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Evaluation of Useful Biomechanical Parameters On Scoliosis Using Finite Element Method

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Abstract

Background: Scoliosis is a deformity of the vertebral column, and shape-changing and deformation of the spine are some critical factors that can cause this abnormality. This condition causes some problems like deflection of the spine in the coronal plane toward medial or lateral. Cobb angle is a measurement for the investigation of the severity of this condition. There are several effective therapies suggested for the reduction of the Cobb angle for patients who has this abnormality. It has suggested that before applying external forces to correct this condition, biomechanical evaluation of this deformity, can be useful during diagnosis.

Methods: The purpose of this study is the evaluation of Cobb angle correction using external forces. For this aim first, the dimensional data of the patient's vertebrae are extracted from CT-scan images using Mimics software, and the vertebral column modeled in Catia software for finite element analysis (FEA). Afterward, the model was imported into Abaqus software to evaluate the effect of forces on the spine model. The study was done by assuming two cases for the spine, one-piece (without a nucleus) and two-piece (with a nucleus) intervertebral disc.

Results: After studying the results of this simulation, it concluded that after applying gravity force to these two cases, the percentage of Cobb angle's reduction was about 0.05 for a two-piece disc and about -0.18 for the one-piece disc. Therefore, the two-piece disc assumption was better for analyzing this parameter. The results of maximum displacement and von misses stress show that the two-piece disc is accurate.

Conclusion: In order to investigate which analysis is appropriate to be selected, choosing a two-piece intervertebral disc model is superlative. Whether our goal is only to examine the stress which is present in the patient model, choosing a one-piece disc is a more optimal duo to take much less time.

Keywords: Scoliosis; Finite element analysis (FEA); Cobb angle; Vertebral column (spine); Intervertebral disc.

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Introduction

Nowadays, due to the different lifestyles and improper use of welfare devices, it is common to develop various kinds of diseases, including the deflection of vertebrae or abrasion of an intervertebral disc. Generally, it believed that probable reasons for this kind of abnormalities are congenital or with the origin of other diseases.[1] Diseases related to deflection of the vertebrae grouped into several categories, including kyphosis, lordosis, and scoliosis.[2] All of these anomalies occur in the anatomical plane of the body.[3]

As shown in Figure 1, scoliosis is one condition in the frontal plane of the body, which intrinsic factors, or musculoskeletal disorders, can cause this condition.[4,5] Cobb's angle characterizes the deflection degree of the vertebrae. Cobb angle is the angle between two vertebras that have maximum deflection compared to the natural anatomic position of vertebrae.[6] In scoliosis, a person's spine curved like S or C shape.[7] At early stages and for children and teenagers who are growing, who are not yet mature and suffer from this condition, the initial treatment plan is to use braces, and the earlier the treatment begins, the full remission is more feasible.[8,9]

However, the deflection of the Cobb's angle in people

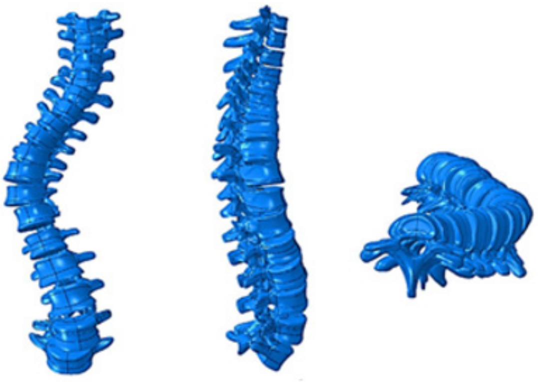

Figure 1. Scoliosis in 3 Anatomical Plane.

suffering from this disease is so high that non-surgical treatment methods are not sufficient, and surgical methods must be used.[10] Today, with the help of biomechanical analysis, it is possible to simulate the patient's spine and apply external loads to predict scoliosis conditions.[11, 12] It worth mentioning the position of the patient before applying forces, how much is the influence of the gravity force and internal forces, such as the forces of the muscle system.[13-17]

In literature reviews that conducted previously, scientists such as Betz et al have been accurately assessed the condition of laying on back, aim to optimize Cobb's angle before surgery.[18] With the use of radiography and instrumentation systems, Kadoury et al. investigated three-dimensional variations in the spine geometry and corrective surgery on scoliosis of teenagers with unknown causes.[19-22]

Vrtovec et al studied providing a full review of existing methods for quantitative measurement about the curvature of the spine, using medical images.[23] Lalonde et al investigated the effect of gravity force on correcting the deformity of the vertebra column in the case of a person who sleeps on his back. In their findings, the force of gravity with the patient's position can contribute significantly to correct the patient's Cobb angle before surgery.[24]

After precise finite element modeling of a patient with scoliosis in the thoracic-lumbar region and estimating the number of modification forces needed, Little and his colleagues found that in addition to the internal forces, the imposition of external forces to reform this condition was essential.[25] Also, in other research,[26] according to CT-scan images, they used the finite element method to model the thoracic-lumbar region of the vertebrae of a patient with scoliosis and investigated the modified vertebrae by orthopedic rods.

In two researches, Salmingo et al, while simulating orthopedic implant rods and patient's vertebrae with scoliosis, they concluded that modification forces during external loading have no direct relationship with the number of orthopedic implant rods' screws, but have direct ratio with the density of screws at a unit of area.[27,28] The geometry of the implant rod investigated before and after the procedure, the angle of the implant's curvature, which known as a Cobb angle, was obtained. The purpose of another research is to present a protocol of applying finite element methods in research about scoliosis, and discussing its current limitations and suggesting aspects for the future.[29]

Abe et al had examined the improvement of material properties in modifying vertebrae' deformity and better effects in scoliosis surgery in recent years. Increasing the mechanical strength of the surgical instruments means that the force of implant is increasing during surgery.[30] In the study of Shahab et al, tomographic images of vertebrae were reconstructed in Mimics software, and the three-dimensional model of the spine using point cloud coordination developed in Matlab software.[31]

Furthermore, Gholampour et al investigated the effect of gravity on movement and angle changes between the cervical vertebrae.[32,33] In the study conducted by Khademi and colleagues, it has found that in finite element analysis (FEA) of healthy vertebrae, choosing the assumption of the two-piece intervertebral disc is more suitable for investigating displacement and change in the angle of vertebrae.[34] many studies and numerical simulations have done on correcting scoliosis with different models of this condition. While the aim of this study is investigating the choice of different assumptions for the patient's intervertebral disc and its direct effect on the degree of Cobb angle correction whenever the gravity force applied in sleeping on the back, there is not particular research about this issue, specifically.

The primary negative feedback from previous researches

Table 1. Mechanical poperties of different investigated regions.

Mechanical Properties	Section Name		
	Vertebrae	**Annulus Section**	**Nucleus Section**
Material	Elastic-isotropic	Elastic-isotropic	Elastic-isotropic
Young modulus (Mpa)	100	4.2	1.5
Poisson ratio	0.29	0.45	0.49
density (ton/mm^3)	$1.21e^{-9}$	$1.061e^{-9}$	$1.342e^{-9}$

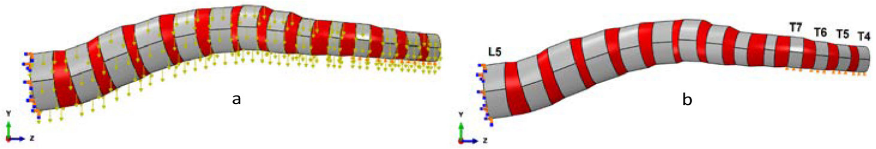

Figure 2. (a) Application of Gravity Force to All Vertebrae, (b) Boundary Condition of Scoliosis Model.

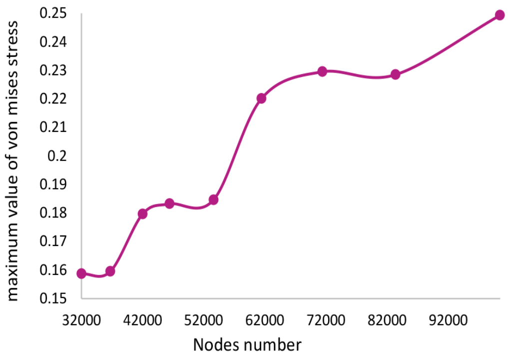

Figure 3. Mesh Independency of Scoliosis Model With One-Piece Disc.

was that there was not any evaluation for the effect of external forces on Cobb's angle correction. Consequently, we decided to investigate the mentioned measurement.

Materials and Methods

The dimensional information of the patient sample received as DICOM format files from an MRI machine, and in order to perform image reconstruction, files imported into Mimics software V10.1.[31, 35] The model of vertebrae from L5 to T4, concerning specifications such as length, width, height, coordination of vertebra's center, angle in the sagittal and coronal plane, and with a structure similar to a cylinder (with an ellipse section), was simulated in Catia software. In order to compare two-piece disc and one-piece disc, the central part of the disc modeled separately. To model, the core part of the disc (Nucleus) concerning the complementary dimensional information,[36] the ratio of length and width of the Nucleus part compare to the Annulus part are calculated, and the nucleus part extracted from the model. Then, the two-piece disc, in which the model has simulated by filling the blank space in the primary model. Moreover, this process has done for all discs. It is necessary to mention that the Cobb angle in this model was between T4 and T11.

Based on Table 1, the mechanical properties of the vertebrae are considered the same for both models.[37] According to Figure 2, the gravity force applied to all vertebras by assuming a one-piece and two-piece intervertebral disc. The purpose of this study is to correct the Cobb angle by investigating the influence of one and two-piece disc' assumptions in the modeling of patient' vertebrae with scoliosis. It has concluded from Figure 2, in order to fix a portion of the spine according to result of another research, displacements and rotations of the lower surface of L5 in three directions X, Y, Z, and the displacements of vertebras from T4 to T7 in Y direction has chosen to fix.[24]

In Abaqus software, to define interactions between surfaces of vertebras that are in contact with each other and internal surfaces of annulus and nucleus part of discs, a tie interaction is defined to preventing movement of vertebrae' surfaces relative to each other and development of error.[38]

Mesh Independency Study

After modeling the scoliosis spine, the model has meshed with multiple elements; then, the FEA was done.[39] biological tissues respond to shear loads more than compressive and tensile forces.[40] Tetrahedral elements do not make the possibility for displacement in vertices of a triangle because of their truss-shaped and triangular geometry and also cannot provide an appropriate response to a shear load. Nevertheless, this issue could solve by using hexahedral elements due to the four corners of this element type. So because of this reason, for vertebrae and discs (both annulus and nucleus), hexahedral elements instead of tetrahedral elements have chosen to be meshed with.[41]

Meshing the vertebrae was conducted ideally with (3D Stress-Linear-Standard) element. Also, eight nodes linear brick element (C3D8R) has used for every two-piece disc (annulus and nucleus section).[42] After finishing meshing and creating nodes, the intended load applied. The number of model' nodes for the one-piece disc is 100471, and the model with the two-piece disc is 175228. This study was done with a dynamic implicit solver, and the total time of solution intended 1 second in Abaqus software.

The independence of meshes investigated to ensure the validity of the numerical simulation. In this study, with altering the size of all model components, the convergence of the numerical value of maximum von misses stress has investigated. To evaluate the independence of mesh

Table 2. Evaluated active parameters.

Models	Parameters				
	Initial Angle Between T4-T11 (Degree)	**Angle After Loading T4-T11**	**Scoliosis Correction Percentage**	**Maximum Von Misses Stress (Mpa)**	**Maximum Displacement (mm)**
One-piece disc	46.387	46.471	-0.181	0.2285	0.4180
Two-piece disc	46.387	46.363	0.0517	0.2609	0.5280

in results that were obtained by Abaqus software, the maximum value of von misses' stress compared between these two models in several different cases with a different number of nodes. As can be seen in Figure 3, the difference between the final and medium size of meshes in model with one-piece and the two-piece disc is 0.21% and 0.087%, respectively. According to these results, convergence condition of results and independence of responses from meshing conditions have provided desirably.

Results

the most critical concern in the treatment of scoliosis disease is the assessment of Cobb's angle. If Cobb's angle reduced, subsequent surgery or other methods, this means that the severity of scoliosis has moderated. Hence in this part, the effect of gravity force due to the vertebrae' weight effective in reducing the Cobb angle is investigated.[43-45]

The next issue is to choose the appropriate assumption for biomechanical simulation of the spine' model. In some studies, intervertebral discs are simulated and analyzed while they considered as one-piece.[25] In some other articles, the annulus section and nucleus part are simulated and analyzed separately.[32] To investigate this issue, all the results of this section compared between one-piece and two-piece intervertebral discs.

In order to find out what is the effect of gravity force due to vertebrae' weight, which is useful in decreasing the Cobb angle and choose the appropriate assumption for modeling of the intervertebral disc, the maximum value of von misses' stress, displacement, and percentage of Cobb angle calculated. Based on the results were illustrated in Table 2, the maximum value of von misses' stress in the scoliosis model with one and the two-piece disc is 0.23 and 0.26 megapascal (MPa), respectively. So the maximum value of von misses' stress in the two-piece disc model is 1.14 times more than stress in the one-piece model. Also, by checking the result of maximum displacement in this analysis, it is found that the maximum displacement in one-piece and two-piece disc models are 0.42 mm and 0.52

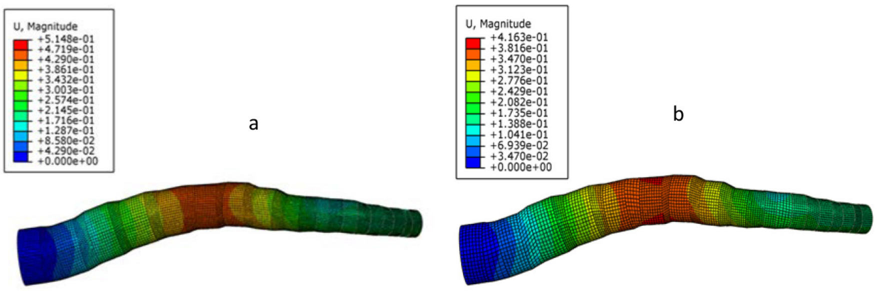

Figure 4. Maximum Displacement of Models After Loading (a) One-Piece Disc (b) Two-Piece Disc.

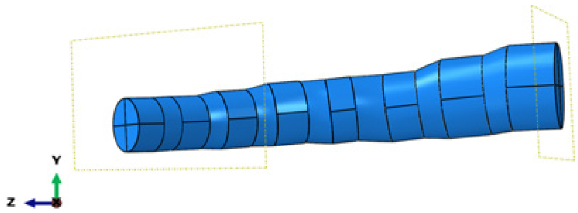

Figure 5. Planes Showing the Initial Cobb Angle Between T4 and T11.

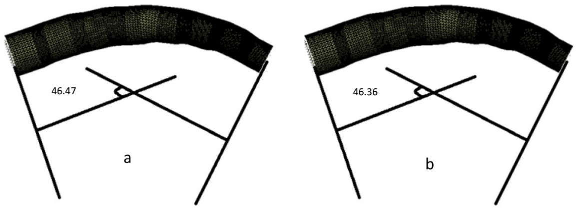

Figure 6. Angle Between T4 and T11 in Scoliosis Model After Loading Gravity in Catia Software-Coronal Plane (a) One-Piece Disc (b) Two-Piece Disc.

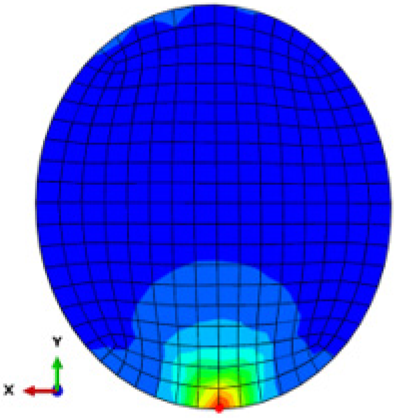

Figure 7. location of Stress Extreme in T7.

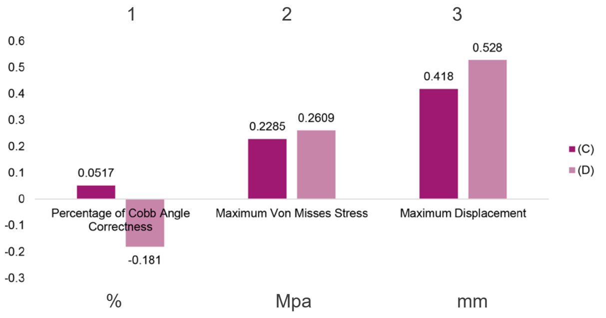

Figure 8. (c) One-Piece Disc Model, (d) Two-Piece Disc Model, (1) Percentage of Cobb Angle Correctness, (2) Maximum Displacement, (3) Maximum Von Misses Stress.

mm, respectively (Figure 4). The maximum displacement in the two-piece disc model is 1.26 times more than the one-piece disc model.

During FEA of models that have considered, after being subjected to load and constraints imposed, the initial model has changed, and all meshes and nodes are displaced. Since our main concern is to calculate the amount of Cobb angle changes in the scoliosis model, after applying the gravity force, Cobb angle measurement is necessary. To investigate the degree of the Cobb angle's adjustment, the final models have transferred to Catia software with 3DXML format, and finally, the angle between the bottom surface of T11 and the upper surface of T4 characterized as new Cobb angle.

As can be seen in Figure 5, the initial angle between T4 and T11 in both models is 46.38 degrees. After the application of gravity force, this angle, in one-piece and the two-piece disc, is about 46.47 and 46.36 degrees, respectively (Figure 6). By subtracting the Cobb angle between T4 and T11 in this model from the angle after application of gravity, the percentage of Cobb angle obtained, which is about -0.18 and 0.05, in a one-piece disc model and two-pieces model, respectively. As the results show, with the same loading and boundary conditions for both models, the percentage of Cobb angle correction in the two-piece disc model is 0.23 % more than the one-piece disc model. According to Figure 7, the occurrence of maximum von misses stress is in T7 because the model of vertebrae T4 to T11 is like an arc and T7 located at the extreme of the arc. So the most tension occurs at this point, which can use in clinical studies for the medical practitioner.

Discussion

Investigating the Correctness of Cobb Angle

It has mentioned before that the primary purpose of this study is to determine the effect of gravity force on the amount of Cobb's angle correctness. In the third section, concerning the results obtained for Cobb angle changes in every two models, the percentage of modification with the same condition, for the two-piece model is 0.11 degrees more than the one-piece model. In Figure 8, as the results of the analysis show that the percentage of correction for a one-piece disc model, contrary to expectation, represents an increase in Cobb angle. In other words, not only is corrective action not taken, but also the patient's condition is getting worse because of the same boundary conditions and loading for both models; this error is due to assuming a one-piece intervertebral disc. For instance, when the specimen studied on the back condition, the gravity force tends to decrease the Cobb angle between the vertebrae. Therefore, the assumption of the two-piece intervertebral disc model is more appropriate for analyzing the Cobb angle modification percentage.

Investigating Displacement

After investigating displacement results in both models, the maximum value of this parameter has happened in the annulus section of the T7 disc in both models, and its value in one-piece and the two-piece disc is 0.42 and 0.52 mm, respectively. According to these results, by adding the nucleus part to the intervertebral disc, the displacement increased about 26.19 %. As shown in Figure 8, displacement's difference obtained between the two models much more compared to corresponding von misses stress' results for the same analysis. Although the analysis of the two-piece disc model takes much more time (about 20 hours) than a one-piece disc model, the modeling of the nucleus section for a two-piece disc model is necessary.

Von Misses Stress Study

According to Table 2, after applying the gravity force and analyzing the model, the maximum amount of von misses' stress in one-piece and two-piece disc model is 0.23 and 0.26 MPa, respectively this means that there is 14% more stress generated in the one-piece disc model in proportion to the two-piece disc model. Now the question is, which assumption is correct? According to the results of another study,[34] as the maximum amount of stress generated in healthy spinal vertebrae is fewer in comparison to the scoliosis sample, choosing a two-piece disc model assumption is more suitable to determine von misses stress in the patient sample.

As shown in Figure 8, the percentage of maximum stress' difference is fewer when compared to the percentage of maximum displacement' differences for each of the two models. Therefore, when the goal is to examine the stress generated in vertebrae during analysis with gravity loading because analyzing a one-piece disc model takes much less time (about 20 hours), this model is more worthwhile.

Conclusion

By comparing between results of stress analysis of patient and healthy samples, which studied in the previous research,[34] and setting our goal to comparing the amount of von misses stress between healthy model and model with scoliosis, in order to investigate which analysis is appropriate to be selected, choosing two-piece intervertebral disc model is more superlative. Whether our goal is only to examine the stress which is present in the patient model, choosing a one-piece disc is a more optimal duo to take much less time.

In such analysis as the present study that the purpose is to investigate the maximum amount of displacement results and the change of Cobb angle, due to significant differences in analysis' results of these two models, although assuming two-piece disc model takes more time to analyze, choosing this hypothesis is more appropriate.

Furthermore, while examining a one-piece disc model, it is obtained that the Cobb angle increased, which means that the assumption of the one-piece disc is entirely wrong. Because in the case of a patient lying on the back, the gravity force and howbeit at a low level reduces the Cobb angle between the vertebrae. Therefore, using the two-piece intervertebral disc model is more appropriate for checking displacements and the percentage of Cobb's angle correctness.

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Conflict of Interest Disclosures

The authors declare no conflict of interest regarding the publication of this paper.

Ethical Statement

The patient provided written informed consent for the publication.

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