Chapter 5

Grading of Vertebral Rotation

The measurement of vertebral rotation has become increasingly prominent in the study of scoliosis. Apical vertebral deformity demonstrates significance in both preoperative and postoperative assessment, providing better impact for bracing or surgical interventions. Precise measurement of apical vertebral rotation can be graded as 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 in observer characteristics during identification of apical vertebrae and its pedicle position. This chapter proposes automatic identification of the apical vertebra and its pedicle boundary using active contour models. The proposed technique is more accurate and reliable compared to manual and computerized system.

5.1 Introduction

Measuring the degree of deformity is important to observe the progress of scoliosis and operative planning. Progression of the deformity in scoliosis, either by increasing lateral deviation and/or increasing axial rotation is the indication to treatment. Cobb angle in the frontal plane is highly influenced
by the lateral deviation and less by the axial rotation [43]. The vertebral rotations are the additional information for the diagnosis of scoliosis [2].

Routine diagnosis of scoliosis uses radiographs as input. However, assessing the extent of rotation of a spinal segment on the transverse plane is difficult. CT technology is widely applied to measure spinal deformity. It can also obtain accurate measurements under supine position. 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 a PA radiograph obtained in a standing position for estimating the vertebral rotation of the apical vertebra.

In 1948, Cobb [36] 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 radiographic film. Cobb graded 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 [2] technique. It divides the vertebral body into six equal segments and identifies the segment that contains the pedicles. Based on the position of the pedicle, five grades of vertebral rotation are determined as shown in Figure 5.1 and grades are listed in Table-2.4. As the vertebral body rotates in the form of an evolving curve, the pedicle outline on the convex side moves to the vertebral outline, while that of its concave counterpart becomes less evident, finally disappearing in severe curves.

Nash-Moe [2] claims that, it is difficult to visualize the spinous process using Cobb method. They suggested the displacement of pedicles instead of spinous process as quantifying parameter for vertebral deformity. The axial rotation has to be quantified by dividing vertebra into six divisions. A circle has to be drawn with diameter equal to the length of vertebra. Line is drawn from the center of two pedicles to the center of the circle. The angle $\theta_1$ and $\theta_2$
Figure 5.1: Pedicle method of determining vertebral rotation (Courtesy [5])

Figure 5.2: Illustration to quantify vertebral rotation
are measured to quantify vertebral rotation for normal, grade +1 and grade +2 as shown in Figure 5.2.

If the rotation of apical vertebra is large, the outer pedicle (i.e., concave side pedicle) will disappear as shown in Figure 5.3. This shows that it is not possible to quantify one of the angles (i.e. $\theta_2$), only grading is done for such cases.

Figure 5.3: Quantifying angle of rotation for grade +3 and grade +4 vertebra

Inaccurate knowledge of vertebral rotation may lead to unnecessary surgical operation [78]. In case of pedicle screw misplacement it incurs risks in the 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 [79]. Evaluation of vertebral rotation is not precise even on a normal spine under ideal conditions. The problem becomes more complicated when applied to the scoliotic spine because of well-known anatomical variations that occur in the vertebrae and secondary to the deforming forces of scoliosis.

The manual determination is 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. This results in different reference
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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.

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 [2]. One advantage of Nash-Moe method is that, pedicle shadows can 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 much distortion in severe scoliotic cases.

The literature review in Section 2.6.2 reported that measurement performed using radiographs do not provide a valuable information as they are not reproducible and reliable. Method for manual measurement are often too complex for routine clinical use as the inter- and intra- observer variability are always present due to the bias in observer characteristics for repeating the measurement of the same parameter. The following section proposes an automated system for identification of apical vertebra and its parameter based on the objective measurement criteria using image processing and analysis techniques. SRS has adopted Nash-Moe vertebral rotation as standard estimation method [41]. This motivated to propose automation of Nash-Moe technique. The aim of this proposal is to reduce the number of false positives referred to decision of apical vertebra in scoliosis with unnecessary exposure to radiation.

5.2 Automatic grading of vertebral rotation

The manual measurement of vertebral rotation is based on the identification of highly deformed vertebra (apical vertebra) and its pedicle position within it [2]. 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 in this thesis works on automatic decision of above mentioned
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Figure 5.4: Pedicle segmentation within the selected apical vertebra

parameters as shown in Figure 5.4. For a given radiograph the horizontal endplate of all vertebrae are retained as explained in previous Chapter 4. The apical vertebra needs to be identified through the analysis of the slopes which represents the inclination of horizontal boundary in terms of subjective parameter. The pictorial identification of apical vertebra is shown in Figure 4.4c.

Further, it identifies pedicles within the selected apical vertebra. Grading of the vertebral rotation depends on the position of the pedicles within the apical vertebrae as per Nash-Moe definition [2]. It demands true identification of the pedicle boundary. Extraction of these pedicles by parametric ACM suffers from initialization. The pedicle boundary and vertebral boundary are very close to one another, which misleads the initial contour during convolving stage. It needs an initialization from the imaging features that is realized by geometric ACM with level set property.
The classic snakes provide an accurate location of the edges only if the initial contour is defined sufficiently near the edges since they make use of only the local information along the contour. Without prior knowledge of the object to be detected, estimating a proper initial position of contours is a difficult task. Also, classic snakes cannot detect more than one boundary simultaneously because the snakes maintain the same topology during the evolution. Such problems are addressed through geometric active contour models through the Level set theory.

5.3 Geometric Model: Level Set

The first step in the level set method is to pick an initial curve. The boundary of the object to be detected which is obtained after evolving the initial curve using Equation 5.1. One of the many advantages of this method is that its accuracy does not depend on the choice of the initial curve. However, the process would be faster if the chosen curve is close to the target object. Assume a circle r1 of arbitrary radius (inner curve) chosen as our initial curve. Then, a smooth implicit function (level set function, $\phi$) is defined in three dimensions such that its intersection with $z = 0$ plane gives $\phi$. In level sets, the front propagation is stated as an initial value termed as $\phi(t)$. There are many ways in which $\phi$ can be defined. One of the simpler ways is using the signed distance function.

Signed Distance Function

The signed distance function, $\phi$ of r1 is defined as

$$\phi(x) = d(x)$$  \hspace{1cm} (5.1)

where $d(x)$ is the distance of the point $x$ from its nearest point on r1. The points inside are assigned a negative distance while the points outside are
assigned a positive distance.

An example of the level-set representation is shown in Fig.5.5. The figure shows the level set expanding outward at a uniform speed in all directions, and as time passes (t=0 to t=2) the level set function (the right column) grows and the corresponding zero-level set curve (left column) changes to a circle of bigger radius. The object boundary is then given by the zero level-set of the steady state (t=0) of this flow.

Figure 5.5: Level-set representation: a circle represented by a level set function and expanded at a uniform speed

As seen in Equation 5.2, partial differential equations are used to evolve the level set function, ideally, \( \phi \) should remain smooth throughout the evolution. However, the level set function may develop points that are not differentiable, resulting in an erroneous output. Such errors may propagate and cause even more errors with time.

Factors Controlling front Propogation

The level set function of r1 and r1 is the intersection of \( \phi \) with \( z=0 \). The value of \( \phi \) at all points on r1 will be zero, i.e. \( \phi(x(t)) = 0 \), where \( x(t) \) is the spatial vector of any point on the front. Since \( r1 \) is a \( 2-D \) curve, the above Equation 5.1 can be rewritten as
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\[ \phi[x(t), y(t), t] = 0 \]  \hspace{1cm} (5.2)

\[ \phi_t + F |\nabla \phi| = 0 \]  \hspace{1cm} (5.3)

\(\nabla \phi\) is the gradient of \(\phi\), \(F\) is the speed of the curve in the direction of the gradient of the level set function. For a given initial curve, \(\phi\) is known and, thus, the only unknown in the level set equation is the speed function \((F)\), which makes it our design parameter. Generally, speed function have two terms. The first term is usually a constant, whose magnitude controls the size of the steps with which the curve moves, while the second term depends on the front geometry and shape. That is, one may write,

\[ F = C + F(k) \]  \hspace{1cm} (5.4)

where \(C\) is the constant term, and \(F(k)\) is the term that depends on the front’s geometry. As an example, \(F = 1 - \epsilon k\) is the commonly-used speed function, where \(k\) is the curvature of the level set function and \(\epsilon\) is a constant.

The curvature of the surface is given by,

\[ k = \nabla \cdot \frac{\nabla \phi}{|\nabla \phi|} \]  \hspace{1cm} (5.5)

\[ k = \phi_{xx}\phi_y^2 + 2\phi_x\phi_{xy}\phi_y + \phi_{yy}^2/(\phi_x^2 + \phi_y^2)^{3/2} \]  \hspace{1cm} (5.6)

Where \(\phi_x\) and \(\phi_y\) are the first derivatives of \(\phi\) in the \(x\) and \(y\) directions, respectively, and \(\phi_{xx}\) and \(\phi_{yy}\) are the second derivatives. Note that if \(\epsilon\) is a positive constant and \(k\) is negative, with the increase in \(k\), force \(F\) increases. As a result, the regions on the curve that have sharp bends will move faster and the curve will continue to sharpen. On the other hand, if \(\epsilon\) is a negative constant, \(F\) decreases with the increase in \(k\). In this case, regions on the curve
that have sharp bends will move slower and will cause the curve to become smooth.

**Terminating Front Propagation**

The final step in front propagation is to stop it when it reaches the boundary of the target object in the image. Using the speed function, the front will evolve until it moves out of the image domain. Hence, it needs to be modified such that its values become significantly small at the boundary of the target object. A simple modification suggested is,

\[
F_Q = Q.F \tag{5.7}
\]

where \(Q(x, y) = 1/(1 + |\nabla G * I(x, y)|)\). In \(Q\), the term \((|\nabla G * I(x, y)|)\) is the magnitude of the gradient of the Gaussian-smoothed image. The gradient will have large values at the boundary of the target object and will be close to zero at all other points. The speed function when multiplied by \(Q\), will have small values at the boundary of the target object but will retain its value at all other points. Thus, the front will propogate with a speed \(F\) until it slows down significantly at the boundary of the target object.

Contrast of the image or edge affects the magnitude of the stopping force at the boundary. In case of poor contrast, although the edge magnitude is smaller, due to the double term, a low-contrast but clearly-defined boundary can still be captured. Noise can greatly affect the segmentation results. Since the algorithm is edge-based and highly localized, noise can present local optimums
where the curve evolution will get stuck. It is generally helpful to smooth the image before applying geometric active contour. Most commonly Gaussian smoothing is applied. The amount of smoothing plays an important role in the success of the algorithm. Smoothing helps in eliminating noise that may hinder the propagation of the front. Out of three different geometric active contour models (fast marching, shape detector, geodesic), we have chosen geodesic as the best estimation for detection of pedicle contour.

Geodesic Active Contour:

The geodesic active contour evolution function is given by equation 5.8. All parameters \(c, \beta, \epsilon\) are set to 1 unless otherwise specified. The edge detector \(g\) used is shown in Equation 5.9, where \(k\) is a positive constant parameter (again, set to 1 unless otherwise specified).

\[
\frac{\partial(\phi)}{\partial(t)} = g(\beta k + c) |\nabla \phi| + \epsilon \nabla(g(\nabla(\phi)))
\]  

\[
g = \frac{1}{1 + (\nabla I/k)^p}
\]

where \(p = 1\) or 2 and \(k\) is a positive constant for edge magnitude adjustment and \(p = 2\) is most commonly used. As shown in Equation 5.8 there are three main speed terms that play a role in advancing the front curvature term, propagation term and advection term.

Curvature term \((\beta \, k \, g \, |\nabla \phi|)\)

This term helps in keeping the curve smooth and it makes the curve to stop at the boundary. On its own without \(g(I)\), \(k \, |\nabla \phi|\) term is a Euclidean length minimizing term, thus keeping the evolving curve smooth. Multiplied by \(g(I)\), the speed term is adjusted to stop at the boundary. In the case of an ideal edge, the term goes to 0 and there will be no movement, however large the
curvature $k$ may be. The curvature of the surface is given by Equation 5.8. In this work after carrying out many simulations it is concluded that a $\beta$ value of 0.8 gives best result.

**Advection term** ($c \, g \, |\nabla \phi|$)

This term helps in pushing the term closer to the boundary and gives a faster convergence. When $c = 0$ the convergence can be quite slow. The constant $c$ can also be used to control the direction of curve flow. The sign of $c$ is set according to direction of movement. For outward movement $c = 1$ and for inward movement $c = 0$. In this work $c = 1$ is used.

**Propagation term** ($\epsilon \nabla (g) \nabla (\phi)$)

This term helps in keeping the front around the vicinity of the edge and locates the boundary in case of weak edges. In the present work value of 0.8 is used.

Extracted apical vertebra with pedicles are given as input to the computer assisted method to automate the Nash-Moe procedure for grading and quantifying the vertebral rotation as shown in Figure 5.6. First step is to divide the extracted apical vertebral body into six equal regions along the coronal direction and count the number of pedicles. In normal spine, both the pedicles are visible as well as both the outer region contains the complete boundary of the pedicles. Computer assisted algorithm counts the number of pedicles, if the result is two and both the pedicle boundary stays in the outer region, then it will be graded as Normal/Grade0. It results with count as two but it is not in the original position, displaced to new position are of two grades, either Grade +1 or Grade +2. Grade +1 means, 50% percent of the pedicles falls in first region and next 50% falls in second region, such vertebrae are graded as Grade +1. If the pedicle has crossed the first region completely, and other pedicle are not clearly visible in the last segment, then it is named as Grade +2. In case of Grade1 and Grade +2, quantification of vertebral rotation is
Figure 5.6: Automatic grading of apical vertebrae
possible. The angle between the centroid of the pedicle boundary will quantify the vertebral rotation. If only one pedicle is visible, then the estimation of vertebral rotation is not possible.

5.4 Results and Discussions

Vertebral rotation is of key significance in prognosis and treatments of scoliosis. It is clinically applicable for both preoperative and postoperative assessment. Radiographs of 150 patients who had scoliosis were selected from KMC Manipal, India. The distance between the X-ray tube and table is constant. This chapter is to examine and compare relative merits of rotational evaluation with grading and vertebral rotation for manual and computerized image analysis system.

Manual Measurement:

The measurement from three different groups are carried out based on the severity. In manual identification it is difficult to do precise marking of apical vertebra and pedicles inside it. The tracing of pedicle boundary is significantly influenced by changes in the vertebral shape. Figure 5.1 describes grades of apical vertebra. Grading using manual method begins with identification of apical vertebra. The position of pedicles is rotated such that vertebral body should be divided into six equal segments in the transverse plane. After marking the pedicle centers on apical vertebra, the grades from 0 to +4 are assigned depending on the location of the pedicles within the segment. The vertebral rotation is quantified using ruler and pencil system by projecting a circle with diameter as that of vertebral body length. Using ruler divide the vertebral body into six segments. Manually mark the centers for the pedicle body. Quantify the angle formed by the line between center of pedicle to center of circle and center of circle to center of vertebra and similarly for the other pedicle. The difference between these angles quantifies vertebral rotation.
Proposed Measurement:

In chapter 4, we discussed about the automatic identification of apical vertebra. Identified apical vertebra is the ROI for successive procedures. After identifying the apical vertebra on the given PA radiograph a computerized program is developed to grade the apical vertebra as shown in Figure 5.6. Segmentation of pedicle boundary inside the apical vertebra are done with level set function. Initial contour are set by computer assistance by mouse clicking. Grading depends on the position of the pedicles. Developed computer algorithm divide the vertebral body into six equal segments. Visibility of pedicle boundary under different segment of vertebral body will grade the apical vertebra. First step to quantify the vertebral rotation is to project a circle with diameter as that of vertebral body length. Centers of the circle should be in line with centers of vertebra. Pedicles are segmented within the apical vertebra using Levet Set models as shown in Figure 5.7c to Figure 5.10c. The five grades of vertebral rotation are determined by dividing the vertebral body into six equal segments as shown in Figure 5.7f to Figure 5.10f. The angle $\theta_1$ and $\theta_2$ of apical vertebra is measured (Figure 5.2). The Vertebral Rotation (VR) of apical vertebra which is the objective criteria of rotation is given by $(\theta_1 - \theta_2)$.

Discussion:

Comparison between manual and proposed system are carried out for different groups of radiographs based on the severity. Each group study involves 5 observers and 15-20 PA radiographs. Each observer independently identified the apical vertebrae without having any prior information about previous measurement. Same protractor, pencil and ruler are provided to reduce measurement variation. Final measurement ends with misgrading because of difficulties in identifying the vertebra and its pedicle boundary. Measurement errors are reported in Table 5.1, it is clearly visible as the severity increases.
measurement error also increases. Computerized image analysis starts with automatic identification of apical vertebra. Further steps are proceeded with computer assistance. Initial contour selection while segmenting the apical vertebra and pedicle boundary tracing caused minor misgrading.

Figure 5.7: Normal Grading (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 \( \theta_1 = 38.3 \theta_2 = 36.4 \ VR = 1.9 \)
Figure 5.8: Grading +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 ($\theta_1 = 36.32 \theta_2 = 43.15$ $VR = 7.17$)
Figure 5.9: Grading +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 ($\theta_1 = 30.96^\circ$ $\theta_2 = 49.55^\circ$ $VR = 19.46)$
Figure 5.10: Grading +3 (a) Original Image (b) Segmented Vertebrae (c) Horizontal Lines (d) Pedicle Initialization (e) Segmented Pedicles (f) Pedicle extraction of Apical Vertebra
Table 5.1: Performance evaluation of the proposed grading system for Nash-Moe definition

<table>
<thead>
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<th>Grade</th>
<th>Manual Consistency</th>
<th>Manual Kappa value</th>
<th>Comp. image understanding Consistency</th>
<th>Comp. image understanding Kappa value</th>
</tr>
</thead>
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<td>0.87</td>
</tr>
<tr>
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<td>92</td>
<td>0.88</td>
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<tr>
<td>+2</td>
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<td>0.69</td>
<td>90</td>
<td>0.87</td>
</tr>
<tr>
<td>+3</td>
<td>76</td>
<td>0.68</td>
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<td>0.76</td>
</tr>
<tr>
<td>+4</td>
<td>78</td>
<td>0.66</td>
<td>79</td>
<td>0.68</td>
</tr>
</tbody>
</table>

5.5 Summary

Quantification 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 PA radiograph 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 currently available grading methods for scoliotic radiographs.