Identification of Apical Vertebra for Grading of Idiopathic Scoliosis using Image Processing

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Abstract Scoliosis is a 3-D deformity of spinal column, characterized by both lateral curvature and vertebral rotation. The disease can be caused by congenital, developmental, or degenerative problems; but most cases of scoliosis actually have no known cause, and this is known as idiopathic scoliosis. Vertebral rotation has become increasingly prominent in the study of scoliosis and the most deformed vertebra is named as apical vertebra. Apical vertebral deformity demonstrates significance in both preoperative and postoperative assessment, providing better appreciation of the impact of bracing or surgical interventions. Precise measurement of apical vertebral rotation in terms of grading is most valuable for the determination of reference value in normal and pathological conditions for better understanding of scoliosis. Routine quantitative evaluation of vertebral rotation is difficult and error prone due to limitations of observer characteristic and specific imaging property. This paper proposes automatic identification of the apical vertebra and its parameter that depends on the objective criteria of measurement using active contour models. The proposed technique is more accurate and is a reliable measurement compared to manual and computer-assisted system.

Keywords Vertebral rotation · Scoliosis · Nash–Moe · Pedicle displacement

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Introduction

Scoliosis is a 3-D deformity involving coronal, sagittal, and axial angulations as shown in Fig. 1. Spinal deformity in scoliosis mainly consists of translations and rotations of the vertebra from their normal position in the spine. It is classified according to its etiology, age of onset, direction, location, and magnitude [1]. Early detection of scoliosis is essential in the prevention of deformity progression. School screening program facilitates early detection because spine condition often develops more during childhood compared to adolescence. It is recommended for children to be screened for abnormal spine curve. But unfortunately, the inaccuracies of the current screening tests result in high rate of false positives [2]. Scoliosis can be caused by congenital, developmental, or degenerative problems; but most cases of scoliosis actually have no known cause and this is known as idiopathic scoliosis.

Measuring the degree of deformity is important to observe the progress of scoliosis, operative planning, and correcting these spinal columns. Progression of the deformity in scoliosis, either by increasing lateral deviation and/or increasing axial rotation is the indication to treatment. The shortcomings of the Cobb angle for describing vertebral rotation are partly eliminated by the vertebral rotation method, in which the pedicle location on frontal radiographs is used as an indicator of the extent of vertebral rotation (Nash–Moe technique). There is a great need for knowledge of vertebral rotation in handling scoliosis. Vertebral rotation is of key significance in the prognosis and treatment of scoliotic curves [1, 9]. It may act as an indicator for curve progression, thus being clinically applicable for both preoperative and postoperative assessment. Inaccurate knowledge of vertebral rotation may lead to unnecessary surgical operations and in the case of pedicle screws, misplacements that incur risks of spinal cord injury.

Fig. 1 Normal vs. scoliosis spine

Routine diagnosis of scoliosis needs radiographs as input. However, assessing the extent of rotation of a spinal segment on the transverse plane is difficult. Although computed tomography (CT) technology is currently widely applied to measure spinal deformity and can obtain accurate measurements, the subject must have a supine position. However, this position reduces mechanical effects due to gravitational force and asymmetry of both lower limbs such as leg length inequality. Another significant disadvantage of CT, apart from its high cost, is patient exposure to radiation. Therefore, a methodology is required that utilizes one anterior–posterior radiograph obtained in a standing position for estimating the vertebral rotation of the spinal column [6].

In 1948, Cobb [15] first proposed a method for assessing the angle of rotation of a vertebra based on the linear offset of the spinous process in relation to position of the vertebral body on X-ray film. Cobb expressed the degree of rotation from normal to the maximal position in terms of “0” to “+4” grading category. Other method to quantify the vertebral rotation of scoliotic spine is Nash–Moe [1] technique. It divides the vertebral body into six equal segments and identifying the segment that contain the pedicles. Based on the position of the pedicle the five grades of axial vertebral rotation were determined as shown in Fig. 2. As the vertebral body rotates in an evolving curve, the pedicle outline on the convex side moves on the vertebral outline, while that of its concave counterpart becomes less evident, finally disappearing in severe curves.

Nash–Moe [1] claimed that, as suggested by the Cobb’s method it is difficult to visualize the spinous process. He suggested in terms of displacement of pedicles instead of spinous process as quantifying parameter for vertebral deformity. By dividing vertebra into six divisions, axial rotation has to be quantified. A circle has to be drawn with

Fig. 2 Pedicle method of determining vertebral rotation (source: [7])

diameter equal to the length of vertebra. Line is drawn from the center of two pedicles to the center of the circle. The angle θ_1 and θ_2 are measured to quantify vertebral rotation for normal, grade 1, and grade 2 are shown in Fig. 3.

If the rotation of vertebra is large, the outer pedicle, i.e., concave side pedicle will disappear as shown in Fig 4. As a

Fig. 3 Quantifying vertebral rotation

Fig. 4 Quantifying angle of rotation for grades 3 and 4 vertebra

result it is not possible to quantify one of the angle (i.e., θ_2) Nash–Moe technique fails in such condition.

Inaccurate knowledge of vertebral rotation may lead to unnecessary surgical operation. In case of pedicle screw misplacement that incur risks of spinal cord injury. Early studies on computerized measurement have reported a potential decrease in measurement error relative to manual protractor and use of wide diameter radiographic markers. Evaluation of vertebral rotation is not precise even when done on a normal spine under ideal condition. The problem becomes more complicated when applied to the scoliotic spine because of well-known anatomical variation that occur in the vertebra and secondary to the deforming forces of scoliosis. In addition, the actual center of the rotation may be changing in the scoliotic spine and it is difficult to look at spine and say how much change in rotation and how much is deformity.

The manual determination usually based on the orientation of vertebral body and pedicle position, shape of vertebra, and other vertebral anatomical features. However, such features do not always represent a good anchor, as the anatomical structures are not always perfectly symmetrical and oriented in the same direction across the whole vertebra. That results in different reference angles for different reference features. Therefore, a preoperative measurement of the degree of vertebral rotation provides the surgeon with information necessary for correct insertion of the pedicle screws at different vertebral levels. The aim of this proposal is to reduce the number of false positives referred to decision of apical vertebra in scoliosis through unnecessary exposure to radiation. Our findings aim to provide better insight into the clinical suitability of presently available grading methods, as well as to under-

score critical concerns that should be addressed in future development of new techniques.

Literature Review

Scoliosis is a complex 3-D deformity with the lateral deviation and rotation of the vertebral bodies among the normal and pathological conditions. Cobb [16] and Nash–Moe [1] are the few methods to evaluate the rotation of the vertebral body by using conventional radiographs. Nash–Moe is the most popular method among all and has been used in clinical practice for the evaluation of the vertebral rotation in scoliosis patients. One advantage of Nash–Moe method was that pedicle shadows could be better seen even after surgery. In comparison to the spinous process, the pedicles are located closer to the vertebral body and, consequently, are not subject to as much distortion in severe scoliotic cases.

Drerup [4, 5] improved the Nash–Moe method by modifying the measurement of the position of anatomical landmark that is the projections of vertebral pedicles. The accuracy of the measurement was affected by ignoring the facts such as increasing vertebral rotation; the radiographic projection of the vertebral body is not constant, resulting in inaccurate measurement of its properties (e.g., width of vertebra).

Benson [2] explained calculation of rotation angle based on the pedicle position in X-ray images that likely resulted in errors: (1) significant changes in the shape of all vertebrae, (2) differences between actual pedicle and pedicle images, and (3) inclination of vertebra on the sagittal plane.

Stokes et al. [8] developed a procedure that separately marked six landmarks on both an anterior-posterior view and oblique X-ray to calculate vertebral rotation angles but it was the least accurate among all methods and had a very complex analytical system.

Instruments for measuring the vertebral rotation angle directly from the radiographic position of the inner edges of both the pedicles and from the center of the inner pedicle were designed by Perdriolle [3]. When such instrument was positioned on the radiographs so that it was lined with the lateral borders of the body of the measured vertebra, the line through the anatomical landmark on the inner pedicle shadow was used. Richards [3] reported that precise measurement of vertebral rotation with the Perdriolle torsinometer should not be expected, especially due to obstruction of anatomical landmarks by metal implants, difficulties in precise marking of the pedicle, and further variation caused by patient positioning. The accuracy of the aforementioned method depends highly on the ability to mark the anatomical landmarks on the radiographs.

In 2005, Kuklo et al. [16] studied reliability analysis for manual adolescent idiopathic scoliosis measurement. They reported that apical vertebral rotation assessed by the technique of Nash–Moe produced good intra observer reliability before surgery but only fair reliability after surgery.

The above study reported that measurement performed in radiographs do not provide a valuable information as they are not reproducible and reliable. Methods for manual measurement are often too complex for routine clinical use and the inter/intra observer variability is always present because of the bias of the observer and inability of the observer to repeat measurement of the same parameter. This paper proposes an automated system for identification of apical vertebra and its parameter based on objective measurement criteria through image processing and analysis techniques. We have taken Nash–Moe for our case study because it is the standardized method by Scoliosis Research Society [13].

Proposed Method

The manual measurement is based on the identification of most deformed vertebra and its pedicle position within it. The measurements are not reproducible and reliable because of human interference in the decision of the apical vertebra and its pedicle position. The proposed method works on automatic decision of above mentioned parameters.

The morphological characteristic of spine radiographs plays important role in grading of these vertebrae's. Manual point placement for vertebral morphometry is time consuming and imprecise; hence less preferred method by the experts on day-to-day basis. Automatic determination of the detailed vertebral shape could enable more powerful quantitative tool for vertebral rotation. The automatic detection of apical vertebra and its parameter pedicle displacement are done using proposed model as shown in Fig 5.

Instead of relying on a highly variable subjective and error-prone manual identification of the apical vertebra and its parameter, it suggests an automated identification of apical vertebra and its parameter. The above requirement can be accomplished using image processing techniques. Basically radiographs are noisy in nature. Linear filtering it not suitable for such radiographs, so we started with the nonlinear filters, such as anisotropic filtering. Filtered output is given as input to the model-based segmentation method that is active contour models. Because of the initialization problem and distance parameter we shifted our self to gradient vector field (GVF) active contour models. Therefore, higher denoising performance is important in obtaining images with high visual quality using relatively lower doses of ionizing radiation. To avoid noise enhancement while restoring the image, a weighted linear isotropic

Fig. 5 Proposed block diagram

diffusive force is incorporated in the filter equation [10]. So radiographs are feed to the anisotropic filtering to enhance the bony regions.

The anisotropic filtering is based on the numerical solution of partial differential equation describing the process of nonlinear anisotropic diffusion [10]

$$\partial f(x, y, t) / \partial t = \text{div}(g(\|\nabla(f)\|) \nabla(f)) \quad (1)$$

where, $f(x, y, t)$ represents the image function. The diffusion coefficient g is a decreasing function of the image gradient norm $\|\nabla(f)\|$. The diffusion process is inhibited around the edges, where the image gradient is high. Different functions can be used giving perceptually similar results such as

$$g(\|\nabla(f)\|) = 1 / (1 + (\|\nabla(f)\|/K)^2) \quad (2)$$

The parameter K controls the rate at which the diffusion coefficient decreases as the norm of the image gradient increases. The value of K is set in relation to the gradient strength of the vertebrae in the region of interest that are preserved during the diffusion process.

The segmentation of vertebrae in radiograph is of prime importance in the assessment of abnormalities of the scoliotic spine. Manual tracing of vertebral boundary is error prone due to inter- and intra-observer subjective variability.

Segmenting structures from medical images and reconstructing a compact geometric representation of these structures is difficult due to complexity and variability of the anatomic shapes of interest.

Fig. 6 Grade, normal; **a** original image, **b** segmented vertebrae, **c** horizontal lines, **d** pedicle initialization, **e** segmented pedicles, **f** pedicle extraction of apical vertebra, **g** quantifying axial rotation ($\theta_1 = 38.302 = 36.4VAR = 1.9$). Grade, +1: **a** original image, **b** segmented vertebrae, **c** horizontal lines, **d** pedicle initialization, **e** segmented pedicles, **f** pedicle extraction of apical vertebra, **g** quantifying axial rotation ($\theta_1 = 36.3202 = 43.15VAR = 7.17$). Grade, +2: **a**

original image, **b** segmented vertebrae, **c** horizontal lines, **d** pedicle initialization, **e** segmented pedicles, **f** Pedicle extraction of apical vertebra, **g** quantifying axial rotation ($\theta_1 = 30.9602 = 49.55VAR = 19.46$). Grade, +3: **a** original image, **b** segmented vertebrae, **c** horizontal lines, **d** pedicle initialization, **e** segmented pedicles, **f** Pedicle extraction of apical vertebra

Edge-based methods imposing subsequent edge linking constraint [10], but it is very difficult to satisfy in case of low dose radiographs. In this method, local gradient edges or texture similarity are not promising because of very low signal-to-noise ratio.

Model free-based techniques which consider only local information can make incorrect assumptions during this integration process and generate infeasible object boundaries. As a result, these model-free techniques usually require considerable amounts of expert interven-

Table 1 Intra-observer error variation while grading scoliosis radiographs through Nash–Moe procedure

Manual	Automatic		
	G1	G2	G3
Mean	2.3	1.7	2.7
STD	1.2	0.9	1.3

tion. Snakes are planar deformable contours that are useful in several image analysis tasks [11, 12], they are often used to approximate the locations and shapes of object boundaries in images based on the reasonable assumption that boundaries are piecewise continuous or smooth.

A snake [11] is a deformable curve $X(s)=[x(s); y(s)]$; $s \in [0; 1]$, which gradually moves from its initial state under the influence of forces and is expected to terminate on the object boundary at equilibrium. The curve evolution can be given by minimizing the snake total energy E :

$$E = \int_0^1 1/2 [\alpha |X'_s(s)|^2 + \beta |X''_s(s)|^2] + E_{\text{ext}}(X(s)) ds \quad (3)$$

where, α and β are weighting parameters that control the snake's tension and rigidity respectively, and $X'_s(S)$ and $X''_s(S)$ denote the first and second derivatives of $X(S)$ with respect to S . The external energy function E_{ext} is derived from the image to take on its smaller values at boundaries. Minimizing the energy functional of Eq. 3 gives rise to the Euler equation

$$\alpha X''(s) - \beta X'''(s) - \nabla E_{\text{ext}} = 0 \quad (4)$$

This can be viewed as a force balance equation:

$$F_{\text{int}} + F_{\text{ext}} = 0 \quad (5)$$

where, the internal force, $F_{\text{int}} = \alpha X'(S) - \beta X''(S)$, discourages the snake stretching and bending and the external force, $F_{\text{ext}} = -\nabla E_{\text{ext}}$, attracts the snake toward the image edges. The equilibrium solution of Eq. 5 represents the final snake curve under the influence of the internal and external forces which are counter balanced with each other. Traditionally, the external force is formed by the gradient of the image or image edge map, which cannot pull the curve towards the desired boundary, if the snake's initial position is far away from the object boundary. To overcome this limitation, the GVF snake model [14] replaces the

traditional external force with the GVF force $v(x; y)$, which is defined as the equilibrium solution of the following vector diffusion equation:

$$\frac{\partial x}{\partial t} = \mu \nabla^2 v - (v - \nabla f) |\nabla f|^2 \quad (6)$$

Where ∇^2 is the Laplacian operator, ∇ is the gradient operator, f is the magnitude edge map of an image, and μ is a regulation parameter. The GVF force is nearly equal to the gradient of the edge map when it is large, but is slowly varying in homogeneous regions. Therefore, the GVF force has larger capture range and under its influence, the snake can move into boundary concavities. GVF is less sensitive to initialization, so we worked with automatic initialization through automatic generation of elliptical structure as we move the mouse on the vertebral body.

The true identification of the apical vertebra for the vertebral measurements needs the horizontal line slope information of all vertebrae. A segmentation procedure gives the complete contour of the vertebrae. Before calculating the horizontal tilt, we retained only the horizontal contours through morphological processing.

Output of the GVF active contour models gives the complete morphometry for the entire vertebra from T1 to L5. As defined in the literature, Nash–Moe procedure needs identification of the apical vertebra as the first stage for analysis. As per the theory, apical vertebra means the most deformed one. If we know the contour of the entire vertebra within T1 to L5, one can easily decide about the apical vertebra. Next step is to evaluate the deformity to identify the apical vertebra. For highly deformed vertebra, its end plates will be tilted in opposite direction. Hence, only the horizontal inclination lines are retained using morphological processing and that resulted with two end plates per vertebra. The vertebra with its end plates having opposite sign (found using Hough Transform) is the apical vertebra. As per Nash–Moe, we need to find the pedicle position in the identified apical vertebra. Again, GVF active contour model is applied to segment the pedicles in the apical vertebra. Later, using the computer-aided system, divide the apical vertebra into six equal segments. Based on the position of the pedicle in the segments grading has been done. For calculating the vertebral rotation, using computer-aided system, we draw a circle with diameter as that of the length of the apical vertebra. Later, we have done the collinear alignment for the circle as well as apical vertebra. Using computer mouse, we draw a lines from centroid of pedicles to the center of a circle. The difference between these angles gives about the vertebral rotation.

Results and Analysis

Initial contour for the segmentation procedure was generated by the automatic generation of elliptical structure on each vertebra as soon as the radiologist moves the mouse on the respective vertebra. The performance of the segmentation technique relies heavily on the strength of the edges. An anisotropic filtering is applied to the images to enhance edges of the vertebrae. This moderately improves the segmentation process. An important parameter for judging the performance of the segmentation algorithm is initial contour. In active contour models, shape information is used alternatively with gradient information, iteratively to segment the image. Our approach allowed the curve to evolve into sharp protrusion in the boundary of the vertebra, since one of the goals of post-segmentation analysis is the estimation of the upper and lower end-plate tilting of the entire vertebral column. Furthermore, it also shows that current segmentation technique can be effectively extended to segment the pedicles within the selected apical vertebra.

Original image of spine and segmented vertebrae with different levels of scoliosis is as shown in Fig. 6a and b, respectively. Slope of all vertebrae is found out from the horizontal lines (Fig. 6c), which are retained from the segmented vertebrae by using morphological operations.

The transition from positive to negative slope gives the apical vertebra. Pedicles are segmented within the apical vertebra using GVF active contour models as shown in Fig. 6e. The five grades of axial vertebral rotation are determined by dividing the vertebral body into six equal segments (Fig. 6f) and identifying the segment that contained the pedicles. The angle θ_1 and θ_2 of apical vertebra is measured (Fig. 6g). The vertebral axial rotation of apical vertebra which is objective criteria of rotation is given by $\theta_1 - \theta_2$.

Table 1 describes the intra observer error variation, while calculating the vertebral rotation for each grading group. We considered eight to ten radiographs in each category. We have taken three experts to calculate the angle at five different intervals. The error estimation in case of automatic/proposed technique is because of initialization step required in getting the boundary. That error is comparatively very less, because will not affect the direct measurement. In comparison with the manual method where errors are introduced at three different stages while deciding the apical vertebra, second is getting the pedicle position and last while dividing the apical vertebral body into six equal segments and angle calculation. From Table 1, we can observe that manual calculation leads to more error variation compared to the proposed automatic calculation.

Conclusion

Calculation of vertebral rotation plays an important role in the diagnosis of scoliosis. It correlates the degree of rotation with the percentage displacement of the pedicle along the vertebral diameter. But the vertebral rotation measurement in the given anterior–posterior radiographs involves considerable uncertainty due to inter-individual variation in the decision of the apical vertebra and position of its pedicles because of the nature of the radiographs. The proposed method works on the true identification of apical vertebra and accurate displacement of the pedicles within it, by extracting the important features from the given radiographs using image-processing techniques. Our findings provide better insight into the clinical suitability of presently available grading methods for scoliotic radiographs.

References

- Nash CL, Moe JH: A study of vertebral rotation. *J. Bone Joint Surg. Am.* 51(2):223–229, 1969
- Benson DR: Roentgen graphic evaluation of vertebral rotation. *J. Bone Joint Surg. Am.* 58:1125–1129, 1976
- Richards BS: Measurement error in assessment of vertebral rotation using the Perdriolle torsion meter. *Spine* 17(5):513–517, 1992
- Drerup B: Improvements in measuring vertebral rotation from the projections of the pedicles. *J. Biotech.* 18(5):369–378, 1985
- Drerup B: Principles of measurement of vertebral rotation from frontal projections of the pedicles. *J. Biotech.* 17(12):923–935, 1984
- Aaro S, Dahlbo M: Estimation of vertebral rotation and the spinal and rib cage deformity in scoliosis by computer tomography. *Spine* 6(5):461–467, 1981
- Mehta MH: Radiographic estimation of vertebral rotation in scoliosis. *J Bone Joint Surg* 55B(3):513–520, 1973
- Stokes IAF, Bigalow LC, Moreland MS: Measurement of axial rotation of vertebrae in scoliosis. *Spine* 11(3):213–8, 1986
- Jeffries BF, Tarlton M, De Smet AA, Dwyer SJ: 3rd and A C Brower computerized measurement and analysis of scoliosis: a more accurate representation of the shape of the curve. *Pediatric Radiology* 134:381–385, 1980
- Perona P, Malik J: Scale-space and edge detection using anisotropic diffusion. *IEEE Trans Pat Anal Mach Intel* 7:629–639, 1990
- Kass M, Witkin A, Terzopoulos D: Snakes: active contour models. *Int J. Computer Vision* 9:321–331, 1988
- Chenyang Xu, Jerry L: Prince, snakes, shapes, and gradient vector flow. *IEEE Transaction Image Proc* 7(3):359–369, 1998
- Vrtovec T, Pernus F, Likar B: A review of methods for quantitative evaluation of spinal curvature. *Eur Spine J* 18:593–607, 2009
- Zhe Lin, Larry S. Davis, David Doermann and Daniel DeMenthon H, Hierarchical part-template matching for human detection and segmentation, *IEEE 11th International Conference on Computer vision* 2007.
- Cobb JR: Outline for the study of scoliosis. *American Academy of Orthopedic Surgeons, Instructional Course Lectures* 5:261–275, 1948
- Kuklo TR, Potter BK, Polly Jr, DW, O'Brien MF, Schroeder TM, Lenke LG: Reliability analysis for manual adolescent idiopathic scoliosis measurements. *Spine* 15:30(4):444–54, 2005