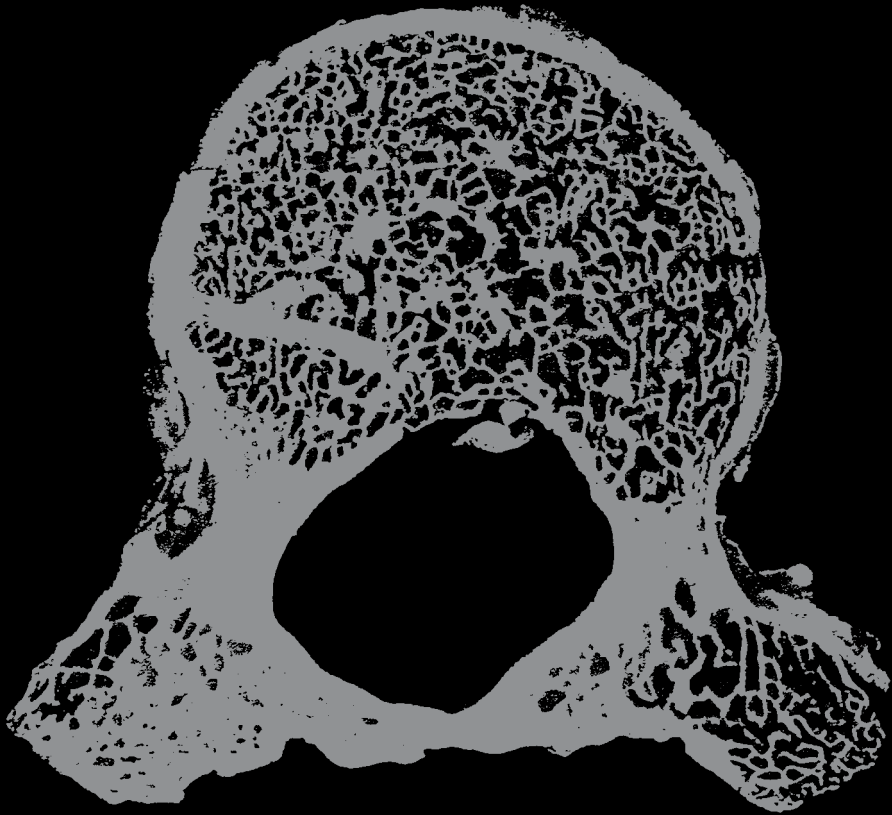


Analysis of preexistent vertebral rotation in the normal spine

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Introduction

Vertebral rotation is an essential component of adolescent idiopathic scoliosis (AIS). Although the typical curves and their associated rotation in AIS have been well described,¹⁻¹⁵ little is known of possible patterns of rotation in the normal, *nonscoliotic* spine. Few studies have dealt with this question, often using relatively inaccurate measurement techniques, one of the problems being reproducible landmark definition.¹⁶⁻¹⁸ Rotation in the normal spine is relevant to the curve patterns seen in AIS. We developed a CT-based computerized and semi-automatic, reproducible measurement method to determine vertebral rotation in the transverse plane from T2 to L5 in *nonscoliotic* spines. The purpose of this study was to determine if there is a preexistent pattern of rotation in the normal *nonscoliotic* spine.

Subjects and Methods

Twenty-five males and 25 females with a mean age of 33.3 years (range, 7-74 years), without clinical or radiological evidence of scoliosis or other spinal pathology had undergone CT examination of the thorax and abdomen for reasons such as pulmonary disease or Hodgkin lymphoma. Scans were made using the Philips Tomoscan AVE and MX 8000 CT scans. The slice thickness was 5 mm. None of the patients had a history of spinal deformity according to the charts; furthermore, the alignment of the spine in the frontal plane was evaluated from the overview scan in all 50 patients. Any deviation from a straight vertebral column led to exclusion of the patient. Vertebral rotation was measured in the transverse plane at all levels from T2 down to level L5, using the method as described below.

CT Measurement Method

We developed a new semi-automated procedure using an interactive application to calculate the rotation angle of the vertebrae. Vertebral rotation was defined as the angle between the longitudinal axis of each vertebra and the midsagittal axis of the trunk (= reference line). The reference line was defined as zero degrees rotation. Rotation to the right was defined as a positive angle, to the left as a negative angle. For each vertebra, a single slice of the CT volume was selected at the center of the vertebral body such that the pedicles were clearly visible.¹⁹ The reference line was defined at level T5 as the line between the center of the spinal canal and the center of the sternum; the longitudinal axis of each vertebra was defined as the line through the middle of the vertebral body and the center of the spinal canal. To be able to calculate the rotation angle of each vertebra fully automatically, we needed to segment the vertebrae and the spinal canal in every selected slice. Furthermore, we also

segmented the sternum at level T5. The spinal canal and the sternum were uniquely defined by a simple region growing step. We also used a region growing step for the segmentation of the vertebrae; in case of a small contrast between the vertebrae and the surrounding tissues, the surplus of segmented tissue was manually erased. Next we calculated the center of mass (COM) of the spinal canal (point A), of the sternum at level T5 (point B), and of the segmented vertebra (point C), because they accurately represent the center of these objects (*Figure 1*). The reference line is the line through points A and B, the longitudinal axis is the line through points A and C. In practice, it could occur that A and C are close together, which may lead to an unstable definition of the longitudinal axis. An elegant and robust way to circumvent this is to calculate the COM only of the anterior half of the segmented vertebral body (point C'). To define this region of interest, two lines perpendicular to the initial longitudinal axis AC were implemented fully automatically (*Figure 2*).

To evaluate the reliability of this method we performed an interobserver and intraobserver analysis. Three different observers manually segmented the slices of T2-T6 in the same four randomly chosen subjects independently. For the intraobserver analysis, Observer 1 manually segmented these slices three times at separate sittings. The vertebral rotation angles were calculated automatically and the obtained results were used to calculate the intraclass correlation coefficient as a measure for interobserver and intraobserver reliability.

Statistics

Statistical analysis was performed by means of SPSS statistical software (SPSS, Inc., Chicago, IL). The observed frequencies of right and left vertebral rotation were used to test the null hypothesis of equal probability with the binomial test. To determine if the mean vertebral rotation angles were statistically significant we used the one-sample T test. To calculate the 95% confidence interval, we used a t-value of $t^{.49} = 2.01$. A *P* value of less than 0.05 was considered to be statistically significant.

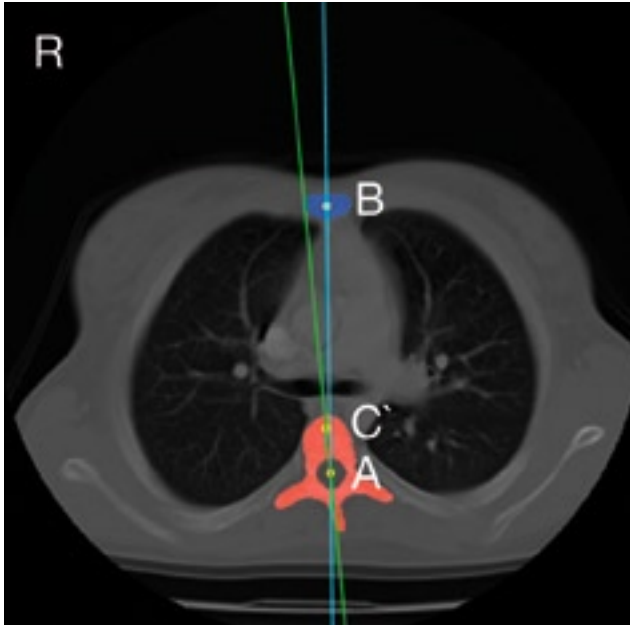


Figure 1. Longitudinal axis of vertebra T5 (red) represented by the line (green) through the COM (A) of the vertebral canal and the COM (C') of the anterior half of the vertebral body. Reference line (light blue) drawn through the COM (point A) of the vertebral canal and the COM (point B) of the sternum (dark blue).

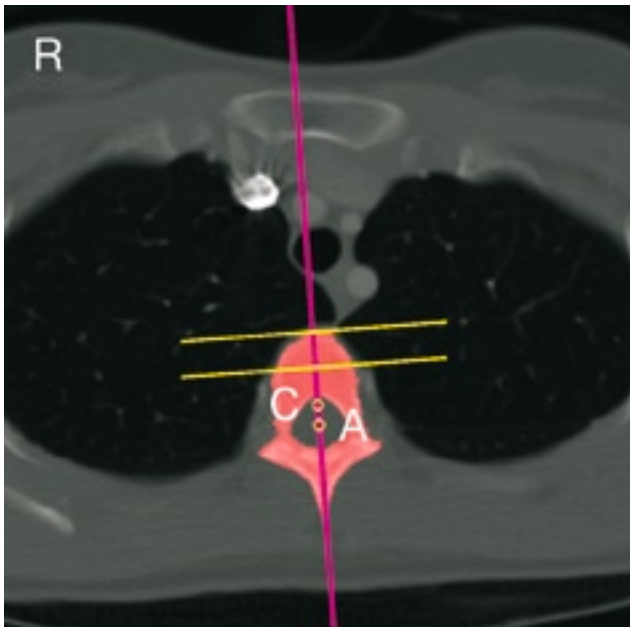


Figure 2. Initial longitudinal axis of vertebra T3 (red) represented by the line (purple) through the COM (A) of the vertebral canal and the COM (C) of the vertebra. The two yellow parallel lines are perpendicular to the initial longitudinal axis defining the anterior half of the vertebral body.

Results

Vertebral rotation in the transverse plane was determined from level T2 down to L5 in all 50 persons. The intraclass correlation coefficient calculated for interobserver and intraobserver reliability of our method were, respectively 0.96 ± 0.06 and 0.99 ± 0.01 (mean \pm SD). *Table 1* demonstrates the observed frequencies of right and left vertebral rotation. In the high thoracic spine (T2-T4), vertebrae showed a predominant rotation to the left. At levels T3 and T4, this proportion differed significantly from an equal right-left distribution ($P < 0.05$). In the mid and lower part of the thoracic spine and the lumbar spine (T5-L5), vertebrae showed a predominant rotation to the right, which was significant at levels T6-T10 ($P < 0.001$) and T11 ($P < 0.02$).

Table 1. Right-left distribution of vertebral rotation (T2-L5).

Vertebra	Direction of rotation		P
	Right	Left	
T2	26 (52%)	24 (48%)	0.888
T3	17 (34%)*	33 (66%)*	0.033
T4	16 (32%)*	34 (68%)*	0.015
T5	30 (60%)	20 (40%)	0.203
T6	42 (84%)*	8 (16%)*	<0.001
T7	41 (82%)*	9 (18%)*	<0.001
T8	42 (84%)*	8 (16%)*	<0.001
T9	41 (82%)*	9 (18%)*	<0.001
T10	38 (76%)*	12 (24%)*	<0.001
T11	34 (68%)*	16 (32%)*	0.015
T12	31 (62%)	19 (38%)	0.119
L1	31 (62%)	19 (38%)	0.119
L2	32 (64%)	18 (36%)	0.065
L3	31 (62%)	19 (38%)	0.119
L4	26 (52%)	24 (48%)	0.888
L5	24 (48%)	26 (52%)	0.888

Right-left distribution of vertebral rotation at T2-L5 in 50 persons with normal, non-scoliotic spines. The observed frequencies of right and left vertebral rotation at each level are given along with the significance level. *statistically significant ($P < 0.05$).

Measurement of the vertebral rotation angle for the whole group showed a mean rotation angle to the left in the high thoracic spine of which T3 and T4 were statistically significant ($P < 0.01$). Vertebrae T5 to L5 had a mean rotation angle to the right, that was significant at level T6 (2.5°) to T11 (1.4°) with a maximum rotation of 2.6° at T7 ($P < 0.001$) (Table 2; Figure 3).

Table 2. Mean vertebral rotation angle (T2-L5).

Vertebra	Mean rotation angle (°)	95 % confidence interval		P
		Lower bound (°)	Upper bound (°)	
T2	-0.1664	-0.9974	0.6646	0.689
T3	-1.0138*	-1.7210	-0.3066	0.006
T4	-1.0176*	-1.7299	-0.3053	0.006
T5	0.6142	-0.2045	1.4329	0.138
T6	2.4886*	1.7472	3.2300	<0.001
T7	2.6118*	1.7585	3.4651	<0.001
T8	2.365*	1.4841	3.2459	<0.001
T9	1.9902*	1.2488	2.7316	<0.001
T10	1.6962*	0.8799	2.5125	<0.001
T11	1.4454*	0.5854	2.3054	0.001
T12	0.8008	-0.2212	1.8228	0.122
L1	0.5156	-0.3637	1.3949	0.244
L2	0.6086	0.2046	1.4218	0.139
L3	0.5612	-0.3446	1.4670	0.219
L4	0.0718	-0.8360	0.9796	0.874
L5	-0.0160	-1.0679	1.0359	0.976

Mean vertebral rotation angles (in degrees) with 95% confidence interval of T2-L5 in 50 persons with normal, *nonscoliotic* spines. *statistically significant ($P < 0.05$).

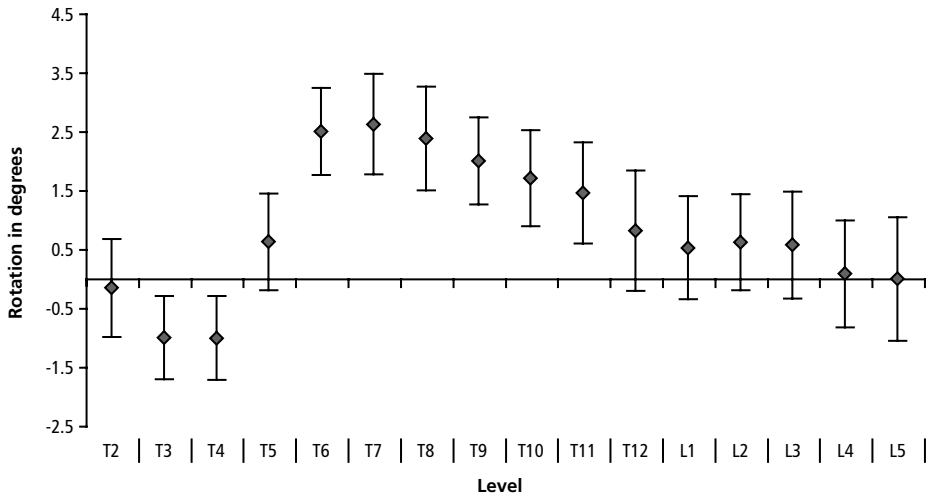


Figure 3. Mean vertebral rotation angles (in degrees, with 95% confidence interval) in the transverse plane at level T2-L5 in 50 persons with a normal, *nonscoliotic* spine.

When this group was separated into males and females, the mid and low thoracic spine (T6-T11) still demonstrated a significant rotation to the right. In females, rotation of the high thoracic vertebrae was also significant to the left, as in the group as a whole. In males, however, rotation in this region became insignificant (*Figure 4*).

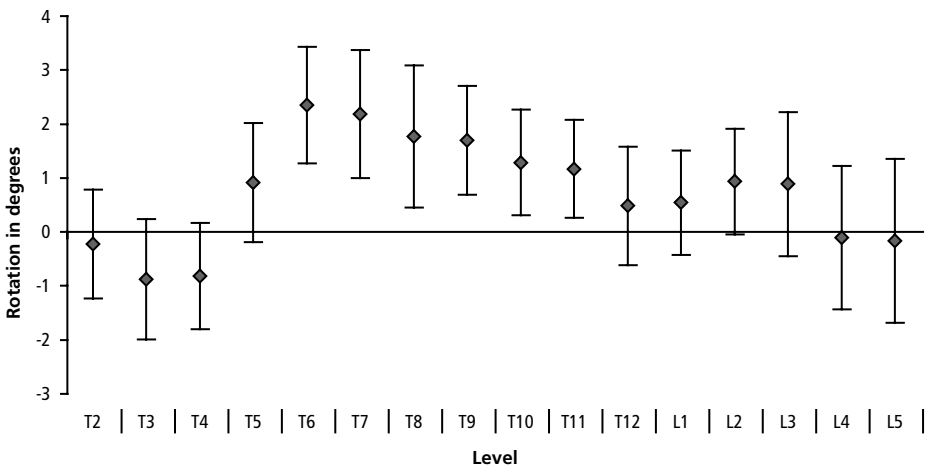


Figure 4a. Mean vertebral rotation angles (in degrees, with 95% confidence interval) in the transverse plane at level T2-L5 in 25 males with a normal, *nonscoliotic* spine.

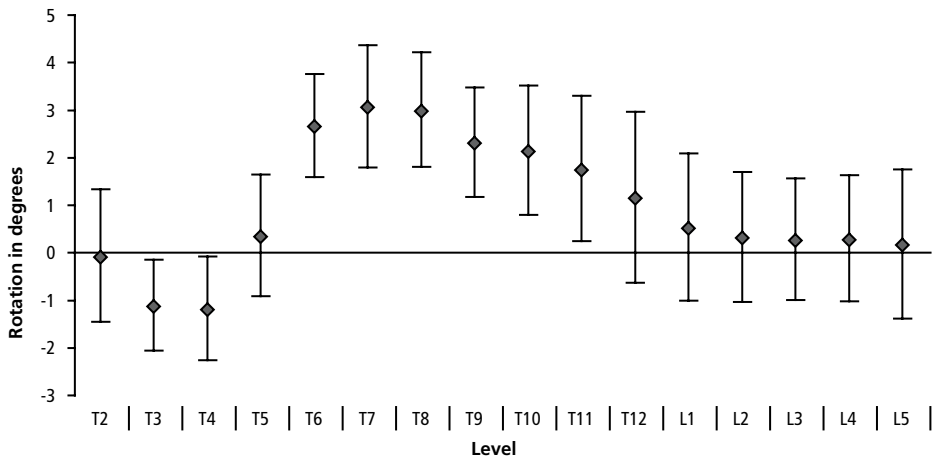


Figure 4b. Mean vertebral rotation angles (in degrees, with 95% confidence interval) in the transverse plane at level T2-L5 in 25 females with a normal, *nonscoliotic* spine.

Discussion

Our study in the normal, *nonscoliotic* spine showed a predominant rotation to the left of the high thoracic vertebrae, and to the right of the mid and lower thoracic vertebrae, which differed significantly from an equal right-left distribution. When males and females were analyzed separately, rotation remained significant to the right in the mid and lower thoracic region, in the high thoracic region however, rotation to the left was only significant in the female group. Around the thoracolumbar junction, this rotation was shown to decrease back towards the midline; however, we did not demonstrate a reversal of its direction to the left in the lumbar spine.

Rotation and lateral flexion of the spine are coupled phenomena²⁰. Vertebral rotation into the convexity of the curve is known to be an essential component of AIS.²¹ The majority of cases shows a structural midthoracic right convex curve with compensatory curves to the left above and below.¹⁻¹⁵ (*Figure 5*).

Several methods have been developed to measure rotation of vertebrae on plain radiographs, based either on the projection of the spinous process^{22;23} or on the projection of the pedicles.^{18;24-26} In idiopathic scoliosis, it is easy to determine the direction of rotation and to get an impression of its magnitude on plain radiographs. However, it is impossible to measure the exact angle of vertebral rotation. Although CT measurements have been shown to be far superior in this respect, problems of finding reliable landmarks, as well as a neutral reference line, remained.^{1;16;19;27-31} In only two studies, vertebral rotation has been measured in the normal, *nonscoliotic*

spine.^{16;18} Furthermore, no other study before has systematically analysed rotation throughout the entire thoracic and lumbar spine.

Because of difficulties and inaccuracies in finding reliable reference points in the methods mentioned previously, we developed a new semi-automatic computerized CT measurement method. Vertebral rotation was defined as the angle between the longitudinal axis of each vertebra and the midsagittal axis of the trunk (= reference line).



Figure 5. A typical example of an idiopathic thoracic curve pattern, with a mid thoracic curve convex to the right and compensatory high thoracic and lumbar curves convex to the left. (Note that the vertebral bodies are rotated away from the midline more than the spinous processes).

Although we considered using the reference line as defined by Aaro *et al*,^{1;27;28} which is a good representation of the anatomic midline of the trunk, we could not use their reference points, because of their proven inaccuracy.³¹ To define our reference line we used the COM of the vertebral canal and the COM of the sternum as reference points, because they accurately represent the center of these objects. Practice revealed that the longitudinal axis of the vertebrae was most accurately defined when

the COM was calculated of the anterior half of the vertebral body. The other reference point we used was the COM of the spinal canal, which forms the axis of rotation in idiopathic scoliosis.^{8;32} Interobserver and intraobserver analysis demonstrated high reliability and reproducibility of our method.

The fact that rotation in the *nonscoliotic* spine is not neutral or randomly distributed is an important finding, because it may explain to a large extent the most prevalent patterns of rotation in AIS. Apparently, once the spine starts to decompensate due to a still unknown cause, it logically follows this already built-in rotational tendency.

The cause of this preexistent rotation is not clear. In the 19th century, anatomists described the fifth to eighth thoracic vertebrae in the normal spine to be asymmetric in the transverse plane, the left sides of their body being flattened by the pressure of the aorta.^{2;7;10;11;33-36} Our CT analysis showed the descending aorta to approximate the vertebral column on the left from T5 down to the thoracolumbar junction. The left anterolateral position of the aorta offers the possibility to exert an asymmetric rotational force to the right.^{34;35} This is in agreement with the results of our study, which demonstrated a rotation to the right of the mid and lower thoracic vertebrae starting at level T5. Furthermore, we observed a rotation to the left of the high thoracic vertebrae, which was more significant in the female group. Although we have no explanation for this opposite rotation, it could possibly be a compensatory mechanism similar to what is seen in AIS (*Figure 5*). In an effort to explain the most prevalent patterns of AIS with its predominance of right sided thoracic curves, predominance of right-handedness as well as the position of the heart and the aorta^{34;35} have been implicated in causing the rotation of the vertebrae. However, data on the direction of rotation in scoliosis in left handed patients^{37;38} and patients with situs inversus are scarce and inconclusive. We are presently organizing a similar study in patients with situs inversus.

Our study, by no means, offers an answer to questions concerning the pathogenesis of idiopathic scoliosis. It does show, however, that there are factors built into the normal, *nonscoliotic* spine that may govern the direction of rotation once scoliosis starts to develop.

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