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The Correlation Comparison of Vertebral Axial Rotation Relative to Curvature and Torsion in Scoliosis by Simplified 3D Spine Model

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Abstract --- **This paper reports a study on correlation comparison of the vertebral axial rotation relative to curvature and torsion of scoliotic spine. The goal of this study is to understand whether the vertebral axial rotation is more correlated to the curvature or to the torsion of the scoliosis spinal deformity. For this purpose, the simplified 3D spine models are constructed on the randomly chosen images of scoliosis patients. The 3D spine model is based on two orthogonal spinal radiographic images taken from coronal and sagittal planes. Superimposed on these two images, the 3D Bezier curves are fitted interactively onto the center of the spine on both coronal and sagittal images. Upon the 3D Bezier Curve fitting, a series of simplified 3D vertebrae are implemented onto the 3D Bezier Curve proportional in size to its axis. The curvature and torsion then are obtained by difference quotients algorithm. In determining the vertebral axial rotation, the measurements are conducted directly on the coronal spine images. The lateral margins and centers of pedicles are used as landmarks for the rotation calculation. The correlation coefficients are calculated from both vertebral axial rotation relative to the curvature and to the torsion found on each vertebra. The strength of correlations from both cases is compared in the table.**

Keywords --- **Simplified spine model, scoliosis, vertebral axial rotation, curvature, torsion, different quotients, correlation coefficient.**

I. Introduction

It is commonly understood that the scoliosis is a three dimensional spinal deformity. The extensive studies have been made to the spinal deformities regarding its curves and apexes in both coronal and sagittal planes. However, these studies have been focused more on the vertebra movements in the coronal and sagittal planes than on the axial rotation. When investigating the spinal deformity, the vertebral axial rotation is often to be one important aspect to be considered [1]-[5]. The vertebral axial rotation movement is generally not the movement in axial plane, but the vertebral rotation about its axis in 3D space. This phenomenon adds the three more rotational components to three dimensional space components for vertebra movement. In defining and observing the scoliosis deformity, there are currently three classification systems to describe the types of deformities and their related treatment suggestions. King classification system is two-dimensional because it takes into account the deformities only in coronal plane [6]. Lenke classification, claiming its three dimensional consideration, has parameters in both coronal and sagittal components [7]-[9]. Recently developed by Peking Union College Medicine, the PUCM classification system added the vertebral axial rotation, the third parameter in the classification system. In theory this addition makes the PUCM system in the consideration of 3D plus a vertebral axial rotation in 3D space [10]. By further investigation some authors concluded that the current surgical techniques for treatment of scoliosis significantly reduced the coronal and/or sagittal plane deformity, but the vertebral axial rotation deformity has not been corrected adequately [11]-[13]. Since the scoliosis deformity correction involves not only the coronal and sagittal planes, but also the vertebral axial rotation, it is necessary to understand the relationship of vertebral axial rotation with deformities in coronal and/or sagittal planes, and whether this rotation is more correlated with the curvature or the torsion of space curve of scoliosis spine. In order to achieve this goal, the Simplified 3D Spine Model program developed earlier was used for constructing the 3D spine models of randomly selected images of scoliosis patients [14]-[17]. The simplified 3D spine model is based on the coronal and sagittal x-ray images of scoliosis patients. The curvature and torsion of scoliosis spine is obtained by the total curvature analysis, which is the sum of square of its curvature and torsion at each level of vertebra [18]-[19]. In determining the vertebral axial rotation, several methods had been proposed by different authors [1]-[5]. The simplest way to obtain the vertebral axial rotation is to directly locate the landmarks on the coronal standing x-ray image [5]. Based on these landmarks, the approximated angle for vertebral axial rotation could be obtained. Upon obtaining the angle of each vertebral axial rotation for each scoliosis spine, two correlation coefficients are calculated. One is between the angle of vertebral axial rotation and curvature for each level of vertebra. Another is between the angle of vertebral axial rotation and torsion for each level of vertebra. Finally, the strength of these two correlation coefficients is compared.

II. Methodology

A. Simplified 3D Spine Modeling

The simplified 3D spine modeling is applied on x-ray images of every randomly chosen scoliosis patients. The image of each patient contains two orthogonal standard spinal radiographic images taken from both the coronal plane and sagittal plane. Three segments of 3D Bezier curves are fitted on the spine center in both coronal plane and sagittal plane images. In order for the smoothness of the multiple Bezier curve connections, the constraints on each joint of connections are imposed. There are equal values of the first derivatives for each connection joint of both endings of Bezier curves. First Bezier curve has 5

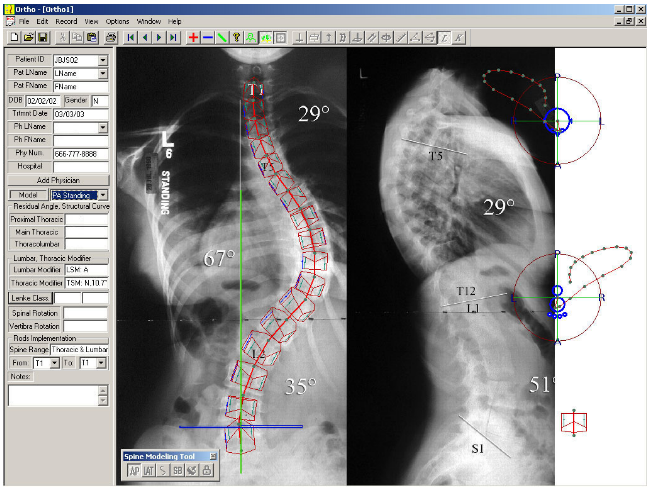


Figure 1. Simplified 3D spine model based on coronal and sagittal spine x-ray images.

segments representing the lumbar spine region. Second and third Bezier curves both have 6 segments representing the main thoracic region and proximal thoracic region. The three 3D Bezier curves are divided into a series of uniformed small segments representing the axis of each vertebra. On each small segment, a polyhedron is centered on this axis. Thus the simplified 3D spine model can be determined by three Bezier curves on which a series of polyhedrons is proportionally implemented representing the simplified 3D vertebrae [15]. Figure 1.

B. Curvature and Torsion by Difference Quotients:

For the parameterized space curve such as central axis of spine, it could be represented as a vector function x(s) with respect of its arc length s, i.e. $x(s) = \left[x(s)y(s)z(s)\right]^T$. Let the τ to be the torsion and the κ to be the curvature. They are defined as:

The curvature $$\kappa = \left|\dot{\mathbf{x}} \times \ddot{\mathbf{x}}\right| \quad (1)$$

The torsion $$\tau = \frac{\det(\dot{\mathbf{x}}, \ddot{\mathbf{x}}, \dddot{\mathbf{x}})}{\kappa^2} = \rho^2 \left|\dot{\mathbf{x}} \cdot (\ddot{\mathbf{x}} \times \dddot{\mathbf{x}})\right| \quad (2)$$

In this application, the 3D curve of central axis is defined by a series of points in 3D space. These points can form a series of connected vectors. From the above equations (1) and (2) for smooth space curve, a discrete form of curvature K and torsion T can be introduced. In such case, the derivative with respect of s in the equations (1) and (2) could be formally replaced by difference quotients, or divided difference. For the vector $x(s)_i$, i = 1,..n, the following equations can be derived,

$$\dot{\mathbf{x}}_1 = \left[\mathbf{x}_1, \mathbf{x}_0\right] = \frac{(\mathbf{x}_1 - \mathbf{x}_0)}{\mathbf{S}_1} = \mathbf{e}_1 \quad (3)$$

$$\ddot{\mathbf{x}}_{12} = 2\left[\mathbf{x}_2, \mathbf{x}_1, \mathbf{x}_0\right] = \frac{2(\dot{\mathbf{x}}_2 - \dot{\mathbf{x}}_1)}{(\mathbf{S}_1 + \mathbf{S}_2)} = \frac{2(\mathbf{e}_2 - \mathbf{e}_1)}{(\mathbf{S}_1 + \mathbf{S}_2)} \quad (4)$$

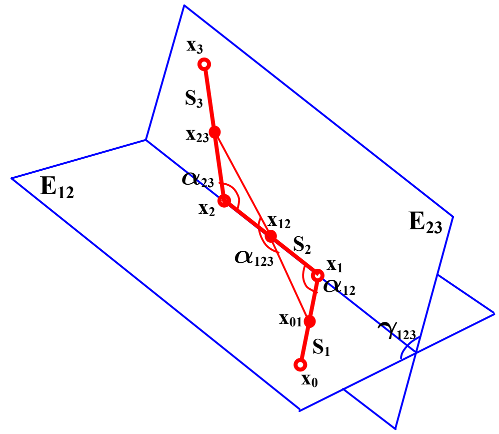


Fig. 2. Curvature and torsion derived by difference quotients.

$$\dddot{\mathbf{x}}_{123} = 6\left[\mathbf{x}_3, \mathbf{x}_2, \mathbf{x}_1, \mathbf{x}_0\right] = \frac{3(\ddot{\mathbf{x}}_{23} - \ddot{\mathbf{x}}_{12})}{(\mathbf{S}_1 + \mathbf{S}_2 + \mathbf{S}_3)} \quad (5)$$

From equation (1) and (2), and notice $\left|\mathbf{e}_i \times \mathbf{e}_i\right| = 0$, we have discrete form of curvature K and torsion T:

$$K_{12} = \left|\dot{\mathbf{x}}_1 \times \ddot{\mathbf{x}}_{12}\right| = \frac{2}{(\mathbf{S}_1 + \mathbf{S}_2)}\left|\mathbf{e}_1 \times \mathbf{e}_2\right| = \frac{\sin\alpha_{12}}{\mathbf{S}_{12}}$$

$$T_{123} = \frac{\det(\dot{\mathbf{x}}_1, \ddot{\mathbf{x}}_{12}, \dddot{\mathbf{x}}_{123})}{\mathbf{K}_{12} \cdot \mathbf{K}_{23}} = \frac{\sin\gamma_{123}}{\mathbf{S}_{123}}$$

Here S_{12} is the average length of segments S_1 and S_2 while S_{123} is the average length of segments S_1, S_2, and S_3.

And the α_{12} denotes the angle of deformity between two vectors $\mathbf{e}_1$ and $\mathbf{e}_2$, while γ_{123} denotes the torsion angle between the two planes determined by the vectors:

$E_{12} = \mathbf{e}_1 \times \mathbf{e}_2$ and $E_{23} = \mathbf{e}_2 \times \mathbf{e}_3$ [18].

In order to make a correlation strength comparison between torsion and curvature with vertebral axial rotation, the both values should be obtained from the center of same vertebra of the scoliosis spine. For this reason, the modified curvature derivation is introduced as follows:

$$\dot{\mathbf{x}}'_{12} = \left[\mathbf{x}_{12}, \mathbf{x}_{01}\right] = \frac{(\mathbf{x}_{12} - \mathbf{x}_{01})}{\mathbf{S}_{12}} = \mathbf{e}_{12}$$

$$\ddot{\mathbf{x}}'_{123} = 2\left[\mathbf{x}_{23}, \mathbf{x}_{12}, \mathbf{x}_{01}\right] = \frac{2(\dot{\mathbf{x}}'_{23} - \dot{\mathbf{x}}'_{12})}{(\mathbf{S}_{12} + \mathbf{S}_{23})} = \frac{2(\mathbf{e}_{23} - \mathbf{e}_{12})}{(\mathbf{S}_{12} + \mathbf{S}_{23})}$$

$$K_{123} = \left|\dot{\mathbf{x}}'_{12} \times \ddot{\mathbf{x}}'_{123}\right| = \frac{2}{(\mathbf{S}_{12} + \mathbf{S}_{23})}\left|\mathbf{e}_{12} \times \mathbf{e}_{23}\right| = \frac{\sin\alpha_{123}}{\mathbf{S}_{13}}$$

C. Vertebral Axial Rotation.

Different ways of measuring the vertebral axial rotation have been proposed by several authors [1]-[3]. They are ranged from directly measuring from standard coronal PA image to gold standard of MRI image access. Although the

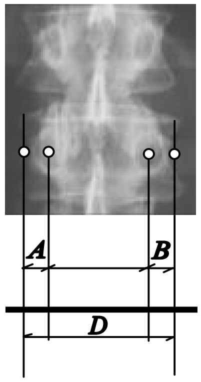


Fig. 3. The landmarks chosen on each vertebra from T2 to L4.

MRI image provides most precise result; the accuracy by directly measuring on the coronal PA image should be adequate in certain circumstances. In theory the vertebral movement has six components $\left[x_i, y_i, z_i, \alpha_i, \beta_i, \gamma_i\right]$. The assumption is made that it only rotates about vertical axis $\left[x_i, y_i, z_i, \beta_i\right]$. The method relies on the position of the spinous process of the pedicles relative to the vertebral body edges and has been found with a mean error of three degrees [5]. The lateral margins and centers of pedicles were used as landmarks for the rotation calculation. From second thoracic to fourth lumbar vertebrae, the left and right lateral margins were measured and recorded as ***D***. Then the distances between margins and centers of pedicles both on left and right sides were recorded as ***A*** and ***B***, as showed in Figure 3. The formula used to determine the angle of vertebral axial rotation is as follows:

$$\tan(\alpha_i) = \frac{a_i - b_i}{a_i + b_i} \times \frac{w_i}{2d_i} \qquad i = 2 \ldots 16$$

From Figure 4, we have:

$$w \approx 2d \;;\; a - b = B - A \;;\; a + b = D - (B - A) \;;$$

Then we have:

$$\tan(\alpha_i) = \frac{B_i - A_i}{D_i - (B_i - A_i)} \qquad i = 2 \ldots 16$$

III. Result

Two sets of correlation coefficients are calculated on each vertebral level from second thoracic to fourth lumbar. Total of 30 scoliosis patients are randomly selected. The first set of correlations is between the angle of vertebral axial rotation and the curvature on each vertebra. The second set of correlations is between the angle of vertebral axial rotation and torsion on each vertebra. The correlation strengths are then compared in Table I. From this table it is shown that the strength of correlations between the vertebral axial rotations and curvatures are stronger than the correlations between the vertebral axial rotations and torsions. This may draw a conclusion that the apex of deformity curve most probably has maximum vertebral

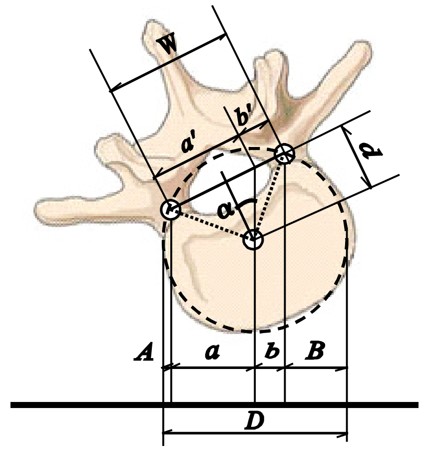


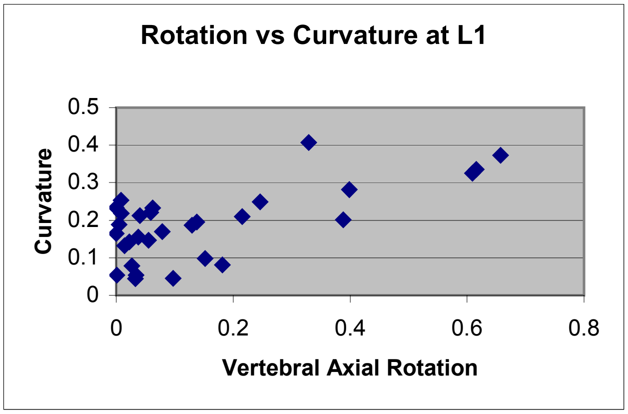
Fig. 4. The axial and coronal projections of landmarks on vertebra.

axial rotation and the neutral vertebra has no vertebral axial rotation [2]. At the same time, the amount of torsion on the vertebra level has less influence on the vertebral axial rotation.

In Figure 5 there are two sample plots showing vertebral axial rotation vs. curvature and torsion on the vertebral level of L1. Such plots were conducted on each vertebral level from T2 to L4.

IV. Discussion

The correlation coefficients are calculated and compared on both vertebral axial rotation relative to the curvature and to the torsion found on each vertebra from second thoracic to fourth lumbar vertebra of scoliosis spine. There are two factors, which could affect the outcome. They are: 1) the number of samples participated in the study, 2) the method for obtaining the angle of vertebral axial rotation. Thirty subjects for statistical comparison are not large enough to draw conclusion. However, it is convincing from the table that the vertebral axial rotation is more correlated to the curvature than to the torsion of scoliosis spine. There are more disputes about the method used to determine the vertebral axial rotation. 1) The shape of vertebra would affect the accuracy of the measurement since anatomical shape of vertebrae from T2 to L4 is different. 2) The orientation of vertebra would also affect the accuracy of the measurement since vertebral axis is not perpendicular to the horizontal plane, i.e. the vertebral axial rotation is the rotation about the axis in 3D space. These circumstances would increase the error for the measurement. In order to obtain accurate measurement on vertebral axial rotation, the gold standard method of 3D reconstruction of each individual vertebra from MRI is preferable. Nevertheless, as a preliminary study, this method of directly measuring on the landmark from coronal x-ray spine image could still give reasonable results.



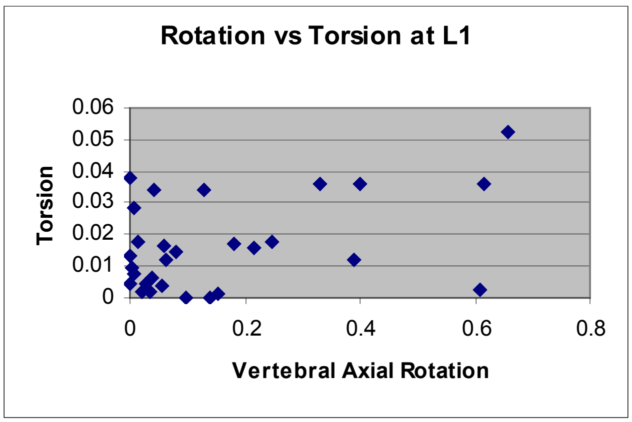


Fig. 5. Vertebral axial rotation vs. curvature and torsion at L1.

TABLE I
CORRELATION STRENGTH COMPARASON OF VERTEBRAL AXIAL ROTATION RELATIVE TO CURVATURE AND TORSON ON EACH LEVEL T2-L4

	CORRELATION COEFFICIENTS ROT-CURV	CORRELATION COEFFICIENTS ROT-TORS
T2	0.031370	-0.102018
T3	0.551997	0.316327
T4	0.657266	0.411207
T5	0.326347	0.239503
T6	-0.060183	-0.194820
T7	0.396281	0.073850
T8	0.483065	0.111505
T9	0.450643	0.145464
T10	0.483598	0.243592
T11	0.412768	0.115564
T12	0.353441	0.064340
L1	0.667444	0.442854
L2	0.481687	0.232085
L3	0.303272	0.254655
L4	-0.085108	-0.013392

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