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VIBRATION ANALYSIS OF FEMUR BONE USING ELMER

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Abstract

Femur bone is one of the most commonly fractured bones of human body, especially for the elderly people. It is one of the longest and largest bones found in human beings. In this paper, vibration analysis of femur bone is studied by the help of finite element simulation to provide more insight in designing bio-aided equipments or protective sports equipments for femur. The simulations were performed using the open source software – Elmer. The vibration patterns for first twenty modes were studied. The vibration analysis show that the natural frequency of vibration varies from 964 Hz to 10.8 kHz. The external excitation on the femur bone must be avoided to coincide with these natural frequencies; otherwise it could lead to fracture of the bone.

Keywords: Biomechanics, Finite element simulation, Femur bone, Vibration modes.

1. Introduction

Finite element analysis [1] is a computer based method for performing numerical analysis which can be used to analyse structures of complicated geometry and inhomogeneous material properties. Finite element method (FEM) is widely accepted and used as an alternative tool for biomechanics modeling [2] which has complicated geometrical shapes and heterogeneous material properties.

The femur bone is the longest and the largest bone found in the human body. It is also known as the thigh bone. It connects to the pelvis at the proximal end to form the hip joint and to the tibia at the distal end to form the knee joint. Femur bone of human body, which takes the largest percentage of the body weight, is one of the most commonly fractured bones in human body.

Hence, extra care and special consideration are required when designing bio-aided equipment or sport protective equipment to avoid the coincidence of the resonant frequencies and the external excitation frequencies.

Nomenclatures

C	Global damping matrix
f	Natural frequency of vibration
K	Global stiffness matrix
M	Global mass matrix
x	Displacement vector, also called as eigenvector
$\dot{x}$	Velocity vector
$\ddot{x}$	Acceleration vector

Greek Symbols

ω	Eigenvalue

For the past few decades, tremendous effort had been spent on determining the natural frequencies of femur bone. Earlier research on femur bone vibration was mainly based on experimental tests involving animals and cadavers. FEM offers a cost-effective alternative in the biomechanical studies of vibration analysis of femur.

Researchers have been studying the vibration characteristic of femur bone since1980s. Khalil et al. [3] obtained natural frequencies and mode shapes of femur bone using experimental and analytical methods. The experimental measurements were made based upon the Fourier analysis of transfer function. For analytical solution, a mathematical model consisting of 59 elements was analyzed using transfer matrix method. The model that they considered was a freely vibrating bone, which is not the real case. In a real structure, bone is constrained between pelvis and tibia. Therefore such a boundary condition is not justifiable. The first 20 experimental natural frequency of femur bone for free-free boundary condition was found to vary from 250 Hz to 7300 Hz. The analytical solution to natural frequency also lies in the same range. However, for the longitudinal mode of vibration, the natural frequencies were 2118 Hz, 4407 Hz and 7264 Hz. In this work, our focus will be on the longitudinal mode of vibration using FEA.

Similar to Khalil et al. [3], Hight et al. [4] performed vibration analysis of human tibia using beam type finite element model and compared with analytical solution and experiment. Dynamic loading of femur bone with stress wave was studied by Richard and Subrata [5]. They used the loading of impact by a steel ball at one end and measuring the measuring the stress wave propagation by two strain gauges.

Thomas et al. [6] has studied the effect of mechanical vibration on human femur. However, they considered a low frequency range from 0 Hz – 500 Hz. Researchers have also used ultrasonic techniques for measuring elastic properties of human bone [7]. Impact response on bone has also been predicted by using simplified finite element model [8]. Finite element simulation was also used to determine orthotropic material properties using modal analysis [9]. Fracture analysis of a femur bone has also been predicted by finite element simulation [10-12].

One of the authors (Tse, KM) has shown various applications of FE simulation [13-15] and computational fluid dynamics [16, 17] in various fields of biomechanics. Author has also performed a vibration analysis of human head-brain-neck model [18].

2. Model

Finite element (FE) simulation prediction depends entirely upon the geometry considered, the loading conditions and boundary conditions. For this reason, accurate FE model of femur bone with accurate geometry are very important. The geometrical information of a patient-specific femur bone was obtained from CT data by Nuaalsy (Nanjing University of Aeronautics and Astronautics, China), using Mimics (Materialise, Leuven, Belgium). An FE model based on this geometrical information was constructed using meshing software Gmsh with 23,728 tetrahedral elements (Fig. 1).

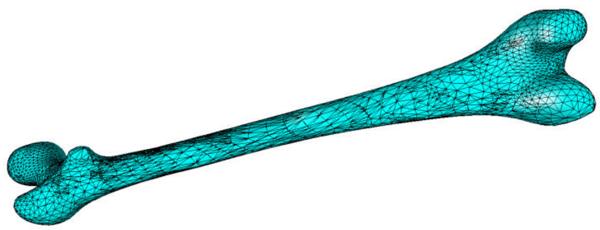

Fig. 1. Meshed Model of the Femur Bone.

3. Material

The femur bone was assumed to have isotropic linear elastic material properties. The density was chosen to be 866 kg/m^3 based on the sample's average of the largest elderly group [19] while the Poisson's ratio was taken as 0.4 [20]. The Young's modulus was computed from the density using the reported correlation in [21] and was found to be 7.585 GPa. To replicate the restriction of motion by the adjacent bones, fixed boundary conditions were applied at the base of both the lateral condyle and the median condyle as well as around the femur neck.

4. Modal Analysis

In order to determining modal responses, modal analysis using FE is performed using open source FE software Elmer. The governing equation of the dynamic response is given as follows:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=0 \quad (1)$$

For undamped free vibration (i.e., $[C]=0$), the solution of the above equation can be written as follows.

$$\{x\}=\{X\}e^{i\omega t} \quad (2)$$

where $\{X\}$ represents the amplitudes of all the masses (mode shapes or eigenvectors). The variable $\omega = 2\pi f$ represents each eigenvector's corresponding eigenfrequency in rads^{-1}, while f represents the natural frequency in hertz. Thus the governing equation mentioned above reduces to:

$$[[K] - \omega^2 [M]]\{X\} = 0 \tag{3}$$

The above equation is known as eigenvalue problem in matrix algebra and is considered as linear by replacing ω^2 by λ. The system, which relies on determining each eigenvector, with its corresponding eigenvalues, is solved by the software Elmer.

5. Results

The result from the modal analysis consists of twenty natural frequencies and their corresponding mode shapes. The natural frequencies are given in Table 1.

Table 1. Mode Number and Natural Frequencies.

Mode Number	Natural Frequency (Hz)
1	946.2363
2	1077.009
3	2043.75
4	2348.073
5	3523.645
6	4109.738
7	4825.301
8	5111.147
9	5423.284
10	6009.456
11	6898.864
12	7106.023
13	7343.545
14	7770.327
15	8444.315
16	8911.491
17	9365
18	9968.934
19	10300.25
20	10792.92

Some of the prominent mode shapes for corresponding natural frequencies are shown in Figs. 2-9. The figures show the displacement profile for the vibration at the corresponding modal frequency. The displacement is displayed in millimeters. However, it is important to mention that the displacement shown is relative displacement as the analysis is modal analysis. The displacement can be appropriately scaled up or scaled down depending on the external excitation force.

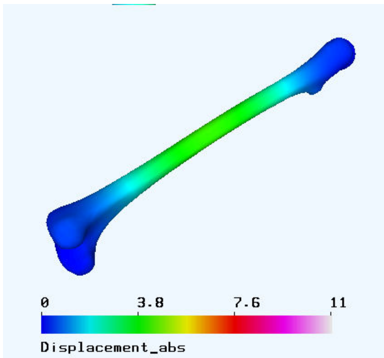

Fig. 2. First Mode Shape.

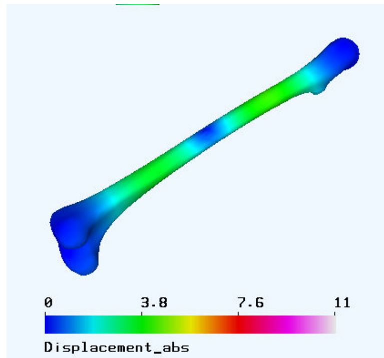

Fig. 3. Fourth Mode Shape.

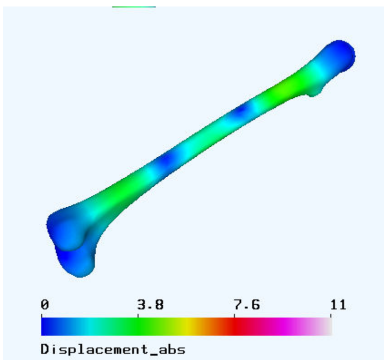

Fig. 4. Sixth Mode Shape.

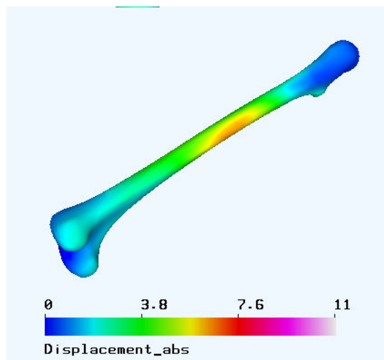

Fig. 5. Eighth Mode Shape.

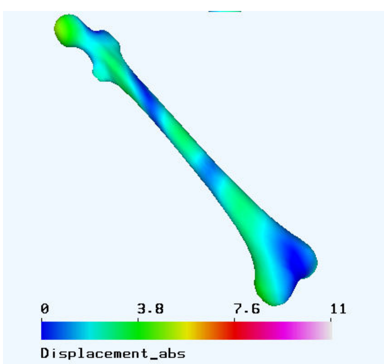

Fig. 6. Eleventh Mode Shape.

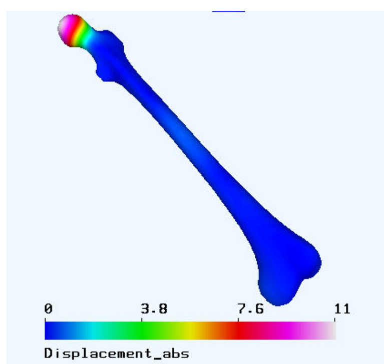

Fig. 7. Twelfth Mode Shape.

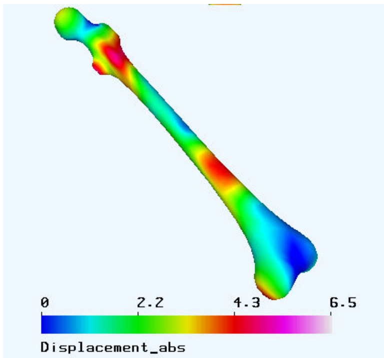

Fig. 8. Seventeenth Mode Shape.

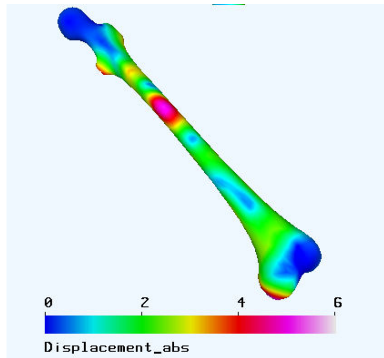

Fig. 9. Twentieth Mode Shape.

6. Discussion

The external loading or excitation on the human body can have severe consequences if the external excitation frequency matches with the natural frequency of the bone. In this work, it is found the natural frequency for first twenty modes of femur bone varies from 946 Hz to 10793 Hz. The results are also in good agreement with experimental work by Khalil et al. [9]. In his work, the longitudinal modes of vibration were identified to have natural frequencies as 2118 Hz, 4407 Hz and 7264 Hz which are close to 4th, 6th and 13th mode predicted by FE simulation. The boundary condition in the experiment was free-free condition, which is not the real case. And therefore the deviation in the results can be thus explained.

In any impact loading or excitation, it should be so designed that the excitation frequency does not coincides with the natural frequency of the femur bone. Otherwise, it could lead to fracture of the bone. The fracture location at a particular frequency can also be predicted from the mode shape. For example at 7106 Hz (Fig. 7) which corresponds to twelfth mode, the bone is likely to fracture from the head (region of maximum displacement and therefore stress). Similarly external excitation at 10790 Hz which corresponds to twentieth mode the bone is likely to fracture at middle shown by the pink region in Fig. 9.

Also a particular type of loading in a bio-aided equipment or during sport activity can lead to excitation of that particular mode. For example an impact load on the middle of femur bone can excite either first mode or higher mode such as twentieth mode. However, it must be noted that higher modes are difficult to excite compared to the lower modes.

7. Conclusion

Mode shapes are very important in evaluating the behavior of any structure to an external response. In this work, FEA of femur bone was performed using a software Elmer. The natural frequencies and mode shapes for femur bone were identified for fixed-fixed boundary condition.

The results were compared with the experimental results in literature and they were in good agreement.

If the external excitation frequency matches with one of the natural frequency of the system, it can lead to large vibrations due to resonance and great damage to the structure.

While designing any biomechanical equipment, or sports equipment, care should be taken that external excitation does not coincide with the natural frequency of the femur bone as predicted. Else, the excitation can lead to fracture of the bone which can be predicted by the mode shape at the corresponding natural frequency.

References

1. Huiskes, R; and Chao, E.Y.S. (1983). A survey of finite element analysis in orthopedic biomechanics: the first decade. *Journal of Biomechanics*, 16(6), 385-409.
2. Mow, V.C.; Ateshian, G.A.; and Spilker, R.L. (1993). Biomechanics of diarthrodial joints: a review of twenty years of progress. *Journal of Biomechanical Engineering*, 115(4B), 460-467.
3. Khalil, T.B.; Viano, D.C.; and Taber, L.A. (1981). Vibrational characteristics of the embalmed human femur. *Journal of Sound and Vibration*, 75(3), 417-436.
4. Hight, T.K.; Piziali, R.L.; and Nagel, D.A. (1980). Natural frequency analysis of a human tibia. *Journal of Biomechanics*, 13(2), 139-147.
5. Pelker, R.R.; and Saha, S. (1983). Stress wave propagation in bone. *Journal of Biomechanics*, 16(7), 481-489.
6. Thomas, A.M.; Luo, D.Z.; and Dunn, J.W. (1991). Response of human femur to mechanical vibration. *Journal of Biomedical Engineering*, 13(1), 58-60.
7. Rho, J.Y. (1996). An ultrasonic method for measuring the elastic properties of human tibial cortical and cancellous bone. *Ultrasonics*, 34(8) 777-783.
8. Pashah, S.; Massenzio, M.; and Jacquelin, E. (2008). Prediction of structural response for low velocity impact. *International Journal of Impact Engineering*, 35 (2), 119-132.
9. Taylor, W.R.; Roland, E.; Ploeg, H.; Hertig, D.; Klabunde, R.; Warner, M.D.; Hobatho, M.C.; Rakotomanana, L.; and Clift, S.E. (2002). Determination of orthotropic bone elastic constants using FEA and modal analysis. *Journal of Biomechanics*, 35(6), 767-773.
10. Haider, I.T.; Speirs, A.D.; and Frei, H. (2013). Effect of boundary conditions, impact loading and hydraulic stiffening on femoral fracture strength. *Journal of Biomechanics*, 46(13), 2115-2121.
11. Grassi, L.; Schileo, E.; Taddei, F.; Zani, L.; Juszczyk, M.; Cristofolini, L.; and Viceconti, M. (2012). Accuracy of finite element predictions in sideways load configurations for the proximal human femur. *Journal of Biomechanics*, 45(2), 394-399.
12. Keyak, J.H.; Rossi, S.A.; Jones, K.A.; Les, C.M.; and Skinner, H.B. (2001). Prediction of fracture location in the proximal femur using finite element models. *Medical Engineering and Physics*, 23(9), 657-664.

13. Lee, S.J.; Liong, K.; Tse, K.M.; and Lee, H.P. (2010). Biomechanics of the deformity of septal L-Struts. *The Laryngoscope*, 120(8), 1508-1515.
14. Bin Tan, L.; Tse, K.M.; Lee, H.P.; Tan, V.B.C.; and Lim, S.P. (2012). Performance of an advanced combat helmet with different interior cushioning systems in ballistic impact: Experiments and finite element simulations. *International Journal of Impact Engineering,* 50, 99-112.
15. Tse, K.M.; Lee, H.P.; Shabana, N.; Loon, S.C.; Watson, P.G.; and Thean, S.Y.L.H. (2012). Do shapes and dimensions of scleral flap and sclerostomy influence aqueous outflow in trabeculectomy? A finite element simulation approach. *British Journal of Ophthalmology*, 96(3), 432-437.
16. Tse, K.M.; Chang, R.; Lee, H.P.; Lim, S.P.; Venkatesh, S.K.; and Ho, P. (2013). A computational fluid dynamics study on geometrical influence of the aorta on haemodynamics. *European Journal of Cardio-Thoracic Surgery*, 43(4), 829-838.
17. Tse, K.M.; Chiu, P.; Lee, H.P.; and Ho, P. (2011). Investigation of hemodynamics in the development of dissecting aneurysm within patient-specific dissecting aneurismal aortas using computational fluid dynamics (CFD) simulations. *Journal of Biomechanics*, 44(5), 827-836.
18. Tse, K.M.; Tan, L.B.; Lim, S.P.; and Lee, H.P. (2012).Characterization of human head-brain-neck vibration behavior, in *4th American Conference on Human Vibration*, 19-20.
19. El Maghraoui, A.; Guerboub, A.A.; Achemlal, L.; Mounach, A.; Nouijai, A.; Ghazi, M.; and Tazi, M.A. (2006). Bone mineral density of the spine and femur in healthy Moroccan women. *Journal of Clinical Densitometry*, 9(4), 454-460.
20. Reilly, D.T.; and Burstein, A.H. (1975). The elastic and ultimate properties of compact bone tissue. *Journal of Biomechanics*, 8(6), 393-405.
21. Keyak, J.H.; Rossi, S.A.; Jones, K.A.; and Skinner, H.B. (1997). Prediction of femoral fracture load using automated finite element modeling. *Journal of Biomechanics*, 31(2), 125-133.