B. J. Van Royen
H. M. Toussaint
I. Kingma
S. D. M. Bot
M. Caspers
J. Harlaar
P. I. J. M. Wuisman

Accuracy of the sagittal vertical axis in a standing lateral radiograph as a measurement of balance in spinal deformities

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B. J. Van Royen (✉) · P. I. J. M. Wuisman
Department of Orthopaedic Surgery,
Free University Hospital,
De Boelelaan 1117,
1081 HV Amsterdam, The Netherlands
Tel.: +31-20-444 2987,
Fax: +31-20-444 2357

H. M. Toussaint · I. Kingma · S. D. M. Bot
M. Caspers
Department of Human Movement Sciences,
The Free University of Amsterdam,
Amsterdam, The Netherlands

J. Harlaar
Department of Rehabilitation Medicine,
Free University Hospital Amsterdam,
Amsterdam, The Netherlands

Abstract Sagittal balance of the spine is becoming an important issue in the assessment of the degree of spinal deformity. On a standing lateral full-length radiograph of the spine, the plumb line, or sagittal vertical axis (SVA), can be used to determine the spinal sagittal balance. In this procedure patients have to adopt a habitual standing position with the knees extended during radiographic examination, though it is not known whether small changes in the position of the lower extremities affects the location of the SVA. The purpose of the present study was to investigate the effect of postural change on shifts of the SVA, and to evaluate whether the SVA as measured on a standing full-length lateral radiograph can be used as an accurate measurement of spinal balance in clinical practice. Sagittal balance was analyzed using a patient with ankylosis of the entire spine due to ankylosing spondylitis, to eliminate segmental movement of the spine. A virtual SVA was constructed for seven different standing postures by cross-referring the coordinate systems from a standing full-length lateral radiograph of the spine with video analysis. The horizontal distance between the SVA and the ante-

rior superior corner of the sacrum was measured for each posture. Small changes in the joint angles of the lower extremities affected the SVA significantly, and resulted in the horizontal distance between the SVA and the anterior superior corner of the sacrum varying from –4.5 to +14.9 cm. High correlations were found between this distance and the joint angle of the hip ($r = -0.959$), knee ($r = -0.936$), and ankle ($r = 0.755$) ($P < 0.01$). The results of the study showed that SVA translations during standing radiographic analysis in a patient with a fixed spine depend on small changes in the hip, knee, and ankle joints. Thus, sagittal spinal (im)balance in ankylosing spondylitis can not be measured from the SVA on a standing lateral full-length radiograph of the spine unless strict procedures are developed to control for the angle of the hip, knee, and ankle joints. The accuracy of the SVA as a measurement of sagittal spinal balance in other spinal deformities, with possible additional segmental movements, therefore remains questionable.

Key words Sagittal balance · Sagittal vertical axis · Spinal deformities · Model · Human posture

Introduction

Sagittal balance of the spine is an important issue in the assessment of the degree of spinal deformities. One of the parameters to evaluate disease severity and progression in kyphosis, scoliosis, or degenerative spinal deformities in clinical practice is a standing lateral full-length radiograph of the spine. Sagittal plane balance can be determined by a vertical plumb line, the sagittal vertical axis (SVA), dropped from the most cephalad visible vertebra in this radiograph. Inclusion of measurements of the horizontal distance between the SVA and a standardized bony landmark of S1 is advised in the evaluation of results from surgical procedures and corrections for different spinal disorders [1, 4–8, 12]. It has been suggested that these measurements can serve as a procedure to determine abnormal alterations in the spinal sagittal plane balance [5, 6]. To ensure the accuracy of the SVA measurement on a standing lateral full-length radiograph of the spine, and prove the principle of using the SVA in evaluating changes of the sagittal balance in spinal deformities, it is important to examine the variables that can lead to errors and may influence the results. It is obvious that the position and inclination of the trunk in spinal deformities during examination is of paramount importance. During radiographic examination of the standing full-length lateral spine, the subject has to stand with extended knees and with the shoulder girdle and pelvis parallel in a relaxed position [11]. However, small variations in the adopted posture are still possible. A small pelvic rotation with hip hyperextension, for example, will shift the anterior superior corner of the sacrum causing a change in the horizontal distance of the SVA to the S1 vertebra [5, 6].

The purpose of this study is to determine the effect of small changes in posture on the position of the SVA in a standing lateral full-length radiograph of the spine, and to evaluate whether the SVA can be used as an accurate measurement for sagittal plane balance in spinal deformities as a proof of principle. We therefore used one patient as a model, who had a fixed spine due to ankylosing spondylitis but a normal range of motion of the hip, knee, and ankle joints. We hypothesized that if a clear effect of the independent variable (posture) on the dependent variable (outcome of the SVA procedure) can be determined, the accuracy of the SVA procedure in kyphotic deformities with a fixed spine due to ankylosing spondylitis is questionable when these postural aspects are not controlled for.

Model

To enable a true evaluation of changes in posture on the outcome of the SVA procedure, compensation of the sagittal balance by segmental movement of the entire spine should not be allowed. The range of motion of the hip, knee, and ankle joints, however, should not be restricted. An ideal model for this purpose is a patient with a fixed spinal deformity. We therefore asked a male pa-

Fig. 1 Schematic drawing. The radio opaque markers enabled cross-referring of the location of the L5-S1 marker on the radiograph to the location of the L5-S1 marker expressed in a reference frame (detail imaging on the right). The sagittal vertical axis (SVA) can be determined by constructing a plumb line from the most prominent point of the spinal process of vertebra C7. The horizontal distance (HD) is the distance in centimeters between the anterior superior corner of the sacrum (O) and the SVA

Fig. 2 Anthropometry of the subject. Measurement of seven different postures was performed during video analysis with markers on the skin

tient, age 43, height 1.58 m, body mass 68.2 kg, known to have spinal kyphosis and ankylosis due to a severe ankylosing spondylitis, to voluntarily participate in this study. Clinical examination showed no movement of the segmental spine, and there was no restriction in the range of motion of the hip, knee, and ankle joints. Standard radiographs of the whole spine showed a classic bamboo spine with complete calcification of the discs and bridging syndesmophytes.

A standard standing lateral full-length radiograph of the spine including radio-opaque markers was made. Radio-opaque markers were attached to the skin, indicating the lumbosacral joint L5-S1 [3] (marker S, Fig. 1) and the spinal process of C7 (marker C, Fig. 1). Care was taken for proper position and fixation of the long cassette film using a radio-opaque plumb line. The C7 vertebra (spinal process) was identified and a plumb line (the SVA) was constructed from the most prominent point of the spinal process of C7. The horizontal distance (HD) between the anterior superior corner of the sacrum (origin O, Fig. 1) and the SVA was measured in centimeters (Fig. 1). In order to limit the exposure to radiation, only one radiograph was made to serve as a reference for SVA analysis based on video recordings. The radio-opaque L5-S1 marker and the marker on the spinal process of C7 were both visible on the radiograph as well as on the video frames (see below). This enabled cross-referring of the coordinate system of the radiograph to the coordinate systems of the video frames. A correction was made for the deviation between the L5-S1 (S) marker and the anterior superior corner of the sacrum on the radiograph (O, Fig. 1): the hori-

Fig.3 Schematic drawing of the video-recorded joint positions of the model maintaining seven different postures. 1. Standing relaxed, 2. standing straight, 3. standing with maximal hip extension and straight legs, 4. leaning forward as far as possible, 5. leaning backward as far as possible, 6. standing with horizontal view and flexion of the knees, 7. standing with maximal extension of the knees. The whole-body balance measured simultaneously with a force plate is marked for each posture

zontal and vertical distance between the L5-S1 marker and the front corner of the sacrum was 2.7 cm and 0.9 cm, respectively. It was verified by data analysis that the position of the skin markers remained the same for all postures. On the basis of the video data a 'virtual radiograph' was constructed for seven different postures of the model, on which the SVA was determined by digitizing the *x-y* coordinates of the markers on L5-S1 and C7 (Fig. 1). The horizontal distance (HD) between SVA and the reference point (*O*) was determined. When the SVA was anterior to the reference point, the HD was assigned a positive value, and when it was posterior to this reference point the HD was assigned a negative value.

Anthropometry of the subject was performed with skin markers and video recorded (JVC SVHS, 50 Hz) for different postures (Fig. 2). White markers with contrasting black circles were placed on the skin to indicate the location of the fifth metatarsophalangeal joint, the ankle joint (the distal part of lateral malleolus), the knee joint (lateral epicondyle), the greater trochanter, the lumbosacral joint (L5-S1), the spinal process of the seventh cervical vertebra (C7), the shoulder (lateral border of the acromion), the elbow (lateral epicondyle), the hand and wrist joint (MCP-5 and ulnar styloid), and the caput mandibula [3]. In the center of the L5-S1 and C7 marker, small radio-opaque discs were attached (see above). Prior to the posture recordings, the optical field of the video camera was calibrated using a reference frame. The accuracy of the position determination of the markers was within 5 mm [16]. The lines connecting two coordinates of a marker position defined nine body segments: the feet, lower legs, upper legs, pelvis, trunk, head, upper arms, fore arms, and hands. The joint angles of the hip, knee, and ankle joints were determined by the front angle between the distal and proximal segment in degrees.

The subject had to maintain seven different postures for a few seconds, standing as motionless and symmetric as possible, during which the position of the markers was recorded. The following postures were recorded: (1) standing relaxed, the individual habitual standing posture, (2) standing straight, (3) standing with maximally extended hips and straight legs, (4) leaning forward as far as possible, (5) leaning backward as far as possible, (6) standing with flexed knees with horizontal view, and (7) standing with maximally extended knees (Fig. 3). The coordinates of the anatomical landmarks in the sagittal plane were determined by digitizing the video frames with the VidiPlus off-line marker identification system and FAMS-lab software program, using a personal computer (Commodore 486-25c) [16]. Simultaneously, static whole-body balance was assessed with a force plate by relating the point of application of the ground reaction force to the plane of support, formed by the feet.

Statistical analysis

Pearson correlation coefficients were calculated to examine the relationship between the horizontal distance to the SVA and the angles of the hip, knee, and ankle joints. Student's *t*-test was used to

examine whether the correlation coefficients were significantly different from zero. A *P*-value equal to or less than 0.05 was considered to be significant.

Results

The horizontal distance (HD) from the anterior superior corner of the sacrum to the sagittal vertical axis (SVA) observed in the seven different postures of the subject is presented in Fig. 4. The mean angles of the ankle, knee, and hip joints, measured over a few seconds, with the standard deviation, are presented in Table 1. The HD to the SVA varies from -4.5 cm (horizontal view with flexion of the knees) to +14.9 cm (weight to the front, as far as possible). Although the instructions for posture 3 (maximal hip extension, straight legs) and 7 (maximal extension of the knees) were only slightly different, the HD showed a considerable difference of 13 cm. An SVA falling posterior to the anterior superior corner of the sacrum with a negative value of the HD was found in postures with maximal hip extension (postures 3, 5, 6) (Table 1). Extension of the knee joints (postures 1, 2, 4, 7) will result in a positive value of the HD to the SVA. The correlations between the angle of the hip joint, the knee joint, the ankle joint, and the observed horizontal distance (HD) to the SVA were

Fig.4 Distribution graph for the horizontal distance between the SVA and the anterior superior corner of the sacrum for the seven different postures in the model (y-axis), measured in centimeters (x-axis). 1. Standing relaxed, 2. standing straight, 3. standing with maximal hip extension and straight legs, 4. leaning forward as far as possible, 5. leaning backward as far as possible, 6. standing with horizontal view and flexion of the knees, 7. standing with maximal extension of the knees. A positive SVA falls in front of the sacrum, and a negative SVA falls behind the sacrum

Table 1 Mean angles of the ankle, knee, and hip joints^a (in degree) with standard deviation in parentheses

Posture	Ankle angle	Knee angle	Hip angle
1	118 (0.35)	199 (0.09)	187 (0.83)
2	123 (0.67)	197 (0.26)	185 (0.61)
3	118 (1.25)	203 (0.32)	188 (1.37)
4	121 (0.73)	190 (0.19)	182 (0.46)
5	118 (0.21)	200 (0.14)	188 (0.66)
6	115 (0.54)	209 (0.15)	188 (0.29)
7	126 (0.65)	186 (0.21)	182 (0.51)

^aJoint angles were defined by the front angle between the distal and proximal segment of a joint

$r = 0.959$, $r = -0.936$, and $r = -0.755$, respectively. These correlations are statistically significant ($P < 0.05$). The range of movement of the body center of mass over the different postures, assessed by the point of application of the ground reaction force, was within 14.16 cm (Fig. 3). Excluding the two extreme postures, where the patient was asked to lean forward or backward as far as possible – postures 4 and 5 – there was a range of movement of 5.55 cm of the whole body center of mass. The correlation of the HD to the point of application of the ground reaction force is $r = 0.917$.

Discussion

Although there is a wide range of normal thoracic kyphosis and lumbar lordosis, the normal sagittal plane curves of the spine tend to balance each other such that the head, trunk, and pelvis are lined up vertically by segmental mobility [2, 5, 6, 10, 15]. Abnormalities of sagittal spinal balance are considered as an abnormal condition [1, 4–8, 14]. In spinal sagittal plane deformities, such as flat back syndrome, lumbar kyphosis, or severe thoracic kyphosis, there is a positive sagittal balance with the SVA falling in front of the sacrum. Increased hip extension is used to compensate for the forward displacement of the trunk center of mass, preserving equilibrium when standing up straight. Finally, when there is a progressive deformity, with the hip joints fully extended, compensation will fail, unless additional flexion of the knee and ankle joints compensates for the increased forward inclination of the trunk. Quantification of sagittal spinal imbalance on lateral radiographs of the whole spine is deemed important in the assessment of the degree of spinal deformity. The effect of small angular joint movements of the lower extremities on the SVA in a standing radiograph has never been examined for these patients. It has been suggested that the effect of position for the radiograph may be relatively small in normal subjects [11, 15], but other authors have showed a wide range of measurements. Jackson and McManus [6] studied 100 adult volunteers and 100 pa-

tients with low back pain, and found the C7 plumb line to fall within a range of –6 to +6.5 cm from the posterosuperior corner of S1 in adult volunteers, and –7.5 to +10.5 cm from the posterosuperior corner of S1 in patients with low back pain. Gelb et al. [5] studied 100 asymptomatic adult volunteers aged over 40 and found the SVA, determined from the middle of the C7 vertebral body, fell on average 3.2 cm (range –10.1 to +7.7 cm) behind the front of the sacrum. Segmental movement of the spine in combination with small changes of the joint angles in the lower extremities may be the reason for these wide ranges of measurements. In addition, standing a subject with their hands resting on a bar in front of them [4, 6, 15] will possibly influence the radiographic measurement of the SVA.

A review of the previous literature showed that the SVA is constructed in different ways and at different levels (e.g., C7 vertebral body, odontoid) [5, 6, 12]. In the current study, the SVA was defined as a plumb line from the most prominent point of the spinal process of vertebra C7. The horizontal distance (HD) was measured from the anterior superior corner of the sacrum to the SVA. The choice of the bony landmarks, however, will influence the reciprocal horizontal distance to the SVA, but not the principle of measurement.

To enable a true evaluation of changes in posture on the outcome of the SVA procedure, a patient suffering from ankylosing spondylitis was used, and it was verified that segmental movement of the entire spine was not possible, while the mobility of the hip, knee, and ankle joints were normal. Therefore, shifts of the SVA could only occur as a result of angular changes of the joints in the lower extremity and not as a result of segmental movement of the spine. In this study, one patient was used as a model for a proof of principle. (Clearly other subjects will have different outcomes whilst showing the same principle.) The instruction of posture 3 (standing with maximal hip extension and straight legs) was comparable with the standard instruction given for a standing lateral full-length radiograph. In this patient with a kyphotic deformity (Fig. 2), however, this instruction resulted in a small compensatory flexion of the knees. Without instructions, the patient will not stand in extreme positions, like postures 4 and 5 (leaning as far as possible to the front and back) when a radiograph is taken. However, in a patient with extreme thoracic kyphosis, it may be impossible to project the full spine on a fixed long cassette film without forcing the patient to flex the knee and ankle joints. As shown, this will translate the SVA and affect the measured HD. The differences in the HD to the SVA found in this study were not found when there was no need for the subject to lean as far as possible backward or forward. Nonetheless, a slightly different instruction to the patient during (virtual) radiography, for example, resulting in postures 1 and 3, induced a rather large shift in the HD of 4.7 cm to the SVA. Furthermore, strong coefficients of correlation were observed, especially for the hip and knee angles, in relation to the measured HD.

Despite the high correlation found between the HD to the SVA and the center of mass position, force plate measurements in a static posture will not be helpful in the evaluation of spinal deformities. In a static posture, the ground reaction force will be continuously pointed in the direction of the center of mass, and the center of mass is projected on the center of pressure in the feet [9, 13]. In order to prevent falling when the center of mass tends to project outside the area of support in severe sagittal plane deformities, postural compensation in the lower extremities is needed. Thus, by definition, body equilibrium in these patients is represented by the center of mass always projecting within the area of the feet (Fig. 3).

A possible limitation of this study is the two-dimensional measurements of a spinal deformity. Two-dimensional radiographic and video measurements always simplify the real three-dimensional posture deformity of the spine. Routine 3D video-based registration may be indicated in the assessment of the degree of spinal deformity in these patients. However, this proposal has not yet been evaluated as a guideline in patients with sagittal plane deformities. In clinical practice, a standing lateral full-length radiograph is still routinely used for analysis of spinal sagittal plane deformities.

Conclusion

Sagittal vertical axis translations during standing radiographic analysis were found to depend on small changes of the angles of the hip, knee, and ankle joints in a model with a fixed spine due to ankylosing spondylitis. This indicates that spinal balance can not be measured from the SVA on a standing lateral radiograph of the whole spine for analyzing these patients with respect to disease severity, conservative treatment, preoperative planning, or postoperative results. In analyzing patients with other spinal sagittal plane deformities, we must be aware of inherent errors in measuring spinal balance on standing lateral radiographs using this technique, although we did not test this. Additional variables that can lead to errors in these patients include the unknown segmental movement of the spine. Standardization of the method to determine the horizontal distance to the SVA in spinal deformities is indispensable and strict procedures must be developed to determine the position of the joints of the lower limbs and the position of the spine simultaneously.

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