Evaluation of the influences of various force magnitudes and configurations on scoliotic curve correction using finite element analysis

Abstract:

Background: Scoliosis is a lateral curvature associated with rotational deformity in the normally straight vertical line of the vertebral column, and the curvature may be moderate to severe. Treatment is based on curvature severity and the age of the subject. A common treatment for this condition is to use an orthosis which may employ a combination of transverse or vertical loads. However, the method by which orthoses control the scoliotic curve to achieve the maximum correction based on force configurations and magnitude.it is not well understood

Method: A single subject with scoliosis participated in this study. The CT-Scan of the subject was used to produce a 3D model of the spine using *MimicsTM*^{TM} software. Finite Element Analysis and deformation of scoliotic curve of the spine under seven different forces and in 3 different conditions was determined by *ABAQUS*^{TM} software.

Result: Theoretical analysis demonstrated that the Cobb angle in scoliosis curve decreased significantly through the application of different forces which achieved different levels of correction.

Conclusion: It can be concluded that current configurations of force application are effective in the reduction of the scoliotic curve. Although only a case study, this model may be useful clinically in subjects with scoliosis to help predict the optimal forces used to achieve maximum correction of scoliosis prior to orthotic treatment. Additionally, it is recommended that this method and the outputs may be directly compared with clinical results.

Key words: Scoliosis; Orthosis; Finite Element Analysis; Computer Modeling.

1. Introduction:

Scoliosis is defined as a lateral curvature of the spine, which is associated with rotational deformity [1-4]. The incidence of scoliosis varies in different countries and may occur as Idiopathic scoliosis, or as a result of other conditions including vertebral bone fracture [1, 4].

Various treatment approaches have been used for this group of subjects which depends on the severity and age of subjects. Different designs of orthoses such as the *Milwaukee*, *Boston brace*, *Rosenberg*, *Miami*, *Cheneau*, *Progressive active short brace* and *Maastricht* orthosis have been used [7-13]. Scoliosis subjects may be required to wear the orthosis for a long period of time to reduce curve severity or progression.

The amount of correction which may be achieved by an orthosis depends upon the location of the curve, the type of curve (single or double) and the duration of orthotic use [13-15]. Correction is achieved through application of individually designed force configurations within the orthosis. Force arrangements vary in orthotic designs and include transverse loads (three point pressure in transverse plane), vertical forces (distraction force applied at the ends of the scoliosis curve) and a combination of the above. Due to the possible side effects of vertical oriented forces, this force pattern is no longer used in current designs of orthoses [16, 17]. There are many studies which evaluate the efficiency of orthoses clinically after a period of use [7, 13, 18-20]. However, there is a paucity of evidence relating to the effect of varying the load configuration compared to scoliosis curve correction.

Although use of Finite Element Modeling (FEM) of the spine in scoliosis has been used for more than 50 years, optimisation of load configuration required to correct the curve has not been studied using a model obtained from patients with specifically assigned model material properties [21]. Based on a review conducted by Wang et al, FEM of the spine in scoliosis may be categorised in three main groups.

These include: understanding the ethology of scoliosis, curve correction based on bracing, curve correction based on surgical approach and improvement of the accuracy of FEM [21].

There are a limited number of studies on the use of FEM on curve correction by the use of orthosis [22-25]. However, in most studies, three dimensional representation of the spine was produced by using X-Ray images, which may contain considerable error. Currently most 3D modeling is produced using CT- and MRI scans of subjects. By using software (such as *Seg3D*™ and *MIMICSTM*™), it is possible to create a 3D model of a segment based on a CT or MRI scan with a high level of accuracy. Moreover, it is possible to assign various material properties, which are calculated automatically by the software. Up until now, there is only one spinal model which was produced based on a CT-Scan of a scoliosis subject. Little and Adam produced a 3D model of a spine based on a CT-Scan to study the effects of ligament and disk stiffness on the flexibility of the spinal curve [26, 27].

This aim of this study is to examine the effect of differing force configuration and magnitude on curve correction on a specific 3D model obtained from a scoliotic subject. The main hypothesis associated with this study is that both magnitude and configuration of applied forces will influence the final correction obtained on a scoliotic curve.

2. Method:

A scoliotic subject with a curve of around 15 degrees was recruited for this study. His age, weight and height were 45 years, 65 kg and 1.74 m, respectively. Appropriate ethical approval was obtained from Isfahan University of Medical Sciences, Ethical Committee. Additionally, the subject was asked to sign consent form before data collection.

2.1. Finite element method and modeling:

The Computed Scan (CT-Scan) images of the spine of the subject were used for 3 dimensional Finite Element modeling. Images can be described as: The 2D parallel planes from the three sagittal, coronal and axial views of the spinal cord with 512×512 pixel in a DICOM format.

Scans were exported to *Mimics*^{TM} software version 10.01 and a 3D model of the spine was obtained. The geometry was subdivided into small 2 dimensional regions (called elements). The spinal model was then exported from *Mimics*^{TM} to *Abaqus*^{TM} software to facilitate change of the elements from triangular to tetrahedral type (from 2 dimensional to 3 dimensional elements). A CT Scan, 3D model of the constructed spine by *Mimics*^{TM} software and the meshed spinal cord in *Abaqus*^{TM} are illustrated (Fig. 1).

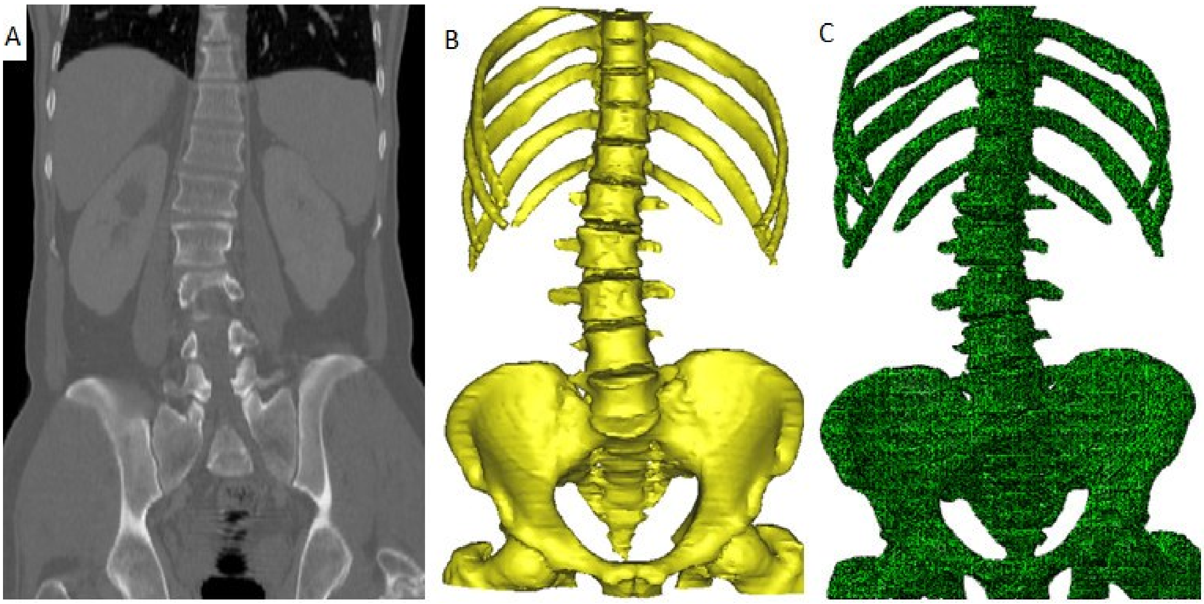

Figure1. A. CT-Scan image, B. 3D model in *Mimics*^{TM}, C. 3D meshed model in *Abaqus*^{TM}

2.2. Materialising:

The Finite Element Method (FEM) requires specified material properties of components. In the next stage the geometry with 3 dimensional elements were imported to *Mimics*^{TM} software to assign the material. The software defines a number of sampling points within each element and interpolates the gray level relating to their coordinate from the original CT scan. Gray level is proportional to apparent bone density. Young Modules (E) was automatically calculated by *Mimics*^{TM} based on the equation developed by Schileo et al. and Morgan et al. (25, 26):

$E=6850\rho^{1.49}$

*In which, E was Young Modules of elasticity and ρ was appearance bone density.

2.3. Boundary conditions and forces:

In this study to decrease the severity of the curve the combination of transverse loads (three points pressure in the transverse plane) and vertical forces (distraction forces applied at each end of the scoliosis curve) were used. Three different conditions were assumed. In the first condition, only one rib is considered to transfer the force, therefore the force was exerted exactly to one rib. In the second approach (condition 2), the applied force was completely transferred to the vertebrae. Finally in the third (condition 3), two ribs were considered to transfer the force. In all cases, the femur on both sides was selected as a fixed constraint (Fig 2).

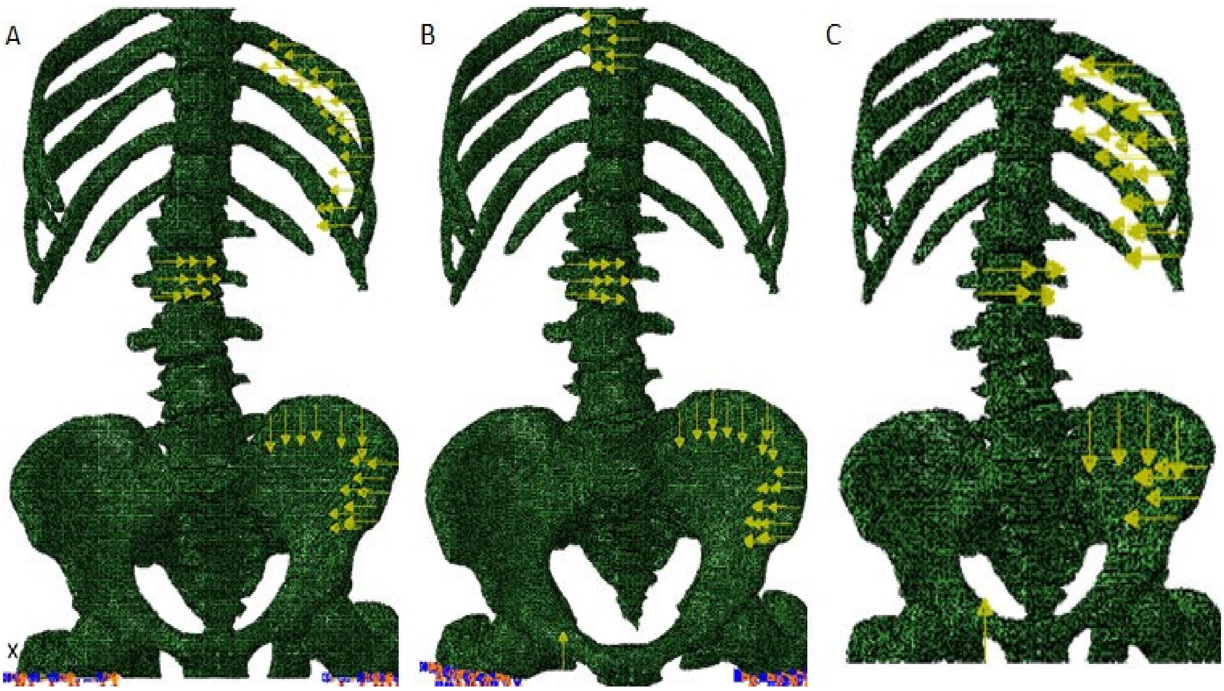

Figure2. Three different conditions used in study: A. Condition 1; B. Condition 2; C. Condition 3.

In each condition different forces from 10 to 70N were applied to demonstrate changes in scoliosis curve. (fig.3)

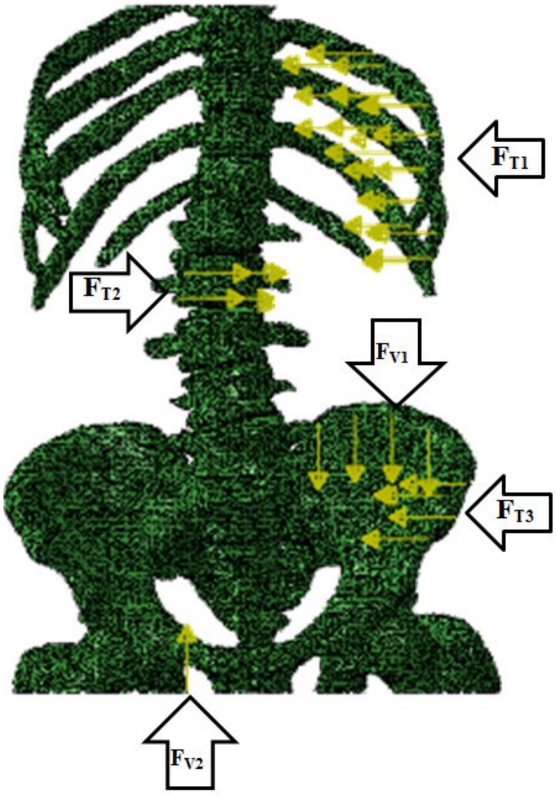

Figure 3. The illustration of the applied force and exact position of exerted forces $F_{T1}=F_{T3}=F_{v1}=F_{v2}$, $F_{T2}=2F_{T1}$

Angles of the scoliosis curve (Cobb angle) were then measured using *Digimizer*™ Software. The Cobb angle is the angle between the lines drawn parallel to the upper and lower endplates of vertebras located at the upper and lower ends of scoliotic curve, respectively. Changes in the angles demonstrate the effects of loads applied by orthoses. The calculation of the Cobb angles in these conditions was conducted by researchers and mean values used for final comparison, (Fig.4).

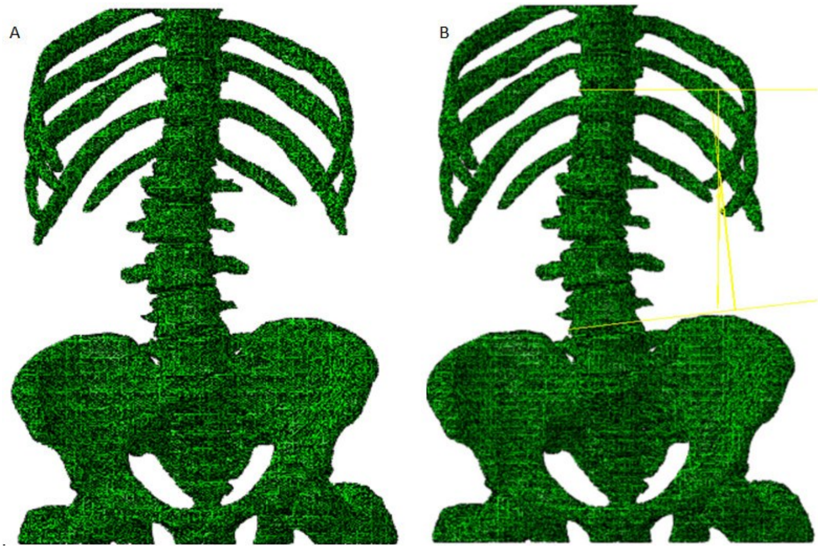

Figure 4. Scoliosis before (A) and after correction (B).

3. Results

The severity of scoliosis of the subject in the normal condition (without applying any transverse or vertical forces) was 15 degrees.

The scoliosis curve decreased to 6.28 degree in condition 1. Curve reduction depended on the magnitude of the applied force (the maximum correction was achieved with force equals to 70N). The correction achieved with configuration 2 varied between 7.93 and 9.69 degrees for 10N and 20N force, respectively. In condition 3 the scoliosis curve decreased from 15 to 7.67 degrees.

Table 1 Final correction of scoliotic curve under 3 conditions and 7 different force configurations.

	Primary	F_1	F_2	F_3	F_4	F_5	F_6	F_7
Condition 1	14.5±1.05	11.591±2.575	11.234±0.954	9.179±3.115	9.418±2.404	8.146±2.283	8.632±3.011	6.285±1.451
Condition 2		7.937±0.51	9.698±2.263	9.559±1.814	9.583±2.122	8.613±3.383	8.054±4.044	8.813±1.461
Condition 3		10.405±2.918	8.754±2.094	9.194±1.783	8.547±2.157	8.078±3.815	8.981±2.772	7.667±0.997

Table1: Final correction of scoliotic curve after applying various forces, F_1=10N, F_2=20N, F_3=30N, F_4=40N, F_5=50N, F_6=60N, F_7=70N

4. Discussion:

A variety of conservative treatment approaches are used for subjects with scoliosis [8-10, 13, 19]. Use of an orthosis is one of the most common conservative treatments recommended for a subject with a curve between 25 degree and 45 degree [28]. The effects of the orthosis in controlling the progression of the scoliotic curve or to decrease it depend on severity of scoliosis, and age of subjects and the type of orthoses used [16, 28]. It is not well understood how orthoses control the scoliotic curve and how to achieve the maximum correction. Most of information regarding the efficiency of orthoses is based on clinical findings. This means that the amount of correction achieved is determined following orthotic use over a long period of time.

This study aimed to determine the effectiveness of different force configuration based on a model from a scoliotic subject. Three conditions of force application were used in this study including transverse load (three point pressure system) and vertical forces directly applied to the spine, through one rib or through two ribs.

Although, this study is a case study and no statistical analysis was conducted, it can be concluded that the configurations of the force applications are effective in reducing the scoliotic curve. It should be emphasised that, although the second configuration also showed a decrease in scoliotic curve it is not possible to load the spine in a scoliotic curve directly. In an orthosis the force is transmitted to the vertebra via soft tissue or the ribs (condition 1 and 3). However, load transfer depends on curve severity, the amount of the applied loads and the force if this can be transmitted through one or two ribs.

Results indicate that it may be possible to determine optimum correction of a scoliotic curve from a 3D model (obtained from CT-Scan of the subject) before orthotic prescription. The accuracy of the output seems to be acceptable as the model is produced from a CT scan of the subject.

This is a preliminary study to determine the effectiveness of various force configurations in scoliosis curve reduction based on *Mimics*^{TM} software. Although a case study, it can be used for a larger number of subjects to determine the efficiency of curve correction prediction before orthotic treatment.

5. Conclusion

The results of this case study demonstrate that the force configuration may be optimised to reduce a scoliotic curve. It is possible to determine the optimum correction of a curve by 3D simulation prior to orthotic prescription and design. It is recommended that this method can be used for a larger number of subjects and the outputs compared with clinical results.

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