# On the Geometric Characterization of the Lenke Classification Scheme for Idiopathic Scoliosis

by

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## Abstract

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Current methods for treating and diagnosing spinal deformities caused by scoliosis are both surgically intensive and rarely allow for complete correction. This is mainly due to the fact that the diagnostic techniques used are rough estimates made by angles defined by observations of 2-D radiographs. By utilizing the latest software, our research is based on designing a tool that creates a 3-D representation of the spine. When creating a three-dimensional spinal model, it becomes possible to determine local curvature and local torsion values at each specific vertebrae. By manipulating these values at discrete locations on the spine, one can generate "virtual" spines in a three-dimensional environment. The Scoliosis Learning Tool includes algorithmic steps that determine the Lenke Classification of the "virtual" spines. The Lenke Classification is the most commonly accepted method for diagnosing spinal deformities.

This patient building program will produce a group of spines with random values for curvature, torsion and initial spinal orientation. An algorithm within the software determines the Lenke Classification of each, and discards any curves that appear unnatural. By defining a metric that places an emphasis on certain geometric similarities, the software is able to define diameters of classification groups and separations between different classification groups. In turn it is possible to determine minor to major differences between spines within the same classification. In doing so, the opportunity exists to possibly find an undiscovered deformity that had previously fallen under another classification category.

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# Contents


**1 Introduction** **1**
1.1 Scoliosis Occurrence . . . . . . . . . . . . . . . . . . . . . . . . . . . 1
1.2 Complications . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2

**2 Diagnosing the Deformity** **3**
2.1 Cobb Angle and Ferguson Angle . . . . . . . . . . . . . . . . . . . 3
2.2 King Moe Classification . . . . . . . . . . . . . . . . . . . . . . . . 5
2.2.1 King Moe type I . . . . . . . . . . . . . . . . . . . . . . . 5
2.2.2 King Moe type II . . . . . . . . . . . . . . . . . . . . . . . 5
2.2.3 King Moe type III . . . . . . . . . . . . . . . . . . . . . . 6
2.2.4 King Moe type IV . . . . . . . . . . . . . . . . . . . . . . 6
2.2.5 King Moe type V . . . . . . . . . . . . . . . . . . . . . . . 7
2.3 Lenke Classification . . . . . . . . . . . . . . . . . . . . . . . . . . 8
2.3.1 Lenke Curve Type . . . . . . . . . . . . . . . . . . . . . . 9
2.3.2 Lumbar Modifier . . . . . . . . . . . . . . . . . . . . . . . 10
2.3.3 Sagittal Thoracic Modifier . . . . . . . . . . . . . . . . . . 11
2.3.4 Using the Lenke Classification . . . . . . . . . . . . . . . 12
2.4 Other Classification Options . . . . . . . . . . . . . . . . . . . . . 13

**3 Correction of Scoliosis** **14**
3.1 Treatment Techniques . . . . . . . . . . . . . . . . . . . . . . . . . 14
3.1.1 Non-Surgical Options . . . . . . . . . . . . . . . . . . . . 14
3.1.2 Surgical Techniques . . . . . . . . . . . . . . . . . . . . . 15
3.1.3 Postoperative Treatment and Long-Term Effects . . . . . 17
3.2 Complications with Treatment . . . . . . . . . . . . . . . . . . . . 17
3.2.1 Overall Concerns of Surgical Treatment . . . . . . . . . . 17
3.2.2 Surgical Treatment– Harrington Instrumentation . . . . . 18
3.2.3 Surgical Treatment– Cotrel-Dubousset Instrumentation . 18
3.2.4 Miscellaneous Complications . . . . . . . . . . . . . . . . 19

**4 Research** **20**
4.1 Three-Dimensional Curves . . . . . . . . . . . . . . . . . . . . . . . 20
4.2 Scoliosis Learning Tool . . . . . . . . . . . . . . . . . . . . . . . . . 22
4.2.1 Patient Generation . . . . . . . . . . . . . . . . . . . . . . 22

4.2.2 "Lenke Light" Classification Scheme . . . . . . . . . . . . 26
4.2.3 Patient/Population Builder . . . . . . . . . . . . . . . . . . 31
4.2.4 Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . 33

**5 Areas for Improvement and Conclusions 42**
5.1 Defining a Curve . . . . . . . . . . . . . . . . . . . . . . . . . 42
5.2 Lumbar Modifier . . . . . . . . . . . . . . . . . . . . . . . . . 43
5.3 The Mathematical Metric . . . . . . . . . . . . . . . . . . . . . 43
5.4 Conclusions . . . . . . . . . . . . . . . . . . . . . . . . . . . . 43

**A Matrices of Metric Data 49**

**B Comparison of Extremal Spines within Classification Groups 65**

# List of Figures


2.1 Demonstration of the method used to determine the Cobb angle. 3
2.2 Demonstration of the method used to determine the Ferguson angle. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 4
2.3 Diagram of King Moe type I created in PatientBuilder. . . . . . . 5
2.4 Diagram of King Moe type II created in PatientBuilder. . . . . . 6
2.5 Diagram of King Moe type III created in PatientBuilder. . . . . . 6
2.6 Diagram of King Moe type IV created in PatientBuilder. . . . . . 7
2.7 Diagram of King Moe type V created in PatientBuilder. . . . . . 7
2.8 Description of Center Sacral Vertebral Line (CSVL). . . . . . . . 10

4.1 Screen shot of patient generation dialog window. . . . . . . . . . 31
4.2 Matrix of population diameter and separation information for group set of 625 patients with metric emphasis placed on lower spine. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 37
4.3 Comparison of 'furthest' spines within classification 1AN for Group 4d. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 40

A.1 Matrix of population diameter and separation information for group set 1a of 625 patients with no metric emphasis. . . . . . . 49
A.2 Matrix of population diameter and separation information for group set 1b of 625 patients with metric emphasis on upper thoracic spine. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 50
A.3 Matrix of population diameter and separation information for group set 1c of 625 patients with metric emphasis on lower thoracic spine. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 51
A.4 Matrix of population diameter and separation information for group set 1d of 625 patients with metric emphasis on lumbar spine. 52
A.5 Matrix of population diameter and separation information for group set 2a of 625 patients with no metric emphasis. . . . . . . 53
A.6 Matrix of population diameter and separation information for group set 2b of 625 patients with metric emphasis on upper thoracic spine. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 54
A.7 Matrix of population diameter and separation information for group set 2c of 625 patients with metric emphasis on lower thoracic spine. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 55

A.8 Matrix of population diameter and separation information for group set 2d of 625 patients with metric emphasis on lumbar spine. 56
A.9 Matrix of population diameter and separation information for group set 3a of 625 patients with no metric emphasis. . . . . . . 57
A.10 Matrix of population diameter and separation information for group set 3b of 625 patients with metric emphasis on upper thoracic spine. . . . . . . . . . . . . . . . . . . . . . . . . . . . . 58
A.11 Matrix of population diameter and separation information for group set 3c of 625 patients with metric emphasis on lower thoracic spine. . . . . . . . . . . . . . . . . . . . . . . . . . . . . 59
A.12 Matrix of population diameter and separation information for group set 3d of 625 patients with metric emphasis on lumbar spine. 60
A.13 Matrix of population diameter and separation information for group set 4a of 625 patients with no metric emphasis. . . . . . . 61
A.14 Matrix of population diameter and separation information for group set 4b of 625 patients with metric emphasis on upper thoracic spine. . . . . . . . . . . . . . . . . . . . . . . . . . . . . 62
A.15 Matrix of population diameter and separation information for group set 4c of 625 patients with metric emphasis on lower thoracic spine. . . . . . . . . . . . . . . . . . . . . . . . . . . . . 63
A.16 Matrix of population diameter and separation information for group set 4d of 625 patients with metric emphasis on lumbar spine. 64

B.1 Comparison of 'furthest' spines within classification 1A- for Group 1b. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 65
B.2 Comparison of 'furthest' spines within classification 1A- for Group 1c. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 66
B.3 Comparison of 'furthest' spines within classification 1AN for Group 1c. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 67
B.4 Comparison of 'furthest' spines within classification 5A- for Group 1c. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 68
B.5 Comparison of 'furthest' spines within classification 5C- for Group 1c. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 69
B.6 Comparison of 'furthest' spines within classification 1A- for Group 1d. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 70
B.7 Comparison of 'furthest' spines within classification 1AN for Group 1d. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 71
B.8 Comparison of 'furthest' spines within classification 1A- for Group 2a. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 72
B.9 Comparison of 'furthest' spines within classification 1AN for Group 2a. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 73
B.10 Comparison of 'furthest' spines within classification 1A- for Group 2b. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 74
B.11 Comparison of 'furthest' spines within classification 1AN for Group 2d. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 75

B.12 Comparison of 'furthest' spines within classification 1AN for Group 3a. . . . . 76
B.13 Comparison of 'furthest' spines within classification 1BN for Group 3a. . . . . 77
B.14 Comparison of 'furthest' spines within classification 1AN for Group 3b. . . . . 78
B.15 Comparison of 'furthest' spines within classification 5AN for Group 3b. . . . . 79
B.16 Comparison of 'furthest' spines within classification 1AN for Group 3c. . . . . 80
B.17 Comparison of 'furthest' spines within classification 1BN for Group 3d. . . . . 81
B.18 Comparison of 'furthest' spines within classification 5AN for Group 3d. . . . . 82
B.19 Comparison of 'furthest' spines within classification 1AN for Group 4a. . . . . 83
B.20 Comparison of 'furthest' spines within classification 1A- for Group 4b. . . . . 84
B.21 Comparison of 'furthest' spines within classification 1AN for Group 4b. . . . . 85
B.22 Comparison of 'furthest' spines within classification 1BN for Group 4b. . . . . 86
B.23 Comparison of 'furthest' spines within classification 1AN for Group 4c. . . . . 87
B.24 Comparison of 'furthest' spines within classification 1AN for Group 4d. . . . . 88

# List of Tables

4.1 Description of parameters used to generate 10,000 diverse patients. 33
4.2 Clinical study for statistical verification of Lenke Classification Scheme conducted on 315 patients [25] . . . . . . . . . . . . . . . . 38
4.3 Verification of data collected by Population Generator for 10,000 patients. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 39

# Chapter 1

# Introduction

## 1.1 Scoliosis Occurrence

Originating from the Greek word *skoliosis*, meaning crookedness, scoliosis is a term that diagnoses lateral curvature in the spine. As defined by the Scoliosis Research Society (SRS) any spine with a measured lateral Cobb angle (see Chapter 2) larger than $10^\circ$ is considered to be scoliotic [37].

Any inherently structural lateral curvature of the spine occurring in the late juvenile or early adolescent portion of skeletal maturity in individuals who are otherwise healthy is classified as adolescent idiopathic scoliosis [31]. Studies show that 2-3% of all children show signs of curvature that could be classified as scoliosis. While curves with smaller magnitudes tend to affect both boys and girls equally, larger curves tend to show a higher prevalence in girls than boys. The ratio of girls to boys affected with scoliosis is 4:1 as the Cobb angle exceeds $20^\circ$.

Curves diagnosed between birth and three years of age are classified as "infantile," between four and ten years of age "juvenile," and any curve noticed between 10 years of age and skeletal maturity is described as "adolescent" [10]. Depending on the age of the patient, the extremity of the curve, and the interest of the individual, there are many options available to treat idiopathic scoliosis.

Observations have shown that the earlier scoliosis occurs in patients, the more likely it will be for the severity of the deformity to increase [31](see also [26] and [35] for further information). It is for this reason that schools administer scoliosis screenings in hopes to recognize the deformity before it progresses [7, 34]. Twenty-two percent of patients that are classified as immature in their skeletal maturity and with a Cobb angle measuring less than $20^\circ$ show signs of progression [31]. In contrast patients closer to skeletal maturity, with Cobb angles measuring less than $20^\circ$, only show a 1.6% chance of progression. For curves with Cobb angles between 20-29°, immature patients show a 68% chance of progression while patients closer to maturity have a 23% chance of progression.

A study by Miller followed 102 patients with idiopathic scoliosis and determined that 68% of curves progressed after skeletal maturity [31]. It was found that curves with Cobb angles less than 30° were least likely to progress, while curves with Cobb angles between 30-50° progress an average of 10-15° throughout the patient's lifetime. The most extreme progression occurs for people who have Cobb angles measured between 50-75°. These progress steadily at nearly 1° per year. The extremity of the curve angle determines the underlying complications that scoliosis will cause.

## 1.2 Complications

Many patients live with idiopathic scoliosis with no prevalence of physical limitations or pain. Some of the complications associated with this deformity include back pain, pulmonary problems and loss of volume in the chest cavity. Depending on the severity of the deformity, the resulting physical appearance of the patient may also have an effect on self image.

Patients with curves showing moderate severity (40-50°) have the same likelihood of experiencing back pain as an average person with no spinal deformity [37]. In a study beginning in 1932 by Weinstein MD *et al*, 161 untreated patients diagnosed with scoliosis were followed for an average of 39.3 years [48]. In the ten years preceding the study, the deformity progressed an average of 3.9°. In 1968, 31% of the test subjects reported daily back pain, while ten years later in 1978, 37% of the subjects experienced daily back pain. A group of 16 patients died during the study due to pulmonary or vascular complications caused by the scoliosis. Five subjects died due to atherosclerotic coronary vascular disease, while the remaining subjects died from other complications, some of which were influenced by scoliosis.

As the curvature of the spinal column progresses, the probability of a respiratory or pulmonary complication increases. For example, in the aforementioned study, a total of 29% of the test subjects experienced shortness of breath that limited their ability to participate in many physical activities. Large curves in the thoracic region tend to be highly correlated with pulmonary symptoms and diminished vital capacity [48]. This is one of the main reasons for efforts over the past 20-30 years to correct spinal deformities.

# Chapter 2

# Diagnosing the Deformity

## 2.1 Cobb Angle and Ferguson Angle

Cobb angle diagnosis has been the most widely used and accepted technique for characterizing spinal deformities over the last few decades [28]. Here, the Cobb angle is a measure of the average curvature of curve segments of the spine as seen in a two-dimensional projection, see Figure 2.1. Each curve segment is delimited by points of inflection and is therefore uniquely convex or concave. For each curve segment the surgeon observes the patient's two-dimensional radiograph and draws two straight lines through the superior endplate of the proximal vertebra and the inferior end plate of the distal vertebra, respectively [9,29]. The corresponding Cobb angle is defined as the angle between those two lines. An alternative method, defining an *analytical Cobb angle*, measures the angle between two straight lines perpendicular to the tangent direction to the curve at the proximal and distal vertebrae, respectively [46].

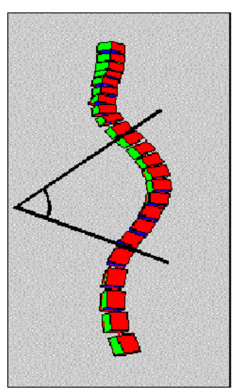

Figure 2.1: Demonstration of the method used to determine the Cobb angle.

Another method of measuring deformation angles in the spine is the Ferguson

Method. Here, the Ferguson angle is defined as the angle between two straight lines drawn through the center of the apical vertebra and the proximal and distal vertebrae, respectively, see Figure 2.2. The apical vertebra refers to the vertebra furthest away from the straight line connecting the centroids of the end vertebrae of the curve segment. Alternatively, an *Analytical Furguson angle* can be computed by replacing the centroids of the end vertebrae with the actual inflection points of the curve, and the centroid of the apical vertebra with the point of maximal deviation on the curve[46].

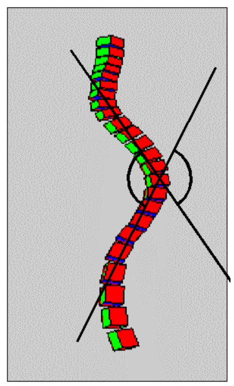

Figure 2.2: Demonstration of the method used to determine the Ferguson angle.

In practice, surgeons use protractors and rulers on actual radiographs or digital versions of these to compute the Cobb and Ferguson angles. While these measures form the basis for characterizing spinal deformities, they fall short of completely describing the three dimensional shape of the deformity, for example, torsion of the spinal column and the rotation of individual vertebra with respect to the spinal column.

In fact, due to external factors affecting the shape of the spine through the course of a day, the Cobb angle does not uniquely define curvature. In a study conducted in Quebec, Canada by Stirling *et al*, the Cobb angles of 19 girls with adolescent idiopathic scoliosis were measured repeatedly in the morning and the afternoon [36] (see also [43] for further information). It was determined that, due to effects of gravity on the spine and other postural factors, the average Cobb angle was 59.7° in the morning and 65° in the afternoon. Subjective factors may also lead to variability in Cobb angle measurements between different surgeons [3,12]. In fact, studies have suggested that the radiographic estimation of Cobb angles can vary up to 7° between different surgeons or over repeated measurements by the same surgeon [25].

## 2.2 King Moe Classification

The King Moe Classification technique combines local measures of Cobb angles to formulate a global understanding of the spinal deformity. This diagnostic technique was widely used in the past but has been recently replaced by the Lenke Classification Scheme (See Section 3 of this Chapter). Specifically, the King Moe method is determined from Cobb angles measured on curve segments in the Anterior/Posterior radiographs. The scheme was defined such that curves with the identical classification would be corrected by similar surgical procedures [23]. The following summary of the King Moe method is based on a review written by Thomas [45].

### 2.2.1 King Moe type I

The King Moe type I spine is a double curve through the lumbar and thoracic spinal regions, see Figure 2.3. Both curves pass through the mid line, or Center Sacral Vertebral Line (CSVL), which bisects the sacrum and is perpendicular to the true horizontal [25]. These curves have a significant residual curvature when the patient bends in a direction that would straighten out the curve. This rigidity indicates that both curves are structural, while curves that correct significantly on the side-bend are considered “flexible” and therefore non-structural. The lumbar curve tends to be larger in Cobb angle as well as more rigid than the thoracic curve.

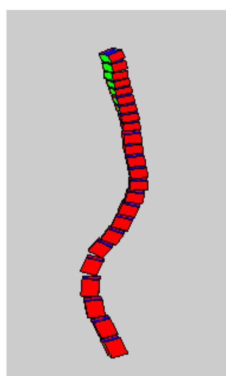

Figure 2.3: Diagram of King Moe type I created in PatientBuilder.

### 2.2.2 King Moe type II

The King Moe type II spine is also a double curve through the lumbar and thoracic spine, although the lumbar curve is less prominent than in King Moe type I. Again, both curves pass through the midline or CSVL of the spine as seen in Figure 2.4. Though the spine appears to have a double curve, the lumbar curve is much more flexible and the thoracic curve is the primary structural curve. Thus, it is believed that it suffices to fuse the thoracic curve, while allowing the lumbar curve to correct itself.

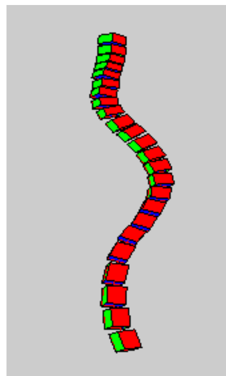

Figure 2.4: Diagram of King Moe type II created in PatientBuilder.

### 2.2.3 King Moe type III

The King Moe type III spine is a single primary thoracic curve, see Figure 2.5. The lumbar curve, while present, does not cross the midline or CSVL, and is significantly less curved than the thoracic curve.

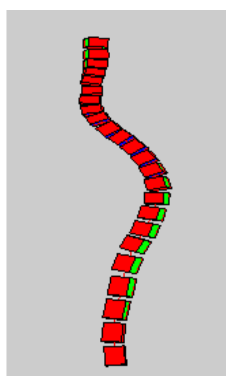

Figure 2.5: Diagram of King Moe type III created in PatientBuilder.

### 2.2.4 King Moe type IV

The King Moe type IV spine is a very long thoracic curve as shown in Figure 2.6. These curves tend to exhibit a marked “C-shape” where the distal infection point is located near the fourth lumbar vertebra (L4) and the proximal inflection point is located in the proximal thoracic or cervical region. The fourth lumbar vertebra is often significantly rotated away from the neutral position. The correct level for fusion is determined by observing which of the lower lumbar vertebrae bends completely back towards the neutral position.

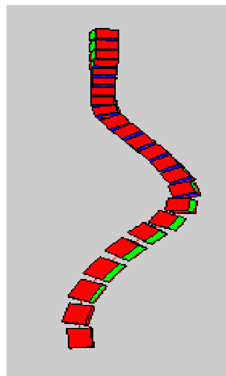

Figure 2.6: Diagram of King Moe type IV created in PatientBuilder.

### 2.2.5 King Moe type V

The King Moe type V spine is a double thoracic curve as seen in Figure 2.7. These thoracic curves tend to extend into the cervical spine and also may have a third compensatory curve in the lumbar region. There tends to be a rotation away from the neutral position near the top endplate of the first thoracic vertebrae (T1). There also tends to be a large amount of torsion in the spine resulting in a rotation of the thoracic region of the trunk. In bending x-rays, the upper curve shows inflexibility and is therefore considered structural.

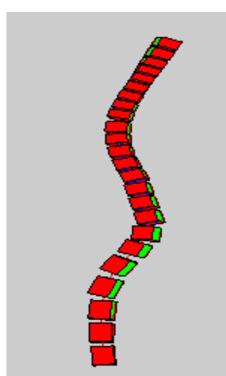

Figure 2.7: Diagram of King Moe type V created in PatientBuilder.

Surgical treatment includes fusion of the upper thoracic curve. If there is an elevation of one shoulder pre-operatively, remote correction of the lower thoracic region could lead to an exaggerated shoulder imbalance. When the shoulders are balanced, but either the proximal thoracic or cervical thoracic curves are rigid, the surgeon should fuse both thoracic curves. If instead proximal thoracic or cervical thoracic curves are flexible, the surgeon may choose to only fuse the lower curve. This is based on the expectation that the upper curve will correct itself.

## 2.3 Lenke Classification

Recently, Lawrence G. Lenke developed a more sophisticated procedure for classifying spinal deformities [25]. This new classification technique, known as the Lenke method, combines the positive attributes of both the Cobb Angle and the King Moe diagnostic routines. The technique was developed as it was found that the King Moe classification showed poor reliability and reproducibility. In order to provide a functional new diagnostic tool, Lenke suggested that his method:

1. Be comprehensive- Include all types of curves
2. Emphasize consideration of sagittal alignment
3. Help define treatment that could be standardized
4. Be based on objective criteria from each curve type
5. Allow for good-to-excellent interobserver and intraobserver reliability
6. Be easily understood and of practical value

Lenke determined that there should be four types of curve pattern locations along the spinal column; Proximal Thoracic, Main Thoracic, Thoracolumbar, and Lumbar. The Proximal Thoracic curve segment has an apex that is located in the $3^{rd}$, $4^{th}$, or $5^{th}$ thoracic vertebra. This curve segment is primarily located in the proximal portion of the thoracic spine but may encompass portions of the cervical spine. The Main Thoracic curve segment has an apex located between the 6th and 11th thoracic vertebrae. This curve segment is primarily located in the thoracic region of the spine. The Thoracolumbar curve segment has a curve apex located between the $12^{th}$ thoracic and $1^{st}$ lumbar vertebrae, while the Lumbar curve segment typically has a curve apex between the $2^{nd}$ and $4^{th}$ lumbar vertebrae [25].

Lenke further suggested that by implementing a routine to determine structural and nonstructural curve segment criteria, it would be possible to determine which portions of the spine would require fusion during surgery. Specifically, the curve segment with the largest Cobb Angle, as measured in the Anterior/Posterior radiograph (also known as the major curve) is always considered structural. Structural curves may also include smaller curves (also known as minor curves) that have little or no flexibility in the bending image. In order for one of the curve patterns to be classified as structural, it must meet one of the following criteria:

- Proximal Thoracic curve pattern must have:
  - Minimal residual coronal curve on bending film of at least 25°;
  - Kyphosis between T2 and T5 of at least 20°.
- Main Thoracic curve pattern must have:
  - Main residual coronal curve of at least 20°;
  - Kyphosis between T10 and L2 of at least 20°.
- Thoracolumbar/Lumbar curve pattern must have:
  - Minimum residual curve of at least 25°
  - Kyphosis between T10 and L2 of at least 20°

Within the Lenke method, there are three subcategories that determine the diagnosis. There are six curve types corresponding to different combinations of structural and non-structural curve patterns. Furthermore, a lumbar modifier is used to quantify the degree of curvature in the lumbar portion of the spine.

### 2.3.1 Lenke Curve Type

**Type 1- Main Thoracic Curve**

A Type 1 Lenke curve type features a structural major curve in the Main Thoracic region and minor non-structural curves elsewhere.

**Type 2- Double Thoracic Curve**

A Type 2 Lenke curve type features a major structural curve in the Main Thoracic region, a minor but structural curve in the Proximal Thoracic region and minor non-structural curves elsewhere.

**Type 3- Double Major Curve**

A Type 3 Lenke curve type features a major curve in the Main Thoracic region, a minor structural curve in the Thoracolumbar/Lumbar region and minor non-structural curves elsewhere. If the Cobb angle of the Main Thoracic curve is equal to the Cobb angle of the Thoracolumbar/Lumbar curve then the Main Thoracic curve is considered major.

### Type 4- Triple Major Curve

A Type 4 curve type features a major curve in the Main Thoracic region, and minor structural curve in both Proximal Thoracic and Thoracolumbar/Lumbar regions. A Type 4 curve may also have a major curve in the Thoracolumbar/Lumbar region as long as the Main Thoracic and Proximal Thoracic regions are both minor and structural.

### Type 5- Thoracolumbar/Lumbar Curve

A Type 5 curve type a major curve in the Thoracolumbar/Lumbar region, and minor non-structural curves elsewhere.

### Type 6- Thoracolumbar/Lumbar Main Thoracic Curve

A Type 6 curve type features a major curve in the Thoracolumbar/Lumbar region, a minor structural curve in the Main Thoracic region and minor non-structural curve in the Proximal Thoracic region. The Type 6 and Type 3 curves differ only by which region is major and structural. As previously mentioned, if the Cobb angle of the Main Thoracic curve is equal to the Cobb angle of the Thoracolumbar/Lumbar curve then the Main Thoracic curve is considered major and therefore is a Type 3 curve.

## 2.3.2 Lumbar Modifier

Lenke proposed that special emphasis must be placed on deformities in the lumbar region as this affects spinal balance as well as proximal curves [25]. Specifically, the Lenke Classification Scheme includes a lumbar modifier that is determined by the alignment of the lumbar vertebrae with respect to the Center Sacral Vertebral Line (CSVL) shown in Figure 2.8. Here, pelvic obliquity is ignored unless the surgeon believes that it increases the degree of spinal deformity.

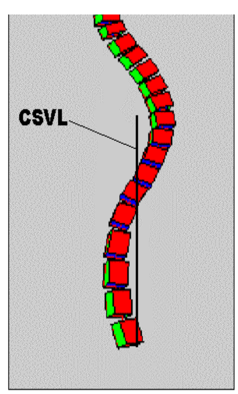


Figure 2.8: Description of Center Sacral Vertebral Line (CSVL).

The modifier is determined by observing the location of the apex of the Lumbar curve, i.e., the most laterally displaced vertebra or vertebral disk from the CSVL. The lumbar modifier can also be used following surgery to assess the position of the lumbar spine. The Lumbar Modifier is broken up into three categories:

- Lumbar Modifier A
  - The Lumbar Modifier A is used to represent a spine for which the CSVL runs between pedicles of the lumbar spine (L1 through L4).
- Lumbar Modifier B
  - The Lumbar Modifier B is used to represent a spine for which the CSVL passes through the pedicle of the apical vertebra in the Lumbar Spine (L1 through L4).
- Lumbar Modifier C
  - The Lumbar Modifier C is used to represent a spine for which there is a large deviation of the lumbar spine from the CSVL. Therefore, the CSVL falls medially to the apical vertebra.

### 2.3.3 Sagittal Thoracic Modifier

In an effort to introduce a three-dimensional analysis to the Lenke Classification scheme, a Sagittal Thoracic Modifier was created. This diagnosis is based on the Cobb angle between the superior endplate of T5 and the inferior endplate of T12, as seen in the lateral radiograph. The Lenke Sagittal Thoracic Modifier takes on three values:

- Hypokyphosis ( - ) :
  - The measured angle is less than $+10^\circ$
- Normal Kyphosis ( N ) :
  - The measured angle is between $+10^\circ$ and $+40^\circ$
- Hyperkyphosis ( + ) :
  - The measured angle is greater than $+40^\circ$

Here, a lordotic curve segment is considered Hypokyphotic.

### 2.3.4 Using the Lenke Classification

The process used to determine the Lenke Classification is to first select the specific Curve Type (Type 1-6). After establishing the Curve Type, the Lumbar Modifier (A, B, or C) should be assigned. Lastly, after observing the lateral radiograph, a Sagittal Thoracic Modifier (-, N, +) is determined in order to create a complete classification, e.g., (1 A -). Restricting attention to curve segments with Cobb angles greater than 10° in the determination of the Lenke type, certain combinations of type and lumbar modifier typically do not occur. For example, curve types with major structural curves in the Thoracolumbar/Lumbar region (i.e., Type 3, Type 4, Type 5, and Type 6) should not allow for a Lumbar Modifier A. This is because in order to have a Lumbar Modifier A, there should be little or no deformation in the Thoracolumbar/Lumbar region.

In order to understand the prevalence of each subcategory, a group of 315 patients treated by Dr. Lawrence Lenke was observed and the percentage of incidence for each was documented [25].

- Prevalence of Curve Type
  - Type 1- Main Thoracic: 40% (126 patients)
  - Type 2- Double Thoracic: 18% (56 patients)
  - Type 3- Double Major: 18% (58 patients)
  - Type 4- Triple Major: 3% (8 patients)
  - Type 5- Thoracolumbar/Lumbar: 18% (56 patients)
  - Type 6- Thoracolumbar/Lumbar- Main Thoracic: 3% (11 patients)
- Prevalence of Lumbar Modifier
  - Lumbar Modifier A: 30% (94 patients)
  - Lumbar Modifier B: 21% (67 patients)
  - Lumbar Modifier C: 49% (154 patients)
- Prevalence of Sagittal Thoracic Modifier
  - Hypokyphosis ( - ): 18% (56 patients)
  - Normal Kyphosis ( N ): 71% (224 patients)
  - Hyperkyphosis ( + ): 11% (35 patients)

Each of the criteria required in this classification scheme has its own significance. The structural characteristics were critical in developing the Lenke Classification scheme. Variances in sagittal alignment allow for the determination of which regions should/should not be included in the arthrodesis.

## 2.4 Other Classification Options

Though the Lenke classification scheme is a more comprehensive way to characterize curvature in a scoliotic spine, additional tools could be employed to assess the fully three-dimensional characteristics of the vertebral column, for example vertebral rotation [11](for more information see [20] and [32]). For small amounts of longitudinal axis rotation, conventional Lateral and Anterior/Posterior radiographs can be used to approximate the amount of vertebral rotation [27]. With increased rotation the vertebral bodies and pedicles lose definition on the radiographs. This is particularly common in patients with rotations exceeding 30° [5]. A more exact means of measuring axial rotation is through a CT scan.

Observations in a study by Aaro and Dahlborn showed that for patients whose Cobb angles in the Anterior/Posterior radiograph did not exceed 40° there was zero asymmetry between the bodies, pedicles and laminae [1]. In curves with Cobb angles exceeding 50°, there was a 61% prevalence of asymmetry in the vertebrae as seen from the Anterior/Posterior radiograph. These observations suggest a strong coupling between large lateral curvatures and rotation of individual vertebrae about the vertebral column. The most rotated vertebrae are typically found at the apex of a curve segment [19] (for more information see [16] and [27]). Such rotation about the longitudinal axis is understood to be the primary underlying factor in the development of a scoliotic rib hump [37].

In a study performed by Birchall *et al* [5], it was found that in most cases the degree of rotation associated with a deformity located within the vertebral body tended to have a minor effect on the overall spinal deformity. In the remaining cases though, the intravertebral deformity was the major factor in producing the curvature. He suggests that MRI evaluation of idiopathic scoliosis may provide a more reasonable three-dimensional representation of complex deformities [5].

# Chapter 3

# Correction of Scoliosis

## 3.1 Treatment Techniques

### 3.1.1 Non-Surgical Options

There are several ways to treat idiopathic scoliosis, and depending on the size of the curvature and extremity of the deformity, the severity of the treatment varies. The most prevalent non-surgical option for treating scoliosis is bracing [37]. When a patient is provided with a brace for treatment, radiographs should be made while wearing the brace. In-brace radiographs that show more than a 50% reduction in the magnitude of the curve tend to have successful outcomes.

Through the first two to three weeks, the patient will be encouraged to increase the wearing time of the brace to that desired by the doctor as quickly as possible. Every four to six months, physical evaluations should be performed to ensure that the patient has not out-grown the brace. Use of the orthosis continues until girls are two years beyond the date of their first menarchy. Certain doctors suggest patients be weaned off of the bracing system, while some recommend direct discontinuation. A follow-up period of several years is necessary.

A study by Carr *et al* [37] showed that following brace treatment, the curves of the patients tended to gradually return to their original magnitudes. It was determined by Rowe *et al* that bracing can be an effective means of treating scoliosis if used correctly. There is a correlation between the length of time that a patient wears a Milwaukee Brace and the effectiveness of the orthosis. Patients using the brace nearly 23 hours a day showed the greatest chance of preventing curve progression. Several more bracing systems were developed with more cosmetic appeal than that of the Milwaukee system.

Follow-up studies comparing the Milwaukee system to a newer orthosis called the Boston brace showed a favorable outcome. Studies determined that the Boston brace was half as likely to fail as the Milwaukee orthosis. Failure was defined as curve progression of more than $45^\circ$ [37].

Most adults with curves larger than $50^\circ$ tend to have spinal fusion surgery. This surgical treatment technique uses instrumentation directly attached to the spinal column allowing for vertebral fusion and structural alignment of the scoliotic spine.

### 3.1.2 Surgical Techniques

There are two types of techniques used to correct scoliosis surgically. Posterior fixation is the most commonly used method among surgeons, while anterior fixation is a more complicated procedure. Typically, posterior fusion involves placing bone graft material along the lamina and facets of the posterior spine [4,41] (see [15] for more information). The first reported posterior spinal fusion was performed in the 1940's. Posterior fusion has a lower rate of pseudoarthrodesis (the fusion of neighboring vertebrae) than anterior fusion methods. By surgically stabilizing the vertebrae, a small "H"-shaped piece of bony material is placed between the bony process of the spine to allow for fusion [30,38]. While posterior fusion involves the fusing of the posterior portions of the spinous processes, anterior fusion refers to the fusion of the vertebral bodies themselves.

The first reported anterior fusion surgery was performed in 1933. Most of these surgeries are performed anteriorly or posterolaterally. Most anterior fusions involve the removal of either a disc or vertebrae and replacing them with bone graft substances to allow fusion. Successful anterior fusions sometimes require posterior fixation as well for ample stability.

#### Screws and Wires

The most common method used to attach instrumentation posteriorly or anteriorly to the spine is by means of wires and screws [40]. There are several screw types available, each having specific size, shape, and function. Cortical screws tend to have closely spaced threading and are used for fixation to cortical bone. A hole must be pre-drilled and tapped before the screws are set. Bicortical screws refer to those that tend to pass through the entire vertebral body and both cortical layers of bone. These screws are typically used to adhere plates to the spinal column anteriorly. Screws with deeper threading and wide thread spaces are called cancellous screws, used specifically for purchase (the ability for a screw to adhere to the surface of bone) in cancellous bone. Cancellous screws are mostly used in posterior fixation surgery as pedicle screws. These screws are difficult to use, but allow for greatest purchase to the vertebrae due to the fact that they pass through the pedicle and into the vertebral body [41]. Translaminar screws usually are used to complete a single level fusion and tend to be placed through the lamina of two adjacent vertebrae.

Wires and cables are typically used as a method to attach two spinous processes in posterior fusion surgery [41]. The wire are made of braided stainless steel or titanium and is available in many diameters. Surgeons tend to either twist the wire together or tie the ends to secure the hold. Wires termed as Songer cables are designed with fastening in mind, provided with a loop on one end and a metal collar on the other to be crimped to secure the connection.

### Plates

Plates tend to be placed on the anterior surface of the vertebral body or along the posterior portions of the spinal column. There are specific plates designed to be used on certain parts of the vertebral column [22](see [41] and [42] for more information). Plating systems tend to be used to correct deformities caused by pseudoarthrosis, kyphosis, severe degenerative disc disease, flat back, and failed posterior surgery. The screws used in the surgery tend to pass through the plate and gain purchase in both cortices of the vertebral bone. Some complications associated with anterior plating systems include screws backing out and causing esophageal wear, as well as screw breakage. The plate and screws used in surgery have very low profile, this is to reduce the amount of sharp edges minimizing the probability of vascular injury [40].

### Rods

The primary use for rods in surgery is to provide stability over a long segment of vertebrae generally located in the thoracic and lumbar region. Most rods tend to be paired on either side of the spinous process, but surgery can be performed with only one rod used [40] (for further information see [18] and [49]). There are several methods of attaching rods to the vertebral column posteriorly. The Luque system utilizes the strength of connecting wires, as mentioned earlier, to maintain a secure bond with the posterior elements of the vertebrae. The Wisconsin system consists of segmental instrumentation that provides an advantage over the Luque system in that it allows for better loading of the curve in the axial and transverse directions [21].

The Harrington system uses a grouping of hooks that wrap around certain jutting surfaces of the spinous process or the lamina. The Cotrel-Dubousset type utilizes the advantages of pedicle screws that connect to the rod for purchase to the spine. Finally the Zielke instrumentation and the Texas Scottish Rite Hospital system are anterior rod systems that utilize vertebral body screws. The prevailing systems in use include the Cotrel-Dubousset system, the Isola system and the Texas Scottish Rite Hospital system. These systems are universal in that they can be attached to the spine by means of either hooks, screws, or interspinous or sublaminar wires. All of these systems allow for correction through a combination of compression, distraction, translation, and cantilever forces.

### Bone Grafts

Bone grafts are generally used in collaboration with anterior plating or posterior rod systems. The main function of this method is to help increase the size of the fusion site in the vertebral column. There are two types of bone grafts used in spinal surgery. An allograft, also known as a homograft, is a graft type that is gathered entirely from cadaver bone or possible donors. Autografts are bone grafts that are removed from the person who is receiving the graft. In a posterior surgery, bone grafts are collected from the posterior portion of the iliac crest, while in anterior surgery the grafts are removed from the anterior portion of the iliac.

Grafts tend to be cut into small pieces that are usually packed into the disc space for anterior spinal fusion surgeries. Structural allografts are used to restore spinal column height after a corpectomy or other surgical techniques that may require the removal of one or several vertebrae. This process tends to use segments of either tibia or fibula bone from cadavers, along with allografting material gathered from the patient. Another option for treatment of these types of surgeries includes the use of titanium cages. These cages act very similarly to structural allografts minus the fact that rather than use cadaver tibia or fibula bone to replace height, a titanium cage packed with bone graft fragments is placed in the spinal void.

### 3.1.3 Postoperative Treatment and Long-Term Effects

After receiving spinal instrumentation to correct the scoliotic curve, braces or casts are deemed unnecessary following the surgery [24,37]. The day following the surgery, patients are encouraged to begin walking, while they are released from the hospital within 4-5 days of surgical treatment. Generally, within two weeks of the surgical spinal fusion, children can return to school. It is suggested that patients avoid participation in athletics for a span of 9-12 months following surgery. This is to allow the spine ample time to create fusion. Following spinal fusion, some sports are prohibited due to their high levels of contact (i.e., football, lacrosse, or rugby).

After spinal fusion, patients tend to develop back pain that is associated to many factors [37]. As the fusion area extends distally towards the lumbar region of the spine, the prevalence of back pain tends to be more pronounced. Other factors contributing to back pain include failing to maintain normal lumbar lordosis and leaving the spine in a position of decompression. Though the exact reasons for the back pain associated with surgical fusion is unknown, pain can be reduced if surgeons make an attempt to use the smallest fusion site possible.

## 3.2 Complications with Treatment

### 3.2.1 Overall Concerns of Surgical Treatment

Since many of the complications associated with idiopathic scoliosis cause patients to show signs of both physical deformities and internal complications, it becomes necessary to attempt to straighten the curve by means of braces or surgery. Surgery has been the underlying technique accepted to treat moderate to severe idiopathic scoliosis curves. Unfortunately, throughout the years of surgical treatment of scoliosis, many problems have been associated with the instrumentation used. There are many means of attempting to create spinal fusion. The main objective of surgical correction for scoliosis is to fuse several vertebrae by means of rods, plates, screws and/or other pieces of instrumentation either anteriorly or posteriorly. The implants are fixed to the vertebral column in order to force the spine to have an "upright" appearance. Because the instrumentation is so close to the spinal chord, surgery is done with extreme caution. The most feared complication of spinal surgery is neurologic deterioration which occurs in about 1% of patients [39]. Historically, the most commonly used instrumentation for treatment of idiopathic scoliosis was the Harrington rod. It has been a means of spinal correction since the 1960's [6,14] (for further information see [33]).

### 3.2.2 Surgical Treatment– Harrington Instrumentation

The Harrington system was the most widely used instrumentation between the 1960's and the mid 1980's [17,44]. Many complications associated with the use of this instrumentation do not occur immediately, and some patients are noticing complications currently from implants used nearly 20 years ago. Between 1961 and 1972 an eleven year follow-up study was conducted on 1,494 scoliotic patients who had received the Harrington instrumentation. A group of 31 patients were observed within one year of surgery, two of the patients experienced problems associated with broken rods with overlap, and seven experienced pseudarthroses. Seven of the 31 patients were operated on a second time, while minor complications included 11 lower hook dislocations, 6 broken rods without overlap, and 10 changes in instrument position. As the observation time increased, more severe complications were noticed.

In a group observed between 1963 and 1966, 47% of the 168 cases had one or more complications. Major complications included two hematomas, three broken rods with overlap, two pseudoarthroses and two serious infections, one resulting in septicemia and death. Though the Harrington system is rarely used in the U.S. currently, there are many people who were diagnosed and treated for scoliosis before other means of spinal fixation were available up until the early 1980's. Unfortunately, many developing countries still perform spinal correction surgery by means of the Harrington system because they are unable to afford more expensive instrumentation.

### 3.2.3 Surgical Treatment– Cotrel-Dubousset Instrumentation

A more recent method of spinal fusion via instrumentation is the Cotrel-Dubousset system. This newer system also has many complications associated with the surgery both preoperatively and postoperatively [6]. This system allows for better fixation and increased correction of vertebral rotation. Unfortunately, if problems are noticed after the operation, this system is much more difficult to remove requiring the use of carbide bits to cut the rods or burr off the set screws.

Though the Cotrel-Dubousset instrumentation utilizes screws for fixation, wires may be used as well in areas deemed necessary by the surgeon. These wires, in some occurrences, break leading to detachment of the segmental implants [47]. In a study conducted by Eberle [13], a set of sixteen scoliotic patients were observed before and after Cotrel-Dubousset instrumentation was applied for an average of 13 months. Complications that occurred during the surgery include the incident of sacral screws pulling out of the respective vertebrae. Other methods of fusion were required to adhere the rod to the spine. Five of the sixteen patients experienced implant failure following surgery. A specific 15-year-old male patient returned five months following surgery with two types of fixation failure. One rod pulled out from the sacral screws, while another pulled out of the bone with the screws still connected to the rod. After his instrumentation was revised, his incision became infected, and the implants were removed. Another patient experienced rod displacement that led to skin erosion located directly over the prominent rod. Other patients experienced minor screw pull-out among other complications. Of the 16 sets of screws placed, seven (44%) failed intraoperatively or postoperatively. Of the medical complications associated with this group of 16 patients, six patients experienced some sort of infection following the surgery. All infections were treated and one required removal of the instrumentation. Four patients complained of neurogenic leg and/or groin pain. One patient received a sacral screw that penetrated anteriorly and was believed to be the cause of the pain [8].

### 3.2.4 Miscellaneous Complications

Many other complications associated with surgical correction of scoliosis have been documented and are common regardless of the instrumentation used. If a surgeon were to select the wrong implants for a scoliotic patient, there could be incident of instrument failure. Complications can start as early as an incorrect diagnosis. This is why it is believed that the current diagnostic techniques are unsatisfactory [41]. Some incidents that may occur in the OR include injury to the spinal cord, dura, vessels, nerve roots and other soft tissues. The most worrisome of all complications is neurological injury. Though it only occurs in 1% of patients, it is a major concern. Many people who have received spinal instrumentation do not follow the guidelines suggested to them by their surgeon. It is recommended that any patient who has obtained any type of spinal instrumentation avoid heavy lifting, exposure to high impact activities, and extreme twisting of the trunk. These actions alone may lead to implant failure. It has been documented that patients who continue to smoke following surgery are more likely to develop pseudarthrosis after fusion [2]. Pseudarthrosis is defined as movement of one or more spinal segments chosen for fusion.

# Chapter 4

# Research

## 4.1 Three-Dimensional Curves

In order to understand the three-dimensional characteristics of spinal deformities, the following terminology has been proposed by Scoliosis Research Society (SRS) [46]. The term *vertebral body line* refers to a curve connecting the centroids of all vertebral bodies, i.e., the fictitious points located halfway between the respective endplates. The vertebral body line serves as a reference for describing the orientation of individual vertebrae and the overall geometry of the spine.

A Cartesian axis system (or basis) is a right-handed coordinate system with axes parallel to 3 orthogonal unit vectors. Typically, the X-axis points in the anterior direction, the Y-axis points in the direction of the patient's left side, and the Z-axis points in the direction of the head. Cartesian axis systems can be introduced:

- on a local level - pertaining to a single or specific vertebra,
- on a regional level - pertaining to a curve or curve segment of the spine,
- on a spinal level - pertaining to the spine itself, and
- on a global level - pertaining to the entire body.

For example, the origin of the spinal axis system is located at the center of the first sacral (S1) vertebra's upper endplate. Its Y-axis is parallel to a line between the anterior superior iliac spines (ASIS) and its Z-axis is chosen to run as close as possible to the center of a specific vertebra (typically the seventh cervical vertebra (C7) or the first thoracic vertebra (T1)).

On a local level, the origin should be placed at the center of the corresponding vertebra. Here, the Z-axis passes directly through the "center" of the endplates, and the Y-axis runs parallel to a line drawn between the two vertebral pedicles. Alternatively, a local coordinate system reflecting the local character of the vertebral body line can be introduced. At any point along the vertebral body line, this *trihedron* axis system is spanned by the tangent vector to the vertebral bodyline, parallel to the Z-axis, the normal vector to the vertebral bodyline, parallel to the X-axis, and the corresponding bi-normal vector, parallel to the Y-axis. Here, the normal vector points in the direction of curvature of the vertebral body line.

Local planes can be introduced to represent regional features of the spine. The *best fit plane* refers to a reference plane that, in a least squares sense, best fits the position of the vertebrae in a specific span of the spine. The plane of maximum/minimum curvature is the plane that is created such that the largest/smallest region of spinal curvature exists when projected onto that plane. Planes on the global level display characteristics of balance and distance.

From a global standpoint, balance refers to the alignment of the patient's head correctly above the pelvis and sacrum in both the frontal and sagittal planes. Part of the goal of treatment for scoliosis is to achieve spinal balance following surgery. A perfectly balanced spine should have a correctly oriented head, horizontal shoulders, and an "evenly distributed trunk" [46]. Balance can not be observed on the local level, but is an attribute of the entire spine. The SRS suggests that spinal balance is a cumulative measure. If the accumulated effect of displacements and angles does not equal zero, then the spine is considered out of balance.

Truncal balance, on the other hand, is a little more complex. The magnitude of the displacement must also take into consideration the volume/mass of the displaced section. Angular balance and global balance can be determined by the orientation of the proximal vertebra and the angle between a line through this vertebra and the Z-axis of the global coordinate system.

There are several ways of quantifying regional spinal characteristics. Spinal length is the distance along the vertebral body line. An apical vertebra is defined as the most laterally deviated vertebra with respect to the end vertebrae of a specified regional curve.

If a deformity is present, the orientation of individual vertebrae may be altered in several regions of the spine. These changes in orientation are referred to as rotations, but the SRS suggests that the changes should be called angulations. This is due to the fact that the orientation change may not be caused by physical rotation. Depending on the deformity, vertebral rotation may occur about each of the three axes in the right handed coordinate system. Rotation in the spinal coordinate system about the X-axis is referred to as vertebral lateral rotation, rotation about the Y-axis is referred to as vertebral sagittal rotation or vertebral flexion/extension rotation, and rotation about the Z-axis is referred to as vertebral transverse plane rotation or vertebral axial rotation.

Orientation can also be determined on the regional level. These rotations of planar regions containing curves are typically measured with respect to the sagittal plane. For example, the orientation of the plane of maximum/minimum curvature is the angle between this and the sagittal plane. The apical angle is the measured angle between the Z-axis of the spinal coordinate system and a line connecting the origin to the centroid of the apical vertebra.

The vertebral body line can locally be described by two properties. Curvature and torsion are measures that are mathematically described by Frenet's formulae (defined below). Curvature is inversely proportional to the radius of the circle that is the closest fit to the curve at a specific point. Changes in local curvature may result in dramatic changes in the overall shape of the vertebral body line "downstream." Torsion is defined as the amount of rotation of the plane of curvature or bending. A positive torsion value represents a rotation in the positive sense about the tangent vector while a negative torsion value represents rotation in the opposite direction.

## 4.2 Scoliosis Learning Tool

By implementing a computer software learning tool in Matlab® that allows users to modify local curvature and torsion values on a model spine, it becomes possible to increase the understanding of the three-dimensional characteristics of scoliotic curves. The Scoliosis Learning Tool provides users with the ability to open multiple windows (anterior posterior, lateral, and three-dimensional) in order to visualize changes in three dimensions. Since most current classification techniques require a surgeon to draw conclusions from an A/P and a Lateral x-ray film, this tool allows for an understanding of changes that may be overlooked by viewing 2-D images.

### 4.2.1 Patient Generation

#### Integration Method of Curve Generation

The Scoliosis Learning Tool implements two different methods for generating a three-dimensional curve. This section describes a method based on the pointwise specification of the local curvature and torsion.

Consider a world reference frame with an origin at a point $O$ and a basis given by the vectors $\bar{n}_1$, $\bar{n}_2$, and $\bar{n}_3$. The position vector from the point $O$ to an arbitrary point $P$ on the curve can be written as:

$$\bar{r}^{OP}(t) = (\bar{n}_1\ \bar{n}_2\ \bar{n}_3)\begin{pmatrix} x(t) \\ y(t) \\ z(t) \end{pmatrix} \tag{4.1}$$

Here, $t$ is a parameter parameterizing the curve and $x$, $y$ and $z$ are appropriate functions of t. The vector:

$$\frac{{}^n dr}{dt}(t) = (\bar{n}_1\ \bar{n}_2\ \bar{n}_3)\begin{pmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{z}(t) \end{pmatrix} \tag{4.2}$$

is tangential to the curve at the point $P$. In fact, provided that

$$\sigma(t) \equiv \left\| \frac{{}^n d\bar{r}}{dt}(t) \right\| \neq 0 \tag{4.3}$$

it is possible to introduce a new parameter $s$ such that $t$ is a function of $s$ and

$$\frac{dt}{ds}(s) = \frac{1}{\sigma(t(s))} \tag{4.4}$$

Thus, if we define:

$$\bar{\rho}^{OP}(s) = \bar{r}^{OP}(t(s)) = (\bar{n}_1 \; \bar{n}_2 \; \bar{n}_3) \begin{pmatrix} x(t(s)) \\ y(t(s)) \\ z(t(s)) \end{pmatrix} \tag{4.5}$$

then

$$\left\| \frac{{}^n d\bar{\rho}}{ds}(s) \right\| = \left\| \frac{{}^n d\bar{r}}{dt}(t(s)) \right\| \cdot \left| \frac{dt}{ds}(s) \right| = 1 \tag{4.6}$$

i.e., the tangent vector

$$\bar{b}_1(s) = \frac{{}^n d\bar{\rho}}{ds}(s) = (\bar{n}_1 \; \bar{n}_2 \; \bar{n}_3) \begin{pmatrix} b_{1x}(s) \\ b_{1y}(s) \\ b_{1z}(s) \end{pmatrix} \tag{4.7}$$

is a unit vector tangential to the curve at the point parameterized by $s$. Since $\bar{b}_1 \cdot \bar{b}_1 = 1$, it follows that:

$$\frac{{}^n d\bar{b}_1}{ds} \perp \bar{b}_1 \tag{4.8}$$

Now let

$$\left\| \frac{{}^n d\bar{b}_1}{ds} \right\| = K(s) \tag{4.9}$$

where $K(s)$ is called the curvature of the curve at the point given by $s$. Then if $K(s) \neq 0$, the unit vector

$$\bar{b}_2 = \frac{1}{K(s)} \frac{{}^n d\bar{b}_1}{ds} \tag{4.10}$$

is perpendicular to $\bar{b}_1$ and points in the direction of curvature. The "binormal" vector is the cross product

$$\bar{b}_3(s) = \bar{b}_1(s) \times \bar{b}_2(s) \tag{4.11}$$

and is a unit vector perpendicular to the plane created by the "normal" and "tangent" vectors. If at a certain $(s_0)$, $K(s_0) = 0$, then both the "normal" and "binormal" vectors are undefined.

It is possible to relate the derivatives of the tangent, normal, and bi-normal vectors to linear combinations of the tangent, normal, and bi-normal vectors as per the Frenet formulae:

$$\begin{aligned} \frac{{}^n d\bar{b}_1}{ds}(s) &= K(s) \cdot \bar{b}_2 \\ \frac{{}^n d\bar{b}_2}{ds}(s) &= -K(s) \cdot \bar{b}_1 + \tau(s) \cdot \bar{b}_3 \\ \frac{{}^n d\bar{b}_3}{ds}(s) &= -\tau(s) \cdot \bar{b}_2 \end{aligned} \tag{4.12}$$

where $\tau(s)$ is known as the torsion at the point s and describes the rate of change of the plane of bending.

The orthonormal right-handed basis $b$ can be expressed as:

$$(\bar{b}_1\ \bar{b}_2\ \bar{b}_3) = (\bar{n}_1\ \bar{n}_2\ \bar{n}_3) \cdot R_{nb} \tag{4.13}$$

where $R_{nb}$ is the rotation matrix from basis $n$ to basis $b$. For example, the rotation matrix can be described in a 1-1 fashion by a set of Euler parameters:

$$R_{nb} = \begin{pmatrix} e_0^2 + e_1^2 - e_2^2 - e_3^2 & 2 \cdot (e_1 \cdot e_2 + e_0 \cdot e_3) & 2 \cdot (e_1 \cdot e_3 - e_0 \cdot e_2) \\ 2 \cdot (e_1 \cdot e_2 - e_0 \cdot e_3) & e_0^2 + e_2^2 - e_1^2 - e_3^2 & 2 \cdot (e_2 \cdot e_3 + e_0 \cdot e_1) \\ 2 \cdot (e_1 \cdot e_3 + e_0 \cdot e_2) & 2 \cdot (e_2 \cdot e_3 - e_0 \cdot e_1) & e_0^2 + e_3^2 - e_1^2 - e_2^2 \end{pmatrix} \tag{4.14}$$

such that:

$$e_0^2 + e_1^2 + e_2^2 + e_3^2 = 1 \tag{4.15}$$

Combining the description of the rotation matrix in terms of Euler parameters with the Frenet formulae, it is possible to show that

$$\begin{aligned} \dot{e}_0 &= \tfrac{1}{2} \cdot (\tau(s) \cdot e_1 + K(s) \cdot e_3) \\ \dot{e}_1 &= \tfrac{1}{2} \cdot (-\tau(s) \cdot e_0 + K(s) \cdot e_2) \\ \dot{e}_2 &= \tfrac{1}{2} \cdot (-K(s) \cdot e_1 + \tau(s) \cdot e_3) \\ \dot{e}_3 &= \tfrac{1}{2} \cdot (-K(s) \cdot e_0 - \tau(s) \cdot e_2) \end{aligned} \tag{4.16}$$

Given any set of initial values for the Euler parameters and known functions of s for the curvature and torsion, these differential equations can be solved for the orientation of the basis $b$ relative to $n$ at any point along the curve. By subsequently solving the differential equation $\frac{d\bar{\rho}}{ds} = \bar{b}_1(s)$ it is possible to find $\bar{\rho}$ as a function of $s$.

The Scoliosis Learning tool allows the user to manipulate values for curvature ($K$) and torsion ($\tau$) and initial orientation, and to instantly recreate the corresponding three-dimensional curve. Each curve is normalized such that the length of the entire spine is 1 in order to compare results between spines without the concern of patient height.

### Impulse Method of Curve Generation

An alternative method is to allow the user to manipulate discrete changes along the vertebral body line of the *trihedron* axis system's orientation. Specifically, a curvature impulse imposes a rotation of the *trihedron* by a certain angle about the bi-normal vector and a torsion impulse imposes a subsequent rotation by a certain angle about the new tangent vector. Indeed, this corresponds to a discretization of the Frenet formulae. The code used for curve reconstruction using the impulse method is shown below:

```
function [dataYY,dataT,dataX,dataY,dataZ]=reconimpulse(main)

tspan = [0,6.972112,13.94422,20.91633,27.88845,33.86454,38.84462,...
        43.8247,48.40637,52.78884,56.97211,60.95618,64.94024,68.9243,...
        72.50996,76.49402,79.48207,82.47012,85.45817,88.44622,91.03586,...
        93.6255,96.61355,100]/100;

dataYY=zeros(length(tspan),12);
e0=main.orientdata(1);
e1=main.orientdata(2);
e2=main.orientdata(3);
e3=main.orientdata(4);
Rotationmatrix=[e0^2+e1^2-e2^2-e3^2 2*(e1*e2+e0*e3) 2*(e1*e3-e0*e2);...
        2*(e1*e2-e0*e3) e0^2+e2^2-e1^2-e3^2 2*(e2*e3+e0*e1);...
        2*(e1*e3+e0*e2) 2*(e2*e3-e0*e1) e0^2+e3^2-e1^2-e2^2];
dataYY(1,:)=[zeros(1,3) reshape(Rotationmatrix,1,9)];
for i=2:length(tspan)
    tangentvector=Rotationmatrix(:,1)';
    dataYY(i,1:3)=dataYY(i-1,1:3)+tangentvector*(tspan(i)-tspan(i-1));
    Rotationmatrix=Rotationmatrix*...
        [cos(main.Kappa(i)),-sin(main.Kappa(i)),0;sin(main.Kappa(i)),...
  cos(main.Kappa(i)),0;0,0,1]*[1,0,0;0,cos(main.Tau(i)),...
  -sin(main.Tau(i));0,sin(main.Tau(i)),cos(main.Tau(i))];
    dataYY(i,4:12)=reshape(Rotationmatrix,1,9);
end

dataT=[tspan(1):.01:tspan(end)];
dataX=spline(tspan,[0 dataYY(:,1)' 0],dataT);
dataY=spline(tspan,[0 dataYY(:,2)' 0],dataT);
```

```
dataZ=spline(tspan,[0 dataYY(:,3)' 0],dataT);
```

Here, the tspan vector provides the percentage distance from L5 to each vertebra relative to the length of the spine.

### 4.2.2 "Lenke Light" Classification Scheme

Using the measuring techniques defined in Lenke [25], the Scoliosis Learning Tool defines the classification of a generated patient. Since the program is unable to provide an A/P bending image, the "Lenke Light" classification is determined using all other measurement techniques defined by Lenke.

Here, the "Lenke Light" classification scheme is only applied to spines for which the T2 vertebra lies within a predefined cylindrical volume in the spinal coordinate system centered on a "nominal" position of the T2 vertebra.

#### Lenke Curve Type

The "Lenke Light" classification scheme determines major/minor and structural/non-structural characteristics of the spinal regions (Proximal Thoracic, Main Thoracic, Thoracolumbar, and Lumbar). The program finds the location and size of all curve segments located in the A/P plane. In order to accomplish this, the software locates the points of inflection along the curve and defines curve segments as all vertebrae contained between those specific inflection points as seen here:

```
aptangent=zeros(3,24);
crosstan=zeros(1,23);
lattangent=zeros(3,24);
for i=1:24
    Rab=reshape(YY(i,4:12),3,3);
    aptangent(:,i)=[Rab(1,1) 0 Rab(3,1)]'/norm([Rab(1,1) 0 Rab(3,1)]);
    lattangent(:,i)=[Rab(1,1) Rab(2,1) 0]'/norm([Rab(1,1) Rab(2,1) 0]);
end

for i=1:23
    crosstan(i)=dot(cross(aptangent(:,i),aptangent(:,i+1)),[0,1,0]);
end

curves=zeros(5,24);
signum=sign(crosstan(1));
k=1; curves(1,k)=1;
for i=2:23
    if (crosstan(i)>0 & signum==-1) | (crosstan(i)<=0 & signum==1)
        signum=-signum;  curves(2,k)=i;    k=k+1;    curves(1,k)=i;
    end
```

```
end
curves(2,k)=24; curves=curves(:,1:k);
```

The first row of the `curves` matrix contains the ‘index number’ of the vertebrae corresponding to the beginning of each curve segment and the second row contains the number of the vertebrae corresponding to the end of each curve segment.

After determining the location of the curve segment, major/minor curves are defined by calculating the Cobb angles of each of the curve segments. To determine the location of the major curve according to Lenke’s criteria, the software must locate the apex of each curve segment. Lenke *et al* defined the apex of a curve segment as the most laterally deviated vertebra from the CSVL. Alternatively using the SRS criteria, the apex is defined as the most laterally deviated vertebra with respect to a line connecting the two inflection points that constitute the beginning and end of the respective curve. This is the method used by the Scoliosis Learning Tool. The code for this application can be seen here:

```
cobbangle=zeros(1,k);
for i=1:k
    cobbangle(i)=acos(dot(aptangent(:,curves(1,i)),aptangent(:,curves(2,i))));
end

[maxcobb,maxcobbi]=max(cobbangle);
curves(3,maxcobbi)=1;

C=[24:-1:18]; T=[17:-1:6]; L=[5:-1:1];

for i=1:k
    temp=YY(curves(2,i),1:3)-YY(curves(1,i),1:3);
    temp(2)=0;
    unit=temp/norm(temp);
    maxapex=0;
    maxapexi=curves(1,i);
    for j=curves(1,i)+1:curves(2,i)-1
        v=YY(j,1:3)-YY(curves(1,i),1:3);
        v(2)=0;
        length=norm(cross(unit,cross(v,unit)));
        if length>maxapex
            maxapex=length;
            maxapexi=j;
        end
    end
    %[maxapex,maxapexi]=max(abs(YY(span(2:end-1),3)));% Lenke Definition
```

```
        if maxapexi<=L(2), curves(4,i)=1;
        elseif maxapexi<=T(12), curves(4,i)=2;
        elseif maxapexi<=T(6), curves(4,i)=3;
        elseif maxapexi<=T(2), curves(4,i)=4;
        end
    end
```

The third row of the `curves` matrix contains a 1 for the major curve and zeros in the remaining curve segments. The fourth row contains the designation of the part of the spine in which this segment lies.

The software assigns a structural or non-structural characteristic to each region of the spine as per the Lenke scheme. As mentioned in the preceding chapter, Lenke defined structural/non-structural criteria by observing residual curves on the bending film as well as kyphosis in the lateral film.

Due to the nature of the "virtual" spines observed by the Scoliosis Learning Tool, it is difficult to predict bending criteria. Therefore, the Scoliosis Learning Tool only uses the information about the lateral kyphosis to determine whether a curve segment is structural or non-structural. After assigning structural/non-structural values to each spinal region, the program associates the appropriate Lenke Type (1 through 6) to the respective region. A structural criterion is designated by a 1, while a nonstructural criterion is designated by a zero in the fifth row of the `curves` matrix. The code associated with this classification method can be seen below:

```
for i=1:k
    if curves(3,i)==1, curves(5,i)=1;
    else
        if curves(4,i)==1 | curves(4,i)==2 | curves(4,i)==3
            if acos(dot(lattangent(:,T(10)),lattangent(:,L(2))))>20*pi/180
               curves(5,i)=1;
            end
        elseif curves(4,i)==4
            if acos(dot(lattangent(:,T(2)),lattangent(:,T(5))))>20*pi/180
                curves(5,i)=1;
            end
        end
    end
end

%lumbar:
lumbar=0;
ind=find(curves(4,:)==1);
if ~isempty(ind)
    ind=find(curves(5,ind)==1);
```

```
    if ~isempty(ind), lumbar=1;  end
end

thoracolumbar=0;
ind=find(curves(4,:)==2);
if ~isempty(ind)
    ind=find(curves(5,ind)==1);
    if ~isempty(ind), thoracolumbar=1; end
end

thoracic=0;
ind=find(curves(4,:)==3);
if ~isempty(ind)
    ind=find(curves(5,ind)==1);
    if ~isempty(ind), thoracic=1; end
end

proximalthoracic=0;
ind=find(curves(4,:)==4);
if ~isempty(ind)
    ind=find(curves(5,ind)==1);
    if ~isempty(ind), proximalthoracic=1; end
end


type='0';
if curves(4,maxcobbi)==3
    if proximalthoracic==0 & (thoracolumbar==0 & lumbar==0), type='1';
    elseif proximalthoracic==1 & (thoracolumbar==0 & lumbar==0), type='2';
    elseif proximalthoracic==0 & (thoracolumbar==1 | lumbar==1), type='3';
    elseif proximalthoracic==1 & (thoracolumbar==1 | lumbar==1), type='4';
    end
elseif curves(4,maxcobbi)==1 | curves(4,maxcobbi)==2
    if proximalthoracic==0 & thoracic==0, type='5';
    elseif proximalthoracic==0 & thoracic==1, type='6';
    elseif proximalthoracic==1 & thoracic==1, type='4';
    end
end
```

The mathematics implemented in the Scoliosis Learning Tool correlate well with those used to determine the Lenke Classification. As previously mentioned, the designation of curves as Type 3 or Type 6 depends on the difference in Cobb angle between the Thoracolumbar/Lumbar and Main Thoracic curves. If the Cobb angle difference between the two is equal to or less than 5 degrees, the diagnosis could be either of the two classification types [25]. In the software, the Scoliosis Learning Tool ignored that specific determination. It was also mentioned by Lenke that the structural major curve could be either in the Main Thoracic region or the Thoracolumbar/Lumbar region in a Type 4 curve . The software does account for this portion of the Lenke classification by allowing a Type 4 curve to be classified with respect to both Main Thoracic structural criterion and Thoracolumbar/Lumbar structural criterion.

**Lumbar Modifier**

The program determines the Lumbar Modifier by again evaluating the projection of the spine on to the frontal plane. The Scoliosis Learning Tool determines the location of the apex of the Lumbar curve segment, and measures the amount of lateral deviation from the CSVL (a vertical line through the origin of the curve). Since all of the curves are normalized to a value of 1, it was determined that any spine with a Lumbar apex that deviates less than 0.03 from the CSVL should be considered Lumbar Modifier A. Any Lumbar apex falling between the normalized distances of 0.03 and 0.044 should be considered Lumbar Modifier B, and any normalized distance greater than 0.044 should be considered Lumbar Modifier C. The code used to generate the Lumbar Modifier can be seen below:

```
lumbmod='A';
profile=max(abs(YY(L(4):L(1),3)));
if profile>=.03 & profile<0.044
    lumbmod='B';
elseif profile>=.044
    lumbmod='C';
end
```

Unlike the coding used to determine the curve type, the Scoliosis Learning Tool defined the apex of the Lumbar curve as the most laterally deviated vertebra from the CSVL. This is consistent with the method examined by Lenke, as opposed to the method used earlier in which the apex is defined as the most deviated vertebra from a line connecting inflection points of the curve segment.

**Sagittal Thoracic Modifier**

The Scoliosis Learning Tool determines the Sagittal Thoracic Modifier as determined by the Lenke scheme. By measuring the Cobb angle between the fifth Thoracic vertebra and the twelfth Thoracic vertebra in the Sagittal plane, the software assigns a value for Hyperkyphosis (+), Normal Kyphosis (N), or Hypokyphosis (-). The code utilized in this portion of the software can be seen here:

```
thormod='N';
```

```
signum=1;
if dot(cross(lattangent(:,T(5)),lattangent(:,T(12))),[0 1 0])<0
    signum=-1;
end
profile=signum*acos(dot(lattangent(:,T(5)),lattangent(:,T(12))));
if profile<10*pi/180, thormod='-';
elseif profile>40*pi/180, thormod='+';
end
```

This classification method is determined using the same criteria as that defined by Lenke. The angles measured were determined in the sagittal plane such that the information would correlate with Cobb angles measured in the lateral film.

### 4.2.3 Patient/Population Builder

A random patient generator and a population generator were developed in order to generate random spines for evaluation. These two plug-ins allowed the software to assign random values for curvature and torsion impulses as well as the initial orientation relative to a nominal spine. The patient generator runs until the spine created can be classified by the Lenke Classification Scheme. If the user chooses to run the population generator, the program will create a user-specified number of patients that meet the expectations of the Lenke Classification Scheme. Figure 4.1 shows the dialog box used to generate random populations. It should be noted that the single patient generator allows for the user to manipulate the allowable ranges for curvature impulses, torsion impulse and the three Euler angles describing the initial orientation of the *trihedron* relative to the spinal coordinate system. The population generator allows for the same manipulation of allowable ranges, as well as modification of the allowable volume for T2 and the number of patients requested.


Figure 4.1: Screen shot of patient generation dialog window.

The population generator creates random patients as described earlier while adhering to the limitations specified in the dialog window. Each specific patient created is saved to a *.mat file and placed in a folder whose name corresponds to the Lenke Classification of the patient generated. For example, if a patient with the classification 6A+ is created, the software first determines whether or not a 6A+ folder already exists. If so, a file corresponding to the number of the patient is created. In other words, if there are already 5 *.mat files in the

6A+ folder (1.mat, 2.mat, 3.mat, 4.mat and 5.mat) the Scoliosis Learning Tool 4.0 will save the current patient as 6.mat, and proceed on to the next random assignment of curvature, torsion and Euler angles.

The code for the random patient generator is shown below:

```
function mainout=random(mainin,camp,tamp,thetaamp,phiamp,psiamp)

rand('state',sum(100*clock))
nos=rand(1,31);
k=[1:7];
a1=camp*(2*nos(1:7)-1);
a2=camp*(2*nos(8:14)-1);
b1=tamp*(2*nos(15:21)-1);
b2=tamp*(2*nos(22:28)-1);
tspan = [0,6.972112,13.94422,20.91633,27.88845,33.86454,38.84462,...
        43.8247,48.40637,52.78884,56.97211,60.95618,64.94024,68.9243,...
        72.50996,76.49402,79.48207,82.47012,85.45817,88.44622,91.03586,...
        93.6255,96.61355,100]/100;

mainout=mainin;
for i=1:7
    mainout.Kappa=mainout.Kappa+a1(i)/i^2*cos(2*pi*i*tspan)+...
a2(i)/i^2*sin(2*pi*i*tspan);
end
for i=1:7
    mainout.Tau=mainout.Tau+b1(i)/i^2*cos(2*pi*i*tspan)+...
b2(i)/i^2*sin(2*pi*i*tspan);
end

theta=mainin.orientdata(5)+thetaamp*(2*nos(29)-1);
theta=acos(cos(theta));
phi=mainin.orientdata(6)+phiamp*(2*nos(30)-1);
phi=atan2(sin(phi),cos(phi));
psi=mainin.orientdata(7)+psiamp*(2*nos(31)-1);
psi=atan2(sin(psi),cos(psi));

Rnb=[1,0,0;0,cos(phi),-sin(phi);0,sin(phi),cos(phi)]*...
        [cos(theta),-sin(theta),0;sin(theta),cos(theta),0;0,0,1]*...
        [1,0,0;0,cos(psi),-sin(psi);0,sin(psi),cos(psi)];
[v,d]=eig(Rnb);
mat=find((real(diag(d)))>0.9999);
vector=v(:,mat);
v1=vector(1); v2=vector(2); v3=vector(3);
gnu=max(angle(diag(d)));
e0=cos(gnu/2); e1=v1*sin(gnu/2); e2=v2*sin(gnu/2); e3=v3*sin(gnu/2);
```

```
Rab=[e0^2+e1^2-e2^2-e3^2 2*(e1*e2+e0*e3) 2*(e1*e3-e0*e2);...
            2*(e1*e2-e0*e3) e0^2+e2^2-e1^2-e3^2 2*(e2*e3+e0*e1);...
            2*(e1*e3+e0*e2) 2*(e2*e3-e0*e1) e0^2+e3^2-e1^2-e2^2];

    if max(abs(Rnb-Rab))>1e-5
        mainout.orientdata=[e0,-e1,-e2,-e3,theta,phi,psi];
    else
        mainout.orientdata=[e0,e1,e2,e3,theta,phi,psi];
    end
```

The random changes in curvature and torsion values are described by a finite trigonometric polynomial whose amplitudes are randomly selected.

It is pertinent to create a diverse population and ensure that each classification category is generated by the software. To do so, the program constructed a population of 10,000 patients. This population is broken down such that there are 16 subgroups of 625 each with differing values for the allowable ranges. A table describing the subgroup sets can be seen in Table 4.1.

Table 4.1: Description of parameters used to generate 10,000 diverse patients.

| Group Set | Number of Patients | Curvature Value | Torsion Value | Theta | Phi | Psi | Weighing Emphasis |
|---|---|---|---|---|---|---|---|
| 1a | 625 | 0.5 | 0.2 | 0.7 | 0.7 | 0.7 | None |
| 1b | 625 | 0.5 | 0.2 | 0.7 | 0.7 | 0.7 | Lumbar Spine |
| 1c | 625 | 0.5 | 0.2 | 0.7 | 0.7 | 0.7 | Lower Thoracic Spine |
| 1d | 625 | 0.5 | 0.2 | 0.7 | 0.7 | 0.7 | Upper Thoracic Spine |
| 2a | 625 | 0.6 | 0.25 | 0.7 | 0.7 | 1.57 | None |
| 2b | 625 | 0.6 | 0.25 | 0.7 | 0.7 | 1.57 | Lumbar Spine |
| 2c | 625 | 0.6 | 0.25 | 0.7 | 0.7 | 1.57 | Lower Thoracic Spine |
| 2d | 625 | 0.6 | 0.25 | 0.7 | 0.7 | 1.57 | Upper Thoracic Spine |
| 3a | 625 | 0.4 | 0.3 | 0.7 | 0.7 | 1.57 | None |
| 3b | 625 | 0.4 | 0.3 | 0.7 | 0.7 | 1.57 | Lumbar Spine |
| 3c | 625 | 0.4 | 0.3 | 0.7 | 0.7 | 1.57 | Lower Thoracic Spine |
| 3d | 625 | 0.4 | 0.3 | 0.7 | 0.7 | 1.57 | Upper Thoracic Spine |
| 4a | 625 | 0.3 | 0.25 | 0.7 | 0.7 | 1.57 | None |
| 4b | 625 | 0.3 | 0.25 | 0.7 | 0.7 | 1.57 | Lumbar Spine |
| 4c | 625 | 0.3 | 0.25 | 0.7 | 0.7 | 1.57 | Lower Thoracic Spine |
| 4d | 625 | 0.3 | 0.25 | 0.7 | 0.7 | 1.57 | Upper Thoracic Spine |

### 4.2.4 Analysis

#### Defining a Metric

In order to geometrically characterize the Lenke Classification Scheme, a mathematical metric is introduced. This is a measure of the difference in geometry of two curves. Specifically, the metric distance between two spines combines information about the differences in initial orientation, curvature impulses and torsion impulses, respectively. For example, given a reference "nominal" spine, an absolute distance can be associated with each spine quantifying its deviation from the nominal spine.

Since the diagnosis of scoliosis primarily refers to deformities in the thoracic and lumbar regions of the spine, differences in the cervical region are excluded from the metric. Instead, the absolute values of the pointwise differences between the curvature impulses, torsion impulses and the Euler angles defining the initial orientation are suitably averaged. The corresponding Matlab® code is shown below:

```
function distance=metric(test1,test2)

test1=renormalize(test1);
test2=renormalize(test2);
theta=[test1.orientdata(5), test2.orientdata(5)];
phi=[test1.orientdata(6), test2.orientdata(6)];
psi=[test1.orientdata(7), test2.orientdata(7)];
curvweight=[2 2 2 2 2 1 1 1 1 1 1 1 1 1 1 1];

distance=(sum(curvweight.*acos(cos(test1.Kappa(2:17)...
-test2.Kappa(2:17))))+(acos(cos(phi(1)-phi(2)))))/(1+sum(curvweight))+...
    (sum(curvweight.*acos(cos(test1.Tau(2:17)-test2.Tau(2:17))))...
+(acos(cos(theta(1)-theta(2))))+(acos(cos(psi(1)-psi(2)))))...
    /(2+sum(curvweight));
```

By suitably choosing the weights in the weighted average defining the metric, it is possible to concentrate on specific regions of the spine. Here, the differences in curvature and torsion are multiplied by a weighing vector before determining the metric. For a metric that places no particular emphasis on a specific region of the spine, the weighing vector consists of all ones. If, instead, emphasis were to be placed on the lumbar spine, the weights corresponding to those vertebrae could be relatively increased. An example of this is shown in the code above where the values of the `curveweight` vector are 2 rather than 1.

### Computing Separations and Diameters

The Scoliosis Learning Tool can be used to compute the metric distance between any two spines either within a particular sub-population, or across different sub-populations as per the Lenke scheme. For example, the diameter of a sub-population is defined as the largest metric distance between any two spines in that population. Similarly, the separation between two sub-populations is defined as the smallest metric distance between an arbitrary spine in one population and an arbitrary spine in the other.

The Matlab® code below calculates the diameter of each Lenke classification sub-population as generated by the population builder:

```
    categories=dir('patients/');
    population.categories={categories(3:end).name};
    h = waitbar(0,'Computing diameters. Please wait...');
    f=1;
    Totaldia=0;
    for i=3:length(categories)
        waitbar((i-2)/(length(categories)-2));
        patients=dir(['patients/',categories(i).name]);
        diameter=0;
        for j=3:length(patients)-2
            load(['patients/',categories(i).name,'/',patients(j).name]);
            test1.Kappa=curvature;
            test1.Tau=torsion;
            test1.orientdata=IO;
            for k=j+1:length(patients)-1
                load(['patients/',categories(i).name,'/',patients(k).name])
                test2.Kappa=curvature;
                test2.Tau=torsion;
                test2.orientdata=IO;
                temp=metric(test1,test2);
                if diameter<temp(1), diameter=temp(1); end
            end
        end
        population.metric(i-2,i-2)=diameter;
    end
    close(h);
```

The following code computes the separations between all pairs of sub-populations per the Lenke scheme.

```
h = waitbar(0,'Computing separations. Please wait...');
    for i=3:length(categories)-1
        waitbar((i-2)/(length(categories)-2));
        patients1=dir(['patients/',categories(i).name]);
        for j=i+1:length(categories)
            patients2=dir(['patients/',categories(j).name]);
            separation=1e5;
            for k=3:length(patients1)-1
                load(['patients/',categories(i).name,'/',patients1(k).name]);
                test1.Kappa=curvature;
                test1.Tau=torsion;
                test1.orientdata=IO;
                for l=3:length(patients2)-1
```

```
                    load(['patients/',categories(j).name,'/',patients2(l).name]);
                    test2.Kappa=curvature;
                    test2.Tau=torsion;
                    test2.orientdata=IO;
                    temp=metric(test1,test2);
                    if temp(1)<separation, separation=temp(1); end
                    if temp(1)>Totaldia, Totaldia=temp(1);end
                end
            end
            population.metric(i-2,j-2)=separation;
            population.metric(j-2,i-2)=separation;
        end
    end
```

A graphical representation of the metric data for one of the previously generated populations by population builder can be seen in Figure 4.2. Here, diameters are collected along the diagonal and the other numbers represent the pairwise separations. The summary of the metric data can be found in Appendix A. Note that a diameter of zero for a specific classification group indicates that it contains at most one patient.

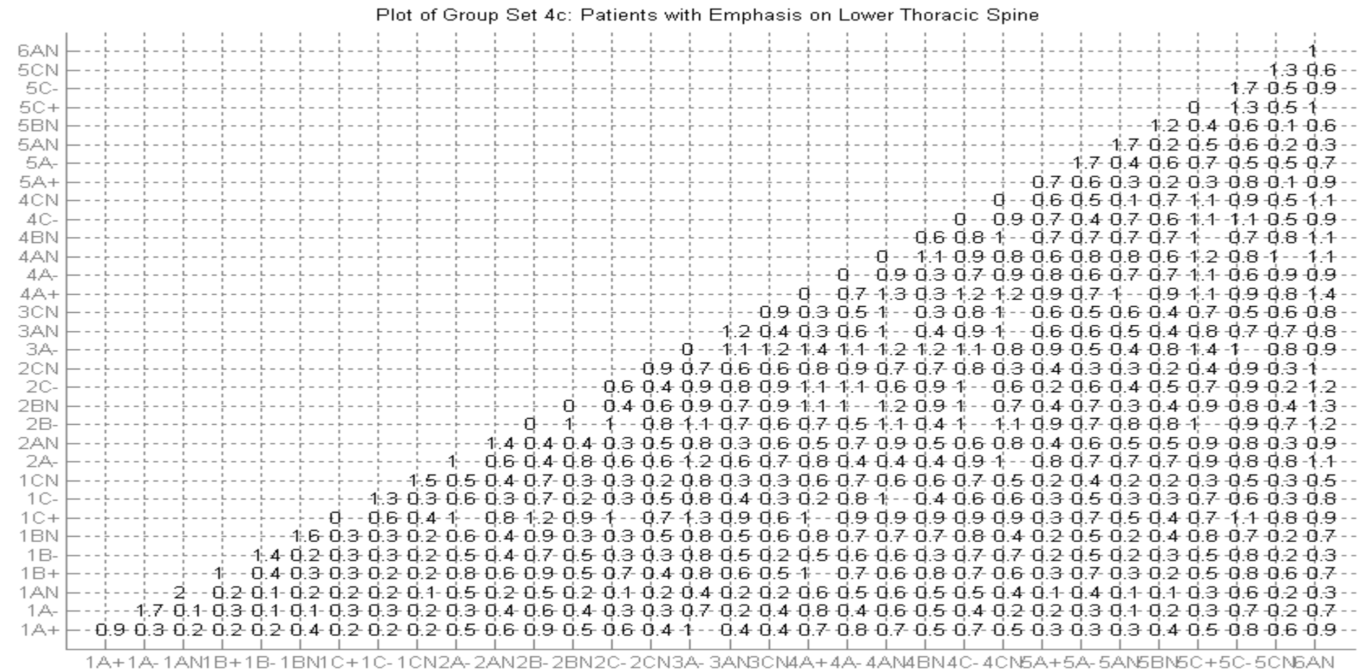


Figure 4.2: Matrix of population diameter and separation information for group set of 625 patients with metric emphasis placed on lower spine.

Although the intention of this metric analysis is to geometrically organize the Lenke classification groups, there is no clear spatial pattern to the numbers defined by the metric.

### Statistical Verification of Population

Lenke *et al* [25] conducted a clinical study on a group of 315 patients with scoliosis to verify the effectiveness of the defined classification method, see Table 4.2. Note that Type 1 is the dominant classification while Type 4 and Type 6 are the least prevalent. The value of the Lumbar Modifier was more evenly distributed through the population although almost half of the patients had a Lumbar Modifier C. A majority of patients (71%) fell into the category of Normal Kyphosis.

Table 4.2: Clinical study for statistical verification of Lenke Classification Scheme conducted on 315 patients [25].

Lenke Clinical Study

| Classification | Number of Patients | Percentage |
|---|---|---|
| Type 1 | 126 | 40.0 |
| Type 2 | 56 | 17.8 |
| Type 3 | 58 | 18.4 |
| Type 4 | 8 | 2.5 |
| Type 5 | 56 | 17.8 |
| Type 6 | 11 | 3.5 |
| Lumbar Modifier | Number of Patients | Percentage |
| A | 94 | 29.84 |
| B | 67 | 21.27 |
| C | 154 | 48.89 |
| Sagittal Thoracic Modifier | Number of Patients | Percentage |
| Hypokyphosis (-) | 56 | 17.78 |
| Normal Kyphosis (N) | 224 | 71.11 |
| Hyperkyphosis (+) | 35 | 11.11 |

In order to determine the validity of the Scoliosis Learning Tool's Population Builder, the population of the 10,000 patients (see preceding section) was broken down in a similar fashion, see Table 4.3. There is a good agreement between the classification types found here as compared to Lenke's data. Again, the most prevalent classification type is Type 1 while Type 4 and Type 6 are least likely to occur. The incidence of Type 2 and Type 3 classifications does not agree as well with the Lenke data.

As mentioned in Chapter 1, any curve segment with a Cobb angle greater than $10°$ is considered scoliotic. The Scoliosis Learning Tool defined any curve segment, regardless of size, as a scoliotic curve. This could be one of the reasons why the Population Builder data did not match the Lenke study more closely. In fact, the program could have over populated the Type 1 and Type 5 categories because it included curves that would normally be considered healthy, and therefore not scoliotic at all.

Table 4.3: Verification of data collected by Population Generator for 10,000 patients.

Scoliosis Learning Tool Data

| Classification | Number of Patients | Percentage |
|---|---|---|
| Type 1 | 5765 | 57.65 |
| Type 2 | 413 | 4.13 |
| Type 3 | 881 | 8.81 |
| Type 4 | 311 | 3.11 |
| Type 5 | 2366 | 23.66 |
| Type 6 | 264 | 2.64 |
| Lumbar Modifier | Number of Patients | Percentage |
| A | 6560 | 65.6 |
| B | 1427 | 14.27 |
| C | 2013 | 20.13 |
| Sagittal Thoracic Modifier | Number of Patients | Percentage |
| Hypokyphosis (-) | 3186 | 31.86 |
| Normal Kyphosis (N) | 6297 | 62.97 |
| Hyperkyphosis (+) | 517 | 5.17 |

There is significant disagreement of the Lumbar Modifier data between the two studies. The Lenke *et al* study suggested that nearly half of the population included in his clinical study were classified as a Lumbar Modifier C. In the population generated by the Scoliosis Learning Tool, nearly 66% of the patients were classified as having a Lumbar Modifier A. This could be mainly due to the fact that the limiting values chosen (as described earlier in the report) were determined by a physical measurement made on a skeletal model and scaled such that they were acceptable for this application.

The Sagittal Thoracic Modifier numbers agreed quite well with those collected in the Lenke *et al* study. As expected the majority of patients had a Normal Kyphosis diagnosis. There were slight discrepancies with respect to numbers associated with diagnoses of Hypokyphosis and Hyperkyphosis.

### Comparison of Extremal Spines within Classification Groups

By locating spines of the same classification group with the largest metric distance from one another, one might be able to assess the geometric uniformity throughout such a classification group. A large difference in the geometry could be indicative of the need to introduce a more finely resolved classification scheme.

A collection of pairs of extremal spines within the classification groups with the largest diameters can be seen in Appendix B. An example of such a pair is shown in Figure 4.3 corresponding to classification 1AN in the 4d sub-population.

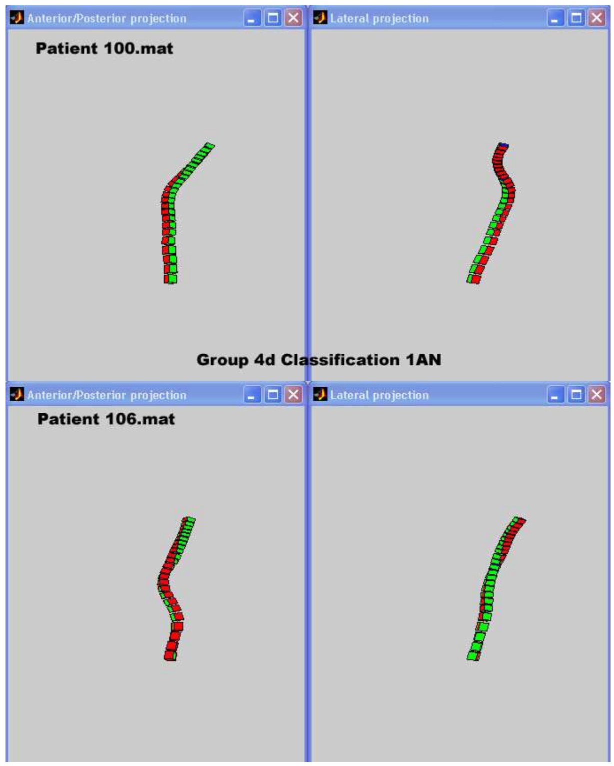


Figure 4.3: Comparison of 'furthest' spines within classification 1AN for Group 4d.

From Figure 4.3, it is quite clear that although the classifications are the same, the overall appearance of the spines is quite different. This leads one to believe that the "Lenke Light" classification scheme may not be the best method for diagnosing spinal deformities, or that one or both of these patients should have been discarded in the first place. This is due to the fact that the classification indicates treatment necessary for the spine in question.

For a spine to be diagnosed as classification 1AN, it must first have a major structural curve in the Main Thoracic region. This implies that the apex of the largest curve is located between the $6^{th}$ and $12^{th}$ thoracic vertebra. Type 1 curves consist of minor non-structural curves in the remaining spinal regions. This indicates that the Cobb angle measurements for the Proximal Thoracic and Thoracolumbar/Lumbar regions are less than 20 degrees in the lateral image. It should be noted that it in patient 106.mat it appears as if there is a notable lumbar curve suggesting that the limits for the Lumbar Modifier classification suggesting it could possibly be a 1BN or 1CN classification.

### Spatial Organization of Classification Groups

With the help of the metric, it should be possible to organize the Lenke classification groups spatially in a manner consistent with the metric diameters and separations. This proved difficult as no apparent pattern could be discerned from the metric data as shown. For example, in Figure 4.2 it is shown that the diameters of 1A-, 1AN, 5A- and 5AN are all close to 2. However, the overall diameter of the population shown in Figure 4.2 is of the same order. This suggests that the classification groups "spatially" surround each other in layers similar to a baseball. This is not consistent with the idea that each classification group could be represented by a convex ball.

# Chapter 5

# Areas for Improvement and Conclusions

## 5.1 Defining a Curve

After simulating the "Lenke Light" classification on 10,000 generated patients, and observing the separations and diameters provided by the software, it has become apparent that there are areas that should be improved regarding further development of the Scoliosis Learning tool. The first notable area for improvement is that the Scoliosis Learning Tool, when determining the "Lenke Light" criteria, assumed that any curve in the spine regardless of Cobb angle, was considered a curve segment. It is suggested by Lenke *et al* that only curves with a Cobb angle greater than $10°$ should be considered a curve segment in the diagnosis.

A second possible area for improvement involves the the definition of the apex of a curve. In the Lenke *et al* study, it was suggested that the apex of a curve be the most laterally deviated vertebra or disc from a Center Sacral Vertebral Line (CSVL). The CSVL was defined as a line that bisected the sacrum and was perpendicular to the true horizontal. For this application the apex was defined as the most laterally deviated disc or vertebra from a line that connected the uppermost and lowermost vertebra in the curve segment in question. It can be understood that in mathematical terms, the apex of a curve is the location of the maxima or minima of that curve. If the curve did not begin and end on the CSVL, and the measurement was to be made with respect to the CSVL, the actual apex of the curve may not exist at the same location as the 'apex' according to Lenke *et al*. This could be problematic due to the fact that minor spatial differences between the location of the mathematical apex and the Lenke et al 'apex' could cause the software to define the location of a curve segment differently than Lenke.

## 5.2 Lumbar Modifier

The Lumbar Modifier classification is another area that may have produced problematic results in the "Lenke Light" classification scheme. First of all, the aforementioned limiting values used to determine the Lumbar Modifier may have been too large. These values were gathered by measurements made on a spinal model and scaled such that they applied to a spine of length one. By comparing the statistical data provided earlier in the report, it is safe to assume that an increase in these limiting values may result in more reasonable results.

The second area for improvement regarding the Lumbar Modifier classification is associated with lumbar balance. The belief is that in order to achieve spinal balance, the vertebrae should be evenly distributed about the Center Sacral Vertebral Line (CSVL). The "Lenke Light" classification scheme determined the Lumbar Modifier with respect to the true vertical. This, in fact, does not account for pelvic obliquity which would alter the direction of the CSVL. Though the program allowed for changes in the initial orientation of the L5 vertebra, it did not suggest these changes may be caused by a pelvic tilt.

## 5.3 The Mathematical Metric

The metric used to determine the diameter and separation between classification groups was calculated by emphasizing different regions in the spine in hope of finding similarities/differences in groups with the same patient generation criteria. The weighing factor implemented, as mentioned above, utilized a vector of all 1's for groups with no emphasis. When attempting to emphasize regions of the spine, the respective values of the weighting vector were changed from values of 1 to 2. It may be suggested that a more effective way of accomplishing this emphasis would be to zero out corresponding regions of the spine not in question while leaving the region of emphasis as values of one. For example, for a metric with emphasis on the Lumbar region, rather than implementing a weighting vector [2 2 2 2 2 1 1 1 1 1 1 1 1 1 1 1 1], a weighting vector [1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0] should be employed. This would allow for a definite emphasis of the region in question rather than a slight modification by doubling values involved with that region.

## 5.4 Conclusions

It is important to understand that mischaracterization of scoliotic deformities in many cases leads to mistreatment. By attempting to understand the problematic areas associated with current diagnostic techniques, it is possible to make progress towards more successful treatment. Scoliosis is a very complicated deformity that has many gray areas and questions surrounding the methods for treatment and correction. With the advantages of three dimensional visualization and mathematical software programs, it is possible to further understand the characteristics of this complicated deformity.

The objective of this study was to characterize the geometry of the Lenke Classification Scheme. By attempting to quantify these scoliotic deformities mathematically, it was determined that the statistical data matched quite well, while the mathematical metric proved to be a step in the right direction regarding geometric quantification.

The initial expectations of this study were to be able to spatially describe these classification groups. Unfortunately, the classification groups overlapped such that it was nearly impossible to visualize the outcome. The results of this study are not as discouraging as it may seem. The Scoliosis Learning Tool, though in need of a few minor software corrections, proved as a successful means of generating large populations of patients with spinal deformities. The software was also successful in determining the "Lenke Light" classification scheme, and this is encouraging due to the fact that this software package can be integrated into software systems in hospitals allowing surgeons to generate the Lenke Classification without the requirement of timely measurements.

Another area of success associated with the Scoliosis Learning Tool, is that it allows for the creation, manipulation, and understanding of spinal deformities in the third dimension. This can be very helpful in training the surgeons of tomorrow, allowing them to gain a better understanding of three-dimensional visualization as well as torsional effects on three-dimensional curves. The Scoliosis Learning Tool provides a solid foundation towards furthering the understanding of scoliotic deformities.

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# Appendix A

# Matrices of Metric Data

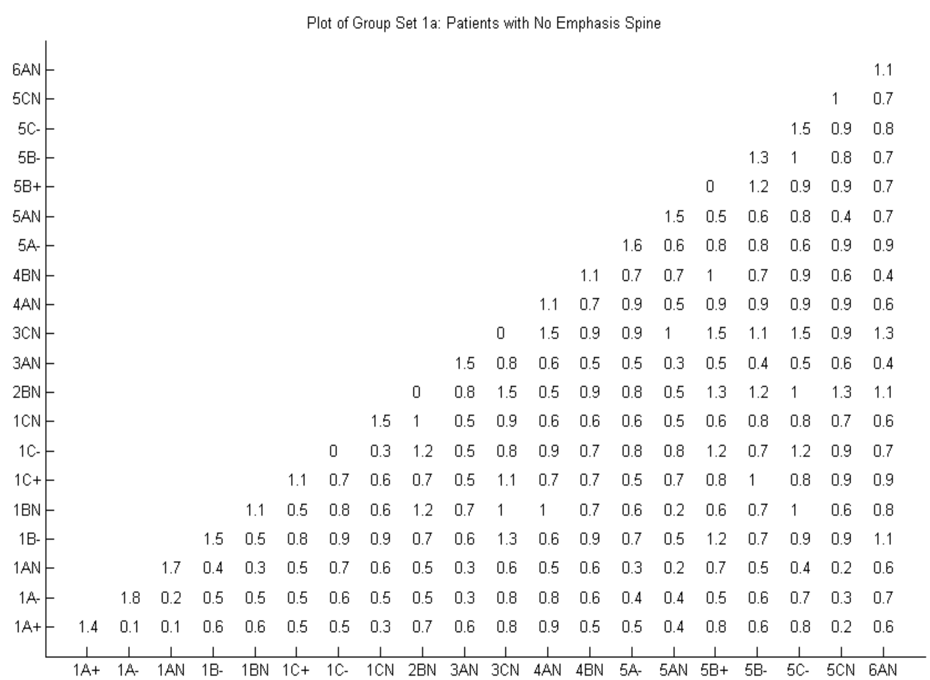


Figure A.1: Matrix of population diameter and separation information for group set 1a of 625 patients with no metric emphasis.

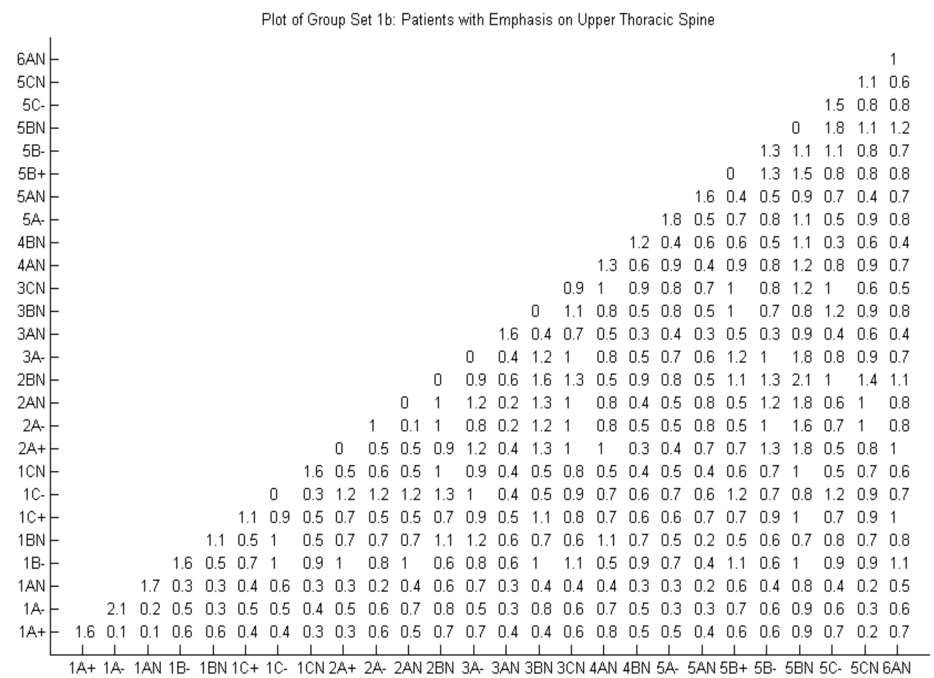


Figure A.2: Matrix of population diameter and separation information for group set 1b of 625 patients with metric emphasis on upper thoracic spine.

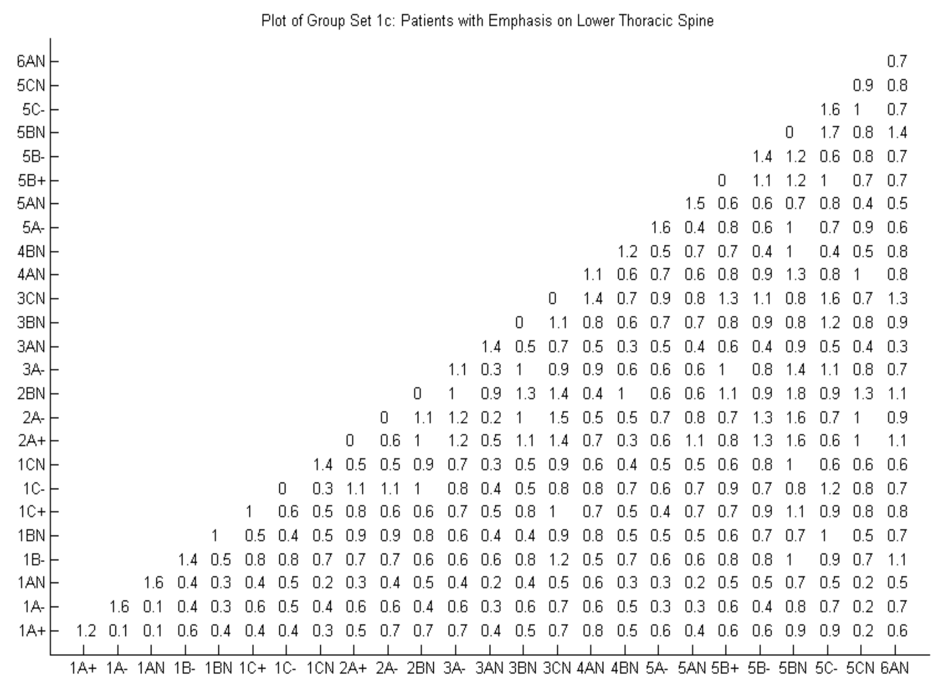


Figure A.3: Matrix of population diameter and separation information for group set 1c of 625 patients with metric emphasis on lower thoracic spine.

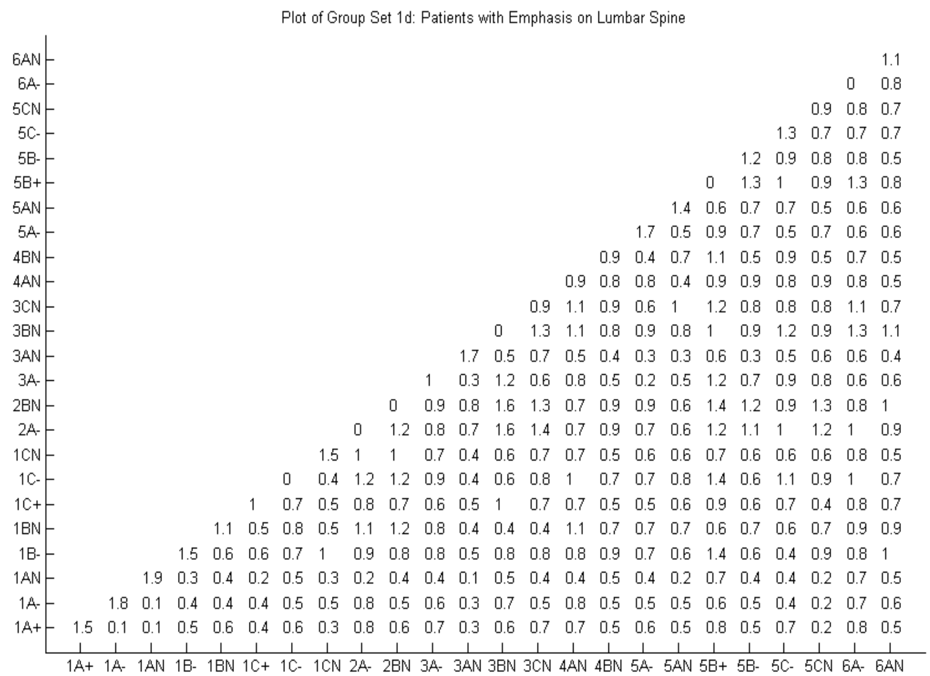


Figure A.4: Matrix of population diameter and separation information for group set 1d of 625 patients with metric emphasis on lumbar spine.

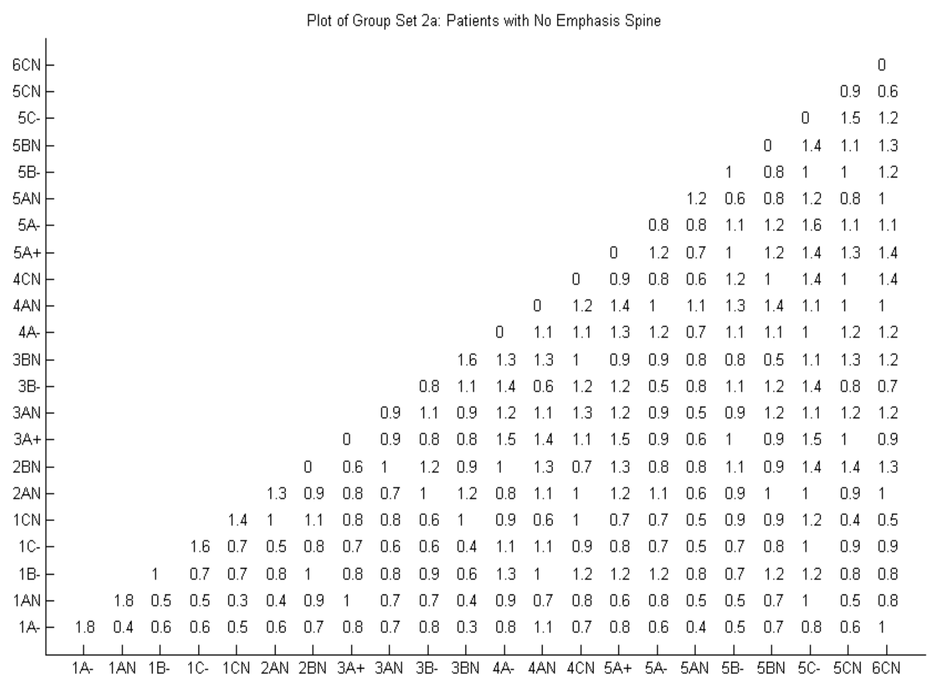


Figure A.5: Matrix of population diameter and separation information for group set 2a of 625 patients with no metric emphasis.

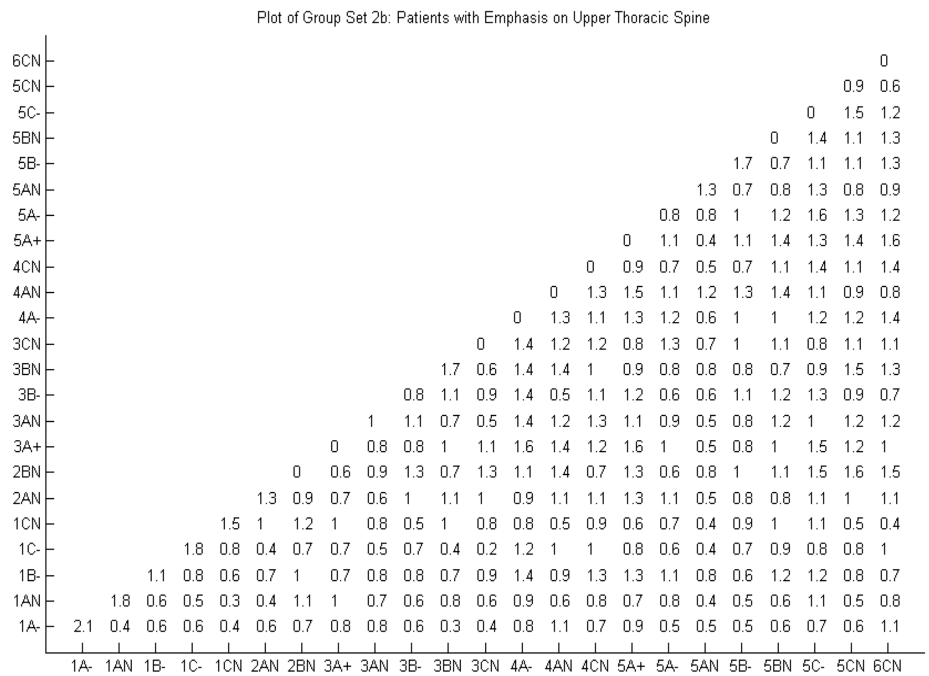


Figure A.6: Matrix of population diameter and separation information for group set 2b of 625 patients with metric emphasis on upper thoracic spine.

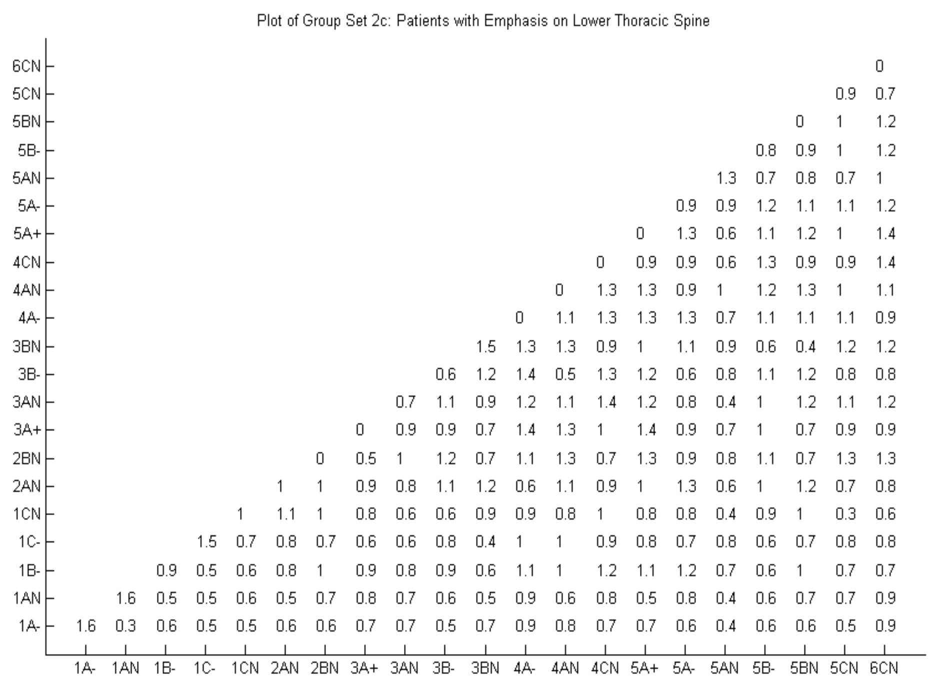


Figure A.7: Matrix of population diameter and separation information for group set 2c of 625 patients with metric emphasis on lower thoracic spine.

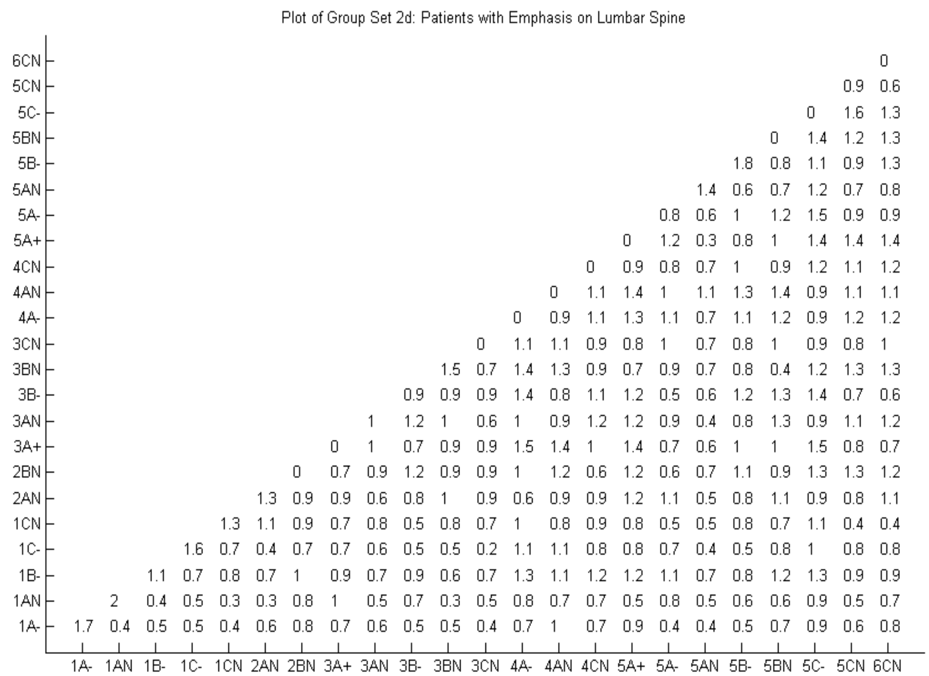


Figure A.8: Matrix of population diameter and separation information for group set 2d of 625 patients with metric emphasis on lumbar spine.

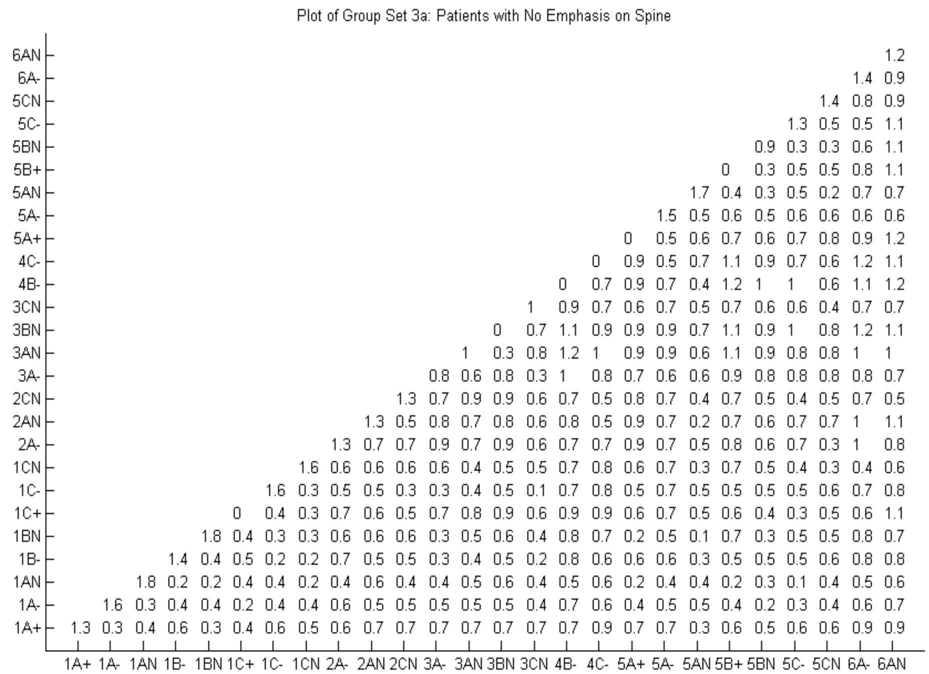


Figure A.9: Matrix of population diameter and separation information for group set 3a of 625 patients with no metric emphasis.

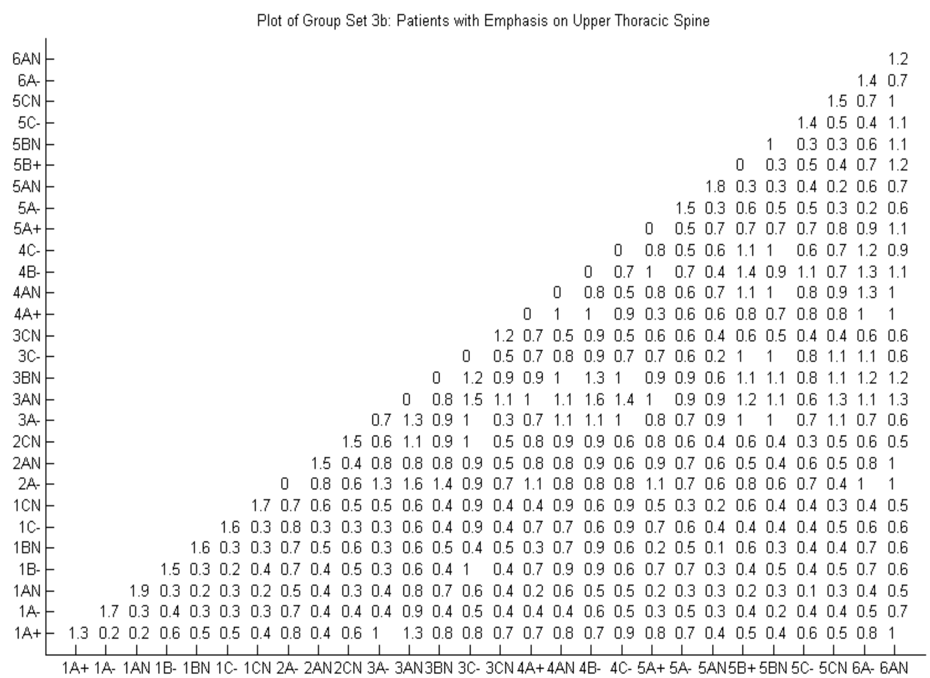


Figure A.10: Matrix of population diameter and separation information for group set 3b of 625 patients with metric emphasis on upper thoracic spine.

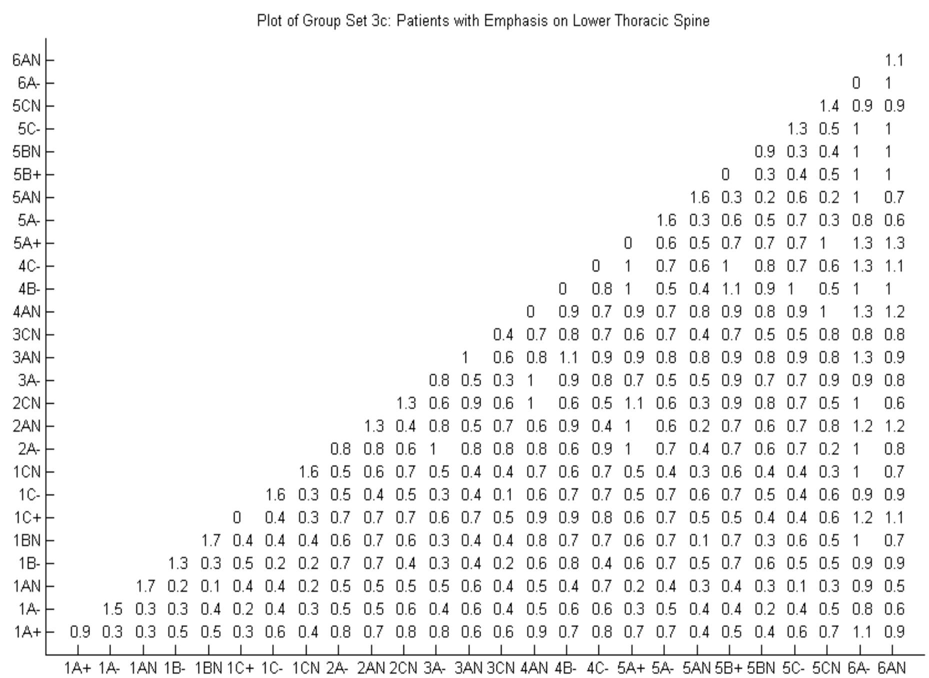


Figure A.11: Matrix of population diameter and separation information for group set 3c of 625 patients with metric emphasis on lower thoracic spine.

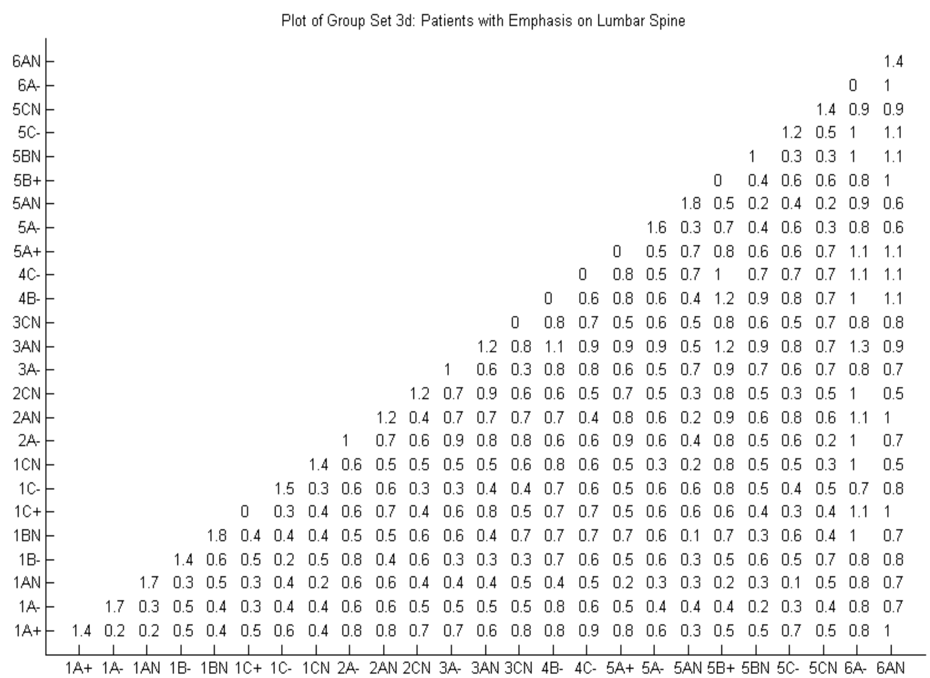


Figure A.12: Matrix of population diameter and separation information for group set 3d of 625 patients with metric emphasis on lumbar spine.

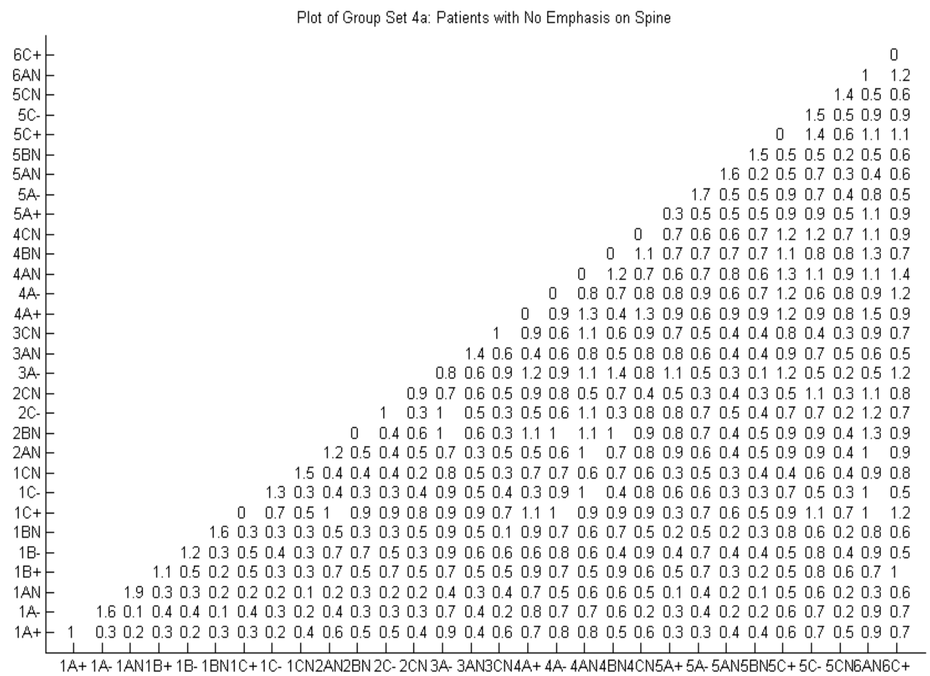


Figure A.13: Matrix of population diameter and separation information for group set 4a of 625 patients with no metric emphasis.

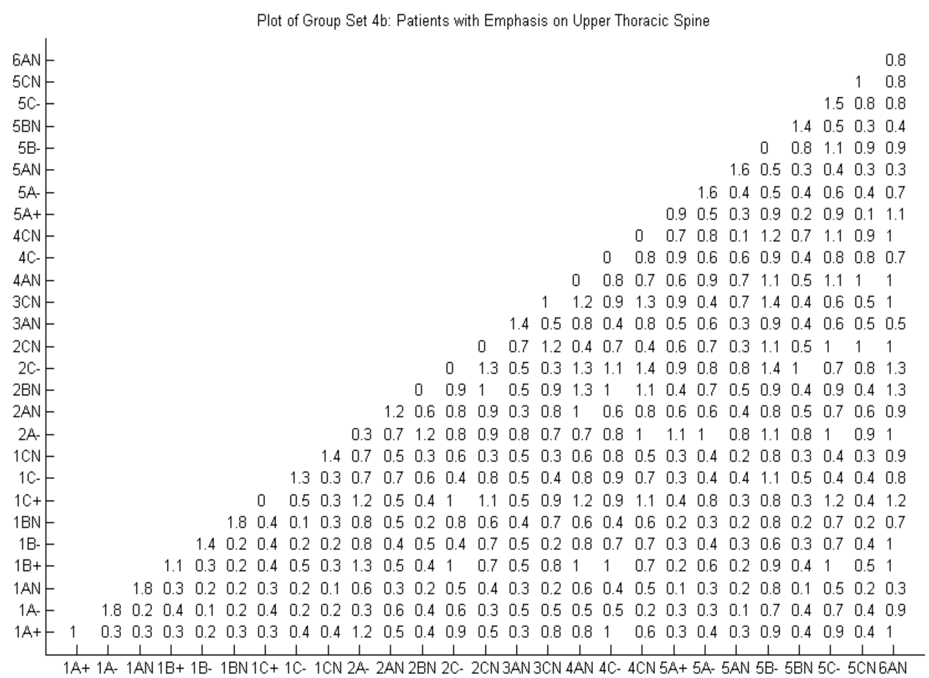


Figure A.14: Matrix of population diameter and separation information for group set 4b of 625 patients with metric emphasis on upper thoracic spine.

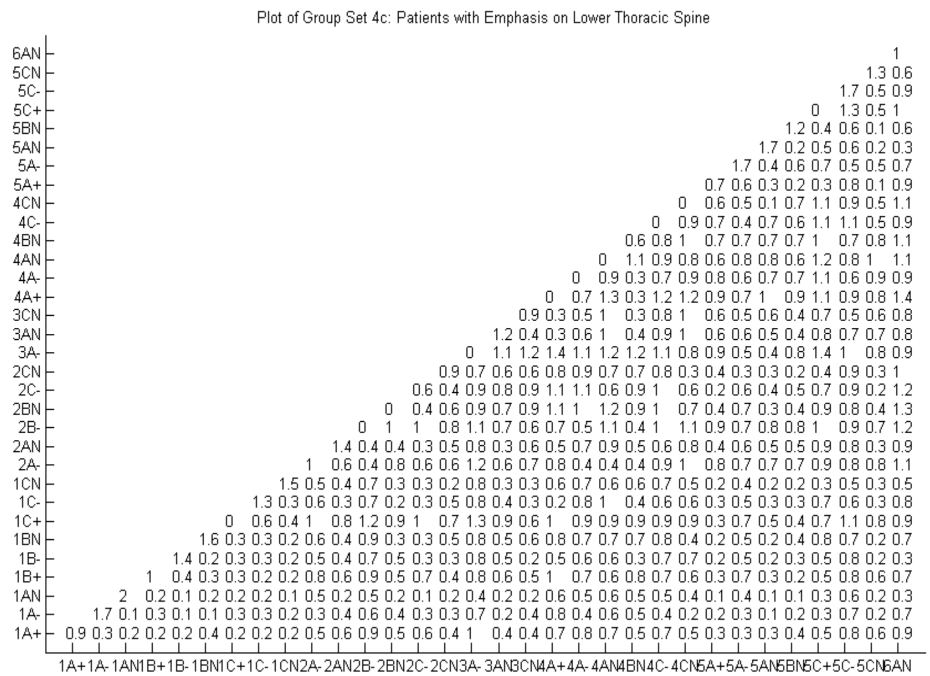


Figure A.15: Matrix of population diameter and separation information for group set 4c of 625 patients with metric emphasis on lower thoracic spine.

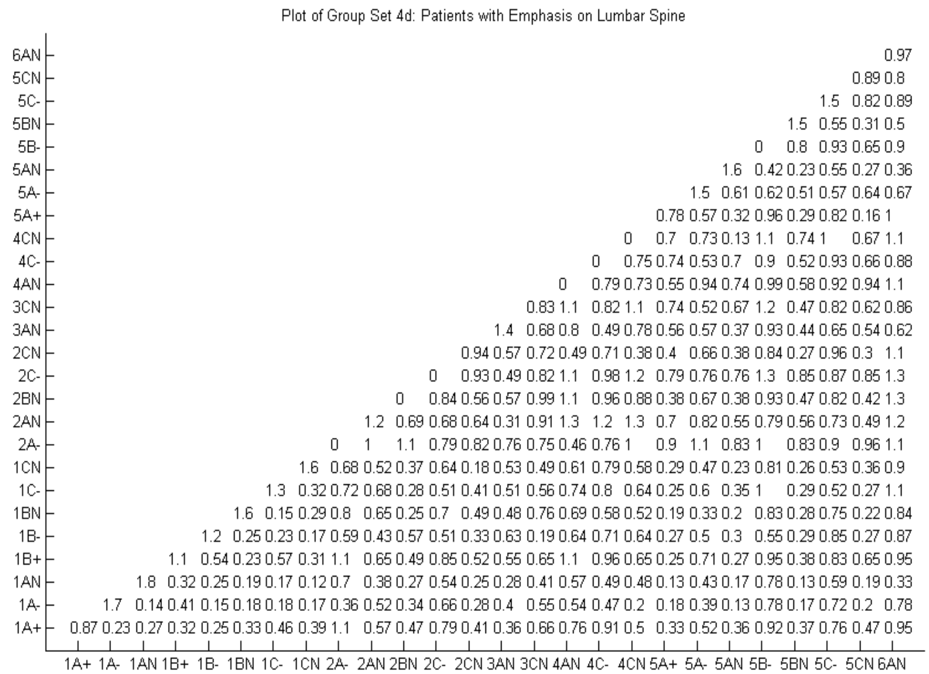


Figure A.16: Matrix of population diameter and separation information for group set 4d of 625 patients with metric emphasis on lumbar spine.

# Appendix B

# Comparison of Extremal Spines within Classification Groups

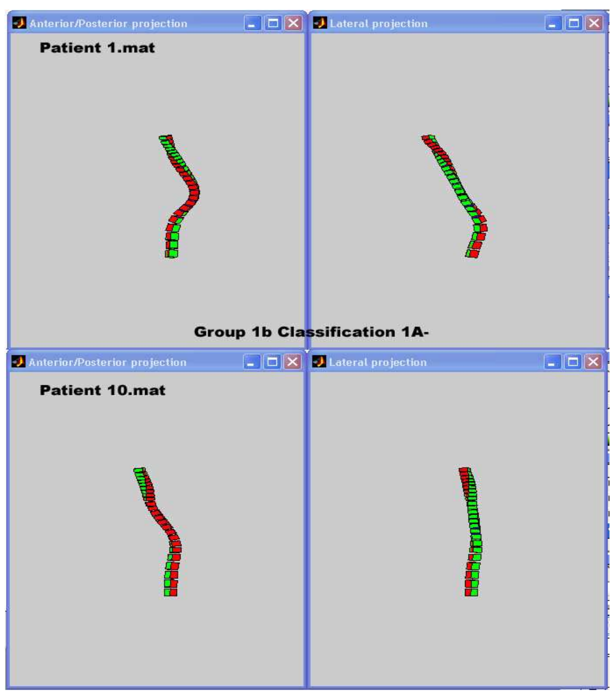


Figure B.1: Comparison of 'furthest' spines within classification 1A- for Group 1b.

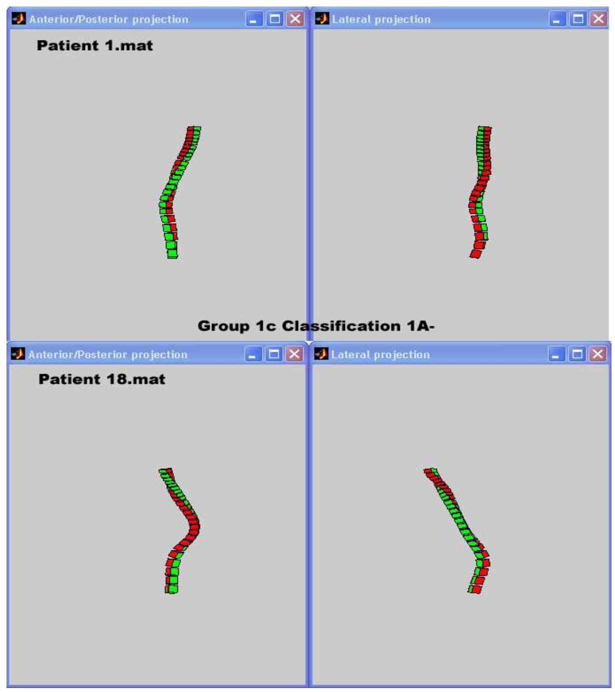


Figure B.2: Comparison of 'furthest' spines within classification 1A- for Group 1c.

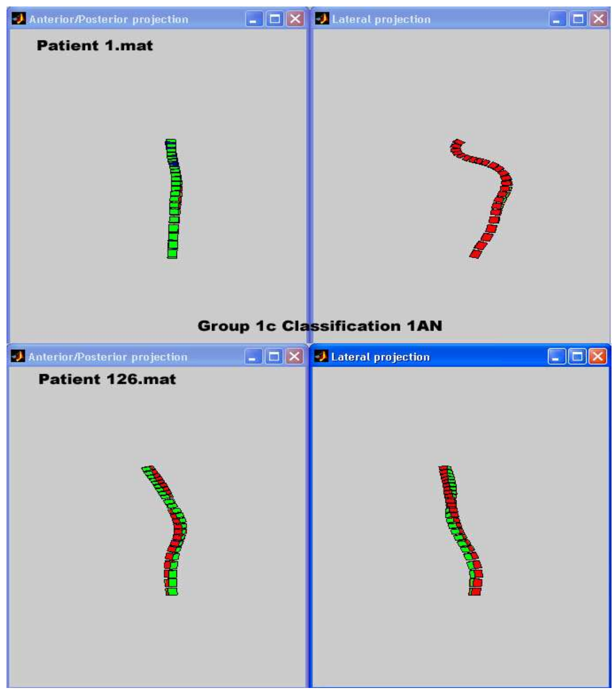


Figure B.3: Comparison of 'furthest' spines within classification 1AN for Group 1c.

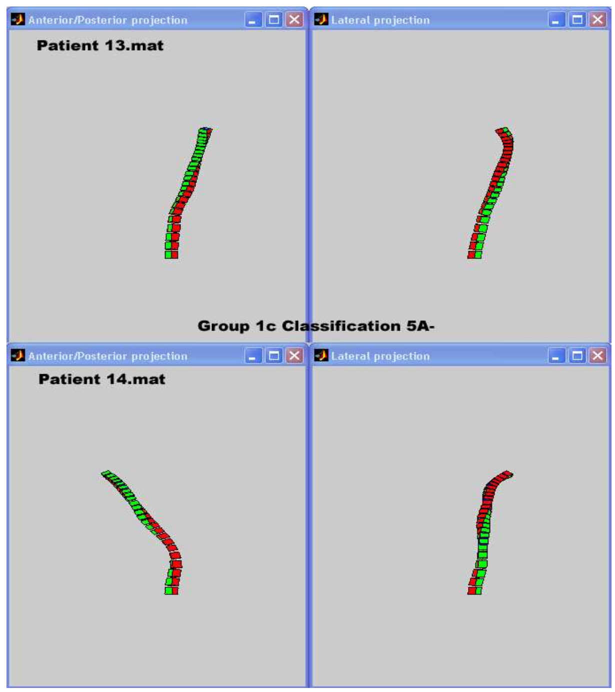


Figure B.4: Comparison of 'furthest' spines within classification 5A- for Group 1c.

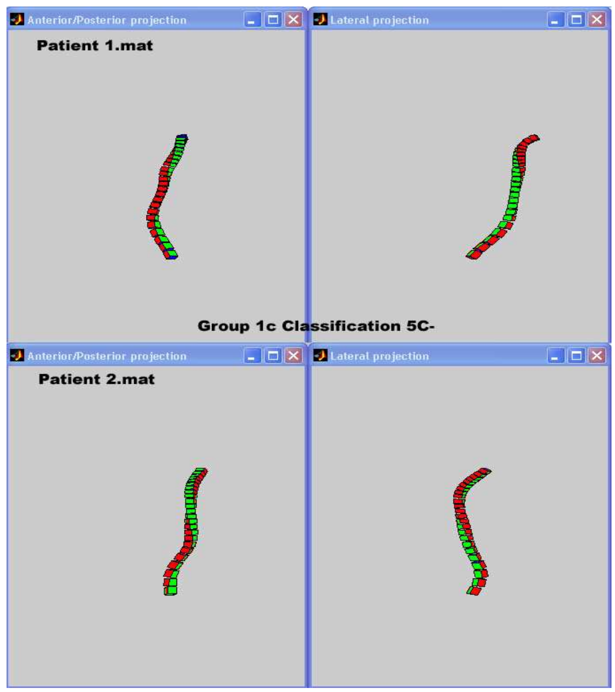


Figure B.5: Comparison of 'furthest' spines within classification 5C- for Group 1c.

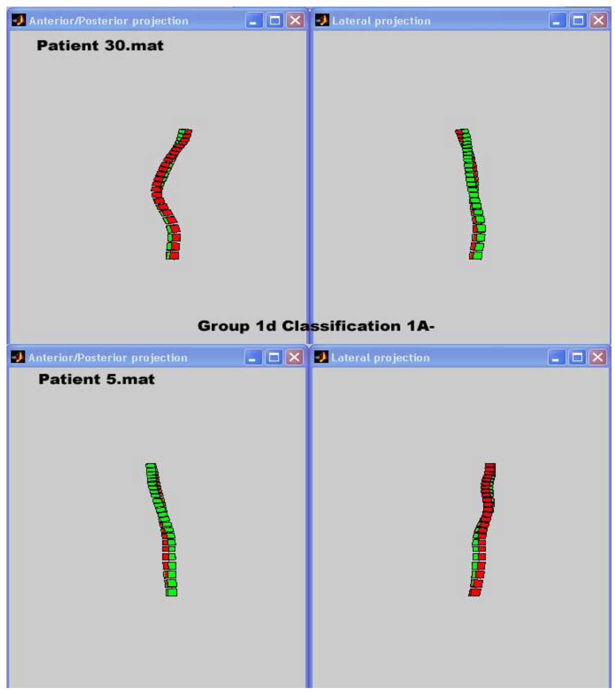


Figure B.6: Comparison of 'furthest' spines within classification 1A- for Group 1d.

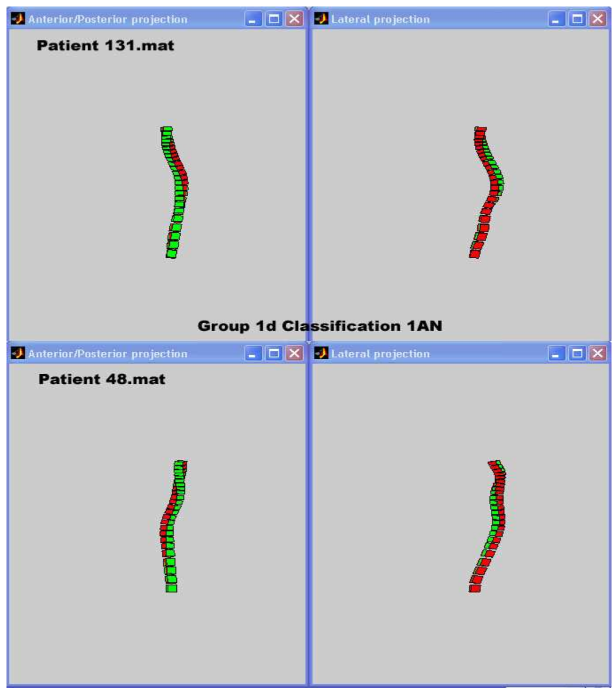


Figure B.7: Comparison of 'furthest' spines within classification 1AN for Group 1d.

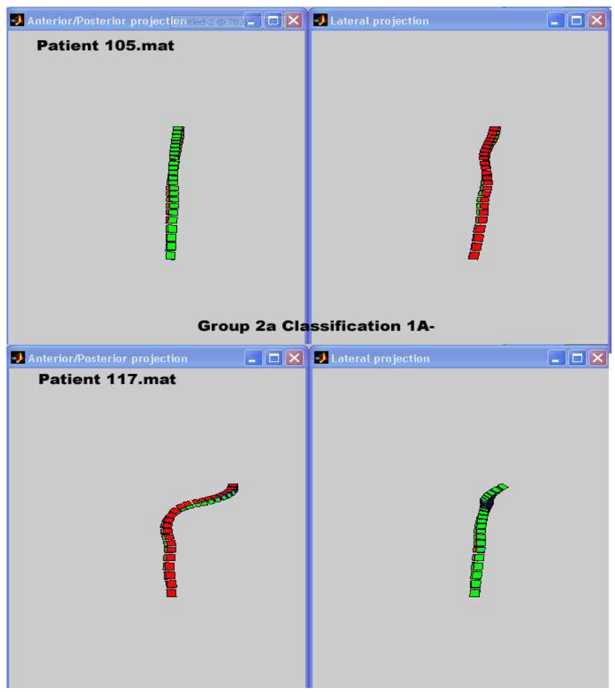


Figure B.8: Comparison of 'furthest' spines within classification 1A- for Group 2a.

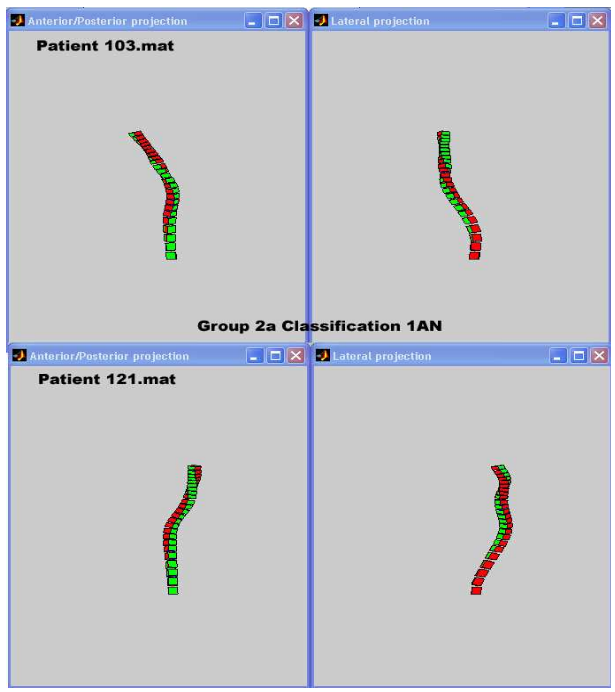


Figure B.9: Comparison of 'furthest' spines within classification 1AN for Group 2a.

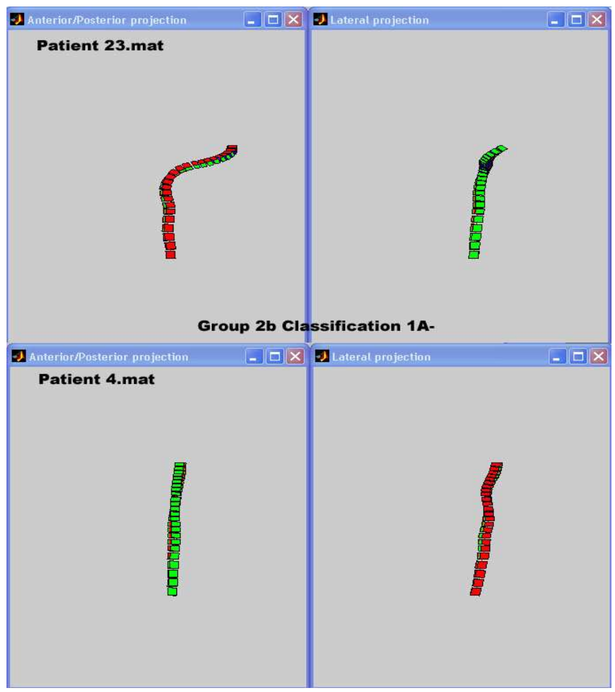


Figure B.10: Comparison of 'furthest' spines within classification 1A- for Group 2b.

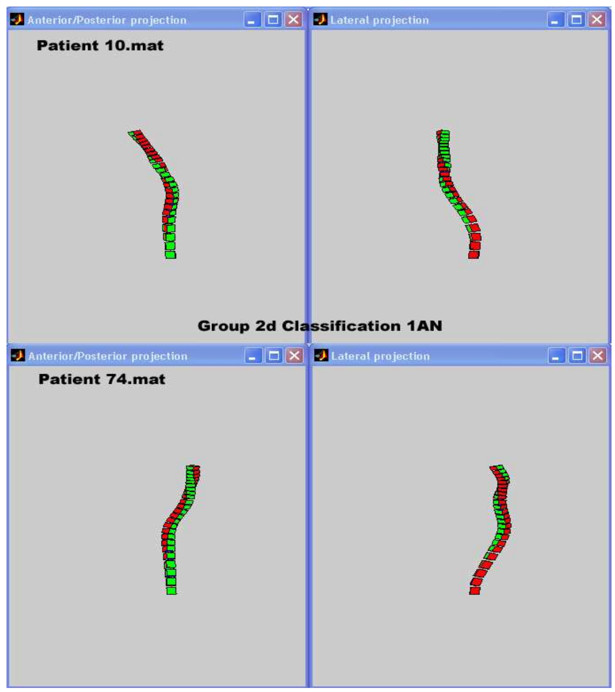


Figure B.11: Comparison of ‘furthest’ spines within classification 1AN for Group 2d.

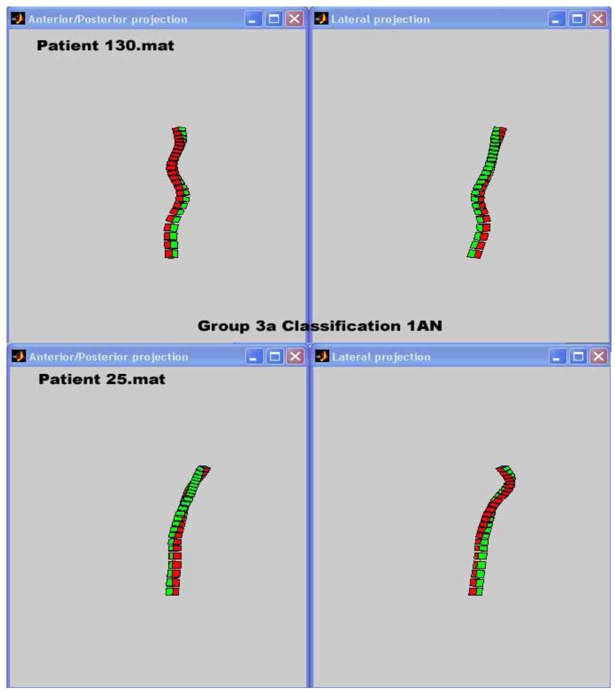


Figure B.12: Comparison of 'furthest' spines within classification 1AN for Group 3a.

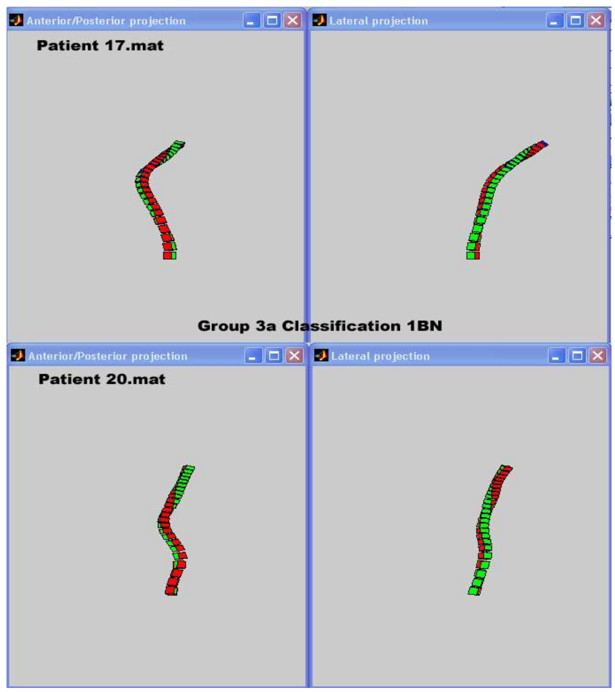


Figure B.13: Comparison of 'furthest' spines within classification 1BN for Group 3a.

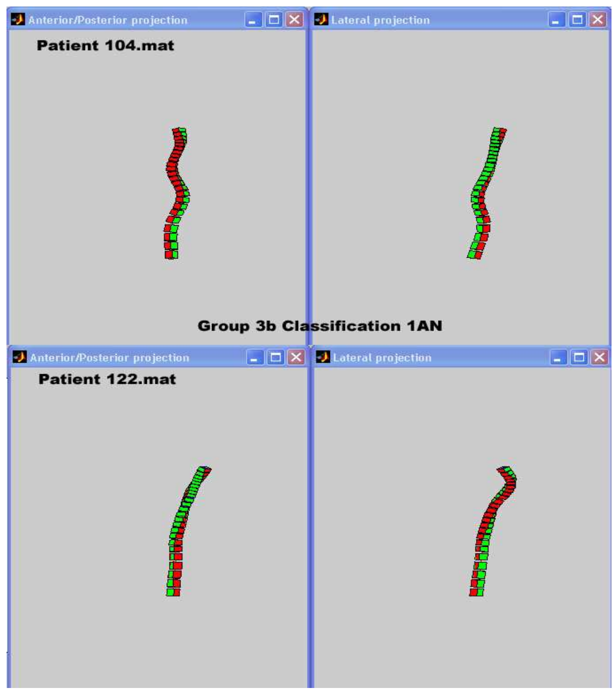


Figure B.14: Comparison of 'furthest' spines within classification 1AN for Group 3b.

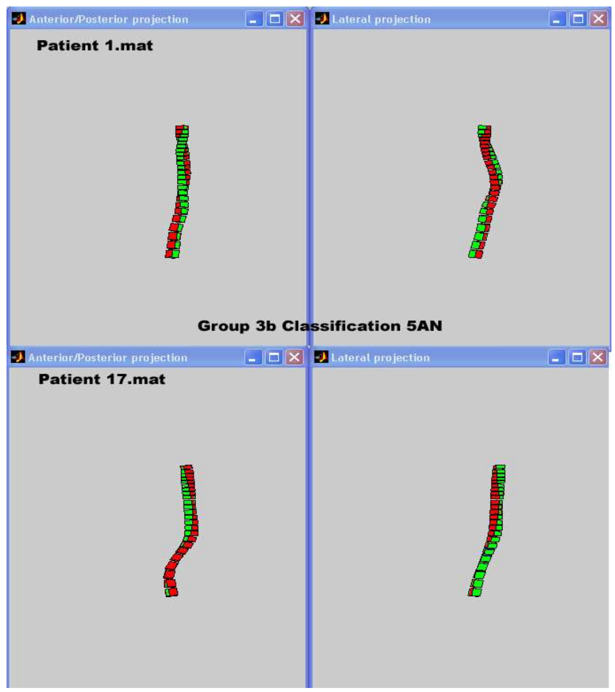


Figure B.15: Comparison of 'furthest' spines within classification 5AN for Group 3b.

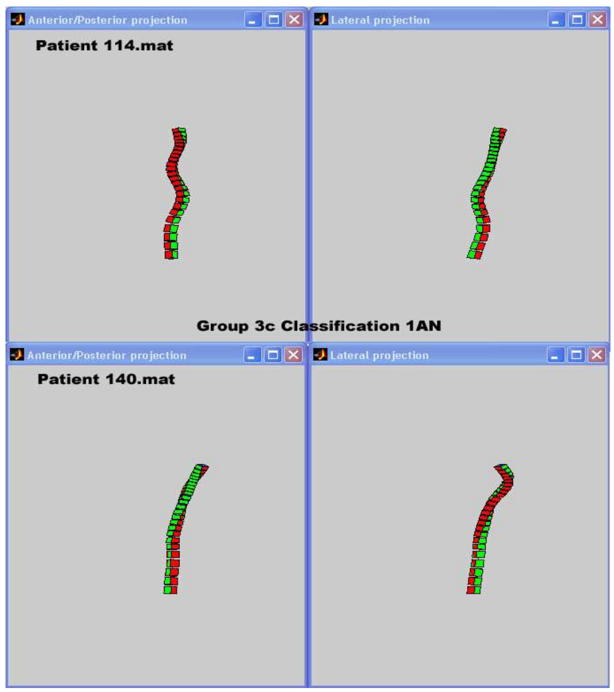


Figure B.16: Comparison of 'furthest' spines within classification 1AN for Group 3c.

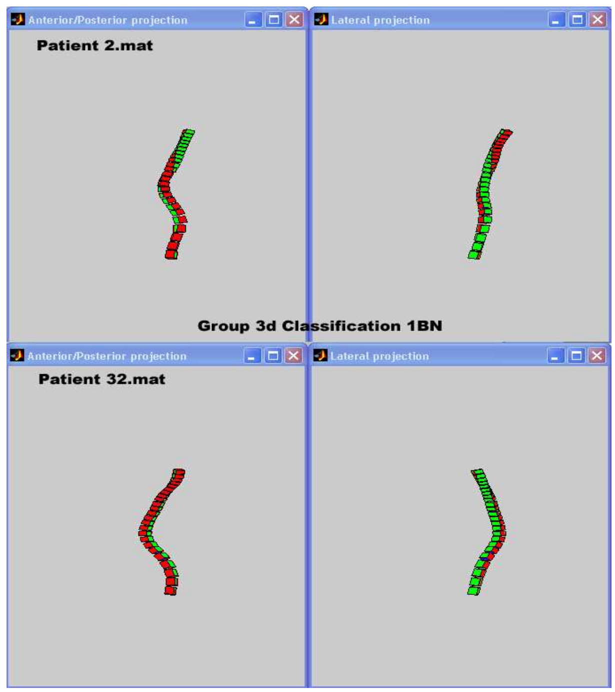


Figure B.17: Comparison of 'furthest' spines within classification 1BN for Group 3d.

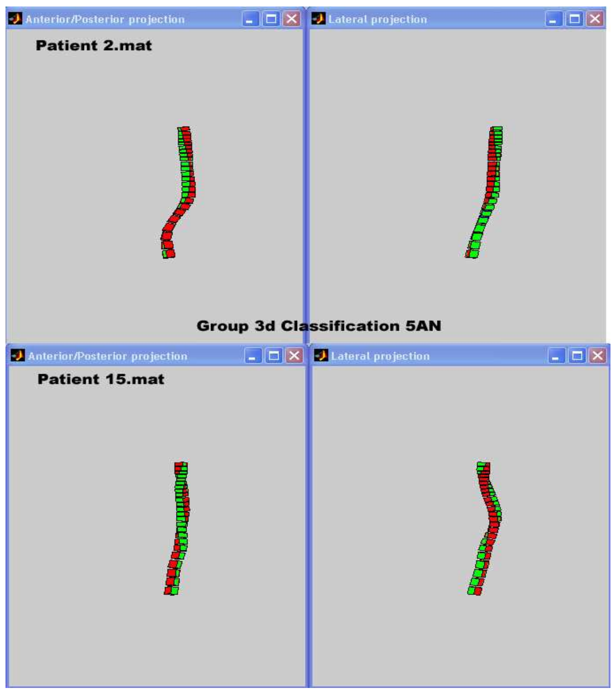


Figure B.18: Comparison of 'furthest' spines within classification 5AN for Group 3d.

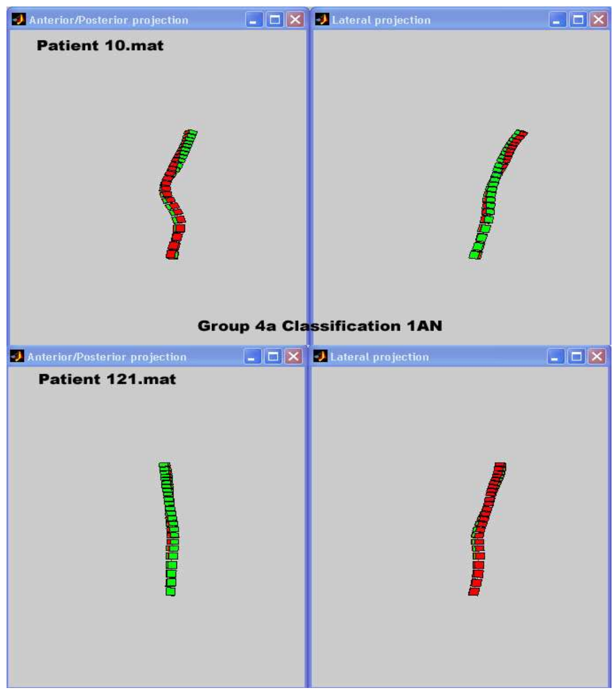


Figure B.19: Comparison of 'furthest' spines within classification 1AN for Group 4a.

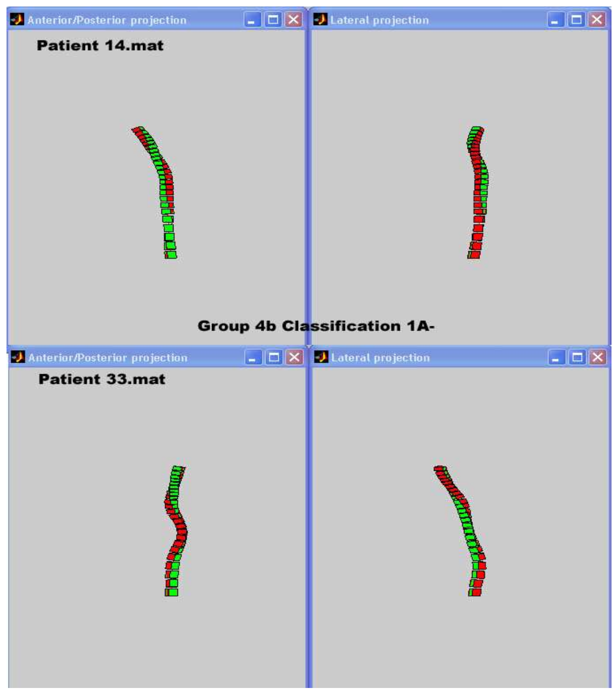


Figure B.20: Comparison of 'furthest' spines within classification 1A- for Group 4b.

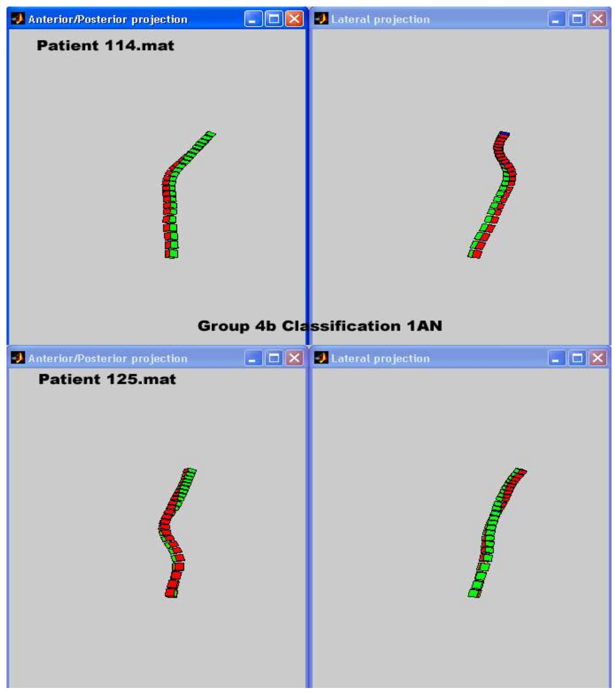


Figure B.21: Comparison of 'furthest' spines within classification 1AN for Group 4b.

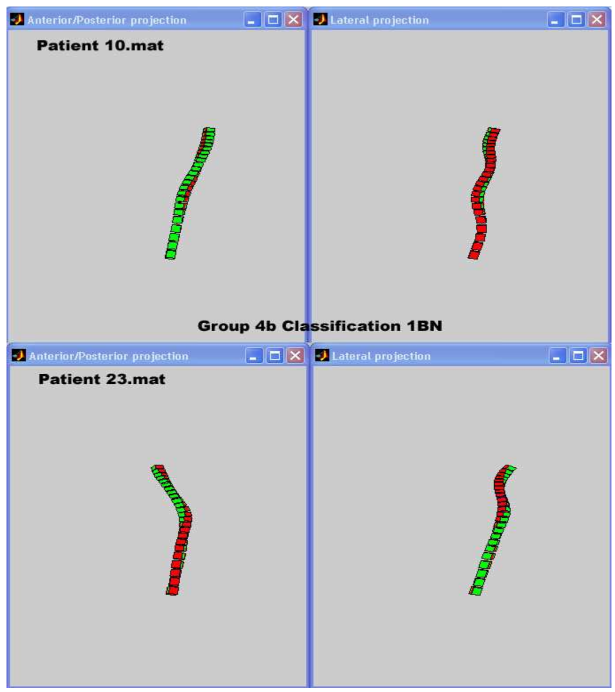


Figure B.22: Comparison of 'furthest' spines within classification 1BN for Group 4b.

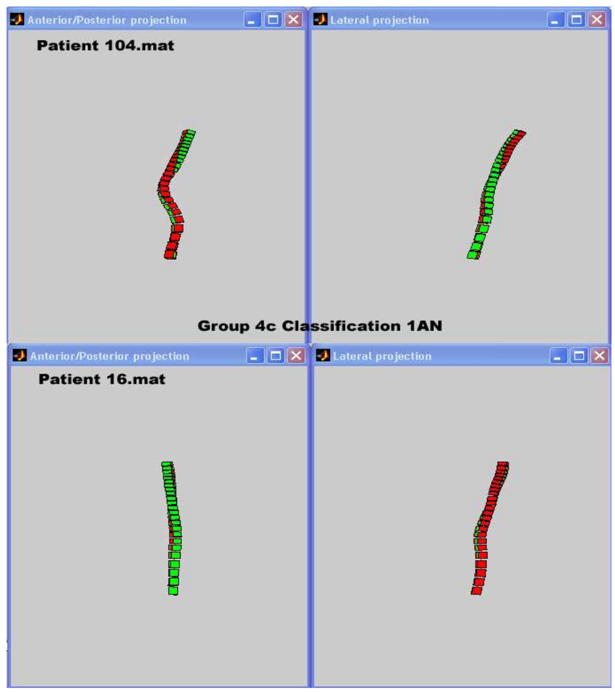


Figure B.23: Comparison of 'furthest' spines within classification 1AN for Group 4c.

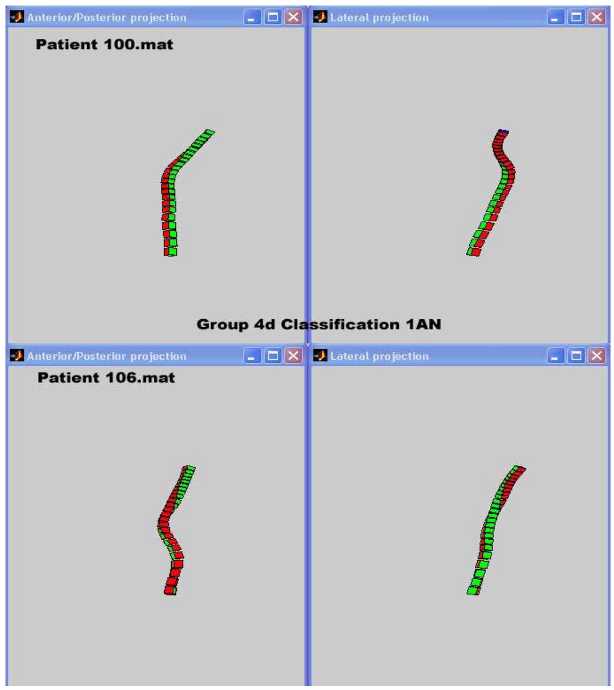


Figure B.24: Comparison of 'furthest' spines within classification 1AN for Group 4d.

## Vita

Dean A. Entrekin

Dean Allen Entrekin was born the first of two sons of Jo Anne S. and Gary F. Entrekin on December 25, 1979 in Downingtown Pennsylvania. He attended Downingtown Senior High school where he graduated in June of 1998 among the top 15% of his class. He attended Virginia Polytechnic Institute and State University where he founded the Virginia Tech Club Baseball Organization. In December of 2002, he received his B.S. in Mechanical Engineering. The following spring he attended the Virginia Tech/Wake Forest University School of Biomedical Engineering Sciences. This thesis will complete his M.S. in Biomedical Engineering. Following graduation, Dean will head back to Southeastern Pennsylvania where he will pursue a career in the field of Biomedical Engineering product development.