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Stress Analysis of the Scoliosis Disorder

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Abstract

Scoliosis is a spine irregular deviation, which known an idiopathic ailment among children and adolescents. Indeed, applying loads on the human spine and the capacity of the vertebral column should be tretated as random variables. The main gola of this study is to compare the maximum stress caused by weight load of a norm
al and scoliosis spinal. To do so, the numerical analyses associated with the inherent random parameters of bones and applied load are performed. Accordingly, the maximum stress for all vertebrae and discs are computed. The maximum stress intensity in the cortical tissue, cancellous tissue and discs was identified. The location of the maximum stresses quantify which vertebrae and discs may get damaged and needed reinforcement and this can provide a model for predicting the location of spinal cord injury.

***Keywords**:* stress analysis, scoliosis, vertebral column, statistical parameters.

1. Introduction

Scoliosis is a common disease that affects many children and adolescents. In a simple definition, scoliosis is a one-sided bending of the spine. When looking at it, the spine is straight and along a straight vertical line, when this flat line is curved, It is called scoliosis or lateral deviation of the vertebral column. Scoliosis is a progressive process that is usually taken just before or during puberty, and it is more common in women than men. Depending on the age of the diagnosis, this disorder is divided into three categories: childhood, adolescence, and youth. There are several types of scoliosis that affects people. Until this time, the most common type is idiopathic. Scoliosis is, in fact, a complex deformity, and its description requires a three-dimensional examination of this abnormality. In only 20% -15 cases, the cause of deformities are known, and in most cases, the cause is unknown, which has been called idiopathic scoliosis. Scoliosis is a serious malformation in which the spine abnormally changes with spinal rotation in three directions (Salmingo et al., 2012). This abnormality progresses over the course of growth, and the asymmetric loads due to spinal deformation cause more deformation, resulting in increased asymmetric loads, and this cycle continues (Stokes, 2007). In most cases, the growth of the spine has been observed in pre-puberty (Shi et al., 2011). Spinal deformation in the idiopathic scoliosis abnormality is generally described as the lateral deformity caused by the lateral spine curvature (Stokes, 1989).

The deformity caused by the spine in this disorder involves deformation and displacement in three directions and the spinal axis rotation (Labelle et al., 2013). Scoliosis causes problems of beauty,

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discomfort and pain, disruption of the patient's social activities at the time of the onset of the disease, and in advanced stages of severe deformity of the spine, impaired walking, impaired cardiovascular function, decreased volume chest, respiratory problems, lung infections, congestive heart failure, and neurological disorders. So far, several treatments for scoliosis have been used. These include muscular maintenance treatments such as physiotherapy, electrical stimulation of the muscles, exercise, stretching, brace as well as various surgical techniques. The effective treatment for the curvature of the spine is to install the rod and curvature correction by loading force. The rod that is mounted on the spine is responsible for bearing the forces created by the spine and skeletal deformation. For this reason, it is very important to estimate the forces needed to be loaded on the rod used in scoliosis curvature repair in a way that does not cause bone failure (Salmingo et al., 2012). Measuring the forces involved in the spine in a living tissue environment is difficult, and numerous studies have been done to measure the distribution of force on the spine and this information is available (Easterby, 2012). In 1989, Stokes examined the spine of 40 patients with idiopathic scoliosis in adults to examine the relationship between the vertebral spinal cord and deviant and lateral curvature in the spinal column in scoliosis and indicated that spinal rotation had a close relationship with deviation. Then, Stokes defined the relationship between the vertebral rotation and lateral curvature in the spine. In 2007, Stokes attempted to find a link between the progression of scoliosis abnormalities during growth and asymmetric loads on the spinal column of a person with scoliosis, taking into account the growing sensitivity of the bone. He measured and graded the measurement of the primary spine curvature of 15 patients. The tensile force of the backbone has been computed based on the physiological methods of muscle stimulation. The results of Stokes's research showed that the difference between progressive and non-progressive scoliosis may be due to different muscle stimulation. In 2011, Shi et al. examined the association between the progression of idiopathic anomalies in adults and the anomalous development of the anterior part of the spine and indicated that the rate of growth stimulated the progression and increased risk of scoliosis. Salmingo et al. (2012) presented a force method based on a finite element analysis to estimate spinal force inputs in a living tissue environment by examining the shape deformation used in the treatment of scoliosis abnormality curvature correction using 3D imaging. They showed that bending stresses depend directly on the curvature angle on the deformed rod. In 2013, Salmingo et al. measured the amount of bar deformation used in the treatment of surgery before and after treatment. They found the correlation between the intensity of the force and the angle of correction by measuring the applied force. Little et al. (2013) tried to find out how deformation was affected by the severity of corrective forces in order to predict the severity of the tension required to treat spinal curvature in scoliosis abnormalities. Their research showed that there is a direct relationship between the compressive forces of the connections used and the degree of curvature change. In 2015, Abe et al. analyzed the amount of force that is necessary to correct spinal cord by limited finite element analyzes and examining 20 patients who underwent spinal cord correction surgery between 2009 and 2011. Schlösser et al. (2014) examined the relationship between the three-dimensional displacements of the vertebrae. In 2015, Cheuk et al. evaluated the mechanical properties of the spinal bones using finite element analysis. If the curvature is more inclement, the surgical operation is recommended patient using the brace and rod. The rod that is installed on the spine is responsible for loading the forces created by the spinal column and skeletal deformation, as well as bringing force to correct the curvature. That is why determining the amount of the applied force in order to correct the curvature is worthy to be taken in deliberation.

Also predicting the possible place of spine vulnerability helps to prevent more serious injuries by using appropriate equipment and treatment.

2.Methods

In order to determine the safety level of the vertebral column systems, there is a need to consider the probabilistic-based approaches. In general, several different limit state functions have been considered for structures including strength, service, fatigue, and extreme events. In this present study, first, the structural component and the statistical parameters of loading and resistance associated with their distributions for normal backbones and scoliosis ones should be determined. Then by finite element analysis, the position and amount of stresses caused by weight load in the normal and scoliosis were measured.

2.1.Mechanical Properties of vertebrae

The intention of this section is to specify the main structural component of the backbone and their presented mechanical properties of those. The vertebral column, also called the backbone or spine, is the main part of the axial skeleton. The vertebral column is made of the series of bones known as "vertebrae" which are connected to each other by intervertebral discs. Normally, there are thirty-three vertebrae (see Henry Gray (1918)) within the vertebral column. The upper part is made of twenty-four vertebrates and the lower part consists of nine bone located in both the sacrum and in the coccyx. There are seven cervical vertebrae, twelve thoracic vertebrae, and five lumbar vertebrae. As a structural point of view, vertebrae and intervertebral discs can be considered as two main structural components for axial load carrying capacity. Each vertebra is composed of cancellous bone (soft part) and cortical bone (the hard part). In this section, the mechanical properties of both cancellous and cortical bone are reviewed. Many studies have been conducted to determine the mechanical parameters, including the density of the vertebrae (Rockoff et al. 1969). Ebbesen et al. (1999) measured different densities of vertebrae such as ash density of cortical and cancellous and bone mineral density. They showed the relationship between age, mass, and density of vertebrae. In addition, Helgason et al. (2008) studied the relationships between the physical and mechanical properties of bone using ash density. They utilized the proposed relationship between the ash and apparent density proposed by Keyak et al. (1994). Accordingly, Ebbesen et al., 1999 tested the yield stress of several vertebrae. In another study, Mosekilde et al., 1987 examined the relationship between ash density and maximum stress. Kopperdahl and Keaveny (1998) conducted a research to evaluate the stress-strain behavior for cortical part of vertebrae. Also, Öhman et al. (2011) conducted a real test to investigate the mechanical properties of bone. Patel et al. (2016) used the Hounsfield unit to predict the stress limit of the bone for cortical tissue. Recently, Azari et al. (2018) collected the mechanical properties of vertebrae. As can be seen, based on the reported literature, the mechanical properties of the bone behave as a random variable. Therefore, in this study, although the moduli of elasticity of bones are considered as the deterministic parameters (Table 1), the yield stresses of vertebrae are assumed to be treated as random normal variables (Table 2).

Table 1
Assumed moduli of the vertebra

	Modulus of elasticity (MPa)	Poisson's ratio
Cortical bone	E_{xx} = 11300	v_{xy} = 0.484
	E_{yy} = 11300	
	E_{zz} = 22000	v_{yz} = 0.203
	G_{xy} = 3800	
	G_{yz} = 5400	v_{xz} = 0.203
	G_{xz} = 5400	
Cancellous bone	E_{xx} = 140	v_{xy} = 0.450
	E_{yy} = 140	
	E_{zz} = 200	v_{yz} = 0.315
	G_{xy} = 48.3	
	G_{yz} = 48.3	v_{xz} = 0.250
	G_{xz} = 48.3	

Where E_{ij} and G_{ij} denote the modulus of elasticity in different directions. And v_{ij} represents the Poisson's ratio of bone in various directions.

Table 2
Statistical parameters of yield stress for vertebrae

Yield Stress - Cortical			
Tension		Compression	
Mean	Standard deviation	mean	Standard deviation
75	13.98	176	28.4
Yield Stress - Cancellous			
Tension		Compression	
mean	Standard deviation	mean	Standard deviation
1.9	0.86	1.78	0.58

It is worth mentioning the fatigue reliability index of the tiba bone was proposed using the statistical data provided by Ghasemi et al. (2019).

2.2.Mechanical Properties of Intervertebral Discs

Intervertebral discs with exerting the flexibility and small movements between the adjacent vertebrae make it possible to bend the entire spine. Intervertebral disc also distributes the load evenly on the body of the vertebrae. The intervertebral discs are extremely resistant under pressure and are very effective in absorbing shock in the spin. The intervertebral discs have three main layers (Adams, 2015): 1- core layer which is called "nucleus pulposus", 2- the intermediate layer which is named "annulus fibrosus", and 3- outer thin layer known as cartilage endplate. The high amount of water in disc causes hydrostatic pressure and viscous-elasticity behavior. Several studies have been conducted to determine the mechanical properties of discs (Iatridis (1995) and Iatridis et al. (1996)). Furthermore, Pollintine et al. (2010) studied the time-dependent changes in the time-spatial shape of the discs and vertebrae in the spinal column. However, Wang et al. (2000) used a 3D viscoelastic verified finite element model to investigate the mechanical properties of the L2-L3 lumbar vertebrae. Larde et al. (1982) studied 36 cases of bone marrow infection in the spine for three years. The mean age of the patients was 42 ± 5 and in the range of 10 to 72 years. In healthy subjects, the CT scan obtained from discs between 73 ± 13 units of Hounsfield on a 1000HU scale. Wintermantel et al. (2006) investigated the condition of 34 patients with lumbar disc herniation the Hounsfield's unite for a healthy part of the disc has been reported between 70 and 80 units. In order to measure the tensile strength of the intervertebral discs, Adams (2015) conducted an experimental study. Table 3 shows the tensile properties of annulus fibrosus, derived from uniaxial tension tests on small annulus samples from human lumbar discs aged 48-91 years. Adams performed preliminary tests indicating that the tensile stress in the intervertebral disc core is about 0.26 MPa (range 0.08-0.64). In addition, Mow and Huiskes (2005) stated that the nature of annulus fibrosis is resistant to tension and elongation at the disc caused by the movement of the adjacent vertebrae and the pressure of the inflammation. Galante (1967) measured the tensile properties of annulus fibrosis and showed that the function of this tissue is a nonlinear, heterogeneous, and anisotropic and it is viscose material and its properties are sensitive to its hydration state.

Skaggs et al. (1994) examined the tensile properties of single-layer samples along the dominant fiber direction, and obtained E values from 60 to 140 MPa, depending on the region of the annulus. Young's modulus was obtained for multilayer samples of 25 MPa in a radial direction of less than 0.5 MPa. The values measured for the Poisson ratio were significantly greater than 0.5, which indicates the anisotropic behavior of the annulus area. Mow and Huiskes (2005) collected and presented the results of various experiments in the biomechanics of the base of orthopedics and biomechanics, including the intraocular properties and mechanical behavior of the discs in swelling, elasticity, pressure and cutting. In addition, in this study, the tensile modulus of internal and external parts of the annulus fibrosus have been presented taken by and Iatridis (1996). in this study, it is attempted to model both annulus and nucleus tissue of disc. Therefore, based on the discussed precious studies in this section, the main mechanical properties of disc including shear relaxation modulus, bulk relaxation modulus, and relaxation time constant are assumed as the deterministic parameters (see Table 3). However, in order to perform the reliability analysis, the yield stresses of annulus and nucleus part of the disc are considered as a random variable, which represented in Table 4.

Table 3
Mechanical Properties of Disc

The Material Constants of Annulus Matrix and Nucleus Pulposus Using the Prony Series			
Relaxation of	Shear Relaxation Modulus	Bulk Relaxation Modulus	Relaxation Time Constant (second)
Annulus matrix, E=8.0 MPa, ν=0.45	g_1=0.399 g_2=0.000 g_3=0.361 g_4=0.108	k_1=0.399 k_2=0.300 k_3=0.149 k_4=0.150	τ_1=3.45 τ_2=100 τ_3=1000 τ_4=5000
Nucleus pulposus, E=2.0 MPa, ν=0.49	g_1=0.638 g_2=0.156 g_3=0.120 g_4=0.0383 g_5=0	k_1=0.0 k_2=0.0 k_3=0. 0 k_4=0.0 k_4=0.0	τ_1=0.141 τ_2=2.21 τ_3=39.9 τ_4=266 τ_4=500

Table 4
Statistical parameters of yield Stress for Disc

Tension		Compression	
average	STD	average	STD
7.30	2.30	3.65	1.15
Yield Stress - Nucleus			
Tension		Compression	
average	STD	average	STD
0.260	0.0819	0.260	0.0819

It is worth mentioning that based on the Ghasemi and Nowak (2016a, 2016b) the statictisal data should be collected for reliability analysis (Ghasemi and Nowak (2017a, 2017b, 2018), Safri et al. (2021), and Soltani et al. (2021).

3.Structural Analysis

3.1.Geometry Modeling

In order to model a backbone, a 3D model of the healthy spine was developed using Rino software. Then, the cancellous and cortical part of the vertebrae simulated according to the collected data. Also, for modeling intervertebral discs, annulus fibrosus was simulated as a layered cylinder and nucleus pulposus simulated as a cylinder. For modeling of ligaments and tendons, the spring replacement model was used. First, a healthy three-dimensional spinal column model was developed. A CT scan of a person with scoliosis developed with EOS technology was used for 3D modeling (see Figure 1).

Fig 1. The CT scan for considered vertebral column and its 3D model

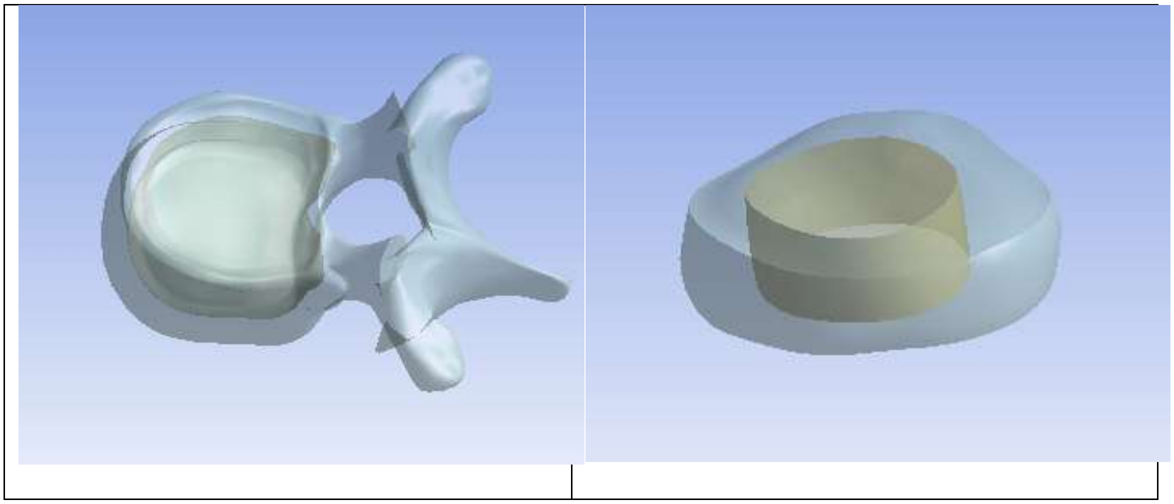

Fig 2. 3D structural modeling of vertebra and disc using ANSYS

The amount of displacement of each vertebra was measured from the CT scan image and applied to a healthy sample model, and the patient's 3D model was prepared. The vertebra is composed of two parts of cortical and cancellous. The intervertebral discs consist of annulus and nucleus as viscoelastic material (see Figure 2).In this research, the ligaments and tendons were also modeled using linear springs with stiffness equal to 205.6 N/mm (see Figure 3).

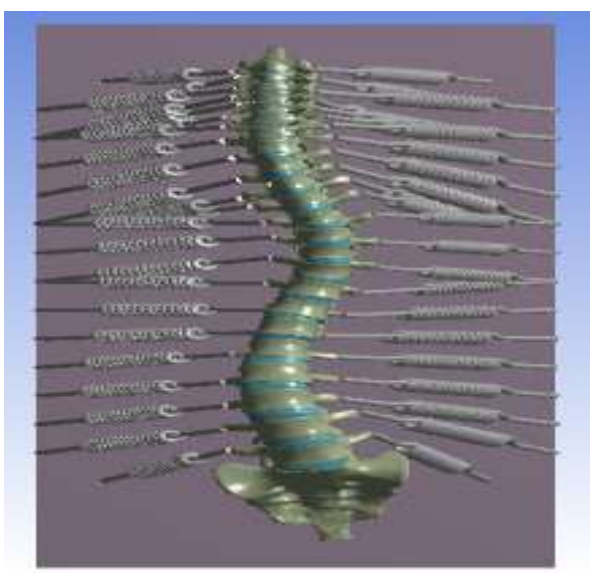

Fig 3. Full vertebral column modeling associated with considered ligaments using linear springs

In addition, the Scoliosis model of the spine developed from normal spine and data getting from by EOS scans and is simulated using the information obtained from the scanned image and prepared sample of the healthy spine. The 3D model used in the Ansys. In order to perform the reliability analysis, there is a need to generate a sufficient number of models. To reach this intention, 24 samples, 12 female samples (20years old 30 kg and 40kg, 35 years old weighing 50 kg, 60 kg, 70 kg and 80 kg) and 12 male samples (20years old 30 kg and 40kg, 35 years old weighing 50 kg, 60 kg, 70 kg and 80 kg) for a healthy case and scoliosis case are generated using ANSYS Workbench software. between the vertebrae evenly. Weight of head assumed about 4.5-5.5 kg, which is represented by two concentrated symmetrical forces on the second cervical vertebra, the C2. Considering the case in a standing position, the upper surface of the Sacrum was defined as fixed support. Thus, the displacement of the sacrum was limited in all directions (see Figure 4).

4.Loads and Supports

For loading, assuming that about 50-60% of the body's weight is tolerated by the spine, this amount divided

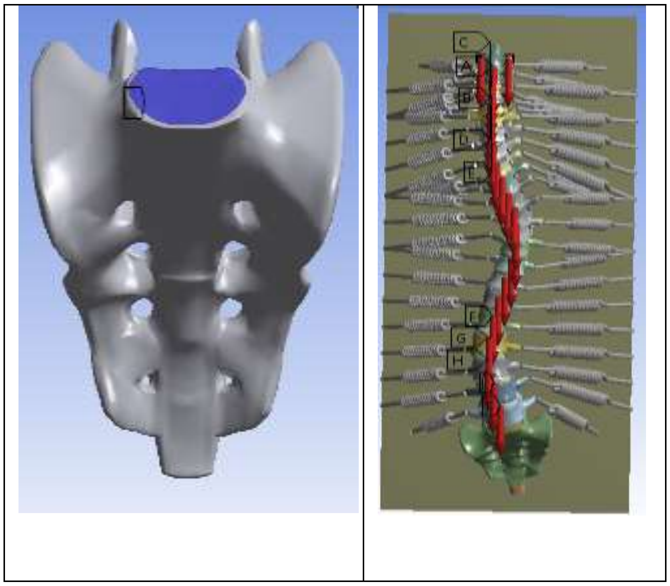

Fig 4. Loading and boundary conditions considered for vertebral column analysis

5.Validation

In order to assess the accuracy of the obtained result, the stresses state of the disc between the 4 and 5 lumbar vertebrae in a standing position subjected to the compression was compared with the presented result of Azeri et al. (2018). As can be seen in Figure (5), the obtained stress results in the current study were reached to almost the same result presented by Azari et al. (2018), which can be considered as a verification of the currently conducted research.

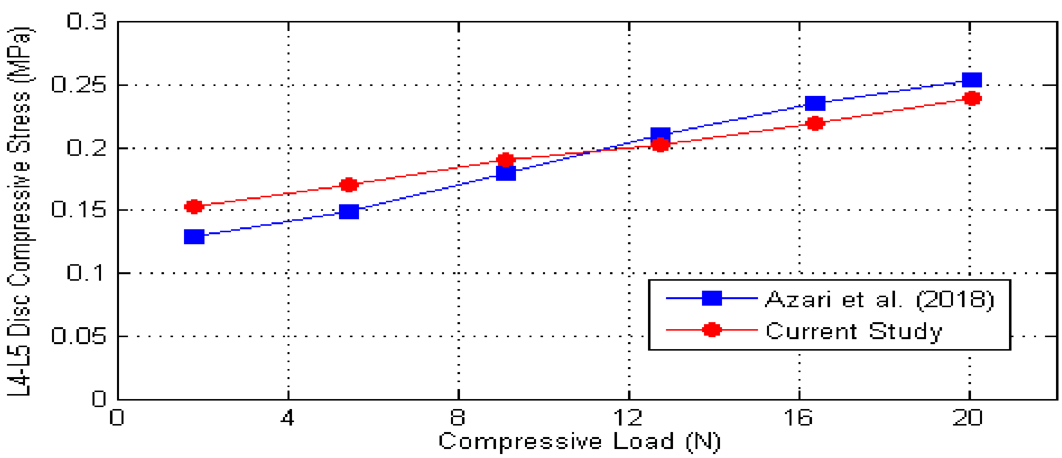

Fig 5. Verification of the FEM results corresponding to the stress state of L4-L5 Disc subjected to the compression

6.Results and Discussions

Accordingly, several FE models with the generated random properties were analyzed to compute the stress states of the vertebral column.

The most vulnerable zones of the normal vertebral column for different human weights are tabulated in Table 5.

Table 5
The most vulnerable zone of normal vertebral column for different human weights

Normal					
Maximum Stress					
Weight (KG)		Cortical	Cancellous	Annulus	Nucleus
30	Tension	T2	C7	C7	T6
	Compression	C7	C7	C6	C7
40	Tension	T2	C7	C7	T6
	Compression	C7	L3-C7	C6	C7
50	Tension	T2	C7	C7	T6
	Compression	C7	L3-C7	C6	C7
60	Tension	T2	C7	C7	T6
	Compression	C7	L3-C7	C6	C7
70	Tension	T2	C7	C7	T6
	Compression	C7	L3-C7	C6	C7
80	Tension	T2	C7	C7	T6
	Compression	C7	L3-C7	C6	C7

As it was observed, the most vulnerable stress zone for normal backbone are placed on discs C5-C6-C7 or T6-T7-T8 and on vertebrae C7, T2, or L3 varies depending on human body weights. In addition, Table 6 represents the most vulnerable zone of the vertebral column associated with the different human weights for one of the considered scoliosis curvature.

Table 6
The most vulnerable zone of scoliosis vertebral column for different human weights

Scoliosis					
Maximum Stress					
Weight (KG)		Cortical	Cancellous	Annulus	Nucleus
30	Tension	T1	T7	C7	T7
	Compression	T1	T10	C6	T10
40	Tension	T1	T7	C7	T7
	Compression	C7	T10	C6	T10
50	Tension	C7	T7	C7	C7
	Compression	C7	T10	C6	C7
60	Tension	C7	T7	C7	C6
	Compression	C7	T10	C6	C6
70	Tension	C7	T8	C7	C6
	Compression	C7	T10	C6	C6
80	Tension	C7	T8	C7	C6
	Compression	C7	T10	C6	C7

Based on the obtained results, the vulnerable stress zones of the considered scoliosis spinal column are placed on discs T6-T7or C7 and on vertebrae T1, T8, T10. Although the most vulnerable zone of scoliosis vertebral column scoliosis curvature (See Figure 6).

varies depending on the curvature, the maximum, based on several FEM performed model in this study, it was observed that the maximum stress states are approximately concentrated on the inflection points of the

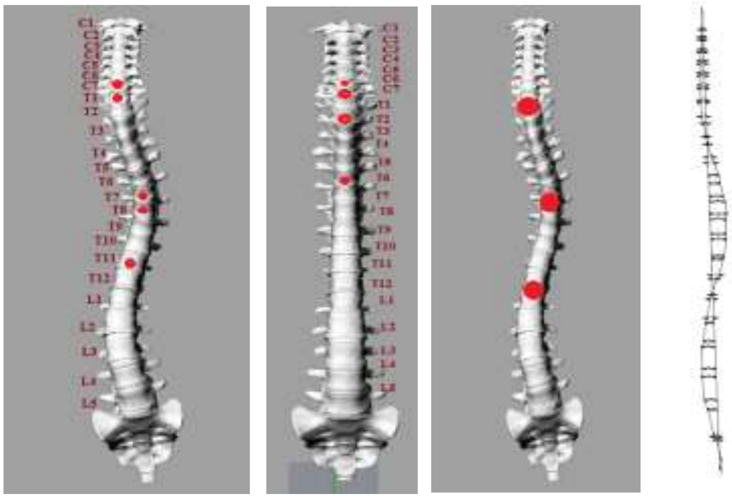

Fig 6. Vulnerability stress analysis of vertebral column for a case study (Scoliosis, Female, 30 KG)

As shown in Figure (6), the maximum stresses were observed near the inflection points of the spinal curvature for a 30 Kg-female-case-study suffered the scoliosis disorder. The reliability analysis of this study was provided in the other paepr by Nouri et al. (2021). The concept of resialnce may be the nex step of this remedy procdure using provided formual by Ghasemi and Lee (2021a, 2021b), which help us to evaluate the robutnsess and redundancy of the under terment into consideration.

7.Conclusions

The scoliosis disorder asymmetrically distributes the weight of the human body throughout the spinal column. Accordingly, the severe damages are observed corresponding to the asymmetrical load distribution. However, in order to redeem the scoliosis disorder, the reliable stress states level of the vertebral column shall be determined. Nonetheless, the statistical parameters of the spinal column showed that the applied load and load-carrying capacity are both random variables. In this study, first, it is attempted to collect statistical parameters of the load and mechanical properties of the structural components of the backbone. Accordingly, several FE models with the generated random properties were analyzed to compute the stress states of the vertebral column. Based on the obtained results, the vulnerable stress zone for both normal and scoliosis spinal column are determined. As it was observed, the most vulnerable stress zone for normal backbone subjected to the self-weight loading are located on discs C5-C6-C7, T6-T7-T8, or T9-T10, and on vertebrae C6-C7, T2-T3, or L2-L3-L4. Although the most vulnerable zone of scoliosis vertebral column varies depending on the curvature, the maximum stress states are approximately concentrated on the inflection point of the curvature. The mean of the maximum stresses generated in each member showed that the curvature of the spinal cord due to scoliosis was directly affected by the stressed area.

Data Availability

- Not applicable.

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