# Modal Analysis of Adult Human Spine Vertebrae Using Numerical Method

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**Abstract.** Human bodies are often exposed to vibrations when they are in the working place or vehicles. The low back pain and the degenerative diseases of the spine are more frequently found in humans exposed to vibration. In order to minimize these diseases, the occurrence of resonance conditions in the human spine body should be prevented; the determination of the natural frequency of each vertebra of the spine is the most required parameter to satisfy no occurrence of a resonant condition. This study aimed to determine the specific fundamental frequencies of the human spine vertebrae. In this paper, a detailed three-dimensional geometrical model of seated human spine vertebral is developed in Solidworks software based on actual vertebral geometry and the finite element model modal analysis is done by using ANSYS software. After FE modal analysis, the resonant frequencies of each vertebra of cervical (7), thoracic (12) and lumber (5) of the adult human spine are obtained and the fundamental frequencies of the vertebrae versus span of the spine are plotted. The result shows that the fundamental frequencies of all vertebra of the spine are different and the mini-mum fundamental frequency is 6.023 Hz for the thoracic spine (T4). In addition, it is revealed that for the whole spine vertebrae the fundamental frequency range is 6–19 Hz. The spine resonant condition may occur at any of this frequency range even though the fundamental frequency of the spine is 6.023 Hz.

**Keywords:** Human spine · Mode shape · Resonant state · Fundamental frequency

## 1 Introduction

Usually, the human body is subjected to a random movement when the person is in the working place, they face many different vibrations daily [1]. Means of transportation, machines, and human activities (e.g. people walking or dancing) may subject the human body to unwanted mechanical shaking or vibration. The exposure of a person for a certain degree of freedom body vibration will cause the comfort problem and health problems [2] as well [1].

Most workplaces where workers are exposed to whole-body vibration involves simultaneous motion in the fore-and-aft (x-), lateral (y-), and vertical (z-) directions [3]. The vertebral spine is the bendable pillar from tail to neck, a composition of individual bones that interlock with each other, the vertebrae. In the human vertebral column, there are

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33 vertebrae numbered and separated into sections: cervical, thoracic, lumbar, sacrum, and coccyx. [4], as shown in Fig. 1.

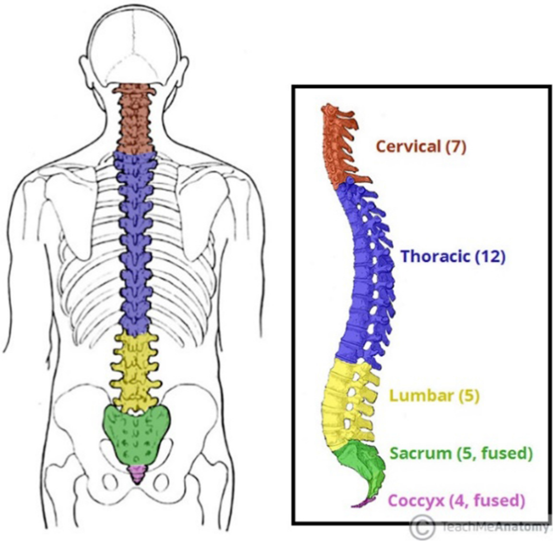



**Fig. 1.** The human spine vertebral structure (https://www.disabledworld.com/disability/types/spinal/spine-picture.php)

Studies on the human body's reply to the whole-body vibration (WBV) have approved that low back pain (LBP) is a major health, social and economic problem with indeterminate etiology [5, 6]. There are no known effective means of low back pain (LBP) prevention and control methods, and it is the leading cause of disability below the age of 45 and also it is the greatest expensive cause of productivity losses [7]. The improvement of seat setups for comfort, taking of rest days from driving, checking for low back pain related health status before working as a driver, and following a better life culture are the commonly suggesting measures for the prevention of low back pain (LBP) [8].

Humans' low back pain (LBP) may arise from any causes which is the discomfort that the person feels between the top of the leg and the ribs [8]. The occurrence of (LBP) is highly related to occupational driving activity and some other related tasks. In the case of Indian Kolkata (Taxi) drivers, the study shows that the LBP has greatly affected their regular domestic, social activates and their ability to work too. Many of the drivers have reported that LBP has disabled them to conduct their regular activities such as the lifting of small water buckets, washing of their clothes at home, taking the bath properly, and carrying on of some duties involving controlled postures [9]. The car drivers subjected to uncontrolled vibration are more commonly exposed to low-back pain (LBP) and progressive diseases than in typical control groups [10–12] because of the continuous whole-body vibration (WBV) reasons to health risks for the lumbar spine [8, 9, 13]. The determination of the definite condition of car driver low back pain needs the study on the diverse vehicle drivers of Pondicherry, and the one - week occurrence of low back pain (LBP) was 23.9% of respondents [14]; due to their occupational exposure, the problem of LBP is mostly significant in auto-rickshaw ( ባጃጅ) drivers [15].

As per various researches finding, the long-term whole-body shaking from the engines of vehicles is the significant mechanical stress factor contributing to the early and accelerated degenerative spine diseases, leading to back pain and prolapsed discs. In addition to this, improper passenger seat care, poor body posture while driving, and the fatigue of back muscles have been termed as the co-factors in the pathogenesis of musculoskeletal illnesses of the operators/driver's spine [8].

The vibrant nature of the operation of the engine and the road excitation are the main causes for the generation of in vibration every automobile, the generated vibration transfers to the cabin through mechanical joints. The human body has direct contact with the seats in the automobile cabin. Therefore, the vibration that comes from the engine will transfer to the occupant through the seat. The frequency of the vibration of any component of the vehicle generated by the engine is called excitation frequency. Resonance will occur when the excitation frequency of the vehicle component (especially the driver seat) is matched with the natural frequency of the environment component (human body) [16].

While assessing human exposure to whole-body movement, usually, the main focus of the studies is to find the resonant frequency of the human body. Because at the resonant frequency, the maximum displacement between the skeletal structure and the human organ will be takes placed, i.e. the biodynamic strain on the body tissue involved. Therefore, placing facts of the resonant frequency of the human body could help on the design of transport systems and industrial buildings so that the experience of vibration close to the body's resonant frequency may be minimized [17]. The force implemented at these special frequency points, where the peak of amplitudes, transforms more into vibration within the structure. The special frequency values, where the structure exhibit higher reactions against the implemented force, correspond to the natural frequencies of the structure [1].

In the case of the human body vibration scenario, the resonance occurs when the excitation frequency of the externally exerted force/load is closed to the fundamental frequency of the human spine. The most serious causes of lumbar degeneration and any related disease are the externally applied load/force and the deformation/strain in the lumbar during resonance [18]. Lumbar degeneration is a spine degenerative disorder and one of the common causes of low-back pain [19]. Therefore, to decrease the occurrence of lumbar degeneration, the occurrence of resonances needs to be prevented by applying curious optimization of any kinds of vibration sources via understanding the dynamic characteristics of the human body in such alike situations. To optimize the vibration source and subsequently prevent resonance, the excitation frequency of the vibration source should be maintained at extremely lower or higher than the natural/resonant frequency of the human lumbar spine, others human body's natural frequency as well. The excitation frequency of the vibration source of any system can be determined and adjusted by controlling and monitoring of the speed the energy source of the system. The challenge is the determination of the exact specific natural frequency of different human bodies.

The value of the excitation frequency of the structure under mechanical vibration is needed to be far from the natural frequencies of the structure; this condition may prevent the injuries caused by vibration. To achieve this condition and in the design of the vibration sources in working and living environments, the determination of the natural frequency of the structure is mandatory [19]. Even though works associated with the human body whole-body vibration (WBV) is rare [3], some investigations measured that the vertical direction natural/resonant frequency of the human lumbar spine in supine posture ranges within 1–6 Hz [11], an average of 4.4 Hz [20]. The extreme displacement effect(strain) for sitting posture, semi-supine, and standing has happened at between 4 and 6 Hz, (5–6 Hz) and 6.7 Hz, respectively [3].

There are various rationales in the analysis of human body natural frequencies based on the assumption of the human spine as a single mass system, the fundamental frequency of the spine is 8 Hz [21]. Different results of human body frequencies may be evaluated if the internal organs are taken to deliberation; it also depends on the position, orientation, and direction of the person subjected to vibration. By considering the partial lower spine finite element only, the natural frequency is determined as 3.5 Hz [19]. The human body is not rigid enough to have one natural frequency. The heart the muscles the bones the kidneys the liver and others have different compositions and densities and hence different natural frequencies. The realistic specific numerical natural frequency value of the human lumbar spine vertebrae has not been determined yet. Even though it is difficult to consider the actual human models due to their properties, geometries, joints, and other nonlinearity, it is possible to address the geometrical nonlinearity effect of the human spine by considering a realistic three-dimensional geometrical model of the spine vertebrae. Also, this study hypothesizes that it is not possible to have a single fundamental frequency for all spine vertebrae because of their geometrical unlikeness. Understanding of the frequency of the human body, specifically, the dynamic/vibrant response of the human spine is mandatory to provide insights into the relationship between vibration and spinal diseases. In order to provide comfortable and healthy travel by decreasing the vibration coming from the chassis of the intercity buses and any other related situations, this paper aimed to determine the fundamental frequency of each human spine vertebrae with the help of a detailed three-dimensional finite element model analysis based on the actual vertebral geometry. To determine the fundamental frequency of the human spinal cord, a complete three-dimensional FE model of the human spine was constructed with referring of the real vertebral geometry by using solidworks CAD modeling software package and the modal analysis was done via finite element method (FEM) with the help of Ansys 17.2 workbench software package. In addition, this study may be supportive in sympathetic further the nature of dynamics of the human spinal cord under the phenomenon of riding of the vehicle or any conditions when the whole body vibrates.

## 2 Materials and Methods

### 2.1 Natural Frequency and Mode Shape

In a free vibration state, there are numerous frequencies in which every structure has a trend to vibrate; these frequencies are usually called natural frequencies. Every natural frequency does have a related mode shape that the model could be assumed when it is vibrating at that frequency [22]. That information, mode shape, is the deformed shape of the structure that is associated with each natural frequency. Mode shape may also call as characteristic shape and fundamental shape. The deflection pattern of the structure associated with the first, second, third, …natural frequency is called the first, second, third, … mode shape; respectively.

Modes of vibration are the characteristic method in which vibration occurs. In a freely vibrating system, oscillation occurs in a certain characteristic frequency, i.e. Natural frequencies of the structure. The frequency of oscillation is termed as modal frequency (or natural frequency) and the shape made by the system is called mode shape. Mode shapes tell us how the structure tends to deform at the specific natural frequencies. The mode shapes tell us which regions would experience high stresses if the deformed shape is similar to the mode shape. Any structure does have its inherent modes. Modes of a structure are depending on its material properties (stiffness, mass, and damping factor), and the initial condition of the configuration of the structure. Every mode of the structure is defined by the natural frequency, mode shape, and modal damping; these are usually called modal parameters.

In structural engineering, it is crucial to determine the deterministic parameters such as strain, stress, frequencies, and corresponding mode shapes of a given set of design configurations. In the several applied engineering problem models that encompass any geometrical and physical factors, it is challenging to have a well-defined value of parameters due to the non-consistency of the mass distribution geometric properties or physical errors, as well as differences coming from the fabrication and assembly; and production procedures. In the same way, it is difficult to have well-defined geometrical and material properties and constraint parameters of the human spine. Due to the nonlinearities of the human body muscle-skeleton system and the nature of the excitation load, it is difficult to construct an accurate analytical mathematical model that could represent the transmission of dynamic loads from the vehicle structure to the occupant. Due to this reason, the utilization of the finite element analysis method is a helpful and valuable approach to address such dynamic response analyses. Since the FE modeling method could able to crack geometrical nonlinearity challenges easily relative to mathematical models.

## 2.2 Geometrical Model

The three-dimensional human spine CAD model can be constructed with the help of different methods, such as anatomy-based method, 3D scanner-based method, digital image-based method, etc. [23]. This study considered a resembled 50 percentile Chinese males' size which is a 75.5 kg of mass and 1.74 m of standing height and then the human spine body model has been developed as shown in Fig. 2, and the parametric data has been adapted from [23].

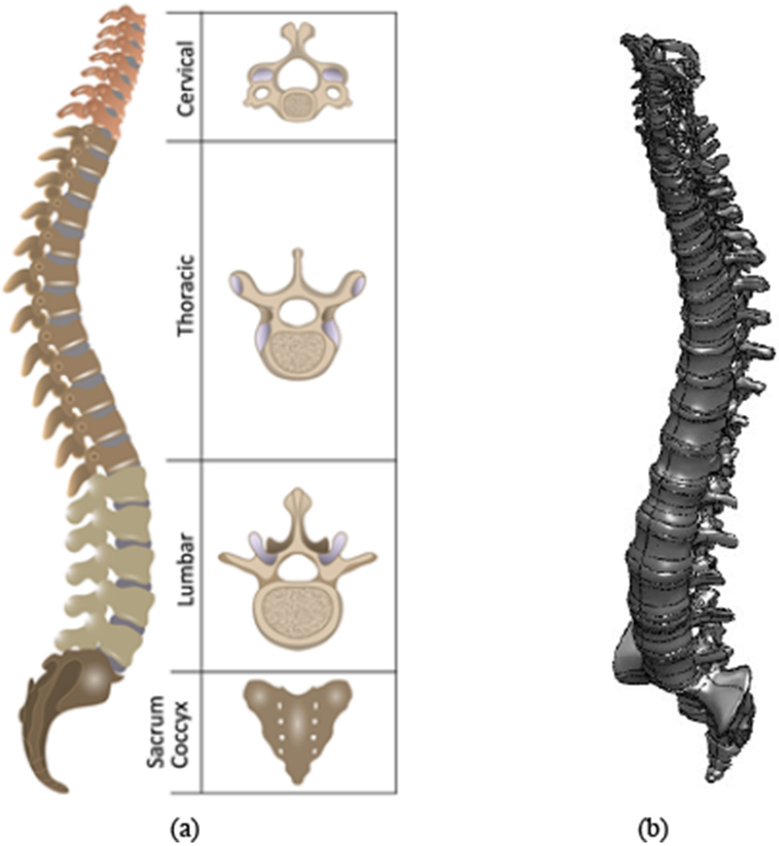



**Fig. 2.** (a) The vertebrae image (https://www.shutterstock.com/search/vertebrae), and (b) 3-Dimensional geometrical CAD model human spine

# 3 Finite Element Analysis

## 3.1 Modal Analysis

The modal analysis technique is used to determine the natural frequencies and corresponding mode shapes of an object. In addition to the determination of the vibration response of complicated structural dynamic problems, this technique is also being used for the identification, evaluation, and validation of the vibration phenomena, integrity assessment, structural modification, and damage detection [24] purposes.

The modal investigation of the human spine body is done to compute the natural frequencies and allied mode shapes. To analyze vibration mode and degree of freedom DOF that contribute to the primary resonance observed in the response of apparent mass, the frequencies and modes have been studied. The equation of motion for free un-damped vibration has been utilized, Eq. (1) [3].

$$[M]\{\ddot{x}\} + [K]\{\dot{x}\} = \{0\} \tag{1}$$

Where: K and M are the stiffness matrix and mass computed from the model, respectively. The solution to Eq. (1) enables to determine the natural/fundamental frequencies and the vibration modes of the physical model.

During free vibration analysis, the natural frequencies and mode shapes of a structure can be determined by using modal analysis. When the object is permitted to vibrate without the application of external excitation, the resulting frequency is called natural frequency. In an actual case, anybody does have unlimited numbers of natural frequencies, however, the modal FE analysis calculates the very important numbers of natural frequencies these are equivalent to the DOF of the computing FE model only and the resulted in lowest frequency is called the fundamental frequency. This work deals with the finding of the fundamental frequency of the human vertebral spine with the free-free analysis, i.e. there is no applied external force to the body.

The finite element model of the spine vertebrae and other bone structures are considered as shown in Fig. 3. For the sake of the good accuracy of the FE model, the whole elements of the lumbar vertebrae CAD model have meshed finely. With the incorporation of reasonable simplifications, the mesh discretization is described by 213,123.00 quadrilateral, 2,135,746.00 tetrahedral, and 655.00 triangular elements connecting by 222,333.00 nodes. The material properties of the human spine vertebral body were taken as shown in Table 1, [23]. Finally, all parts developed as vertebrae are characterized as stiff parts, joined to each other by joints in which rotation and translation are allowed [25].

## 4 Result and Discussion

In principle, six-dimensional vibration modes may be used to represent a three-dimensional uninterrupted structural body. During driving of the vehicle, the vibration of the driver will have six degrees of freedom for any occupants as well. Even though the occupants or the driver do have tri axial displacements, the spine mainly performs the vertical motion during full-body vibration or WBV [13, 26], due to the upward nature of the load. Due to its great influence effect on the modal analysis, the vertical direction displacement of the human spine body has been considered for both mode shape curve and natural frequency analyses.

### 4.1 Natural Frequencies of the Spine

Figure 4(b) shows the contour image of the modal analysis results of the vertebrae found in the lumbar, thoracic, and cervical spines. Figure 4(c) describes the natural frequency results of each vertebra of the whole region of the spine with the help of the spine vertebrae(x-direction) versus their fundamental frequency (y-direction) graph plot.

From the graph, Fig. 4(c) the minimum fundamental frequency is evaluated at the thoracic spine region for T4 and T5 with a value of 6.023 and 7.002 Hz, respectively. These minimum fundamental frequencies are the most common causes of spine discomfort and degenerative disease because the minimum fundamental frequency is significantly where the resonant condition occurs in any structure which is subjected or vibration.

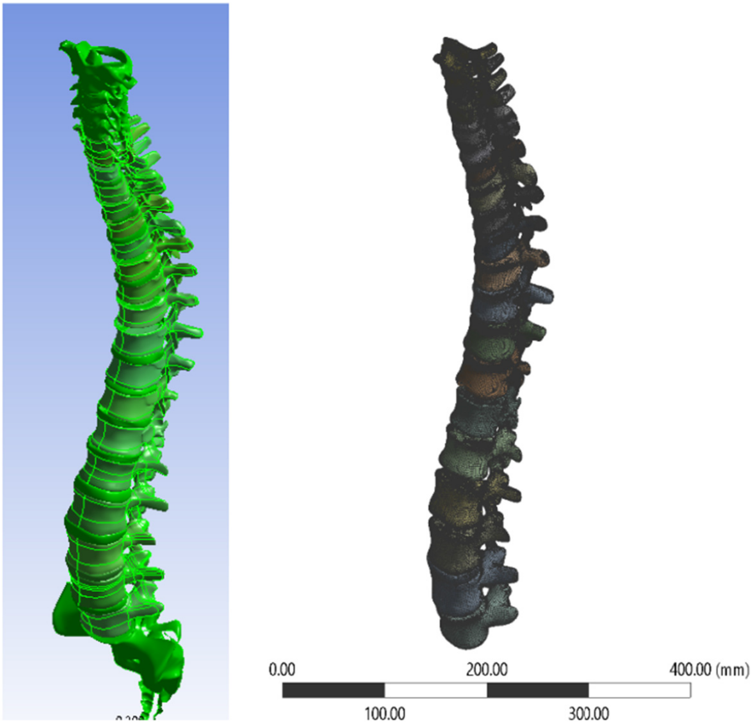



**Fig. 3.** The meshed FE model

**Table 1.** The material property of human spine vertebrae.

| Structure/body | Elastic modulus E (MPa) | Poisson's ratio $\mu$ | Density $\rho$ (kg/m$^3$) |
|---|---|---|---|
| Human spine vertebrae | 12,000 | 0.3 | 1700 |

From Fig. 4, it can be stated that if the excitation frequency lies on one of the frequencies in the region (6–19 Hz), the driver or the occupant most likely feel discomfort since the resonance is occurring. At the condition of resonant, for vehicle drivers and the occupants, a small vertical force transmitting from the engine and road nature may able to create huge stress in the root of the vertebrae i.e. that make a big possibility to happen a bone fracture. Therefore, the excitation frequencies of any occupation which possibly create vibration should be maintained at very Farley low or high frequency of a range of (6–19 Hz).

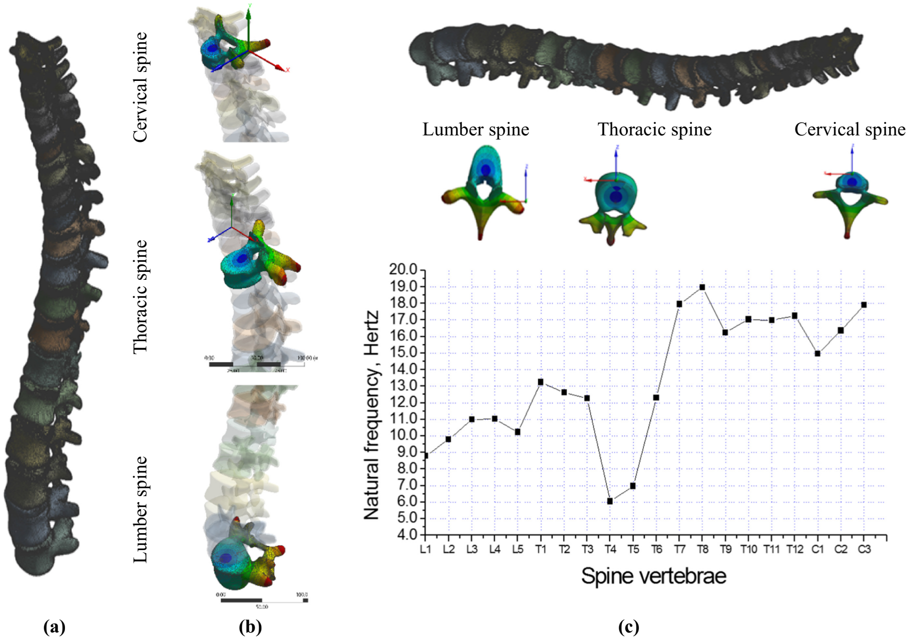
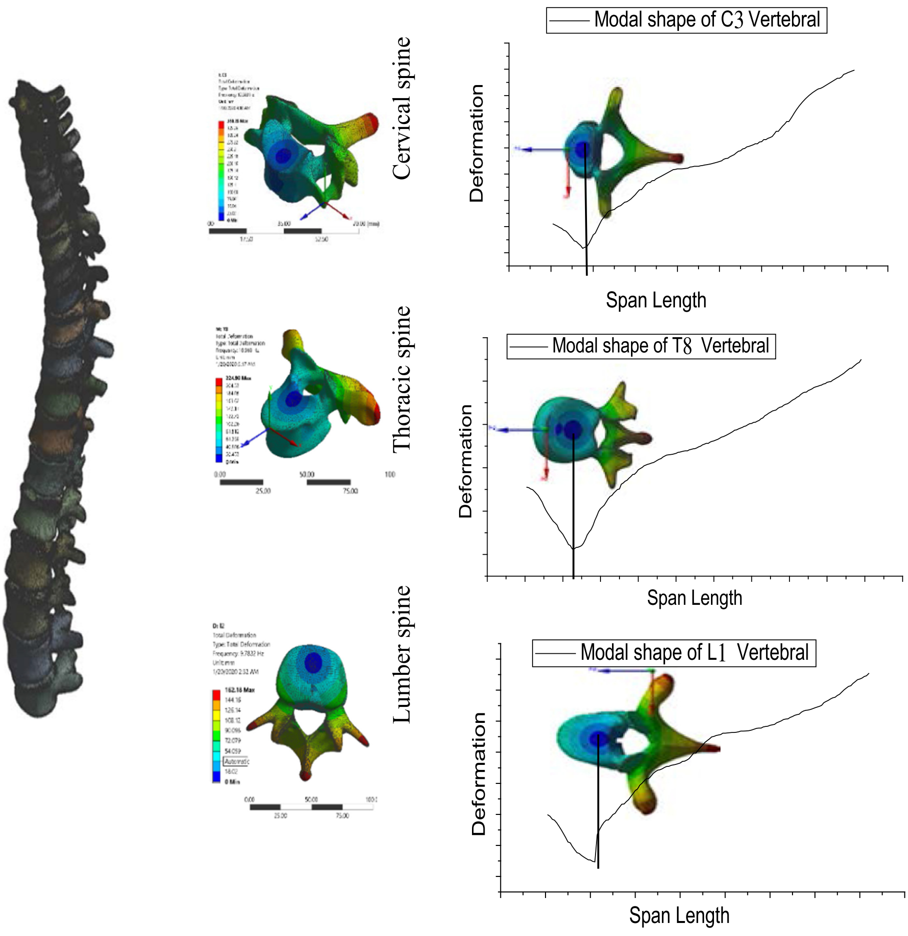



**Fig. 4.** (a) The meshed model, (b) the modal analysis of the human spine vertebrae, and (c) the vertebra of the human spine versus the fundamental frequencies value graph

## 4.2 Mode Shape of the Spine

Figure 5 shows the modal analysis, fundamental frequency, and corresponding mode shape, results of the L2, T8, and C3 vertebrae of a human spine. Figure 5(b) shows the contour image results of the total deformation and natural frequency of L2, T8, and C3 vertebrae; in the same way Fig. 5(c) describes the modal shape of these vertebrae at corresponding fundamental frequencies.

As shown in Fig. 5(b), the maximum vertical displacement is evaluated at the tip vertebra or process of the whole three regions of the spine (the lumbar, thoracic, and cervical spines) and the minimum displacement has occurred around the center of vertebras. This is happening because processes are the free ends and the central part of the vertebral body (spinal cord) is where the constraint is applied. From the basics of structural mechanics, when a structural member is subjected to a certain load, the maximum stress will occur at the region where minimum displacement has occurred and minimum stress will occur at the region where maximum displacement has occurred. This leads to say that the main cause of the vehicle's driver discomfort is the pain at the root or center of the vertebra of the whole spine. Since, these regions are where the maximum stress is occurring. From this, it is suggested that drivers sit with maintained leaned on the backrest of the seat, the occupants as well. Because maintained lend sitting of the drivers and passengers may prevent the occurrence of maximum stress at the root of the vertebra by distributing the exciting load towards the contacted region [23].




(a) (b) (c)

**Fig. 5.** (a) The meshed model of the spine, (b) the natural frequency results, and (c) the modal shape graphs of the L2, T8, and C3 vertebrae of the spine.

## 5 Conclusion

In general, this study concludes that even though the nature of the material of all vertebrae of a human spine is considered as the same, its fundamental frequency couldn't be a specific constant value because of their shape, size, and other geometrical non-uniformities. This study revealed that the minimum fundamental frequency of an adult human spine is around 6.023 Hz evaluated at the thoracic spine region, (T4). But it is not necessarily mean that the resonant phenomenon of the human spine vertebrae takes place at this specific excitation frequency, instead resonant of the human spine may occur in the frequency range of 6–19 Hz. Therefore, to reduce the occurrence of resonant of the human spine body, the excitation frequency of externally applied load should be maintained far from this range. This study didn't consider the influences of human factors such as BMI (body mass index), sex, and age on the natural or resonant frequency of human spine vertebrae. Besides, muscles were not included in the current spine FE model. Future studies may investigate the effects of human factors and muscle activations on the human spine's fundamental frequency.

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