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Access to a three-dimensional measure of vertebral axial rotation

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Abstract Scoliotic curvatures can only be assessed through three-dimensional (3D) procedures. Measurement of the axial vertebral rotation appears to be of primary importance for such techniques. Nevertheless, traditional methods are based only on 2D data, obtained through antero-posterior radiographic projections of the spine. A 3D method is described in this study, taking into account the sagittal tilt of the vertebrae. Only such a measurement provides a real 3D method for a true appraisal of the scoliotic spine. The practical implications are developed.

Key words Scoliosis · Rotation · Three-dimensional analysis · Radiographic artefact

Introduction

The spinal distortion that gives rise to a scoliotic curve includes both a rib hump and an axial rotation of the apical vertebra. The location and extent of axial rotation can provide considerable information on the nature of the deformity. The earliest method of detecting an axial rotation was from the lateral displacement of the shadow of the spinal process with respect to that of the vertebral body on coronal plain radiographs. Subsequently, Grossiord et al. [12] and Nash and Moe [21] showed that the position of the pedicle shadow with respect to those of the vertebral body wedges and the posterior arch provided a more sensitive index. They also showed that accurate calibration of the X-ray machine was most important, as the coronal view of the spine provides only a frontal projection of the vertebrae, and hence a qualitative evaluation of the axial rotation.

Several authors [4, 5, 7, 8, 19, 20, 24, 32] have used a variety of geometrical formulae that take into account the diverse anatomical frames of the vertebrae as projected in coronal radiographs to develop a quantitative measurement of axial rotation, implicitly referred to the global referential system. Indeed, the concept of axial rotation of the scoliotic curve vertebrae requires a single referential system for all the vertebrae. The accuracy of these methods has been assessed [14, 28, 29, 32, 35] and the shadows of the anatomical features were found to be distorted [9, 25, 31 35]. These evaluations have also been compared to those drawn from CT scans and ultrasound images [1, 2, 12, 16, 17, 18, 28], and it has been shown that the measurement technique must be standardized to allow the comparative assessment of findings [29].

However, none of the above methods use sagittal data, consequently they do not produce a true three-dimensional (3D) measurement of the axial rotation of each vertebra. The 2D data provide what is referred to in this paper as “apparent rotation”. True 3D measurements must also take into account the sagittal tilt of the vertebrae. This report analyses the concept of introduced rotation and its implications, and then describes a method of obtaining a true 3D evaluation of vertebral axial rotation.

Materials and methods

3D reference axes and 3D displacements

The reference system used in this study was the SRS, described by Stokes in 1994 [33]. The axial rotation of each vertebra is expressed with respect to the transverse plane of the global referential system for the whole body, which is also the horizontal plane for anatomists. The position of each vertebra in the normal spine can be defined within this system. Each vertebra in the scoliotic curve becomes tilted both laterally and sagitally with respect to its normal position. This displacement is the result of rotation around one or more of the three vertebral referential axes – the local references. A tilt in a local plane occurs around an axis that is perpendicular to this plane (Fig. 1)

Empirical proofs of the introduced rotation phenomenon

Two coronal radiographic views of a vertebra were taken before and after an oblique tilt. At the first step, the vertebra was horizontal both in its coronal and sagittal axis, but was in a position of known axial rotation (15°). The first radiographic view (Fig. 2 A) showed an axial rotation expressed in a global system and measured using the Perdriolle method (20°). At the second step, the vertical axis of the vertebra was tilted 30° obliquely without any change in axial rotation. A second radiographic view (Fig. 2 B) allowed a new axial rotation measurement (10°) and demonstrated a difference between the two axial rotation measurements.

In an inverse order, we positioned the vertebra with its vertical axis tilted 30° obliquely, and without any axial rotation. An axial rotation measurement on the first radiographic view (Fig. 3 A) showed a 0° axial rotation. At a second step the vertebra was set upright again without a change in axial rotation. A second radiograph (Fig. 3 B) and a new axial rotation measurement shows a different zero value (10° using the Perdriolle method). These two manipulations demonstrate an axial rotation, which is an artefact, that we named “introduced rotation”. This phenomenon is similar to the effect produced by a cardan shaft.

The “introduced rotation” concept

In the above examples, the final position of the vertebra was the result of a single and direct tilt, but the measurement was made with two successive tilts. Ombredanne et al. in 1937 [22] pointed out this fact, which was also known as “the paradox of Codmann”.

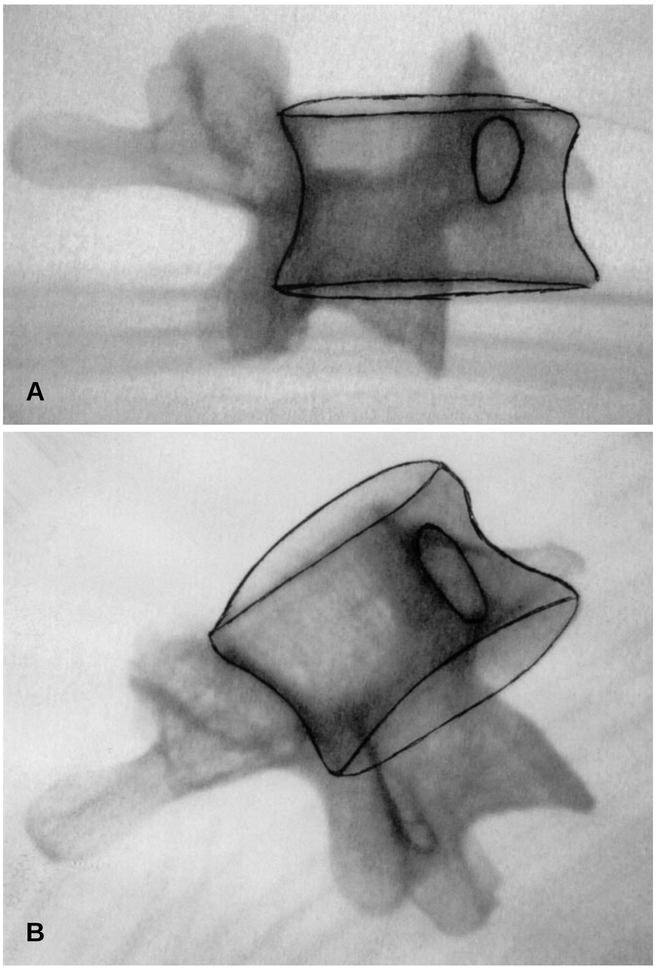


Fig. 2 **A** The vertebra is horizontal both in its coronal and sagittal axis, with a known axial rotation (15°). **B** The vertebra is tilted 30° obliquely without any change in axial rotation: the axial rotation measurement is 10°

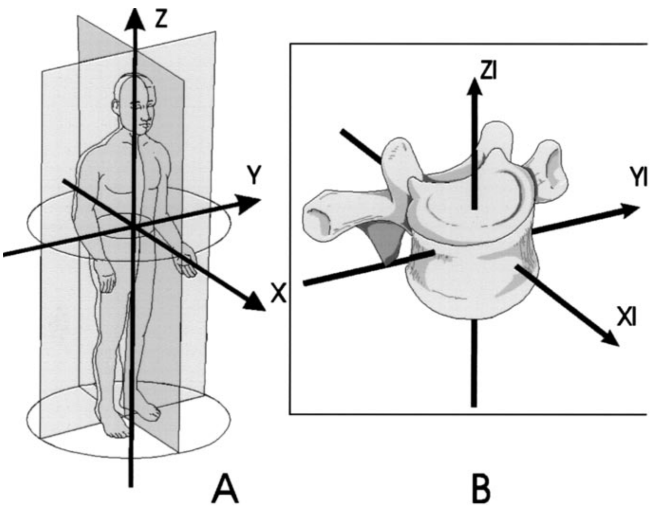


Fig. 1 Planes and axes in **A** the global referential system *X*, *Y*, *Z* and **B** the local vertebral system *Xl*, *Yl*, *Zl*

The non-medical software Design 3-DTM (Softkey) allows virtual representation of schematic figures of vertebrae and their motion – in this case successive tilts around their local axis. The axis of vision is strictly centred on constructions. Marks are placed above each modulate so as to be more perceptible.

The size of the introduced rotation depends on the extent of the tilts, and its direction depends on the order in which these tilts occur. Hence, the way in which the load is shifted to a new 3D position is most important. The absolute rotations produced by tilting an object in its sagittal plane and then in its frontal plane, and vice versa, are similar, but the rotations are in opposite directions (Fig. 4).

A formula describes these rotations. It was first intuitively obtained and then numerically validated, using a literal matrix calculation:

$$\sin(\textit{induced rot.}) = \frac{\sin(\textit{frontal tilt}) \times \sin(\textit{lateral tilt})}{1 + \cos(\textit{frontal tilt}) \times \cos(\textit{lateral tilt})}$$

where the lateral and frontal tilts are expressed in the global reference system and the “introduced rotation” in the global system. If

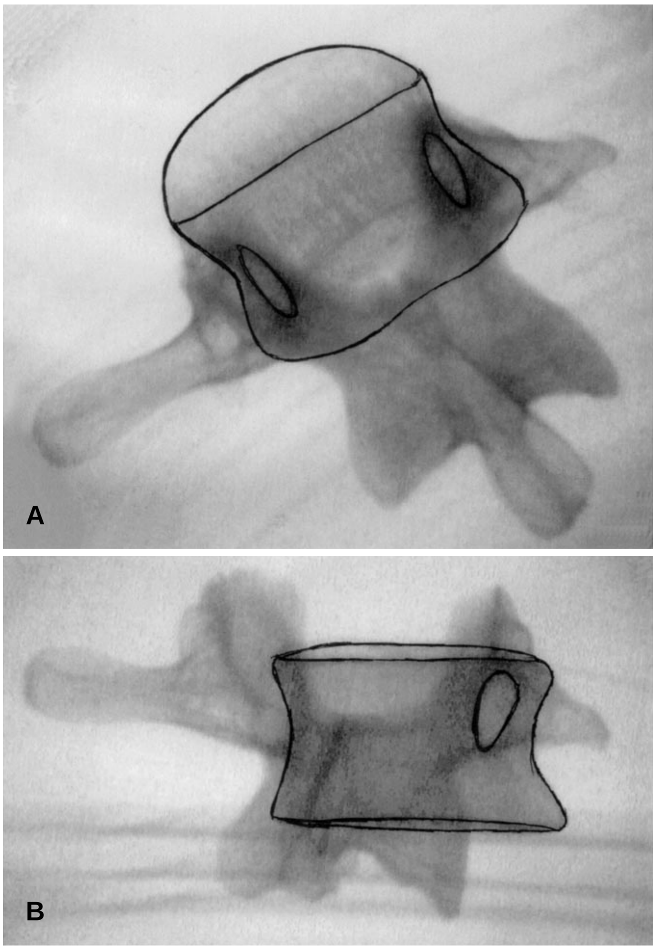


Fig. 3 **A** The vertebra is tilted 30° obliquely, without any axial rotation. **B** The vertebra is set upright without change in axial rotation: the axial rotation measurement is 10°

the tilt in any one plane is zero, then the introduced rotation is also zero. Table 1 shows the values of "introduced rotation" for various sagittal and lateral tilts of the vertebrae. They were computed using the above formula.

Similarly, when a vertebra is tilted in a single plane, for example around its sagittal axis, its frontal radiographic image remains unchanged. Thus its apparent axial position remains the same (zero, if it was initially zero).

The position of every vertebra in a scoliotic curve changes at the same time in both the frontal and sagittal planes, thus producing an "introduced rotation", which is greatest at the end vertebrae. However, all the current methods of measuring the axial rotation of a vertebra neglect this phenomenon.

The expression of these measures according to the global reference system leads to an effective change of referential, since the slope of each vertebra is not the same. This change could be direct and immediate, but it is painlessly carried out, using two successive rocking motions, the first in the coronal plane, the second in the sagittal plane. This movement implicitly involves two successive real rotations. As this results in cancellation of the tilt of the vertebra in the global coronal plane, no information is provided on its tilt in the sagittal plane. These unintentional but real rotations in two planes are equivalent to a rotational artefact: hence the name "introduced rotation".

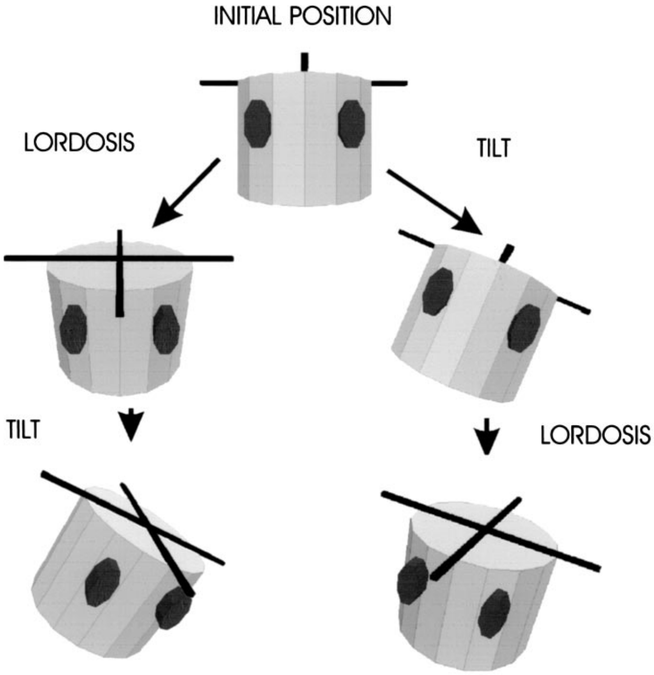


Fig. 4 "Introduced rotation". Positioning the "vertebra" in lordosis then in lateral tilting generates an introduced rotation with value similar to but in the opposite direction from the rotation generated by movements of similar intensity but undertaken in an inverse order

Table 1 "Introduced rotation" (in degrees) according to various sagittal and lateral tilts of the vertebrae. In the shaded row and column, the frontal and sagittal tilts of the vertebrae are expressed according to the global reference system. The value of the introduced rotation is positive when the vertebra is sloped right forwards or left backwards, it is negative when it is sloped left forwards and right backwards

	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75
5	0	0	1	1	1	1	2	2	2	2	3	3	3	4	4
10	0	1	1	2	2	3	3	4	4	5	5	6	6	7	8
15	1	1	2	3	3	4	5	5	6	7	8	9	10	11	12
20	1	2	3	4	4	5	6	7	8	9	10	12	13	14	15
25	1	2	3	4	6	7	8	9	10	12	13	15	16	18	19
30	1	3	4	5	7	8	10	11	13	14	16	18	19	21	23
35	2	3	5	6	8	10	11	13	15	17	19	21	23	25	27
40	2	4	5	7	9	11	13	15	17	19	21	24	26	29	31
45	2	4	6	8	10	13	15	17	19	22	24	27	30	32	35
50	2	5	7	9	12	14	17	19	22	25	27	30	33	36	39
55	3	5	8	10	13	16	19	21	24	27	30	33	37	40	44
60	3	6	9	12	15	18	21	24	27	30	33	37	40	44	48
65	3	6	10	13	16	19	23	26	30	33	37	40	44	48	52
70	4	7	11	14	18	21	25	29	32	36	40	44	48	52	56
75	4	8	12	15	19	23	27	31	35	39	44	48	52	56	61
80	4	8	13	17	21	25	30	34	38	43	47	52	56	61	66

The apparent axial rotation produced by measurements made on a frontal view of the spine is a combination of the real axial rotation and of an artefactual rotation named "introduced vertebral rotation". Hence, the real axial rotation (the "proper rotation"), as defined above, provides a method of evaluating the axial rotation of a vertebra in three dimensions.

Discussion

This study focuses on the problem of the introduced rotation resulting from the need to take X-ray pictures in specific planes, and its influence on the accurate 3D evaluation of spinal curvature. It makes no attempt to assess other sources of artefact, the deformation of the vertebra itself, the intrinsic twist and wedge shape of the vertebra, the problems of parallax, or even whether using a pedicular view is good or bad [14, 25, 28, 29, 31, 35]. It does point out that it is necessary to take the introduced rotation into account when making a real 3D evaluation of vertebral axial rotation. Thus two real orthogonal views of the spine are needed for such measurements.

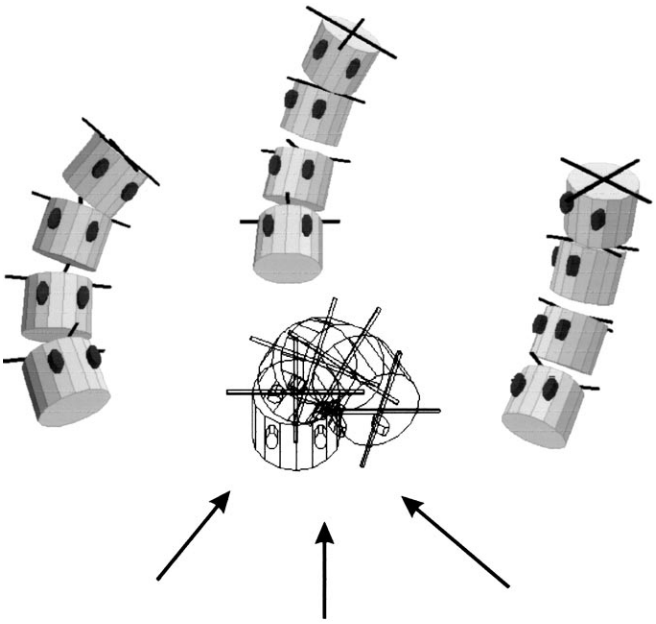


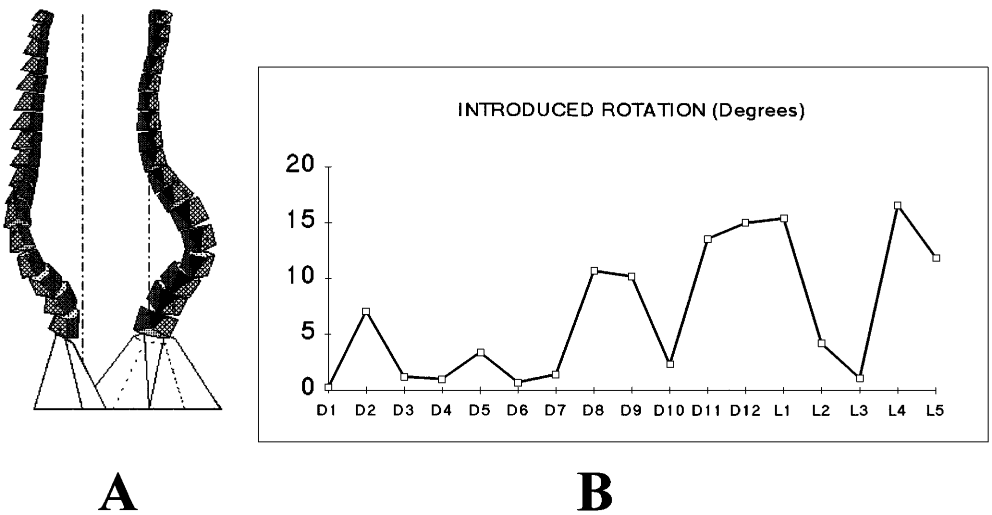
Fig. 5 Intervertebral rotations and artefact of projection: the "rotation between vertebrae" measured by graphic techniques differs according to the angle of ray impact

A structural scoliosis curve can be analysed by evaluating each of the intervertebral axial rotations derived from measurements of the axial rotation of each vertebra involved in the spinal curve. The standard method of performing such measurements gives different data depending on the different X-ray axes of view used, although the scoliotic curve remains unchanged (Fig. 5). However, when the proper rotation is measured by subtracting the variable introduced rotation, the data for any given vertebra were the same for all X-ray angles of view.

The introduced rotation must also be taken into account in clinical practice. Analysis of lumbar scoliosis, shown in Fig. 6, is particularly distorted by introduced rotation, particularly for the vertebrae with the greatest combination of tilts. Introduced rotation is least important at the top of the curve (L2–L3). Similarly, the rotation of the vertebra showed on the Fig. 7 is zero, or a false rotation [29], when measured by the standard method, although there is a real axial rotation. In this example the values of the proper rotation and introduced rotation are the same, but opposite. This explains why some scoliotic deformities in which there is a lateral curve and a rib hump show no axial rotation on the standard frontal X-ray view, while a real axial rotation is present.

Like traditional measurements of axial rotation on frontal radiographs, CT scans are accurate only for very small vertebral tilts [1, 2, 10, 16, 28, 34]. When the tilt increases simultaneously in the frontal and the sagittal planes, the distortion increases as a parabola and the traditional measurements become unworkable. Many years ago, Ombredanne built a model of a scoliotic lateral curve by piling small cylindrical blocks one upon the other along a flexible vertical plane. He realized that there was

Fig. 6 A, B "Introduced rotation" for a lumbar degenerative scoliosis. **A** The 3D representation (Rachis), **B** the "introduced rotation" for each vertebral level



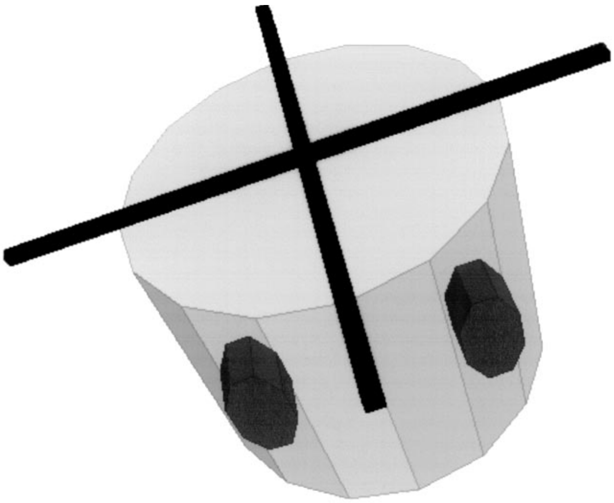


Fig. 7 Zero apparent rotation by graphic measure, but real actual rotation

no rotation of the cylindrical blocks. However, when he bent the vertical plane backwards or forwards, which also moved the lateral curve, there was axial rotation of the cylinders. He did not realize that when the sequence of tilts begins with a steady lateral tilt, then tilting the vertical plane backwards (as in lordosis) causes axial rotation in just the same way as in the vertebrae of a structural scoliotic curve, with displacement of the spinous process towards the concavity of the curve. Surgery could also take advantage of this phenomenon, with the object of a better reduction, at least for the flexible part of the axial rotation.

Conclusions

Our purpose was not to explain the axial rotation of the vertebrae of a scoliotic curve, but to set up a measurement that allows a correct virtual representation of a real state of axial rotation of the scoliotic vertebrae.

Measurements of axial rotations on radiographs must be three-dimensional. Standard graphical measurements do not take into account vertebral tilts in all three planes, and are thus not 3D measurements. This gives rise to a projection artefact, which is proportional to the degree of tilting. We set up a correction of this miscalculation. Only the proper rotation, which takes account of the introduced rotation, provides a real 3D measurement of vertebral rotation. In usual practice, evaluation of scoliosis and its correction must also take introduced rotation into account, especially when the coronal or sagittal tilt of the vertebra is more than 30°.

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