Vibration and Modal Analysis of Femur Bones

Adane Minuye[1], Mesfin Gizaw[2]

[1,2]Addis Ababa Science and Technology University, Ethiopia
[1]adaneminuye14@gmail.com

Article Info

Article history:

Received Sep 15, 2021
Revised Nov 28, 2021
Accepted Jan 19, 2022

Keywords:

Femur Bone
FEA
Modal Analysis
Natural Frequency

ABSTRACT

A review of vibration and modal analysis of bone is studied. Specifically, more focus is given to femur bone to provide more insight of where fracture occurs and how it can be protected. Also, modal and vibration analysis are done on femur bone applied to two boundary situations that are free- free and fixed-fixed. Natural frequencies and natural vibration modes are established for these two differing boundary situations. According to the mode structure, the normal frequency of the free-free boundary case ranges from 0 to 1381.1 Hz. Also, for fixed-fixed boundary situation it varies from 1211 Hz to 7856.4 Hz. On the basis of these two boundary situations mode structure is confirmed and fracture part can be simply informed. In order to avoid the fracture of femur bone avoid coincidence of external excitation frequency with these natural frequencies. This analysis gives more vision in constructing bio- aided material or protective sports material for femur.

Corresponding Author:

Adane Minuye,
Addis Ababa Science and Technology University, Ethiopia
Email: adaneminuye14@gmail.com

1. INTRODUCTION

(Burdzik, 2018)have studied lifestyle of people which has been changed from early decades with new technologies due to which people used to travel by trains, buses, airplanes and cars. While travelling by air, on water, rail or road, human body feels an ill effect due to vibration generated from different segments of the transport mechanism. Human body is exposed to vibration situations with daily life activities like walking, running, working etc., or when the body comes in contact with vibrating objects while person standing on a vibrating floor, sitting on a vibrating chair or lying on a vibrating bed.

Many researchers and authors have studied human body vibration for more than 50 years. (GRIFFIN et al., 1998) have considered the movement of seat vibration to the head and examine the unfortunate reactions of whole-body vibration. They have also consumed the mechanical, psychological and physiological features of whole-body vibration. (E.T. Ingólfsson et al., 2012) have achieve a literature review for Pedestrian-induced oblique vibrations of footbridges and discover the several aspects for footbridges strategy to minimize the retrofit charge because of vibration. (Tiemessen et al., 2007) have conducted a survey research for drivers in order to decrease whole-body vibration revelation and to attempt to identify a result to decrease whole-body vibration WBV is caused by a variety of factors, including posture, plan consideration, period of vibration, and amplitude of vibration. (Leboeuf-Yde, 2000) have performed Whole-body vibration and low back pain. They came to the conclusion that there is a straight link between WBV and low back discomfort and proposed techniques to lessen WBV. They found that WBV is induced though leg.

(Valentini, 2012) have assumed the human spine vibration using numerical dynamic representation. The modeling strategy is based on the application of the dynamic spline formalism to generate a reduced characterization with a minimal group of variables, which is then compared to the literature result. (Pionteck et al., 2017) have done FE Model and operational modal investigation was done on lower limbs and determines the specific frequency which is harmful for these limbs. After determining this harmful frequency, they develop specific materials that have ability to absorb certain precise frequencies and reduce the number of vibrations perceived by the lower limbs of humans.

(Sadeghi & Bakhtiari-nejad, 2019) & (P. B. Kumar & Parhi, 2017)showed Femur bone (thigh bone) is the lengthy bone in the body of the human. This bone links the knee to the pelvic bone that sustains most of the body weight. Fracture of the hip and femur bone are of the most common bone fractures in humans, especially in the elderly. When performing physical activity and sudden blows it needs investigating the natural frequencies and the mode structure of the vibrating devices. In order to understand the vibrating and dynamic behavior of the bone and more attention should be given to geometry.

(Khalil et al., 1981) The natural frequencies of a femur bone were determined through experimentation and research. Fourier analysis and the Transfer Matrix approach were used to produce the experimental and analytical results, respectively. A mathematical model with 59 parts was investigated utilizing the transfer matrix approach for an analytical solution. The model under consideration was an easily vibrating bone, which is not the case. Bone is confined between the pelvis and the tibia in a genuine structure. As a result, such a boundary criteria is unjustifiable. The first 20 empirical natural frequencies of femur bone for free-free boundary state were discovered to range between 250 and 7300 Hz. The analytical answer to natural frequency is likewise in this region. However, the natural frequencies for the longitudinal type of vibration were 2118 Hz, 4407 Hz, and 7264 Hz.

The impact of vibrations on the femur bone was investigated by (Thomas et al 1991). Whereas limited part examination was used to forecast a Femur fracture by (Grassi, L. et al 2012) and (Haider et al 2013).

(A. Kumar et al., 2014) and (Kharatmal et al., 2020) recommended that the fundamental goal of the Femur bone investigation is to get the natural frequencies, instinctive vibration modes, and possible parts of fracture in the bone using computer simulation based on FEA. The results were obtained for two diverse boundary situations which are free-free and fixed-fixed. The simulation result is compared to the literature result were found to be in good agreement. Although any mode from the first to the highest can be excited by an external load, lower nodes are simple to excite.

2. CAUSES OF FEMUR BONE FRACTURE

2.1. External excitation

(O. T. and M. J. Griffin, 1997) studied trouble of standing human subject while subjected them to sinusoidal vibration in three different directions such as fore-and-aft, vertical and in oblique directions. 12 human subjects have been considered and analyze the discomfort experienced at 4 Hz vibration situations at magnitudes of 10 different values. In fore and aft direction at frequency of 4 Hz human subject is more sensitive than in vertical direction. (Burdzik, 2018) investigate the effects of vibrations caused by the action of the vehicle floor on passengers in a car. The way of transmission through the feet and lower limbs, loins, and chest to the head was calculated using vibration mechanics.

(S. K. and M. J. Griffin, 2012) used FEM to progress 2-D model of human responses exposed to WBV; Spine, head, viscera, buttock and pelvis tissues were modeled by using mass element, beam and spring. With the changing of posture from “erect to slouch” under vibration situations, causes to increases deformation i.e., shear in tissue of entire body beneath pelvis. Experimental study exhibited that while seated human body subjected to WBV, principal resonance for driving point impedance and apparent mass was found to be between 3 and 5 Hz. Described two models i.e., discrete and continuum; in discrete model, spine is treated as layered structure and for continuum models the spine were treated as homogeneous rod and beam. The objective of study was to developed a biomechanical model to compared a mode structure of model.

(A. Kumar et al., 2014) and (Nassar & Almudhaffar, 2014) did vibration analysis on human femur to analyze the natural frequencies, to draw the mode structures. They determine the part of the bone fracture using a computer simulation based on the FEA. Finite element Analysis or Finite Element Method is a calculation technique used for the investigation of compound geometries. The femur bone investigation is exposed to fixed-fixed and free- free boundary situations and natural frequencies and natural vibration forms are recognized. The mode structure reveals that the natural frequency of the free-free boundary situation ranges from 0 to 1381.1 Hz, whereas the natural frequency of the fixed-fixed boundary situation ranges from 1211 to 7856.4 Hz. The outcomes of this study express that the highest prospect of bone fracture is through bone shaft and neck part. As a result, external excitation frequency must be avoided in order to correspond with these natural frequencies in order to avoid femur bone fracture.

(Kharatmal et al., 2020)The main cause of failure of the femur bone is sudden and continuous vibration. Critical failure of the bone can arise if the natural frequency of the bone is equivalent to its excitation frequency due to resonance. It was observed that the fracture can arise at either the bone shaft or on the neck part of the bone.

2.2. Age

(P. B. Kumar & Parhi, 2017),(Nassar & Almudhaffar, 2014)& (Wargante & Warhatkar, 2020)Aged human(elders) bone is prone to osteoporosis which is a disorder categorized by little bone mass and microarchitectural degeneration of bone tissue, inducing to greater bone fracture. Women are three times as likely than males to develop osteoporosis. Women experience bone loss during perimenopause, which is related with oestrogen deficiency, a menopausal disease. Osteoporosis occurrence in Women age over 80 years is about 70%. It occurs when the struts that form the mesh-like network within bones become weak, delicate, and simply broken as a result of a simple bump or drop. These damaged bones are sometimes referred to as delicateness fractures. Even though fractures can happen in every area of the skeleton, low-trauma injuries most typically affect the wrists, hips, and spine (e.g., a fall from standing height). The pain associated with osteoporosis is caused by these fractures. It is the most general metabolic bone situation and is becoming an progressively serious issue, impacting 200 million people globally.

(Nokes, 1999), (Pinar Arpinar, Beyza Simsek, Onder Cem Sezgin, 2005)The unique relationship between material properties and resonant frequencies has directed to the use of vibration. The vibration method is a non-invasive method for detecting the difficulty of extensive bones as well as assessing the influence that osteoporosis may have on mechanical qualities. This method has also been used to regulate the rate of healing of fractures, identify the incidence of a bone fracture, and detect loosening of hip prosthetic.

(Wargante & Warhatkar, 2020) If the length, weight and size of the bones are different, the first fundamental frequency is roughly the same. It intends that if the age of the subject is close to the same, the regular frequencies are likewise near to each other.

Table 1. Experimental natural frequencies (HZ) goat femur bones

Mode Number	Bone 1	Bone 2	Bone 3	Bone 4	Bone 5
1st	25.6	25.5	27.75	27.5	25.6
2nd	96	95.5	115.2	98	85.33
3rd	160	158	198.4	160	170.7
4th	224	221.8	280	226	251.7
5th	288	285.8	363	290	307.2
6th	353	350	460	356	370.5
7th	425	436	531.2	430	454.6

This table shows the natural frequency is nearly similar for equally aged people.

3. MODAL ANALYSIS

Modal analysis was did in ANSYS using Finite Element analysis to get modal characteristics such as natural frequency and related mode structures. The following is the governing equation for the dynamic response;

$$[\boldsymbol{M}]\{\ddot{x}\} + [\boldsymbol{C}]\{\dot{x}\} + [\boldsymbol{K}]\{\boldsymbol{x}\} = \boldsymbol{0} \quad \text{eq.1}$$

Where $[\mathbf{M}]$, $[\mathbf{C}]$& $[\mathbf{K}]$ are the global mass, damping and stiffness mediums of the structure; $\{\ddot{x}\}$, $\{\dot{x}\}$ &$\{\boldsymbol{x}\}$ are the nodal acceleration, velocity and displacement vectors correspondingly. For undamped free vibration (i.e., $[\boldsymbol{C}] = \boldsymbol{0}$), the result of the above expression can be written as follows Eq. 2.

$$\{\boldsymbol{x}\} = \{\boldsymbol{X}\} \quad \text{eq.2}$$

Where $\{\mathbf{X}\}$ signifies the amplitudes of all the masses (mode structures or eigenvectors) and $\boldsymbol{w} = \boldsymbol{2\pi f}$ signifies each eigenvector's corresponding eigen frequency in rads-1, while **f** signifies the natural frequency in hertz. Thus, the foremost equation mentioned above lessens to the following Eq.3:

$$[[\boldsymbol{K}] - \boldsymbol{w}^2[\boldsymbol{M}]]\{\boldsymbol{X}\} = \boldsymbol{0} \quad \text{eq.3}$$

The natural frequencies of the bone plate arrangement are obtained by giving the material properties (Young's modulus, Poisson's ratio and density) as input in ANSYS workbench. (D.C.Wirtz 2000) The material properties chosen for the research of the femur bone are Young's modulus – 7.585GPa, Poisson ratio- 0.35, Bone density- 866kg/m3. While doing modal analysis fixed-fixed boundary situation is applied to the femur bone plate structure.

Table 2. Synthesis of Review for Related Work

No	Author(year)	Purpose	Method	Findings	Similarity	Differences
1	M. J. Griffin et al., 1997	Cause of bone fracture	Finite element analysis	Vibrating system come in contact with body causes vibration	Bone fracture happens by a cause	External excitation is the cause of bone fracture
2	Almudhaffar , et al. (2014)	Cause of bone fracture	Finite element analysis	If the weight, length, and volume of the bones are different, the first fundamental frequency is roughly the same.		Osteoporosis is the cause bone fracture
3	(Khalil et al 1981)	modal analysis of femur bone	Experimental analysis	Obtain natural frequency	The effect of vibrations on the femur bone was studied	Uses Fourier analysis and transfer matrix
4	(A. Kumar et al., 2014)	Modal analysis of femur bone	Finite element analysis	Obtain natural frequency any mode of vibration		Uses computer simulation

4. RESULTS AND DISCUSSION (FINDINGS OF THE STUDY)

The modal examination yielded the following ten natural frequencies and mode structures with free-free and fixed-fixed boundary circumstances:

Table 3. Mode number and coinciding normal frequency for two boundary situations

Mode number	Natural frequency (HZ) for free-free	Natural frequency (HZ) for fixed-fixed
1	0	1211
2	3.20E-03	1268.9
3	4.61E-03	2818.1
4	1.02E-02	2983.9
5	1.07E-02	4918.2
6	1.08E-02	5044.6
7	448.56	5220.9
8	523.74	7160.3
9	1109	7663.2
10	1381.1	7856.4

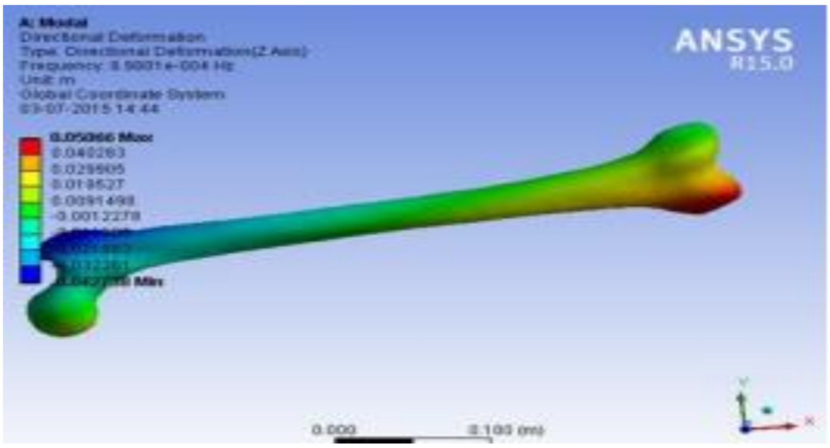

Figure 1. Mode Structure 6 for free-free boundary situation

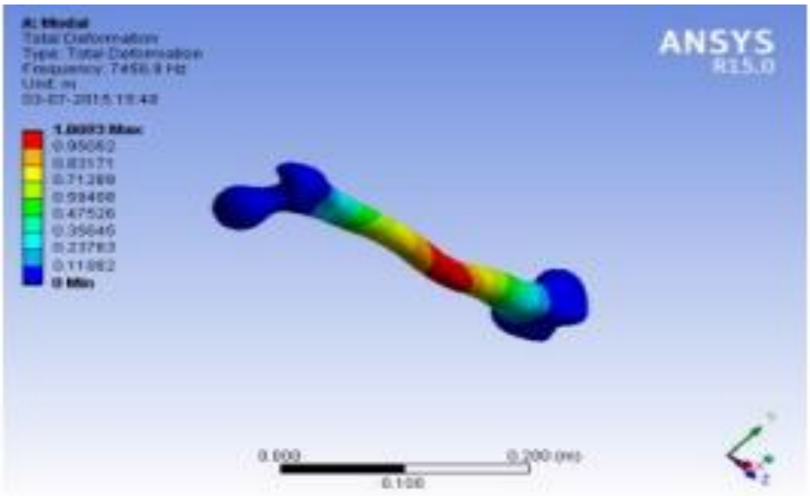

Figure 2. Mode Structure 1 for fixed-fixed boundary situation

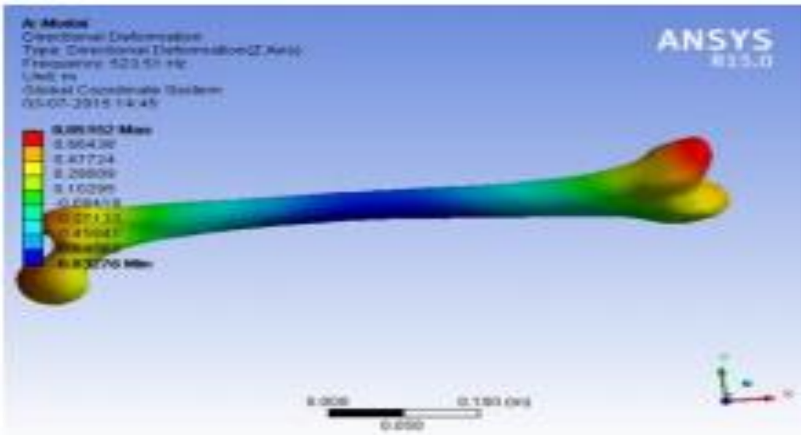

Figure 3. Mode Structure 8 for free- free boundary situation

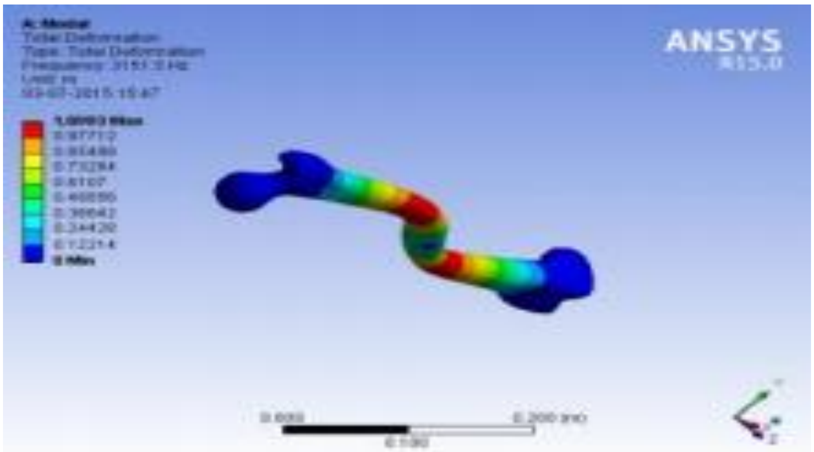

Figure 4. Mode Structure 7 for fixed-fixed boundary situation

The FEM based Ansys software solved the hip bone modal examination and we find the natural frequency and mode structure. In orthopedic issues, modeling of boundary situations and joints are very difficult issues and they might have no exclusive outcomes. The table shows the first 10 natural frequencies of Free-Free and Fixed-Fixed boundary situations. In free-free boundary situations all DOF of boundaries are subjected to variations while in fixed-fixed boundary situations all DOF are constrained in the boundaries. The outcomes are also in better contract with new work by (Khalil et al 1981).

The modal frequency outcomes are free vibration data; if femur bone is exposed to forced vibration, the chances of fracture increase. To avoid the fracture during external loading the model should be changed so that the forced frequency does not match to the natural frequency. During forced excitation state the fracture position can be easily determined by looking the specific mode structure. Example; for mode 6 fracture part is at the shaft of the bone and for mode 7 @neck region of the bone.

4.1. Research gap

From literature review, it has been observed that numerous works have been done in the field effect of vibration on human body. This is to improve the comfort stage and lessen the tendency of getting resonance with intended product for human use. To fill gaps as per literature review, a current study has been performed that are as follows:

a. It has been observed that mostly analytical and experimental work has been performed on Asia, US, European human subjects in comparison to Ethiopian human subjects using FEM.

b. Modal analysis has been performed using FEM didn't consider muscle effect on bone vibration analysis.

c. Vibration and modal analysis weren't done for free-fixed boundary situation.

d. Forced vibration wasn't analysed.

By considering above mentioned gaps found from literature review, current study has been performed to fill above mentioned gaps.

4.2. Future trends of the study

Failure detection direction; investigate the failure mode analysis using free-fixed boundary situation.

Simulation direction; simulate the modal and vibration analysis of bone using FEA on ANSYS software in order to point specific fracture part.

5. CONCLUSION

In this review, vibration analysis of human body, femur bone, causes of failure and techniques of fractured bone fixation is analyzed. Journals and articles are reviewed which was done since 1981.

After all the following conclusion are drawn

- FEM approach is used to perform modal and vibration analysis. Different parameters have been considered while performing modal and vibration analysis.
- Fracture of femur bone occurs at either the neck or on the shaft part of the bone.
- Low bone mass is associated with fracture.
- If age of persons is near to each other they have almost similar natural frequency irrespective of weight and height.
- Generally, fracture of bone can be removed by avoiding coincidence of external excitation frequency with the natural frequencies.

ACKNOWLEDGMENT

For his support, a heartful thank and gratitude forwards to my advisor Mesfin Gizaw (PhD).

REFERENCES

[1] R. Burdzik, "Analysis of vibration propagation in the human body," *J. Meas. Eng.*, vol. 6, no. 4, pp. 271–276, 2018.

[2] D. C. Wirtz, N. Schiffers, T. Pandorf, K. Radermacher, D. Weichert, and R. Forst, "Critical evaluation of known bone material properties to realize anisotropic FE-simulation of the proximal femur," *J. Biomech.*, vol. 33, no. 10, pp. 1325–1330, 2000.

[3] E. T. Ingólfsson, C. T. Georgakis, and J. Jönsson, "Pedestrian-induced lateral vibrations of footbridges: A literature review," *Eng. Struct.*, vol. 45, pp. 21–52, 2012

[4] L. Grassi *et al.*, "Accuracy of finite element predictions in sideways load configurations for the proximal human femur," *J. Biomech.*, vol. 45, no. 2, pp. 394–399, 2012.

[5] G. S. Paddan and M. J. Griffin, "A review of the transmission of translational seat vibration to the head," *J. Sound Vib.*, vol. 215, no. 4, pp. 863–882, 1998.

[6] O. Thuong and M. J. Griffin, "The vibration discomfort of standing people: relative importance of fore-and-aft, lateral, and vertical vibration," *Appl. Ergon.*, vol. 43, no. 5, pp. 902–908, 2012.

[7] S. Kitazaki and M. J. Griffin, "A modal analysis of whole-body vertical vibration, using a finite element model of the human body," *J. Sound Vib.*, vol. 200, no. 1, pp. 83–103, 1997.

[8] I.T. Haider, A. D. Speirs, and H. Frei, "Effect of boundary conditions, impact loading and hydraulic

stiffening on femoral fracture strength," *J. Biomech.*, vol. 46, no. 13, pp. 2115–2121, 2013.

[9] T. B. Khalil, D. C. Viano, and L. A. Taber, "Vibrational characteristics of the embalmed human femur," *J. Sound Vib.*, vol. 75, no. 3, pp. 417–436, 1981.

[10] S. K. Kharatmal, P. Ravindrannair, K. Sridhar, M. A. M. Ali, and V. Rajashekhar, "Structural and vibrational analysis of femur bone using FEA," in *Lecture Notes in Mechanical Engineering*, Singapore: Springer Singapore, 2020, pp. 535–551.

[11] A. Kumar, H. Jaiswal, T. Garg, and P. P. Patil, "Free vibration modes analysis of femur bone fracture using varying boundary conditions based on FEA," *Procedia mater. sci.*, vol. 6, pp. 1593–1599, 2014.

[12] P. B. Kumar and D. R. Parhi, "Vibrational characteristics and stress analysis in a human femur bone," *Mater. Today*, vol. 4, no. 9, pp. 10084–10087, 2017.

[13] S. Lings and C. Leboeuf-Yde, "Whole-body vibration and low back pain: a systematic, critical review of the epidemiological literature 1992-1999," *Int. Arch. Occup. Environ. Health*, vol. 73, no. 5, pp. 290–297, 2000.

[14] M. Almudhaffar, A. A. Nassar and H. A. Kareem. "Vibration of bones: a case study on human femur", *Basrah Journal for Engineering Science.* vol. 14, no. 2, pp.:229-39, 2014.

[15] L. D. Nokes, "The use of low-frequency vibration measurement in orthopaedics," *Proc. Inst. Mech. Eng. H*, vol. 213, no. 3, pp. 271–290, 1999.

[16] P. Arpinar, B. Simsek, O. C. Sezgin, G. Birlik, and F. Korkusuz, "Correlation between mechanical vibration analysis and dual energy X-ray absorptiometry (DXA) in the measurement of in vivo human tibial bone strength," *Technol. Health Care*, vol. 13, no. 2, pp. 107–113, 2005.

[17] A. Pionteck, X. Chiementin, M. Munera, S. Murer, D. Chadefaux, and G. Rao, "FE model and operational modal analysis of lower limbs," *Appl. Sci. (Basel)*, vol. 7, no. 8, p. 853, 2017.

[18] P. K. Satapathy, B. Sahoo, and L. N. Panda, *Static and Modal Analysis of Functionally Graded Bone Plate at Femur Bone Fracture Site*.

[19] A. M. Thomas, D. Z. Luo, and J. W. Dunn, "Response of human femur to mechanical vibration," *J. Biomed. Eng.*, vol. 13, no. 1, pp. 58–60, 1991.

[20] I. J. Tiemessen, C. T. J. Hulshof, and M. H. W. Frings-Dresen, "An overview of strategies to reduce whole-body vibration exposure on drivers: A systematic review," *Int. J. Ind. Ergon.*, vol. 37, no. 3, pp. 245–256, 2007.

[21] P. P. Valentini, "Modeling human spine using dynamic spline approach for vibrational simulation," *J. Sound Vib.*, vol. 331, no. 26, pp. 5895–5909, 2012.

[22] A. Wargante and H. Warhatkar, *Experimental Vibration Analysis Of Goat Femur Bones*. 2020.