extremities exert a strong effect on the horizontal distance between the C7 plumb line and S1 [19]. Therefore, we developed a method for deformity planning for sagittal plane corrective osteotomies of the spine in AS that renders measurements of the SVA independent from any position of the lower extremities. This was achieved by assessing the SVA on a lateral radiograph of the spine that was positioned in such a manner that the SEA was 40°, thus imitating the zero position of the hip joints [6].

Surgical correction of the spine based on the correction of the CBVA alone would restore the normal view angle, but will leave the hips in full extension. Therefore, in contrast to others [2,3], we emphasize that the amount of lumbar correction should be related to both the CBVA and the SEA.

To implement our method in practice, we retrospectively analyzed two patients treated by a closing-wedge lumbar osteotomy. In the first case (case 1), the lumbar osteotomy corrected the sagittal spinal balance with respect to the SEA and SVA. The postoperative correction of the SVA proved to be clinically sufficient without change at follow-up. The results show a decrease of the SVA of 13 mm at 6 years follow-up. For two reasons, we consider this decrease to be within the error of measurement. First, analyzing the lumbar correction angle by the

Cobb method on a lateral radiograph inherently involves errors of measurement [11]. The relation between the correction angle φ and the SVA (Fig. 5) shows that an error of measurement of approximately 2° of the postoperative correction angle φ accounts for this 13 mm difference. Second, two different kind of radiographs were used for our measurements: the postoperative degree of correction (φ) was measured on a lateral radiograph of the lumbar spine, while the SVA coordinates were measured on a standing full-length lateral radiograph. Obviously, additional errors may be assumed due to differences in projection angle. In case 2, the sagittal spinal imbalance was more severe. This imbalance was compensated by a pronounced posterior tilting of his sacrum, reducing the SEA to almost 0°. Postoperatively, the SVA and SEA were not normalized. In fact, these values matched the preoperative values of case 1. Could this result be anticipated for? With the use of our method, the answer is "yes". The nomogram of case 2 showed that with an intended correction of 23° , the osteotomy level should fall far below the sacrum (Fig. 4). Mathematically, a reduction of the SVA to 50 mm by operating at level L4 requires a 46° closing-wedge osteotomy (Fig. 5). However, with this technique, the maximum correction is anatomically limited. From an anatomical point of view, an anterior opening-wedge osteotomy [14] may be considered if the calculated angle φ proves to be over approximately 35° [16,18].

Since our method showed that restoration of sagittal spinal balance relies on precise deformity planning, there is a need for a more exact and controllable surgical procedure. For this purpose, a special measurement device has to be developed; for instance, a customized mechanical or computer-assisted goniometer that can be placed onto the transpedicular screws adjacent to the closing-wedge osteotomy prior to correction. In this way, measurement of the achieved correction angle during the closing maneuver would be possible.

The optimum postoperative SVA in patients with TLKD resulting from AS is not known. It is not likely that the ideal postoperative SVA should intersect the posterior edge of the sacral endplate, as is the case in healthy persons [5, 8, 9, 12,21]. We would expect that the optimum postoperative SVA lies anterior to S1. The explanation is as follows. In normal subjects in the upright position, the COM is positioned anterior to the SVA. In patients with a TLKD, however, the COM is positioned posterior to the SVA. Surgical correction of sagittal spinal balance means placing the COM above the line intersecting the femoral heads. Consequently, since the spine is rigid, the SVA remains anterior to S1. Therefore, to prevent over-correction of the TLKD, we suggest that the SVA is planned to lie between 50 and 100 mm anterior to S1. However, since lumbar osteotomy is sparsely performed [16], we need data based on controlled international multicenter trials to determine the optimum position of the postoperative SEA and SVA. In conclusion, our method is a strong tool to quantify TLKD due to AS. It can be used for analysis of disease progression in AS, and serves as a tool for preoperative deformity planning for sagittal plane corrective osteotomies of the spine in AS.

Appendix

Consider an ankylosed spine, the position of which is defined by the posterior edge of the sacral endplate and the center of vertebral body C7 (Fig. 2). The horizontal axis of the spinal co-ordinate system is chosen at an angle of 40° with the sacral endplate, for reasons given above. The origin of the co-ordinate system (O) is chosen at the posterior edge of the sacral endplate. The position of the center of the vertebral body of C7 then is given by (x_{C7}, y_{C7}). Consider further a point R with co-ordinates (x_R, y_R), around which the upper part of the spine rotates posteriorly after a closing- or opening-wedge osteotomy. Due to the osteotomy, the spine is divided into a lower part OR, with length S_{low}, and an upper part RC7, with length S_{up}. We further define angle θ between line RC7 and a vertical line through R.

Given (x_{C7}, y_{C7}) and (x_R, y_R), the length of the upper spine part S_{up}, and the desired correction angle φ as determined with SEA and CBVA (Fig. 1), the new co-ordinates of C7 (x_{C7}*, y_{C7}*) can be calculated with

$$x_{C7*} = x_R + S_{up} \cdot \sin(\theta - \varphi) \tag{1}$$

$$y_{C7*} = y_R + S_{up} \cdot \sin(\theta - \varphi) \tag{2}$$

As the SEA is at 40° and the origin of the co-ordinate system is at the posterior edge of the sacral endplate, x_{C7}* defines the position of SVA from C7* and therefore the sagittal balance of the spine after correction. Using

$$\sin(\theta - \varphi) \sin(\theta \cdot \cos(\varphi) - \cos(\theta) \cdot \sin(\varphi) \tag{3}$$

$$S_{up} \cdot \cos(\theta) = y_{C7} - y_R \tag{4}$$

$$S_{up} \cdot \sin(\theta) = x_{C7} - x_R \tag{5}$$

can be rewritten as

$$x_{C7}{*} = x_R + (x_{C7} - x_R) \cdot \cos(\varphi) - (y_{C7} - y_R) \cdot \sin(\varphi) \tag{6}$$

Knowing the position of C7 and R, and having chosen the correction angle φ , Eq. 6 allows the calculation of the resulting SVA. In order to find the best vertebral level for osteotomy, consider a case of AS, placed in a spinal co-ordinate system as described above (Fig. 2). For every combination of x_{C7}* and φ , a series of rotation points R on a line satisfies Eq. 6. The mathematical expression of this line can be found by rewriting Eq. 6 into

$$y_R = y_{C7} - \frac{x_R - x_{C7}{*} + (x_{C7} - x_R) \cdot \cos(\varphi)}{\sin(\varphi)} \tag{7}$$

Using Eq. 7, nomograms can be constructed to determine the best level of correction for each desirable φ and SVA (Fig. 4).

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