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Thoracic Pedicle Morphometry in Vertebrae from Scoliotic Spines

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Study Design. A morphometric analysis of thoracic pedicles in vertebrae from scoliotic specimens.

Objective. The objective of this study was to quantify the changes occurring in thoracic pedicles affected by a scoliotic deformity.

Summary of Background Data. There exists a lot of controversy in the literature concerning the shape and size of thoracic pedicles in idiopathic scoliosis. In recent years, thoracic pedicle screws are being used more frequently in corrective spine surgery, but few studies have evaluated the morphology of scoliotic thoracic pedicles.

Material and Method. Thirty scoliotic specimens with curves presenting various degrees of severity were studied using a three-dimensional digitizing protocol developed to create a precise three-dimensional reconstruction of the vertebrae. Twenty-two parameters describing specifically the pedicles were then calculated for each vertebra from these reconstructions. Every scoliotic specimen was then matched with a normal specimen to provide for a representative control group and comparisons were made on pedicle width, length, height, surface, and orientation.

Results. A total of 683 thoracic vertebrae were measured (325 scoliotic and 358 normal vertebrae). Pedicles located on the concavity of typical right thoracic curves were found to be significantly thinner than their normal counterparts with a maximal mean difference of 1.37 mm at T8. The pedicles on the concavity of the high thoracic compensatory curve were also found to be significantly diminished with a maximal mean difference of 1.68 mm at T4. Mean left pedicle width at T8 (concavity) and mean right pedicle width at T4 (concavity) were found to be 4.08 mm and 2.60 mm, respectively. Pedicle length was found to be slightly increased, and pedicle height was found to be slightly decreased in pedicles from scoliotic spines with no preference for concavity or convexity. Pedicle orientation and inclination were unchanged with respect to each corresponding vertebral body.

Conclusion. These results are of critical importance for clinicians performing spinal corrective surgery in patients with AIS. Pedicle width is significantly diminished on the concavity of scoliotic curves. Our results advocate caution in the use of pedicle screws in the thoracic spine especially on the concave side of the curve. [Key words: scoliosis, thoracic vertebrae, spine, biometry, comparative study, anthropometry, computer models, bone screws] **Spine 2004;29:239–248**

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Surgical correction of scoliotic deformities has been dramatically improved with the use of the Cotrel-Dubousset instrumentation.[1,2] Improved sagittal balance and better curve correction have been demonstrated with this type of instrumentation. Pedicle screws have been used in the lumbar spine and more recently in the thoracic spine.[3] Some authors believe that pedicle screws are better designed than hooks to control vertebral rotation especially in the thoracic curve.

Thoracic pedicle screws have a higher pullout strength,[4] provide increased curve correction,[3,5,6] and improved restoration of the sagittal profile.[7] This has led to an increased use of pedicle screws for the correction of scoliotic deformities. However, pedicle screw use carries the risk of major neurologic and vascular complications.[8] Therefore, thoracic pedicle screw insertion in adolescent idiopathic scoliosis (AIS) remains highly controversial.

A review of the literature provides limited information about the local changes occurring in idiopathic scoliosis. Most reports are made on a few isolated anatomic specimens with major curvatures, and most of the knowledge we currently have regarding the local changes are based on these observational studies. Several representations of scoliotic vertebrae exist in the literature. However, often these are artistic representations of isolated cases and may therefore not represent accurately the local changes occurring at the vertebral level.[9–12] There is also a lot of controversy in the literature regarding isolated observations made by different authors or, in some cases, the same author.[13] In an attempt to quantify changes occurring at the level of the pedicles, Liljenqvist *et al* reported that pedicle size is significantly smaller in thoracic pedicles located on the concavity of thoracic scoliotic curves,[14] but the study was limited only to this aspect of scoliotic vertebrae. Another limitation of this study is the absence of a control group as concave pedicles are compared to pedicles located on the convexity. In another study by O'Brien *et al*, the authors reported on a radiographic study of thoracic pedicle anatomy in a group of 29 patients with AIS who had both radiologic and computed tomography (CT) scan examinations.[15] Their analysis did not show a significant diminution in the pedicle diameter of patients with AIS. They concluded by suggesting that "the deformity itself (rotation), rather than the local vertebral anatomy, increases the degree of difficulty and potential danger of this technique *versus* nonscoliotic spines."[15] They further suggested that if pedicle screw insertion is possible and relatively safe, "the pedicle-rib unit provides an ample target for screw insertion."[15] Their radiographic analysis did not provide, however, an analysis of the concave pedicles and could therefore not be correlated to their CT scan findings. This study also did not present a control group, as pedicles on the concavity were again compared with their corresponding pedicle on the convexity.

In a more recent paper, Liljenqvist *et al*[16] have suggested again that the pedicles on the concavity of scoliotic curves were significantly smaller than the convex pedicles. Their analysis also showed no difference in pedicle length and chord length. They finally evaluated the relation of the chord to the vertebral canal and found that "the width of the epidural space on the concave side was significantly smaller than that on the concave side at all levels"[16] except at T4, T5, and L4.

The authors of the current paper have recently suggested[17] that there exists a characteristic deformation pattern with progressive vertebral wedging and with the maximum deformity being found at the apex of the curve. Progressive thinning of the pedicle width was found on the concave side of the curve as well as variation of facets surfaces around the apex of the curve. The facet changes were not related to the concavity or convexity but did differ in size, especially with severe curvatures. These findings were more important in the thoracic spine. This first morphometric analysis of 30 scoliotic specimens compared to 30 normal specimens did evaluate the typical changes seen in scoliotic deformities.

The purpose of this paper is to report quantitative measurements pertaining to thoracic pedicle morphometry of a group of 30 scoliotic specimens with a comparative group of 30 normal specimens. Clinical relevant parameters including pedicle width, height, length, inclination, orientation, and maximal pedicle screw length have been evaluated for thoracic vertebrae.

■ Materials and Methods

The thoracic vertebrae presented here are a subgroup of a large database of 30 complete scoliotic specimens matched to 30 normal specimens that have been described previously.[17] For this study, the focus is on thoracic pedicles and how their shape is modified in specimens presenting varying degrees of scoliotic deformities.

Specimen Selection. Thirty scoliotic specimens were identified from two major osteological collections. The first 15 specimens are part of the Hamann-Todd Osteological Collection found at the Cleveland Museum of Natural History. This collection contains over 3000 complete skeletal specimens including postcranial material. The other 15 specimens are part of the Robert J. Terry Collection found at the National Museum of Natural History in Washington, D.C. This collection contains over 1700 specimens. Scoliotic specimens were selected by assembling the thoracic and lumbar segments manually and observing their natural configuration and retaining those that presented typical characteristics of thoracic idiopathic scoliosis, namely vertebral body wedging at the midthoracic apex and a rotational deformity of the curve. Vertebral wedging and rotation had to be present on at least three consecutive levels with a minimum 10% vertebral height difference between the concave and convex sides at the apex of the curve. Vertebral wedging produced these configuration changes. Examination of the specimens did not include intervertebral disc changes, as these had been resected at the time of dissection. Cobb angle and the exact degree of deformity were therefore not available. Although the scoliotic specimens seemed to be of the idiopathic type, this term cannot be applied to this sample because the medical and radiologic history was not known. All of the 4700+ specimens were screened for scoliosis, and any specimen with evidence of a congenital deformity was excluded. All 30 scoliotic specimens were then matched for age, gender, race, height, and weight with a normal specimen from the corresponding collection. Both collections keep an extensive record on each specimen including postmortem photographs, pathology, and dissection reports as well as anthropometric measurements taken at the time of dissection. All these parameters were reviewed and incorporated in our analysis. Radiographs are also available for selected specimens showing severe spinal deformities.

Digitizing Procedure. The digitizing procedure has been described in detail and can be found elsewhere.[17,18] A short description follows.

For each vertebra, manual digitization of approximately 200 points each representing a precise anatomic landmark was performed using a three-dimensional digitizer. The device used to perform the measurements on the different vertebrae was the Fastrack (Polhemus, VT), which works by generating near, low frequency, magnetic field vectors from a single assembly of three colocated antennas that are fixed in space working as the transmitter. These magnetic field vectors are then detected by a set of colocated antennas remotely placed (stylus), acting as the receiver. This receiver is linked to a computer that transforms the received signal using a mathematical algorithm creating a set of three coordinates indicating the exact three-dimensional position of the receiver in relation to the transmitter referential.

The digitizing protocol was developed by our research group.[17–19] Each point was always located at the same landmark and points were taken in a specific order to diminish measurement errors. A PVC frame, to which the magnetic source was fixed, prevented each vertebra from moving during the measuring procedure by maintaining them rigidly. The source was connected to the Fastrack module, which calculated the exact three-dimensional position of the stylus (receiver) and relayed this information to the computer.

After the measurements were done, each vertebra was then reconstructed using computer graphics software while being still held in place in the PVC frame (Figure 1). This provides an excellent quality control, virtually eliminating any gross measurement error. Modifications to the dataset can be made im-

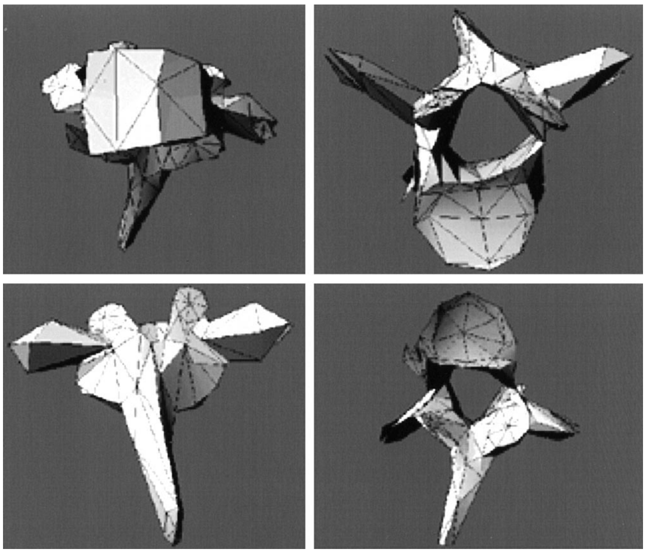

Figure 1. Thoracic vertebrae from scoliotic spine reconstructed using the digitizing protocol. Note the characteristic changes seen in scoliosis, namely vertebral wedging, pedicle width changes, and articular facets surface changes.

mediately after visual inspection of the three-dimensional reconstruction while the vertebra is still held in the PVC frame, ensuring a high degree of reliability.[17,18]

Each set of points was then relocalized in a local coordinate system. This is a crucial step to allow for comparison between different specimens especially when comparing different angles calculated in the local coordinate system. A computer program was designed to modify the orientation and position of the vertebrae in space without affecting its actual shape.[17,18] The local coordinate system used was the one adopted by the Scoliosis Research Society defining the frontal plane as Y0Z, the sagittal plane as X0Z, and the horizontal plane as X0Y.

Computer software was then developed to calculate specific parameters from these sets of points. In total, 22 parameters were calculated describing specifically the pedicles for each thoracic vertebra. Pedicle length, height, width, and surface (anterior, median, and posterior) were calculated. Pedicle screw length was calculated using two points at the entry and exit points of a projected pedicle screw anatomic trajectory using anatomic landmarks. These were then compared to normal vertebra with analysis of variance (ANOVA) calculations to establish the presence of interaction and Student t tests ($P = 0.05$) were performed to quantify these interactions.

■ Results

A total of 683 thoracic vertebrae were measured, 325 from 30 scoliotic specimens and 358 from 30 normal specimens. Twenty-one male specimens and 9 female specimens were identified (Table 1). The relatively high male-to-female ratio is due to the higher proportion of males in each collection. This can be explained by the fact that the 2 collections were assembled with unclaimed bodies between 1920 and 1940, which were usually male bodies. A large proportion of the scoliotic specimens (21 specimens) were right thoracic curves. A distribution according to King's classification can be found elsewhere.[17]

Table 1. Sex Distribution and Mean Age of Scoliotic and Normal Specimens

	Scoliotic	Normal
Female	9	9
Male	21	21
Thoracic vertebrae	325	358
Mean age (yrs)	44.2	44.1

Pedicle Width

Minimal pedicular width was measured for both right and left pedicles. This distance was the smallest diameter taken at the midsection of the pedicles. Table 2 illustrates the mean and standard deviations for each thoracic level in both scoliotic and normal specimens. The maximal difference of 1.37 mm was found at T8 for left pedicles (at the apex of a typical right thoracic curve; Figure 2) and at T4 for the superiorly adjacent curve for right pedicles with a mean difference of 1.68 mm (Figure 3). The minimal width for normal and scoliotic specimens was found in the midthoracic area (T4–T7) with increasing pedicle diameter both proximally and caudally. Changes in pedicle width can also be seen in the lower thoracic area, but these changes are less significant.

Pedicle Length

Pedicle lengths were calculated for both right and left pedicles and are represented in Figures 4 and 5. Right

Table 2. Means and Standard Deviations for Right and Left Minimal Pedicular Width

Level		Normal (mm)	Scoliotic (mm)	Difference (mm)	*P* Value
T1	Right	***7.77 (1.17)***	***6.79 (1.38)***	***0.97***	***0.002***
	Left	***7.69 (1.44)***	***6.65 (1.50)***	***1.04***	***0.002***
T2	Right	***5.84 (1.09)***	***4.73 (1.25)***	***1.10***	***0.000***
	Left	**5.79 (1.35)**	**5.04 (1.29)**	**0.75**	**0.035**
T3	Right	***4.74 (0.94)***	***3.19 (1.35)***	***1.54***	***0.000***
	Left	4.60 (1.08)	4.32 (1.34)	0.28	0.268
T4	Right	***4.28 (0.76)***	***2.60 (1.37)***	***1.68***	***0.000***
	Left	4.04 (0.97)	4.04 (1.19)	0.00	0.995
T5	Right	**4.32 (0.90)**	**3.64 (1.51)**	**0.68**	**0.045**
	Left	4.10 (1.00)	4.00 (1.41)	0.11	0.716
T6	Right	5.08 (0.90)	4.65 (1.40)	0.43	0.238
	Left	***4.82 (0.91)***	***3.78 (1.61)***	***1.05***	***0.003***
T7	Right	5.26 (1.02)	5.23 (1.30)	0.03	0.923
	Left	***5.09 (0.97)***	***4.00 (1.41)***	***1.09***	***0.010***
T8	Right	5.32 (1.29)	5.16 (1.10)	0.16	0.531
	Left	***5.41 (1.18)***	***4.04 (1.03)***	***1.37***	***0.000***
T9	Right	5.87 (1.27)	5.40 (1.09)	0.47	0.155
	Left	***6.06 (1.23)***	***4.93 (1.26)***	***1.13***	***0.000***
T10	Right	**7.00 (1.35)**	**6.10 (1.30)**	**0.90**	**0.017**
	Left	***6.83 (1.65)***	***5.80 (1.49)***	***1.03***	***0.004***
T11	Right	7.95 (1.61)	7.58 (1.44)	0.38	0.377
	Left	***8.38 (1.23)***	***7.20 (1.68)***	***1.19***	***0.002***
T12	Right	**8.30 (1.63)**	**7.11 (2.00)**	**1.18**	**0.030**
	Left	**8.30 (1.56)**	**7.20 (1.80)**	**1.10**	**0.017**

Significant levels ($P < 0.05$) are in bold, and levels with $P < 0.01$ are in italics.

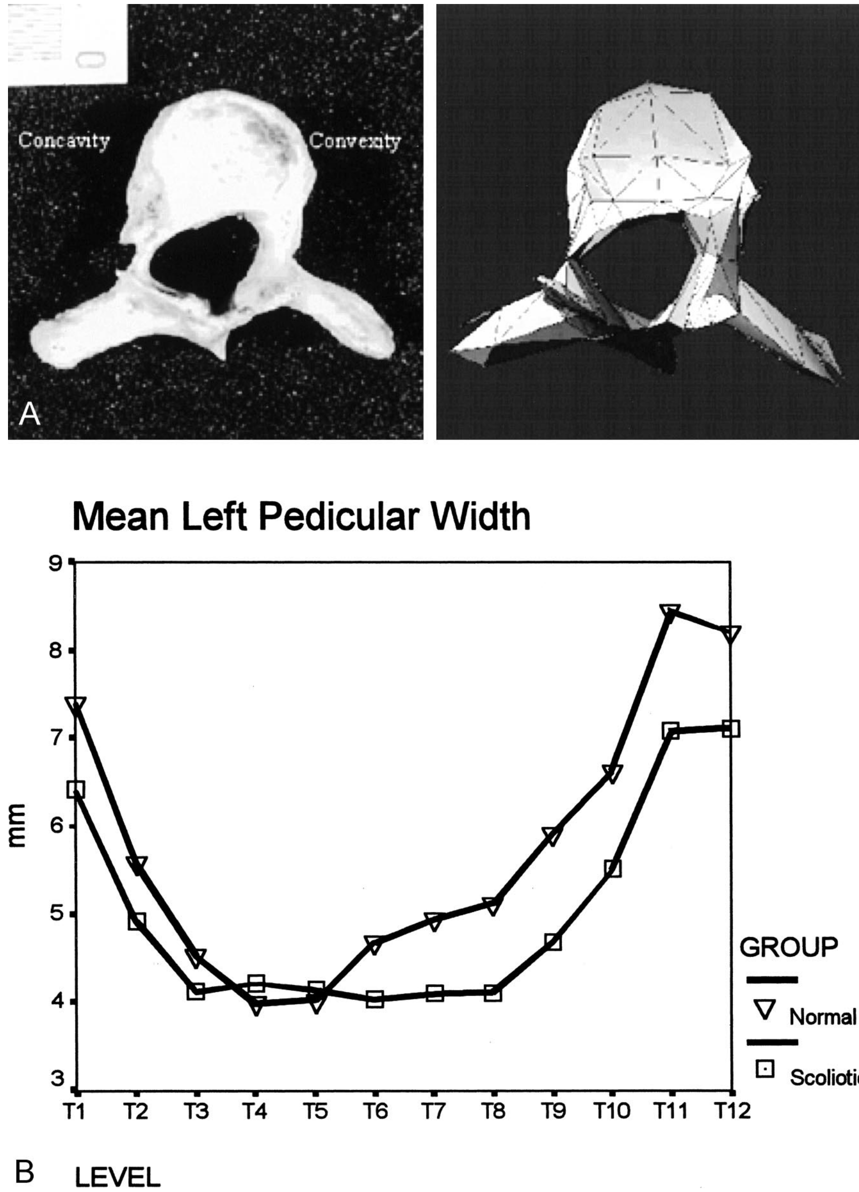

Figure 2. Mean left pedicular width. Typical thoracic vertebra presenting a characteristic deformation of the pedicle located on the concavity of a scoliotic curve as seen from above.

and left pedicles from scoliotic specimens were found to be significantly longer than their normal counterparts ($P = 0.007$) with no association with curve convexity or concavity. Maximal right and left screw length were found to be unchanged (Figures 6 and 7), and this may be due to the fact that small changes found at the level of the pedicle length did not affect the overall screw length significantly. This last measure took into account the best trajectory and maximal bone length for pedicle screw insertion.

Pedicle Height

Pedicle height was obtained at three positions along the axis of the pedicle (anterior, midsection, and posterior). The heights of thoracic pedicles from scoliotic specimens are statistically smaller (between 0.5 and 1 mm) than their normal counterparts, and this remains true at all positions along the pedicle length. There is again no relation with the convexity or concavity of the curve. Pedicle height increases from T1 (8–9 mm) to T12 (15–16 mm).

Pedicle Orientation and Inclination

Pedicle orientation was obtained by calculating the angle formed by the pedicle long axis and the sagittal plane and reported in the transverse plane. Each vertebra being measured separately and relocated in the local coordinate system, we obtained comparable results between vertebrae from scoliotic and normal specimens with no significant differences. Right and left pedicle orientations were not affected significantly (Figures 8 and 9). The orientation varied from cephalad to caudal with the more proximal pedicles being more externally oriented. This orientation changes dramatically from about 30° at T1° to 10° at T4 and then remains fairly constant between 5° and 10° throughout the rest of the thoracic spine.

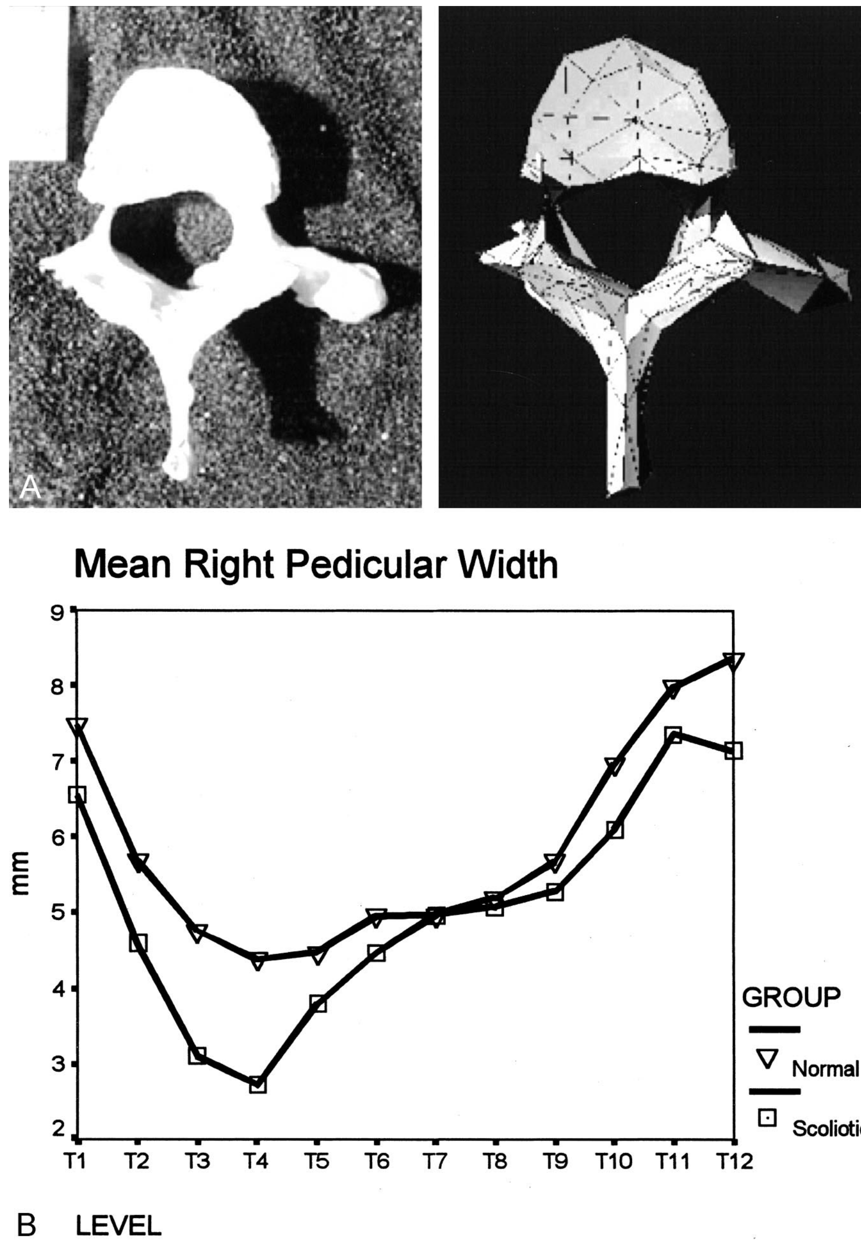

Figure 3. Mean right pedicular width. Right pedicle width shown to be markedly decreased on concavity of a superiorly adjacent thoracic curve as seen from below.

Pedicle inclination was then calculated between the long axis of the pedicle and the transverse plane of the vertebra and reported in the sagittal plane for right and left pedicles. No significant changes were noted between vertebrae from scoliotic spines when compared to normal specimens. Pedicle inclination varied from caudal to cephalad by first increasing steeply from T1 to T2, stabilizing between 6° and 10° for most of the thoracic spine and finally declining in the lower thoracic segment (Figures 10 and 11).

■ Discussion

A precise knowledge of the changes affecting vertebrae in scoliotic spines is essential to perform accurate implant placement. Pedicle screws are a relatively safe technique if used carefully in experienced hands, but may lead to serious complications results if not used properly. Understanding the local changes affecting vertebrae in scoliotic deformities is mandatory to prevent such mistakes.

Normal thoracic pedicle anatomy has been reported by several authors,[20–22] and recent work has focused on identifying characteristic changes seen in vertebra from scoliotic specimens.[14] Except for one study,[17] all studies evaluating scoliotic specimens compared pedicles located on the concavity with the ones located on the convexity without a proper control group to compare measurements to. This study analyzed the morphometric changes occurring in thoracic pedicles from 30 scoliotic specimens and compared them to thoracic pedicles from a comparative control group.

One of the characteristics of the current digitizing method is that it records the exact surface measurements of the object measured. This is in contrast with other imaging techniques (CT scan, magnetic resonance imag-

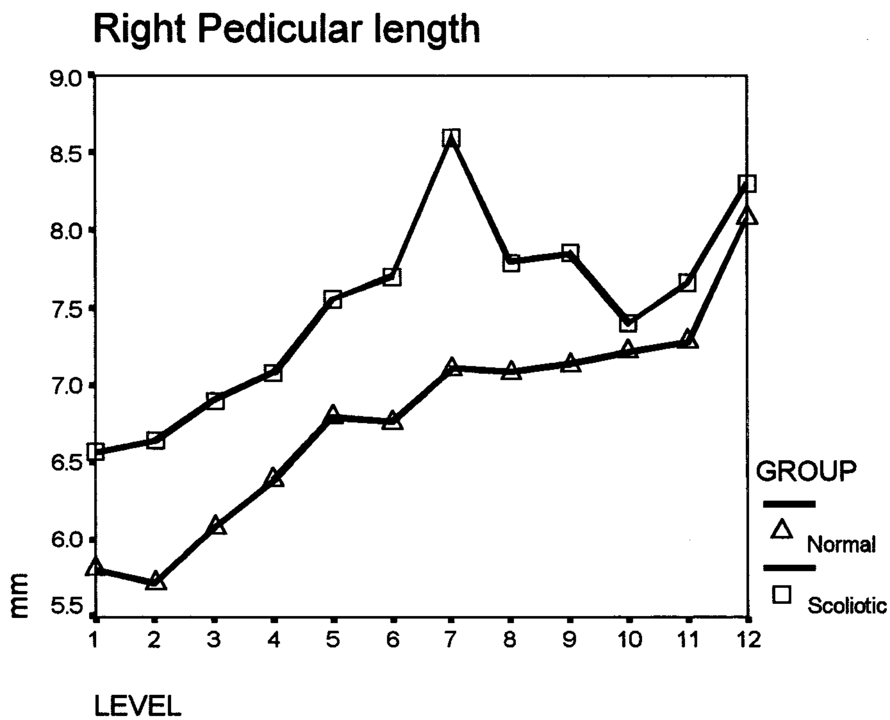

Figure 4. Right pedicular length.

ing) used by several other authors where measurements are made on two-dimensional images.[14–16] The limitation of these imaging techniques resides more specifically in obtaining a perfectly oriented image in the transverse plane of the vertebrae directly at the level of the smallest diameter of the pedicles. Although improved plane orientation can be obtained by frontal and sagittal segmental alignment, scoliosis deformities are truly three-dimensional deformities, and minor variations can lead to major measurement differences at the level of the pedicles.

As already mentioned, a lot of controversy exists in the literature as to which side is more significantly affected by a decrease in pedicle width. One of the first papers on the subject by Enneking *et al* reported thinner pedicles on the convex side of one scoliotic specimen.[13] Artistic representations[9–11] have also often been contradictory presenting pedicle changes and neural arch de-

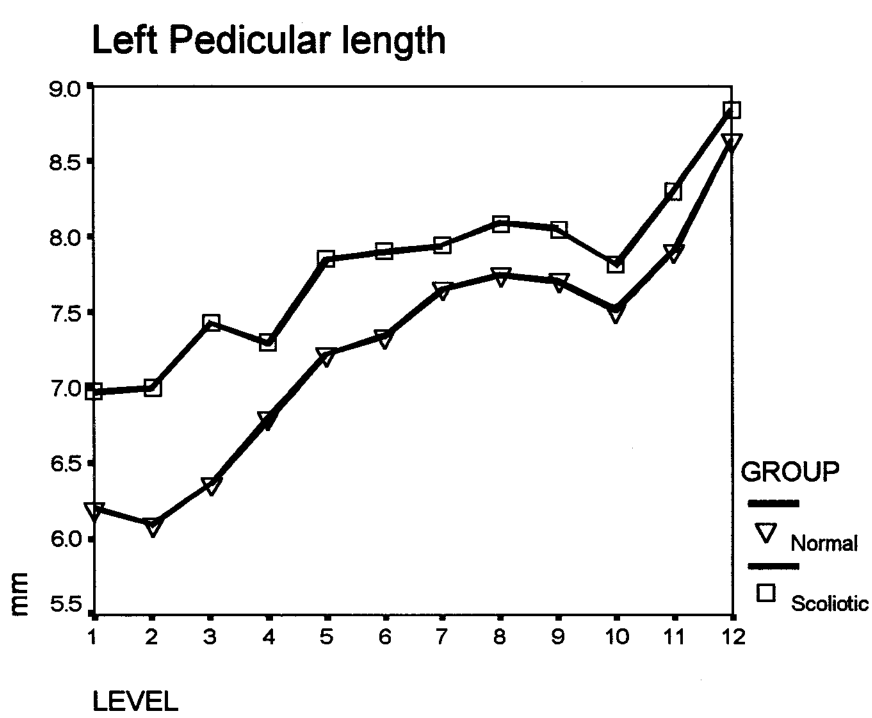

Figure 5. Left pedicular length.

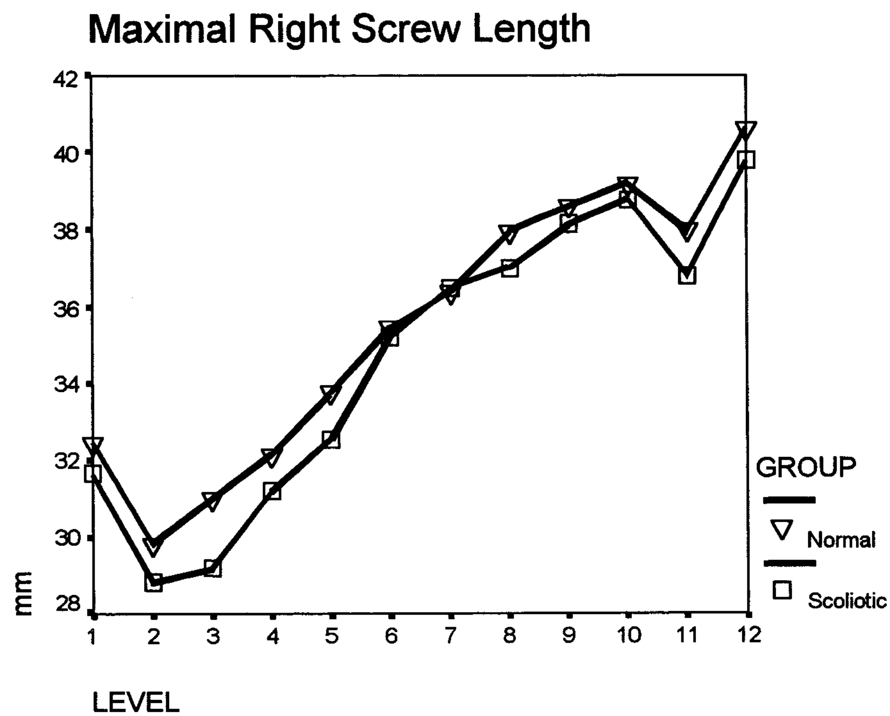

Figure 6. Maximal right screw length.

formations in different manners. These isolated observations and artistic representations are probably responsible for the controversy surrounding the pedicle anatomy in scoliotic deformities.

The results presented in this study show that pedicle width is affected more at the apex of a typical right thoracic curve and the superior adjacent left thoracic curve. Pedicles located on the concavity of typical right thoracic curves were found to be significantly smaller than their normal counterparts with a maximal difference at T8. The pedicles on the concavity of the high thoracic compensatory curve were also found to be significantly diminished with a maximal difference at T4. This difference slowly decreases towards the neutral vertebrae where the changes were not significant. This implies that pedicle screw insertion should technically be easier in the neutral zone than at the apex. As mentioned previously, O'Brien *et al* have suggested that the pedicle-rib complex provides ample target for screw insertion and is a viable alternative to pedicle screw insertion.[15] This could probably be a safe alternative

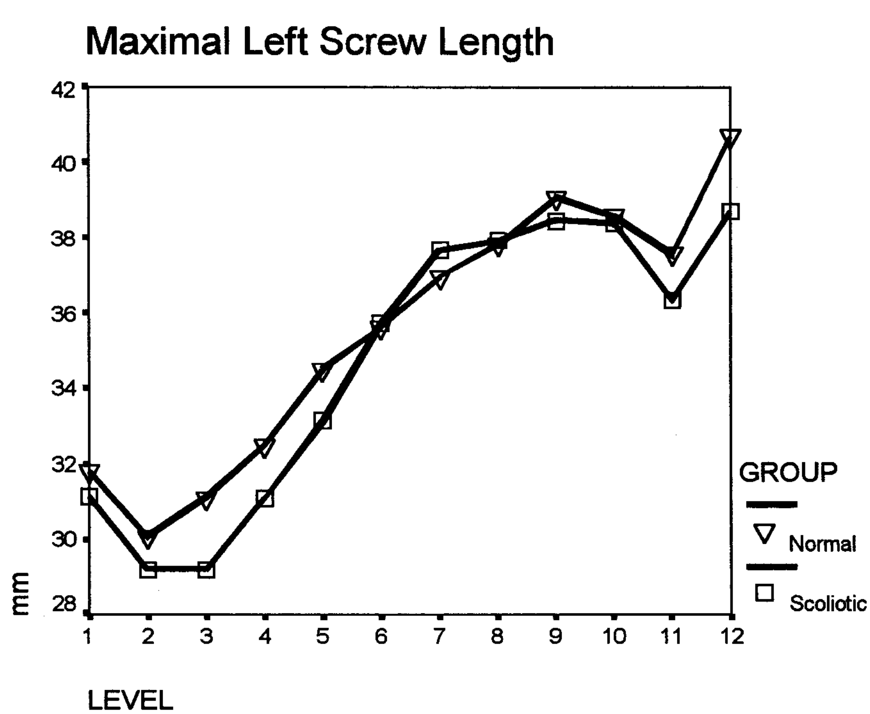

Figure 7. Maximal left screw length.

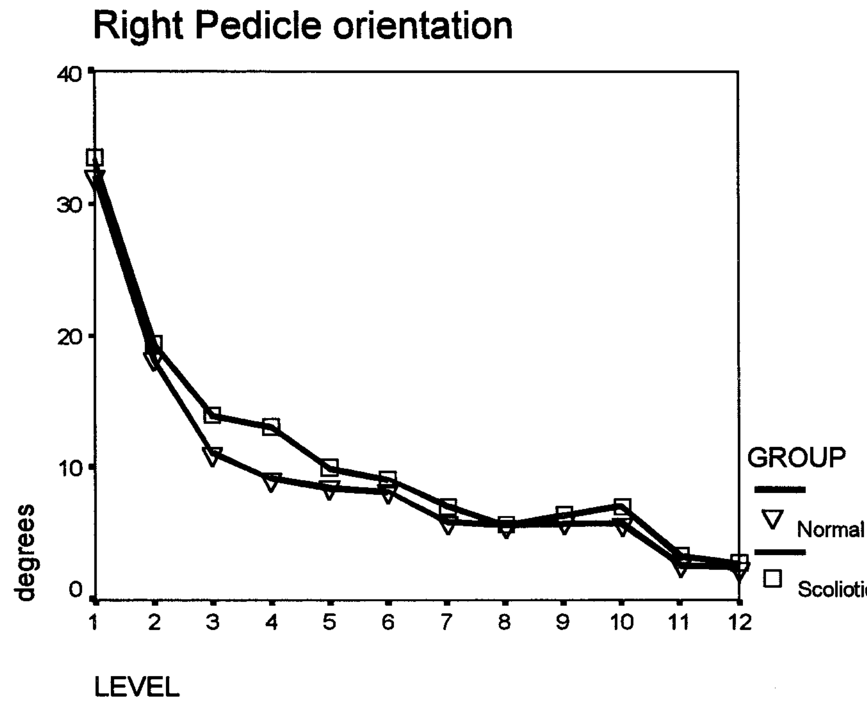

Figure 8. Right pedicle orientation.

to pedicle screw insertion at the apex of the concavity in moderate to severe scoliotic deformities.

The situation of the neural elements to the concave thoracic pedicle is not negligible, as some authors have reported a very close relationship of these neural elements with the concave thoracic pedicle.[23] This raises some additional concerns about pedicle screw insertion at the apex of the concavity.

Orientation and inclination results may seem counterintuitive to most clinicians, as pedicle screw insertion in a severe scoliotic deformity will be affected by vertebral rotation and angulation. The technique used to measure the individual vertebra does not take into account these regional changes because each vertebra is digitized individually. The advantage of relocalizing the vertebrae in a local coordinate system is that it allows for a precise analysis of the inclination and orientation of the pedicles relative to the vertebra. Our results show that there was no statistical difference between vertebra from scoliotic and normal specimens regarding inclination and orien-

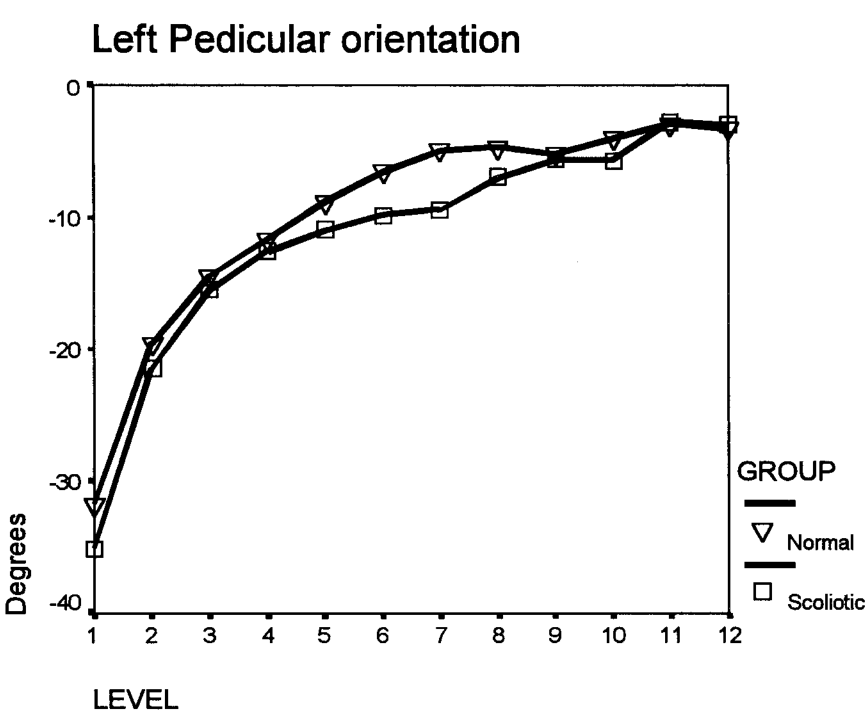

Figure 9. Left pedicular orientation.

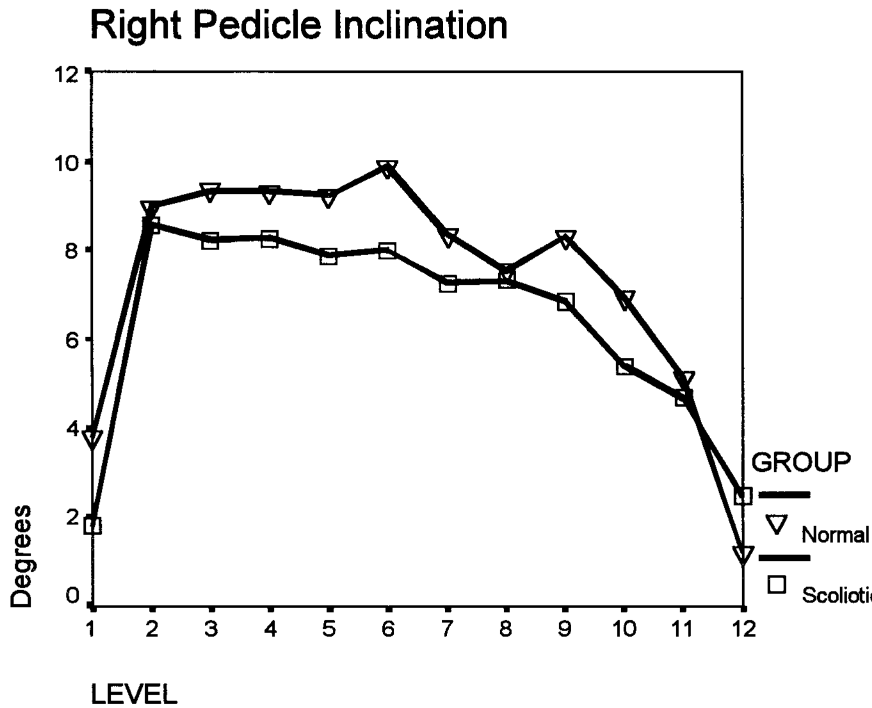

Figure 10. Right pedicle inclination.

tation of thoracic pedicles. The entry point and orientation of the pedicle, although smaller on the concavity, does not seem to be affected by the local deformity. The relative three-dimensional vertebral body position, however, plays a crucial role in the final screw placement when the regional deformity is taken into account. This regional deformity is maximal at the apex of the curve. In other words, once the three-dimensional location of a specific vertebra is known, the entry points and pedicle screw orientation are the same as in a normal vertebra.

Maximal screw length was not affected by the scoliotic deformity, but pedicle length was, with longer pedicles found in scoliotic specimens. It has been hypothesized that early closure of the neurocentral junctions could theoretically be responsible for the early development of scoliosis.[24] If this was the case, one would expect an asymmetry in the length of the pedicles, which was not found in this study.

The changes observed raise some interesting questions as to the origin of the deformity observed. Are these

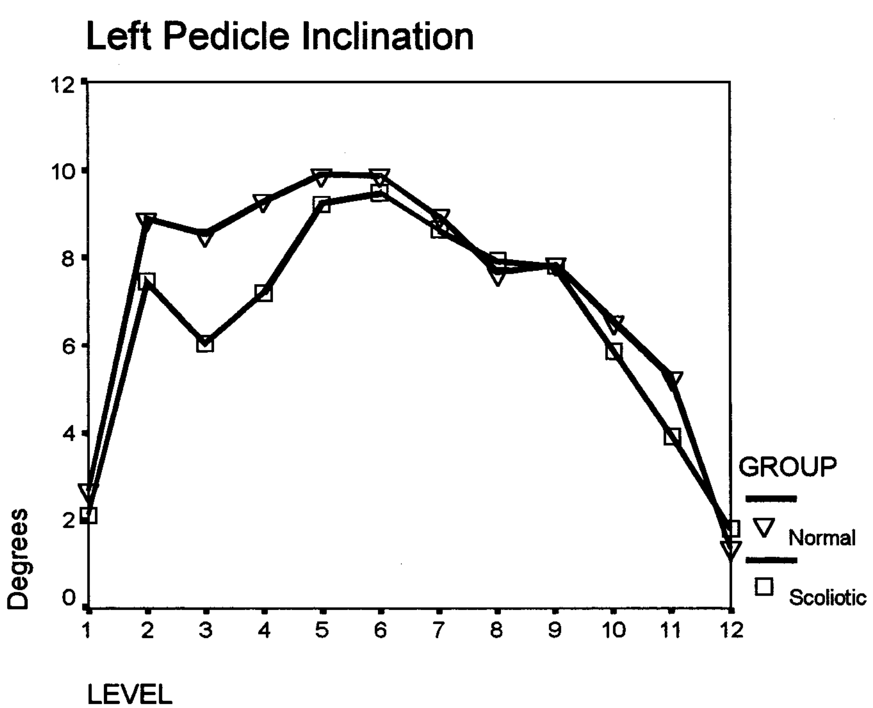

Figure 11. Left pedicle inclination.

changes secondary to external forces acting to remodel the vertebral body or are these changes the precursor of the regional deformity? Vertebral wedging could be the initiating factor creating a relative force imbalance, therefore, beginning a vicious circle with progressive wedging creating more imbalance. But this does not completely explain the changes observed in the posterior elements, especially at the level of the pedicles. Could the pedicle shape be modified by external forces such as the head of the rib or the spinal cord beating relentlessly for years on the concavity of the scoliotic curve?

It is not possible from the data available in this study to provide any insight into the development and progression of scoliosis, as the specimens are fixed in time. The information obtained from these anatomic studies should, however, help to develop better three-dimensional imaging tools that should in turn improve our understanding of the evolution of these scoliotic deformities. Our results are consistent with the Liljenqvist *et al* findings regarding pedicle width.[14,16] To our knowledge, this is the most descriptive and largest database of thoracic vertebrae from scoliotic spines available in the literature.

It is not the authors' intention to recommend the use of one fixation method over another. Thoracic pedicle screws provide better frontal and sagittal control of the deformity and a better correction of the vertebral rotation. To the authors' knowledge, however, there is no study proving that a better correction in the thoracic spine using pedicle screws results in a better outcome than other segmental types of instrumentation. It seems logical that a straighter spine would probably produce a better outcome, but to what extent? Restoring spine balance, improving the sagittal profile, and correcting Cobb angle should provide better long-term outcome. Are these potential benefits worth the risks associated with thoracic pedicle screw insertion, especially on the apical concavity of moderate to severe scoliotic deformities? Long-term studies need to address these questions.

■ Conclusion

A total of 325 thoracic vertebrae from scoliotic specimens and 358 thoracic vertebrae from normal specimens were measured. Based on the anatomic measurements made, the authors advocate caution with the use of pedicle screws on the concavity of scoliotic curves, especially at the apex of moderate to severe deformations. The pedicle width decreased progressively from the neutral zone towards the apex of the curve. Adjacent curves were also affected with changes occurring also in a similar pattern. Pedicle length was greater in vertebrae from scoliotic specimens when compared to normal specimens. The local deformity as well as the regional rotational deformity should be taken into consideration when pedicle screw instrumentation is to be used.

■ Key Points

- Thirty scoliotic specimens from two major osteological sources were identified and measured.
- Pedicle width is significantly smaller on the concavity of moderate to severe thoracic curves.
- Orientation and elevation of thoracic pedicles with respect to each corresponding vertebral body do not seem to be affected by the scoliotic deformity.
- We advocate caution in the use of pedicle screws in the thoracic spine, on the concave side of the curves, in patients with moderate to severe scoliotic curves.

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