Evaluation the Sensitivity of Bone Natural Frequency as a Diagnosis Tool to Identify Bones Integrity

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Abstract. This study explain the reason behind the low sensitivity of the natural frequency for the changes in bone health. The mechanical properties of the bone were reduced by placing the bone in boiling water for 2 hours and the mass of the bone was reduced by placing the bone in diluted acidic medium for 24 hours. The natural frequency of the bone samples (10 samples) was calculated in three cases (fresh, after boiling, and after acidic treatment). The natural frequency was calculated theoretically by using finite element analysis based upon CT-Scan DICOME images and experimentally by using impulse test. The difference between the results in the two methods was less than 15%. The boiling process caused a reduction in the natural frequency while the acidic treatment caused an increase in the natural frequency compared with the natural frequency of the fresh condition. The mutual influence of these two component cannot be separated. This mutual influence will reduce the sensitivity of the natural frequency as diagnosis factor for the changes in the health condition of the bone.

Keywords: Bone, finite element, modal test, natural frequency.

1. Introduction

Evaluation of bone integrity requires certain diagnosis procedures that are mostly radioactive, very expensive, and time consuming. The investigation of alternative diagnosis procedure was the main concern for the researchers. Several fields of research were explored to invent nonradioactive test device and frequency analysis was one of those fields of study. The natural frequency was the first factor to be investigated for the used as diagnosis tool to identify the physiological health condition of the bone. Natural frequency evaluated by many researchers by different methods for animal and human bones in two ways (in-vitro and in-vivo).

This field of study started in the early 1970, when Thompson et al. [1] conducted several experiments on dog radii to extract the resonant frequency. The aim of work was to investigate the mechanical properties of the bone by taking into consideration the effect of twist in the principle axis,
shear deformation, and viscoelastic behavior. Jurist and Kianian [2] calculated the resonant frequency of the ulna bone. Three models were used to illustrate the effect of the boundary condition, skin, and accelerometer weight effect. William P. Doherty et al. [3] investigated the efficiency of the resonant frequency as an evaluation factor for the bone integrity. The results showed that the resonant frequency sensitivity to the changes occur in the bone is lower than that for the mass and stiffness. Thompson et al. [4] presented an in-vivo experimental study to investigate the resonant frequency of ulna bone. The arising problem in the in vivo test is the effect of the soft tissue, which can influence the results due to the heavy damping. This damping will require higher energy load waves to insure the excitation of the system, but this increase in the energy will involve pain and discomfort to the patient. Viano et al. [5] presented a theoretical and experimental study for the human femur to investigate the elastic property and bone mineral density change due to aging. Timothy K. Hight [6] investigated the natural frequency of the tibia bone by using finite element model to calculate the natural frequency by taking into consideration the influence of irregularity in shape and different boundary conditions at proximal and distal ends. Kahlil et al. [7] investigate the resonant frequency of the human femur bone for different modes of shape (transverse in the maximum and minimum inertia plane, torsional, and longitudinal). G. Vander Perre et al. [8] conducted in vivo and in vitro tests to evaluate the structural dynamics properties of the bone (natural frequency, mode shape, and damping ration). P. Cornelissen et al. [9] conducted a study focusing on the effect of the boundary conditions on the calculated natural frequency of human tibia. J. C. Misra and S. C. Samanta [11] investigated a mathematical model for the transverse vibration of the human tibia. G. Van Der Perre et al. [12] presented a study to evaluate the mechanical properties in group of patient infected by osteoporosis. Béatrice Couteau [13] studied the frequency analysis of human femur bone taking into consideration the material properties and the geometrical explicitly. Pinar Arpinar et al. [14] presented a study to evaluate the bone strength by using vibration analysis and dual energy x-ray absorptiometry Bekir Bediz [15] conducted an in vivo and in vitro study to evaluate the structural dynamic properties change of human tibia by using vibration analysis. G. Campoli et al. [16] conducted a study to explain the effect of bone shape and density distribution on the resonant frequency of the bones. All the studies conducted by using the frequency analysis provides important information on the factors influencing the values of the natural frequency for different modes of vibration. The behavior of the natural frequency change due to the effect of bone diseases was the main goal of investigation to invent a new diagnosis procedure to distinguish between the normal and abnormal health conditions.

2. Finite Element Analysis

Bones have a very complicated shape and building 3-dimensional modal is not easy by using traditional ways. In addition, mechanical properties and density values change along the bone. In order to overcome those problems CT-Scan DICOME (Digital Imaging and Communications in Medicine) were used to build the three-dimensional modal (Figure 1). Those images has the size of 512×512 pixels. CT-scan device type GE Medical Systems Discovery CT 750 HD was used and the images were taken with the same setting (KVP 120, slice thickness 2.5 mm, and tube current 120 mA).
The DICOME images was used to build the three-dimensional modal by using MIMICS software and the meshed modal produced by using TET-4 elements by using 3-matic software. The material assignment was done by using MIMICS software again based upon the gray-scale value for each pixel (Figure 2). The modal analysis for the meshed modal was solved by using ANSYS software version 14.5. The natural frequency for different modes of vibration were evaluated (Figure 3). This analysis will be repeated in three cases fresh, after boiling, and after acidic treatment.

Figure 1: CT-Scan test for the bones.

Figure 2: Flow chart for the construction of the FEA model.
Material and Experimental Analysis

In this study, two bovine bones were selected (Humerus and Tibia). These bones are different in length and weight. They were collected from different animals. The bones were subjected to severe condition to produce an influence on their organic and inorganic materials to reduce its stiffness and mass.

Viscoelastic behavior is exhibited due to the presence of the collagen fibers [17]. Therefore, the bone is placed inside boiling water to affect the organic materials (collagen) inside the bone matrix without influencing the inorganic materials. This treatment will disturb the bone matrix, and will results erosive pits on the surface, the protein will be lost, crystallizing increased, porosity increased as result of collagen lost [18]. The bones were submerged into boiling water for three hours.

In order to simulate the calcium efflux from the bones, the bone will be placed inside diluted sulfuric acid. Sulfuric acid will work as reducing agent and react with the salts (mainly with the calcium). This chemical reaction will significantly reduce the calcium content and the mass of the bone will be reduced [19].

The natural frequency will be extracted experimentally by using impulse test. This test is conducted by using impulse hammer, accelerometer, and dynamic signal analyzer. The bone was placed on soft sponge in order to simulate the free-free boundary conditions. Figure 4 shows the experiment setup. Impact hammer was used to excite the bone by tapping along the bone and in different locations. Minimum excitation force was 140 N. Although the duration of the excitation force was 0.25 s, it provides enough energy to excite the system. The excitation was recorded by channel 1, and the response was recorded by using channel 2. Both of the excitation and the response were stored in the software for further processing (FRF). This experiment was repeated for all the bones samples in different conditions (fresh, boiled, and sulfuric acid treatments).

Figure 3: Modal analysis solution by using ANSYS software version 14.5.
4. Result and discussions

Tables (2 & 3) illustrate the natural frequencies of the bones (Humerus & Tibia) before and after the treatments. These tables demonstrate the results obtained from finite element analysis and experimental part, discrepancy between the results obtained from the two methods, and percentage of decrease in the natural frequency due to boiling treatment, and percentage of increase in the natural frequency due to the acidic treatment effect.

Table 1: Natural frequency (Hz) of Humerus.

| No | Fresh Exp | Fresh FEA | Fresh Disc | Boiled Exp | Boiled FEA | Boiled Disc | %↓ H2SO4 Exp | %↓ H2SO4 FEA | %↓ H2SO4 Disc |
|----|-----------|-----------|------------|------------|------------|------------|-------------|-------------|--------------|
| 1  | 941       | 1090      | 14.2%      | 911        | 939        | -3.0%      | 2.6%        | 1052        | 1131         | -9.2%        | 10.5%        |
| 2  | 5365      | 5549      | 3.5%       | 5120       | 5022       | 2.4%       | 4.3%        | 5536        | 5355         | 3.5%         | 3.3%         |
| 3  | 5654      | 5938      | 4.9%       | 5485       | 5272       | 3.7%       | 3.0%        | 6210        | 5575         | 10.0%        | 8.9%         |
| 4  | 6022      | 6110      | 1.4%       | 5713       | 5629       | 1.5%       | 5.3%        | 6684        | 6465         | 3.2%         | 9.7%         |
| 5  | 6734      | 6733      | -0.1%      | 6436       | 6083       | 5.4%       | 4.5%        | 7056        | 7062         | -0.2%        | 4.5%         |
| 6  | 7001      | 7210      | 2.8%       | 6753       | 6871       | -1.9%      | 3.7%        | 7372        | 8075         | -9.5%        | 5.0%         |
| 7  | 7110      | 7264      | 2.0%       | 6953       | 7440       | -6.8%      | 2.2%        | 7556        | 8427         | -11.1%       | 6.0%         |
| 8  | 7953      | 8040      | 1.2%       | 7730       | 8112       | -4.7%      | 2.6%        | 8469        | 9286         | -9.6%        | 6.2%         |

Figure 4: The modal test For Fresh bone.
Table 2: Natural frequency (Hz) of Tibia Bovine bone.

| No | Fresh Exp | Fresh FEA | Fresh Disc | Boiled Exp | Boiled FEA | Boiled Disc | %↓ | H2SO4 Exp | H2SO4 FEA | H2SO4 Disc | %↑ |
|----|-----------|-----------|------------|------------|------------|-------------|-----|-----------|-----------|-------------|-----|
| 1  | 721       | 789       | 8.3%       | 671        | 681        | -1.0%       | 3.5%| 759       | 668       | -13.3%      | 4.8%|
| 2  | 4152      | 4257      | 2.5%       | 3712       | 3767       | 1.5%        | 10.6%| 4662      | 4248      | -9.8%       | 11.1%|
| 3  | 5372      | 5183      | -3.7%      | 5245       | 5327       | 1.6%        | 2.3%| 5519      | 5462      | -1.0%       | 2.6%|
| 4  | 6052      | 6151      | 1.6%       | 5345       | 5610       | 4.8%        | 11.7%| 6595      | 6770      | 2.7%        | 8.1%|
| 5  | 7274      | 7323      | 0.6%       | 6862       | 6688       | -2.7%       | 5.7%| 7475      | 8262      | 9.7%        | 2.6%|
| 6  | 7981      | 8205      | 2.8%       | 7671       | 7412       | -3.6%       | 4.0%| 8500      | 8612      | 1.4%        | 6.0%|
| 7  | 8833      | 8415      | -5.1%      | 8140       | 8265       | 1.8%        | 8.0%| 9462      | 8873      | -6.8%       | 6.7%|

The agreement between the finite element analysis and the experimental results is good (less than 15%). The tables above show clearly that the natural frequency changes after boiling. The natural frequency value decreased in all samples after treatment. The amount of this decrease is almost the same for the two samples (200-300 Hz). This converging can be related to stability of treatment condition for all samples. The natural frequencies of the bone after the acidic treatments are higher than the fresh bone natural frequency. The increase in natural frequency is between 400-700 Hz.

The natural frequency of the bones after the acidosis treatment is higher than the boiling treatment natural frequency. The increase is in the interval 700-1000 Hz. A conclusion can be achieved from these results the calcium efflux has a greater impact on the natural frequency than the collagen transformation.

Although the finite element analysis provides us with the ability to investigate unlimited number of modes of vibrations, but the restriction was in the experimental part of the work. Modes of vibration, which were extracted from the experimental work, are compared with their counterparts in the finite element analysis results. Some frequencies were dropped, because it was difficult to capture their counterpart in one of the three cases (fresh, boiled, and acidosis treatment).

5. CONCLUSIONS

The sensitivity of the natural frequency to the changes in the bone health conditions was relatively low. The explanation done by the researcher relate the low sensitivity to the mass and stiffness change. In this study, the bone stiffness was decreased by disorder the organic materials inside the bone matrix. This decrease in the stiffness results a decrease in the natural frequency of the bone. The mass of the bone was decreased by the chemical reaction and this decrease results an increase in the natural frequency of the bone. The impact of the mass on the natural frequency is greater than the stiffness and the bone length has a minor effect on the bone natural frequency. The influence of these two factors (stiffness and mass) cannot be separated in the real life and the superposition of their opposite effect will reduce the change in the natural frequency when the bone health condition of the bone is changed.
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