A biomechanical study of the scoliotic thoracolumbar spine

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Abstract. Scoliosis is a disease of the spine which leads to corkscrew curvature occurring due to a combination of genetic and environmental factors. The abnormal curve is generally observed during the growth spurt just before puberty. Scoliosis has been classified into three different forms namely idiopathic, congenital and neuromuscular. When no specific cause for spinal defect is identified, the deformity is called idiopathic scoliosis. The patient specific scan model falls in the category congenital scoliosis. Mild cases of scoliosis can be treated by physiological treatments. Severe cases of scoliosis may have vertebral twisting, vertebral fusion and semi developed vertebral deformation. Severe cases of scoliosis could lead to adjacent organ damage, especially the heart and lungs. Large number of patients experience various back problems rendering day to day activities and normal physiological motion difficult. In most of the cases, scoliosis needs multiple surgical corrections with various implant rods and screws attached to the vertebrae. The purpose of this study is to investigate the effect of upper body load on the scoliosis affected region located at the junction of thoracic and lumbar region of the spine before surgery. The CT scan of the model is segmented and meshed to conduct studies such as stress concentration analysis, strain analysis and deflection in the segments.

1. Introduction
The human spine or the vertebral column is a component of the axial skeleton. It provides support and strength and permits the human body to lean, bend stretch and rotate. The human spine is vulnerable to many injuries and diseases like scoliosis, whiplash and low back pain [1]. The vertebral column is divided into four curved regions namely cervical curve, thoracic curve, lumbar curve, and the sacral curve. The cervical region comprises of seven vertebrae, the thoracic curve comprises of twelve vertebrae and the Lumbar curve consists of five vertebrae. The sacral curve comprises of sacrum and coccygeal vertebrae. The intervertebral discs separate two vertebrae. Spinal canal is housed by the vertebral column. Spinal canal protects and encloses the spinal cord. Spine can be damaged and lead too many problems, in that scoliosis was one of the most complex problem and it is treatable.

Scoliosis is a deformity of the spine, complex in nature due to vertebral rotation and deviation of the coronal plane from the median which forms the lateral curvature [2]. In addition to this kyphosis and physiological lordosis on the sagittal plane may increase or decrease [3]. While scoliosis can be...
caused by conditions such as cerebral palsy and muscular dystrophy, the cause of most cases of scoliosis is unknown [4, 5]. The patient affected by severe case of scoliosis is not only physiologically affected but has far reaching effects such as the psychology of the patient and his family because of negative emotions, depression and psychological trauma experienced [6]. Evolution of instrumentation over the past 4 decades has made surgical management of the scoliotic spine possible. [7] Scoliosis needs surgical correction with implant rods and screws attached to the vertebrae [8]. Severe cases of scoliosis could lead to adjacent organ damage, especially the heart and lungs, apart from back problems rendering day to day activities difficult. Surgical treatment is difficult and is prone to high risks and postoperative complications. Therefore, the comprehensive analysis from the coronal, axial and sagittal planes of intraoperative orthopaedics is a must [9].

In the proposed study the three-dimensional model of the Computed Tomography scan of the patient with congenital scoliosis was segmented. The model was further used for analysis using Finite Element Analysis. Finite elemental models help understand the underlying mechanisms of dysfunction and injury which leads to better diagnosis, prevention and improved treatment of the clinical problems of the spine. Finite Elemental models are categorised into two types namely static study models and dynamic study models. The results of the patient specific research study provided for future studies and research.

2. Materials and methods
The de-identified DICOM files from a CT scan of a 17-year-old female patient with severe congenital scoliosis were obtained after IRB approval. As part of pre-surgical evaluation, Full length MRI of the spine, CT scans along with the full-length lateral and positive radiographs of the spine of the patient were obtained. Computed tomography scan was obtained from SIMS hospital Chennai. The thoracic and lumbar region of the patient’s spine in the scan showed deviation in comparison to a healthy spine scan, which indicated the affected region.

2.1. Three dimensional FEA model construction
The CT scan images were saved in standard digital imaging and communications in medicine (DICOM) format. Computed Tomography images imported: The CT images and the data about the vertebral column of the chosen patient was imported to MIMICS 14. The distance between each of the 361 slices (slice interval) of the CT scan images was 0.5 mm. In order to ensure no errors were in the top, bottom, front and back positions of the images appropriate value of bone tissue grey was selected, and a range of 0-3000 after submission of the images to the Mimics image processing software (figure 1, 2). Each vertebra was cropped and segmented.

![Sagittal view of the scan.](image1)

![Anterior view of the scan.](image2)

The models of vertebrae from T1 to T12 in the thoracic region and L1 to L5 of the lumbar region was generated and their STL files were generated to import it into Geomagics Design X64 software of
3D systems. The imported files were refined using the command subdivide and smooth so that the rough edges and rough surfaces are smoothened to create a surface model as shown in Figure 3-5. 3D model was developed and meshed in ANSYS 19.0. Finite element model of the ligamentous thoracolumbar spine comprised of vertebrae, intervertebral discs and posterior elements along with the following ligaments: supra-spinous (SSL), ligamentum flavum (LF), interspinous (ISL), transverse (TL), anterior longitudinal (ALL), posterior longitudinal (PLL), and capsular (CL) as shown in Figure 6. It was assumed that the material properties were homogeneous and isotropic, and the data was obtained from previously published literature [10-12] and shown in Table 1. In order to simulate the ligaments, two-node link elements along with resistance tension only. The elements were then arranged in anatomical direction. 20-node solid element used for the modelling of the cortical bone, disc and cancellous bone. The disc nucleus comprises of gel like substance whereas the disc anulus consists of fibres embedded in the ground substance. The region of facet joint was considered as a problem of nonlinear three-dimensional contact by using surface to surface contact element. The coefficient of friction was set to 0.1.

2.2. Boundary and Loading Condition
In the thoracolumbar spinal model all the inferior surfaces of the bottom most vertebra L5 were fixed completely. The thoracolumbar spine was subjected to various loads at various levels. 50N weight as the load of the head at T1, 350N weight of the upper extreme on T6 and 450N at T8 were applied on the superior surfaces of the mentioned vertebrae (Figure 7).

| Table 1. Material properties of the FEM of thoracolumbar spine [10-12]. |
|-----------------------------|-----------------|-----------------|-----------------|
| Components                  | Young’s modulus (MPa) | Poisson’s ratio | Cross-sectional area (mm²) | Element |
| Cortical bone               | 1200             | 0.26            | -               | Solid 185 |
| Cancellous bone             | 100              | 0.2             | -               |          |
| Posterior elements          | 3500             | 0.25            | -               |          |
| Disc                        |                  |                 |                 |          |
| Nucleus                     | 1                | 0.499           | -               |          |
| Ground substance            | 4.2              | 0.45            | -               |          |
| Fiber                       | 450              | 0.3             | 0.76            | Link 10  |
| Ligament                    |                  |                 |                 |          |
| ALL                         | 20               |                 | 63.7            |          |
| PLL                         | 20               |                 | 20              |          |
| TL                          | 58.7             |                 | 3.6             |          |
| LF                          | 19.5             |                 | 40              | Link 10  |
| ISL                         | 11.6             |                 | 40              |          |
| SSL                         | 15               |                 | 30              |          |
| CL                          | 32.9             |                 | 60              |          |
3. Results and discussion

The three-dimensional patient specific finite element model of scoliosis affected vertebrae was developed from T1 to L5 and analysed for stress distribution, displacement in vertebrae and disc. Special attention was given to the scoliotic region during analysis to understand the severity and the root cause of the problem. In this study, the meshed model was subjected to only static load and the deformation and stress concentration on the model was investigated. Compared to other vertebrae, T8 – T10 segments showed maximum stress concentration due to its shape deviation from the normal spine axis. The von mises stress and deformation plot is shown in figure 8 and 9 after analysis.
After applying the uniformly distributed load on the vertebrae, results showed unpredictable variation in the displacement and stress pattern in the individual vertebrae and disc. Due to non-uniform deformity in the spine curvature the displacement was high in T7 and L4 vertebrae. While, comparing the disc displacement D5 and D8 shown more displacement compare to other discs. The T7 vertebrae and D8 disc displacement were high because that segment is the starting stage of the scoliotic region. Further, L4 vertebrae and D5 disc also showed higher displacement may be due to non-uniform deformity of spine curvature. The displacement plot for vertebrae and discs are shown in figure 10, 11.

**Figure 8.** Lateral view of analysed model.

**Figure 9.** Anterior view of analysed model.

**Figure 10.** Displacement in vertebrae from T1 – L5.

**Figure 11.** Displacement in discs from D1 – D13.

**Figure 12.** Stress distribution in vertebrae from T1–L5.

**Figure 13.** Stress distribution in discs from D1–D13.
Similarly, the stress distribution was more in the scoliotic region and in the lower level lumbar segment. Von mises stress values at T9 and T10 vertebrae along with the adjacent lower level vertebrae showed high values. This proves that the scoliotic region experiences high stress values. There is sudden raise in the value of von mises stress value for the disc lying in between D8 and D10. Especially, since D9 showed very high stress value compared to other discs. However, the Disc D11 adjacent to scoliotic region disc does not experience the same level of stress value. But, last two disc again showed the stress raiser. This proves that the stress concentration is maximum at the end of the thoracic and lumber region in the scoliotic condition. The stress distribution for Vertebrae and discs are shown in figure 12 & 13.

4. Conclusion
The spine with congenital scoliosis was modelled and analysed. FE analysis on the pre-surgery model help understand the stress concentration and displacement patterns. The study revealed high stress concentration on the vertebra and the disc comprised in the scoliotic region. The extracted model was subject specific and the spine curvature was more complex, ergo difficult to segment the normal and defected vertebrae from the CT scan. During the past two decades, many research works have focussed on post-surgery condition. Author felt that, this study may pave pathways for future studies in this field of pre-surgery condition.

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