System Reliability Analysis of the Scoliosis Disorder

Fatemeh Nouri
Qazvin Islamic Azad University
Seyed Hooman Ghasemi (hooman.ghasemi@auburn.edu)
Qazvin Islamic Azad University https://orcid.org/0000-0003-2103-5221

Research article

Keywords: target reliability, scoliosis, vertebral column, system reliability, statistical parameters

Posted Date: October 2nd, 2019

DOI: https://doi.org/10.21203/rs.2.15444/v1

Version of Record: A version of this preprint was published at BMC Musculoskeletal Disorders on March 31st, 2020. See the published version at https://doi.org/10.1186/s12891-020-03230-4.

Abstract

Background: Scoliosis is a spine abnormal deviation, which is an idiopathic disorder among children and adolescents. As a matter of the fact, distribution of loads on the patient's spine and load carrying capacity of the vertebral column are both random variables. Therefore, the probabilistic approach may consider as a sophisticated method to deal with this problem.

Method: Reliability analysis is a probabilistic-based approach to consider the uncertainties of load and resistance of the vertebral column. The main contribution of this paper is to compare the reliability level of a normal and scoliosis spinal. To do so, the numerical analyses associated with the inherent random parameters of bones and applied load are performed. Then, the reliability indices for all vertebrae and discs are determined. Accordingly, as the main innovation of this paper, the system reliability indices of the spinal column for both normal and damaged backbone system are represented.

Results: Based on the required reliability index for normal spinal curvature the target system reliability level for scoliosis disorder is proposed.

Conclusion: Since the proposed target reliability index is based on the strength limit state of the vertebral column, it can be considered as a reliability level for any proposed treatment approaches.

Background

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 deformity 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, 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 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 the 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.

However, the applied load and the structural resistance of the backbone system are both random variables which involved the uncertainties. Therefore, there is a need for a probabilistic approach to estimate the load carrying capacity of the scoliosis disorder. To do so, in this study, first, it is attempted to collect the inherent uncertainties parameters impacting on the load carrying capacity of the vertebral column. Then, the reliability index of each disc and vertebra is calculated using reliability analysis. After that, the system reliability index of the backbone is represented for both normal and abnormal vertebral columns. The obtained system reliability level of the normal vertebral column is expected to be considered as target system reliability. Accordingly, the abnormal backbone particularly the scoliosis one can be cured using any proposed method including the surgery to retrieve the reliability level to the normal one.

Methods

In order to determine the safety level of the vertebral column systems, there is a need to consider the probabilistic-based approaches. Reliability index is a world-widely measure to evaluate the safety level of a component or a system with consideration of load and resistance distributions. The main step in reliability analysis is to determine the Limit State Function, which can be constructed based on the expected performance level of the structure. In general, several different limit state functions have been considered for structures including the strength, service, fatigue, and extreme events. In this present study, in order to investigate the resistance-ability of the backbone system due to the normal load, the strength limit state function is considered. Therefore, 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, the reliability level of each structural component is computed using Monte Carlo simulation. Finally, the reliability indices of both mention system (sound and damaged due to the scoliosis disorder) are calculated.

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 bone 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 the 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 (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 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).

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

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- 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 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.

Structural Analysis

Geometry Modeling

For modeling, a 3D model of the healthy spine was developed using Rino software. Then, cancellous and cortical part of vertebrae simulated according to the collected data. Also, for modeling intervertebral discs, annulus fibrosus was simulated as a layer cylinder and nucleus pulposus simulated as a cylinder. For modeling of ligaments and tendons, 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).

The amount of displacement of each vertebra was measured from the CT scan image and applied on 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 are consisted 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).

In addition, Scoliosis model of 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 the 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.

Loads and Supports

For loading, assuming that about 50–60% of the body's weight is tolerated by the spine, this amount divided 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 standing position, the upper surface of the Sacrum was defined as a fixed support. Thus, the displacement of the sacrum was limited in all directions (see Figure 4).

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 was reached to the almost the same result presented by Azari et al. (2018), which can be considered as a verification of the current conducted research.

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 normal vertebral column for different human weights are tabulated in Table 5.

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 for the most vulnerable zone of the vertebral column associated with the different human weights for one of considered scoliosis curvature.

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 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 scoliosis curvature (See Figure 6).

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.

System Reliability

Failure Mechanics

The vertebral column consists of the two main structural components which may fail in different manners. In this study, the tension and compression principal stress states of cortical and cancellous are compared with the yield stress limit to figure out the failure mechanism of vertebrae. Accordingly, the vertebral probabilities of failure are determined based on the parallel probability of failure of both cortical and cancellous either corresponding to the tension yielding limit or compression yielding limit states. The same scenario may happen for intervertebral discs. It means both tension and compression stress states within annulus and nucleus are compared with the yielding tolerance of annulus and nucleus to specify the failure probability of intervertebral discs. Eventfully, the vertebral system failure probability is consists of a series model of vertebrae and intervertebral discs.

Reliability analysis

Here in this section, based on the obtained stresses results of the vertebral columns, the reliability index for each component of the spine was calculated. As it was mentioned, in order to perform the reliability analysis, there is a need for the establishment of the limit state function. There are several limit states associated with the various structural performance concerned (Ghasemi and Nowak 2016a, 2016b, 2017a, 2017b, 2018, and 2019). In this study, the strength limit state function is considered as the backbone performance function. Therefore, the reliability indices for both cortical and cancellous of vertebra tissues, and both tissues of intervertebral discs (annulus and nucleus) are computed. In general, the reliability indices can be determined using the distributions of the structural resistance (R) and applied load (Q). If the limit state function is formulated as a linear function and the load and resistance distributions follow the normal one, the reliability index can be computed using the following equation.

[Due to technical limitations, this equation is only available as a download in the supplemental files section.] (1)

where μR and μQ present the mean value of load and resistance. Also, σR and σQ denote the standard deviation of load and resistance. However, the establishment of the limit state function requires a closed form equation. In this study, as a-state-of-the-art, a novel procedure is utilized to determine the reliability index. In this innovated procedure, first, the stress's state of all elements are ascertained using finite element analysis. Then, the most vulnerable zones of the vertebral column due to the axial loading conditions are recognized. Accordingly, several FEM models of the vertebral column are created based on the random variables of the material and geometry. Finally, based on the obtained random stress results, the distribution of the applied loads are determined. On the other hand, based on the collected data of stress limit of backbone components the resistance distribution of vertebrae (cortical and cancellous) and intervertebral discs (annulus and nucleus) are generated. Hence, the reliability index of each component is determined.

Finally, the system reliability indices of the normal and scoliosis backbones are determined. To capture this intention, the system reliability formulation is constructed with consideration of the parallel and series algorithm for the given backbone. Since the applied forces on the vertebrae are distributed between cortical and cancellous, cortical and cancellous within the vertebrae are constituted a parallel system. The same condition can be observed for intervertebral discs, in which both tissues of annulus and nucleus construct the parallel system. The failure of the parallel systems can be derived using the following equation:

[Due to technical limitations, this equation is only available as a download in the supplemental files section.] (2)

where Pf is the probability of the system failure, and Pfi is the failure probability of the i^{th} component. However, the load contribution between the vertebrae and discs can be assumed as the series system. The governing equation to describe the failure probability of a series system can be written as follow:

[Due to technical limitations, this equation is only available as a download in the supplemental files section.] (3)

Results And Discussions

In the previous section, after extracting the stresses of each element, the reliability indices for all components of the spine were obtained for both normal and scoliosis ones. The obtained result for each component was taken to the account to determine the reliability index of each component. Accordingly, the system reliability index was calculated. Table (7) represents the failure probability of the normal and scoliosis spin for the various human weights.

Also, the corresponding reliability indices are presented in Table 7 for both normal and scoliosis spines at the different body weights.

Figure (7) compares the system reliability indices for both normal and scoliosis vertebral column. As can be seen, by increasing the overall weight of the human body the reliability index is decreased. In addition, due to the enhancement of the asymmetrical loading effect, the differences of the system reliability indices for heavier weights are being more significant.

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 vertebral column shall be determined. Nonetheless, the statistical parameters of spinal column showed that the applied load and load carrying capacity are both random variable. 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-weigh 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. Accordingly, the reliability analysis was conducted to determine the reliability level of the structural component of the vertebral column including disc (for both Annulus and nucleus) and vertebra (for both cortical and cancellous). Finally, as the state-of-the-art, the reliability of the whole system for both normal and scoliosis vertebral columns were calculated using Monte Carlo simulations. In this paper, the obtained system reliability for the normal vertebral column is proposed as a target reliability system. Eventually, the proposed target reliability can be considered as the appropriate measure for any type of scoliosis treatment to retrieve the vertebral column to the acceptable performance level.

Abbreviations

β: Reliability index

E: Modulus of Elasticity

g = Shear Relaxation Modulus

k = Bulk Relaxation Modulus

μ_Q = mean value of loading

μ_R = mean of resistance

v = Poisson's Ration

P_f: Probability of failure

Q = Random variable of loading

R = Random variable of resistance

σ_Q = Standard deviation of loading

σ_R = Standard deviation of resistance

τ = Relaxation Constant

Declarations

Data Availability

Not applicable.

Ethics approval and consent to participate

Not applicable.

Consent to publish

The authors are confirming their consent for publication

Availability of data and materials

Not applicable.

Competing interests

Not applicable.

Funding

Not applicable.

Authors' Contributions

All authors have a major contribution for this version of the submitted manuscripts.

Acknowledgements

Not applicable.

References

1. Abe, Y., Abe Y, Ito M, Abumi K, Sudo H, Salmingo R, and Tadano S. (2015), "Scoliosis corrective force estimation from the implanted rod deformation using 3D-FEM analysis" Scoliosis10(2): S2
2. Adams, M. A. (2015). Intervertebral disc tissues. Mechanical properties of aging soft tissues, Springer: 7–35.
3. Azari, F., Arjmand N., Shirazi-Adl A., and Rahimi-Moghaddam T. (2018), "A combined passive and active musculoskeletal model study to estimate L4-L5 load sharing" Journal of biomechanics 70: 157–165.
4. Cheuk, K. Y., et al. (2015). "Evaluating bone strength with finite element analysis for Adolescent IdiopathicScoliosis (AIS): a case-control study with HR-pQCT" Scoliosis10(1): O20
5. Easterby, R. (2012). Anthropometry and biomechanics: theory and application, Springer Science & Business Media.
6. Ebbesen E. N., Thomsen J. S., Beck-Nielsen H., Nepper-Rasmussen H. J., and Mosekilde L. (1999). "Age-and gender-related differences in vertebralbone mass, density, and strength." Journal of Bone and Mineral Research 14(8): 1394–1403.
7. Galante JO. (1967), "Tensile properties of the human lumbar annulus fibrosus" Acta Orthopaedica Scandinavica 38(sup100): 1–91.

8. Ghasemi S. H. and Nowak A. S. (2016a), “Mean Maximum Values of Non-Normal Distributions for Different Time Periods”, International Journal of Reliability and Safety, Vol. 10, No. 2.
9. Ghasemi S. H and Nowak, A. S. (2016b), “Statistical Parameters of In-A-Lane Multiple Truck Presence and a New Procedure to Analyze the Lifetime of Bridges”, Journal of Structural Engineering International, Association for Bridge and Structural Engineering IABSE, Vol. 26, No. 2, pp. 150–159.
10. Ghasemi S. H. and Nowak A. S. (2017a), “Reliability Index for Non-Normal Distributions of Limit State Functions”. Structural Engineering and Mechanics, Vol. 62, No. 3, pp. 365–372.
11. Ghasemi S. H. and Nowak A. S. (2017b), “Target Reliability for Bridges with Consideration of Ultimate Limit State”, Engineering Structures, vol. 152, pp. 226–237.
12. Ghasemi S. H. and Nowak A. S and (2018), “Reliability Analysis of Circular Tunnels with Consideration of the Strength Limit State”. Geomechanics Engineering, Vo. 15, No 3, pp. 879–888.
13. Ghasemi S. H., Kalantari H., Abdolahikho S., and Nowak A. S, (2019),”Fatigue Reliability Analysis of Medial Tibial Stress Syndrome”, Material Science and Engineering: C, Vo. 99, pp. 387–393.
14. Gray H. (1918), Anatomy of the Human Body. Philadelphia: Lea & Febiger, https://upload.wikimedia.org/wikipedia/commons/5/54/Gray_111_-_Vertebral_column-coloured.png.
15. Helgason, B., Perilli, E., Schileo, E., Taddei, F., Brynjolfsson S., and Viceconti M. (2008), “Mathematical relationships between bone density and mechanical properties: a literature review”, Clinical biomechanics 23(2): 135–146.
16. Iatridis J. (1995), “Mechanical behavior of the human nucleuspulposus in shear” Proceeding of the 41th Annual Meeting of the Orthopaedic Research Society, 1995.
17. Iatridis JCM, Weidenbaum M., Setton, LA, and Mow, V., (1996). “Is the nucleus pulposus a solid or a fluid? Mechanical behaviors of the nucleus pulposus of the human intervertebral disc”, Spine, 21(10): 1174–1184.
18. Kopperdahl D. L. and Keaveny T. M. (1998), “Yield strain behavior of trabecular bone”, J Biomech 31(7): 601–608.
19. Keyak J. H., Lee IY., Skinner H. B. (1994), " Correlations between orthogonal mechanical properties and density of trabecular bone: Use of different densitometric measures”, Journal of Biomedical Materials Research 28(11):1329–36
20. Labelle H., et al. (2013), “Screening for adolescent idiopathicscoliosis: an information statement by the scoliosis research society international task force”, Scoliosis 8(1):17.
21. Larde D., Mathieu D., Frija J., Gaston A., and VasileN. (1982), “Vertebral osteomyelitis: disc hypodensity on CT”, AJR Am J Roentgenol. , 139(5): 963–967.
22. Little J.P, Izatt MT, Labrom RD, Askin GN, and Adam CJ. (2013), “An FE investigation simulating intra-operative corrective forces applied to correct scoliosis deformity”, Scoliosis 8(1): 9.
23. Mosekilde L., Mosekilde L., and Danieisen C. C., (1987), “Biomechanical competence of vertebral trabecular bone in relation to ash density and age in normal individuals”, Bone, 8(2): 79–85.

24. Mow, V. C. and R. Huiskes (2005), “Basic orthopaedic biomechanics & mechano-biology”, Lippincott Williams & Wilkins.
25. Öhman, C., et al. (2011), “Compressive behaviour of child and adult cortical bone”, Bone, 49(4): 769–776.
26. Patel S., Lee J., Hecht G., Holcombe S., Wang S., and Goulet J. (2016), “Normative vertebral Hounsfield unit values and correlation with bone mineral density”, Journal of Clinical & Experimental Orthopaedics, 2: 14.
27. Pollintine P., Tunen M., Luo J. Brown M. D., Dolan P., and Adams M. A. (2010), “Time-dependent compressive deformation of the ageing spine: relevance to spinal stenosis”, Spine 35(4): 386–394.
28. Rockoff S. D., E. Sweet and Bleustein J. (1969), “The relative contribution of trabecular and cortical bone to the strength of humanlumbar vertebrae”, Calcified Tissue Research 3(1): 163–175.
29. Salmingo R. A., Tadano S., Fujisaki K., Abe Y., and Ito M. (2013), “Relationship of forces acting on implant rods and degree of scoliosis correction”, Clinical Biomechanics 28(2): 122–128.
30. Salmingo R., Tadano S., Fujisaki K., Abe Y., and Ito M. (2012), “Corrective force analysis for scoliosis from implant rod deformation.” Clinical Biomechanics 27(6): 545–550.
31. Schlösser T. P., et al. (2014), “Three-dimensional characterization of torsion and asymmetry of the intervertebral discs versus vertebral bodies in adolescent idiopathic scoliosis”, Spine 39(19): E1159-E1166.
32. Shi L., et al. (2011), “Biomechanical analysis and modeling of different vertebral growth patterns in adolescent idiopathic scoliosis and healthy subjects”, Scoliosis 6(1): 11.
33. Shirazi-Adl A, El-Rich M, Pop DG, Parnianpour M. (2005), “Spinal muscle forces, internal loads and stability in standing under various postures and loads—application of kinematics-based algorithm”, European Spine Journal 14(4):381–392.
34. Skaggs D., Weidenbaum M.., Iatridis JC A. Ratcliffe A., and Mow V. C. (1994), “Regional variation in tensile properties and biochemical composition of the human lumbar annulus fibrosus”, Spine 19(12): 1310–1319.
35. Stokes I. A. (1989), “Axial rotation component of thoracic scoliosis”, Journal of orthopedic research 7(5): 702–708.
36. Stokes I. A. F. (2007), “Analysis and simulation of progressive adolescent scoliosis by biomechanical growth modulation”, European Spine Journal 16(10): 1621–1628
37. Wang J. L., Parnianpour M., Shirazi-Adl A., and. Engin A. (2000), “Viscoelastic finite-element analysis of a lumbar motion segment in combined compression and sagittal flexion: Effect of loading rate”, Spine, 25(3): 310–318.
38. Wintermantel E., Emde H., and Loew F., (1985), “Intradiscal collagenase for treatment of lumbar disc herniations”, Acta Neurochir (Wien), 78(3–4): 98–104.

Tables

Table 1. Assumed moduli of 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	$E_{xx} = 140$	$v_{xy} = 0.450$
	$E_{yy} = 140$	
	$E_{zz} = 200$	$v_{yz} = 0.315$
	$G_{xy} = 48.3$	
	$G_{yz} = 48.3$	$v_{xz} = 0.250$
	$G_{xz} = 48.3$	

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

Table 3. Mechanical Properties of Disc

The Material Constants of Annulus Matrix and Nucleus Pulposus Using the Prony Series			
Relaxtion 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

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

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

Table 7. Failure probability of the normal and scoliosis vertebral column subjected to the human weight

		30 KG	40 KG	50 KG	60 KG	70 KG	80 KG
Normal Spine	P_f						
Normal Spine		4.10					3.75
Scoliosis Spine	P_f	2.					3.18
Scoliosis Spine		3.45	3.05	2.91	2.85	2.81	2.73

Figures

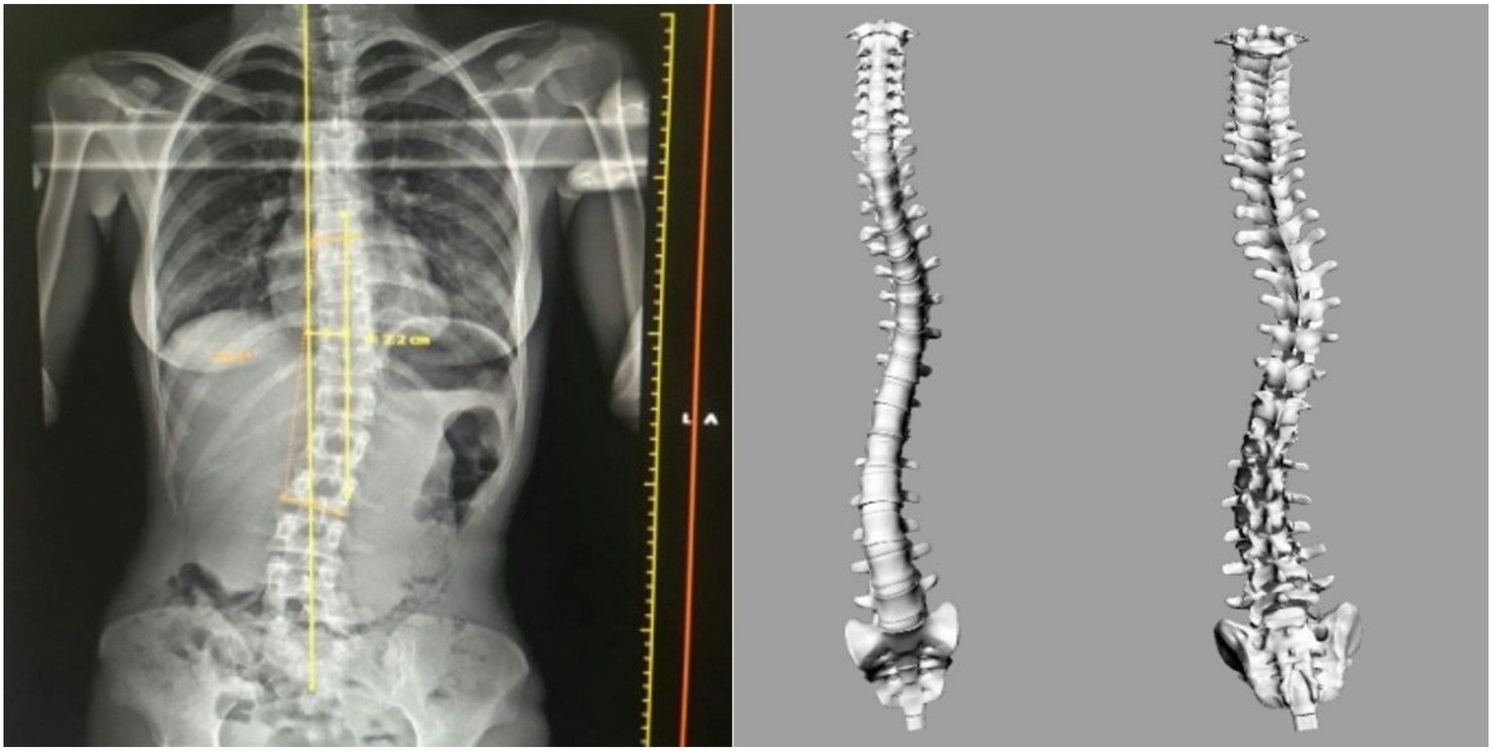

Figure 1

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

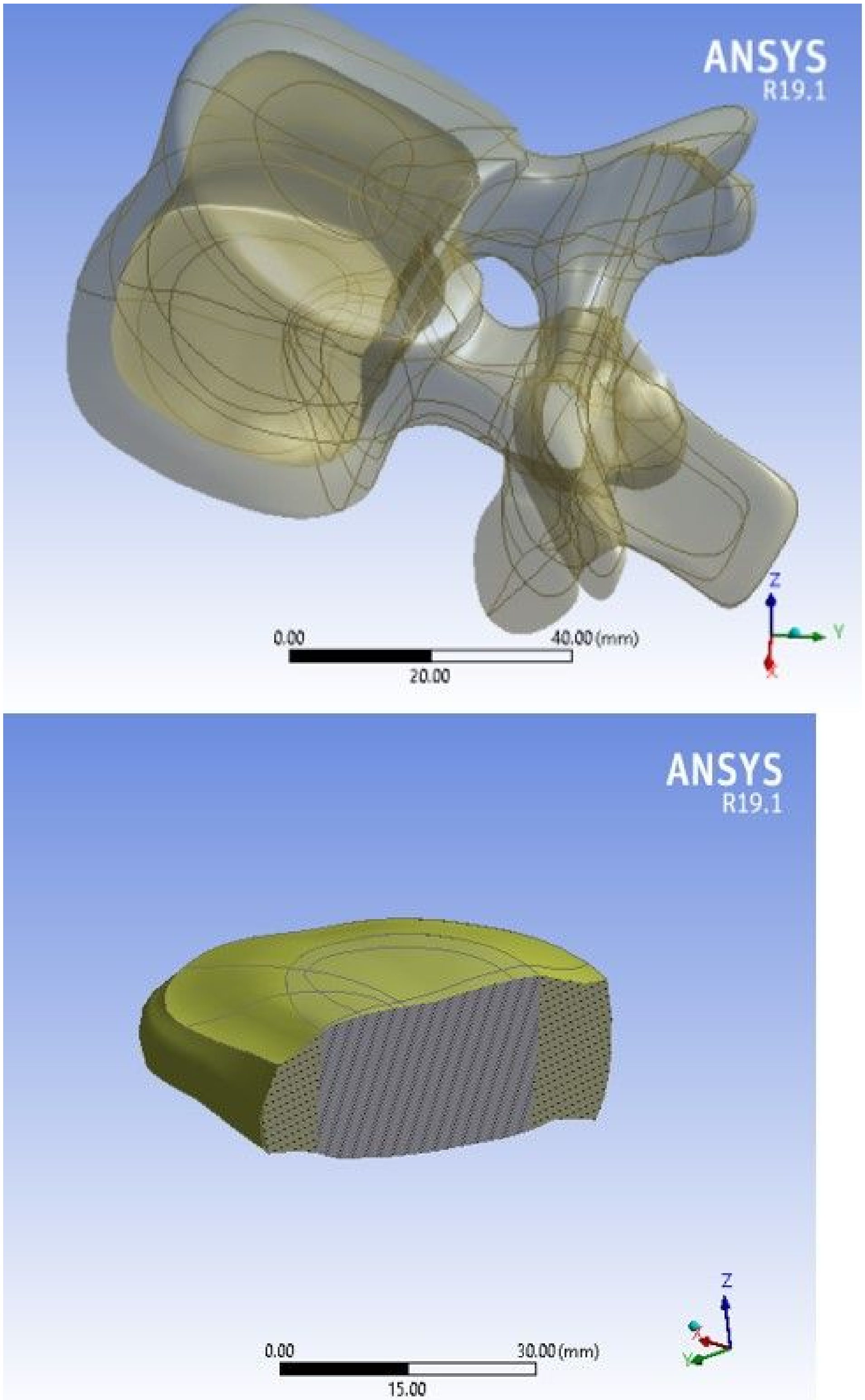

Figure 2

3D structural modeling of vertebra and disc using ANSYS

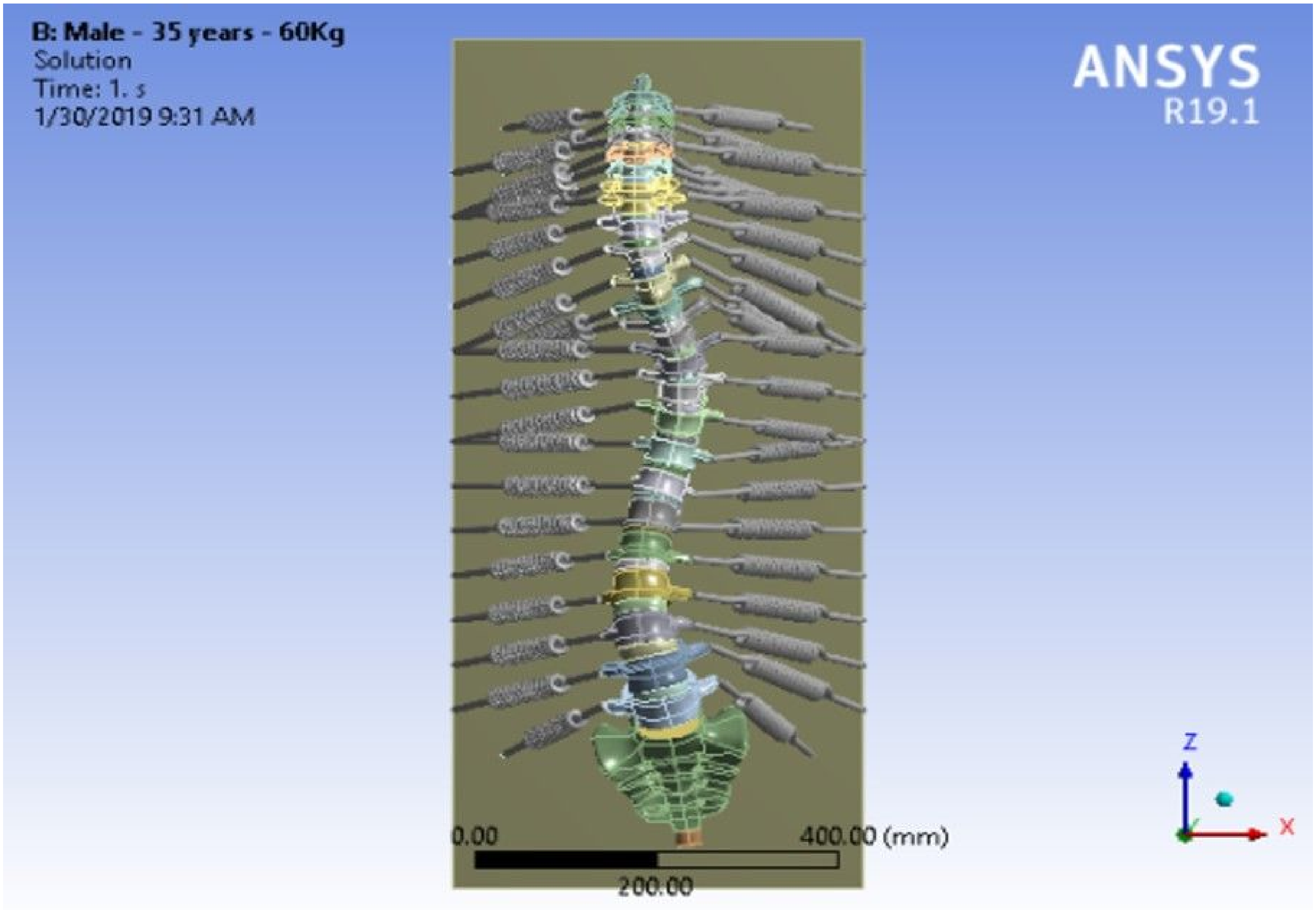

Figure 3

Full vertebral column modeling associated with considered ligaments using linear springs

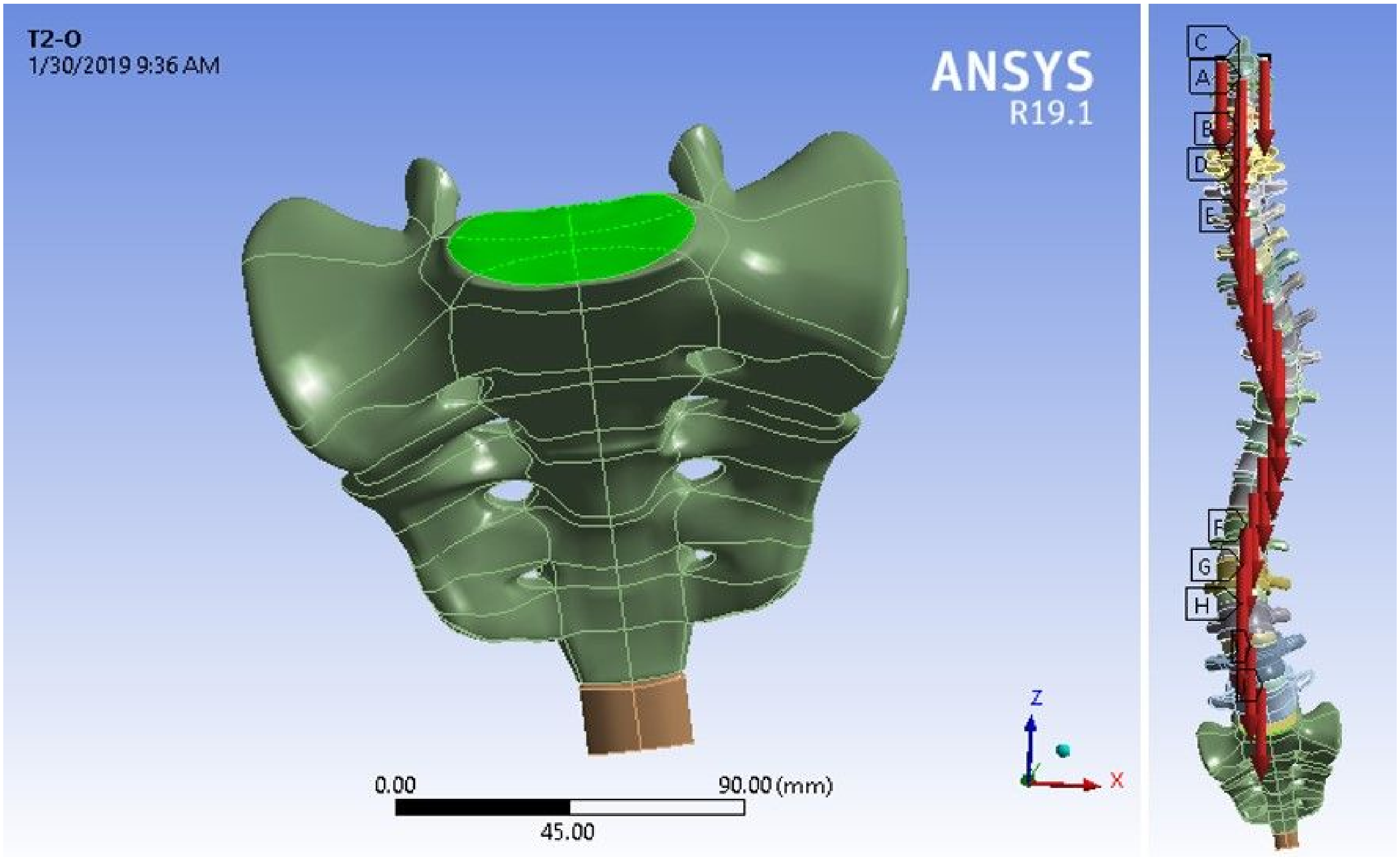

Figure 4

Loading and boundary conditions considered for vertebral column analysis

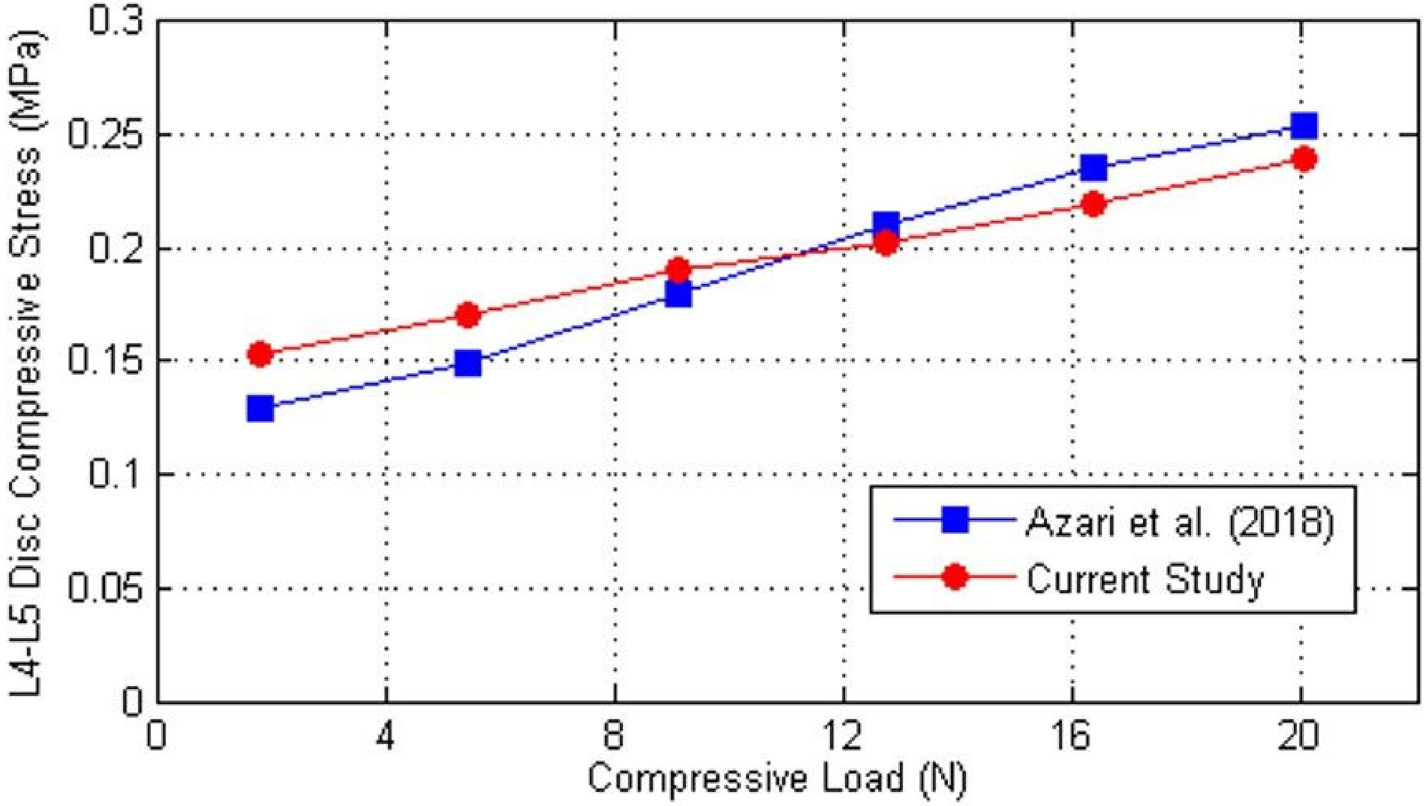

Figure 5

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

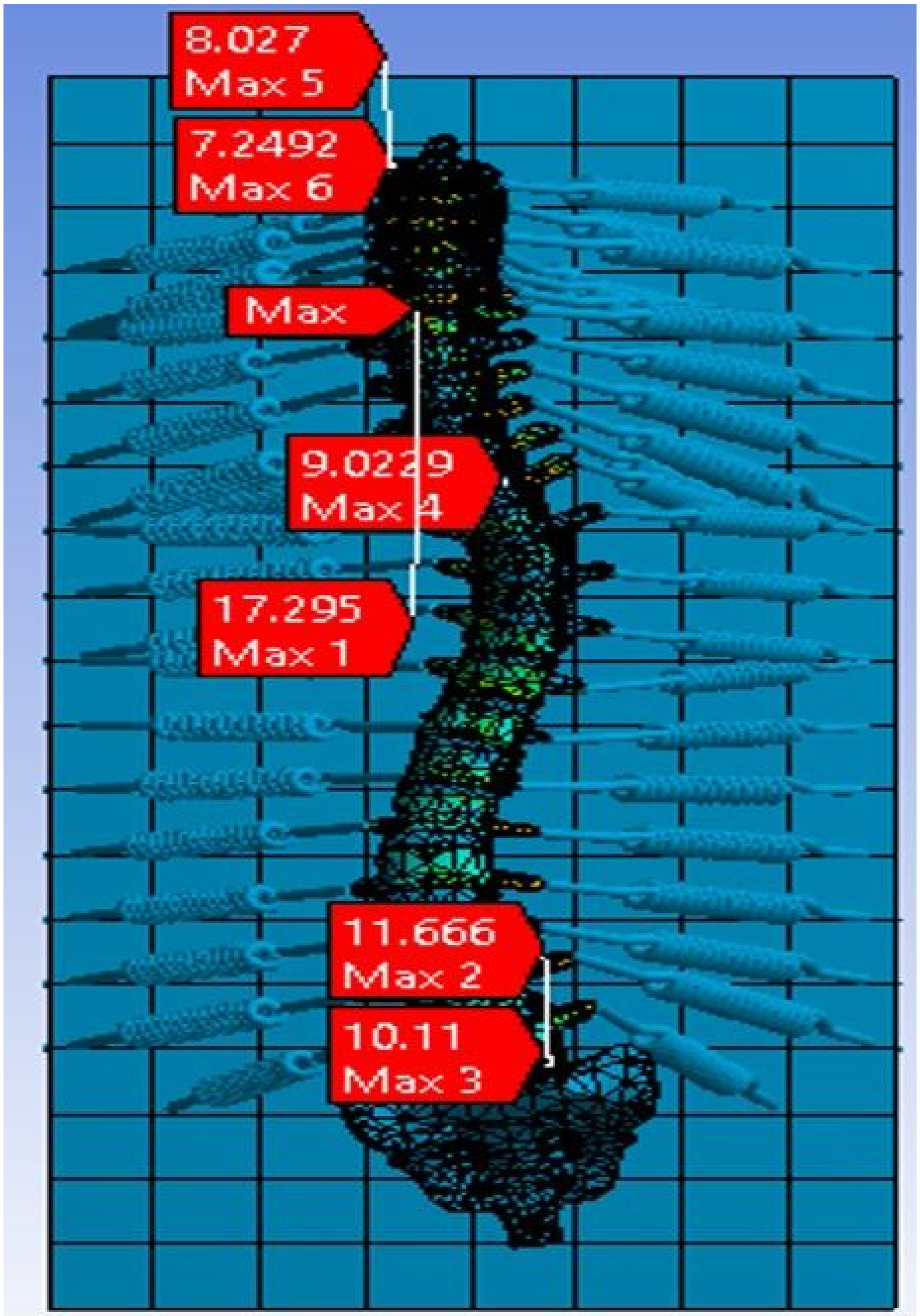

Figure 6

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

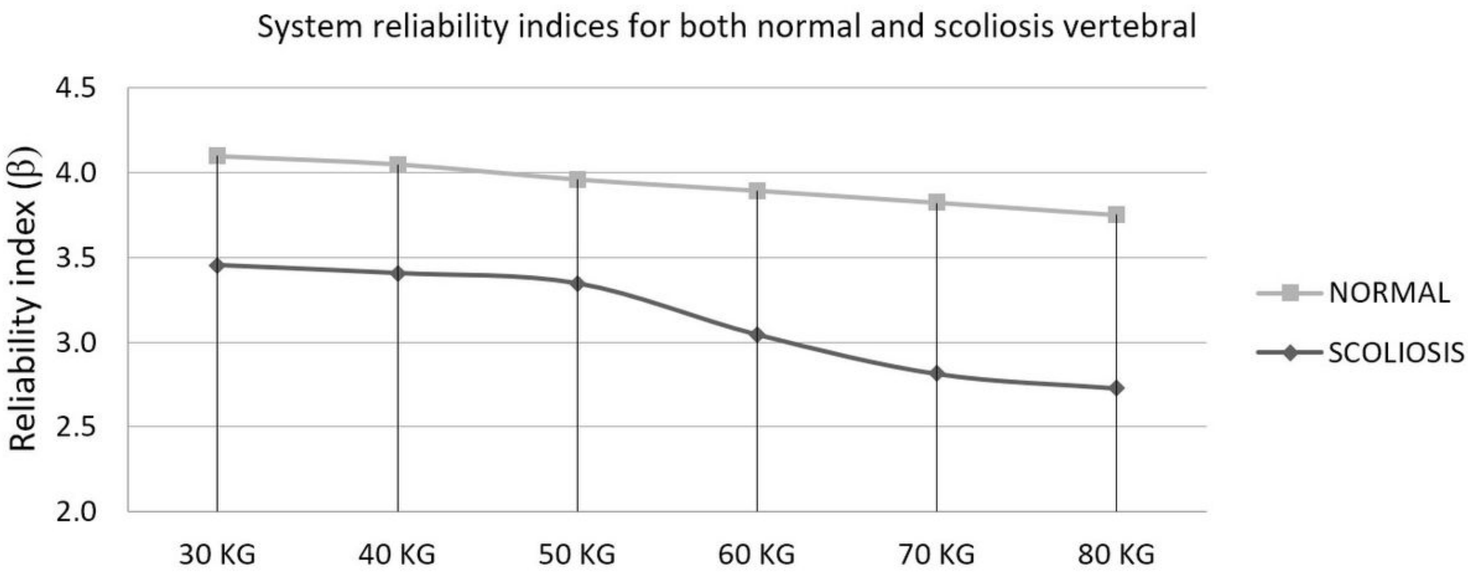

Figure 7

System reliability indices for both normal and scoliosis vertebral column with consideration of the different human body weights

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- eq2.jpg
- eq1.jpg
- eq3.jpg