Determining mechanical parameters of the bone using a vibro-acoustic method

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1 INTRODUCTION

Human bones are energy absorbing complex composite structures that have an irregular hollow structure filled with marrow and surrounded by soft tissue and muscles. They have two types of structure, cortical and cancellous bone, both having the same mineralized collagen composition. Cortical bone may generally be considered solid; cancellous bone consists of a complex open-celled porous network of rod- and plate-shaped elements termed trabeculae. The porosity of human cancellous bone ranges between 70% and 95%, the remaining volume being perfused with bone marrow [1]. Bone quality is a composite of properties that make bone resist fracture, such as its microarchitecture, accumulated microscopic damage, the quality of collagen, mineral crystal size, and bone turnover [2].

The common technique used to determine the mechanical properties of the bone is conventional mechanical testing which is invasive and destructive. The strength of the bone can be estimated from measured stiffness of the bone using mechanical test although it is inappropriate *in-vivo*. The mechanical behaviour of the bone structure [3] has been predicted using finite element analysis (FEA) which is a non-destructive computer software. The bone imaging techniques in vivo has combined with FEA [4-6]. Most recently Langton *et al.* [7] has combined ultrasound computed tomography (UCT) with FEA to predict the stiffness of bone. They have demonstrated that UCT_FEA based upon quantitative attenuation images provided a comparable estimation of gold standard mechanical test stiffness of 84% compared to microCT-FEA. Current recommendations for the assessment of patients for bone mineral density (BMD) and fracture risk have several difficulties, and they are not suitable for international use. To date, no satisfactory evidence exists either supporting or refuting the usefulness of the vibro-acoustic technique.

Aygun[8,9] has developed a vibro-acoustic technique that combine the acoustic wave propagation techniques and viscoelastic bone system to analysis and assess the acoustical and mechanical properties of human bones. The aim of this paper is to use the vibro-acoustic technique to analyse and assess the acoustical and mechanical properties of human bone by demonstrating if variations in sound propagation through the bone can be detected. Firstly, the force generated by an impact hammer is applied to the human tibia in vivo and its corresponding response is detected by using an accelerometer at 15 cm distance from the impact hammer. The distance between the accelerometer and the impact hammer is increased and same measurements are repeated to see if the structural borne sound waves are attenuated while they are propagating through the human tibia. A human tibia is used for vibro-acoustics measurements, and results from bone tibia are presented in this paper to explain the process of determining acoustical and mechanical parameters of human tibia. Secondly, measurements are performed on sawbones with and without perforations to determine the resonance frequencies from transfer function curve and to see if fundamental, second and third resonance frequencies, mentioned in previous works carried out on dry human bone and dog femora [10-11], can be observed in their frequency dependent function. Finally, modal analysis of the human bone and replica bone (sawbone) are carried out using the viscoelastic bone system to estimate mechanical properties of the bone from acoustical parameters deduced from frequency dependent transfer function.

2 MEASUREMENTS

Measurements were carried out on the tibia bone which is the second longest bone in the human body to the femur. An impact hammer was used to generate a force to vibrate the bone. The responses were detected along the bone surface using an accelerometer. The Impact hammer and accelerometer were connected to signal conditioning units which were fed to a data acquisition system which was connected to a computer to save and analyse the data obtained from measurements. Electronic interference was removed by 10000 acquisition averages per second. Unwanted noise that recorded with applied force and detected responses were filtered by using the Wavelet toolbox in MATLAB. Signals were decomposed to eliminate the noise. The signals were reconstructed for further analysis after the noise was removed from the signals. The force generated by impact hammer was applied to human tibia in vivo, and its responding signals were detected at different positions along surface of the bone using an accelerometer. The responding signals were detected at 15 cm, 20 cm and at the ankle. Vibration of the bone generates structural borne acoustic waves that travel through the bone structure and along the soft tissue covering the bone. The input forces applied to bone are given in Figure 1a, and their corresponding responses are shown in Figure 1b.

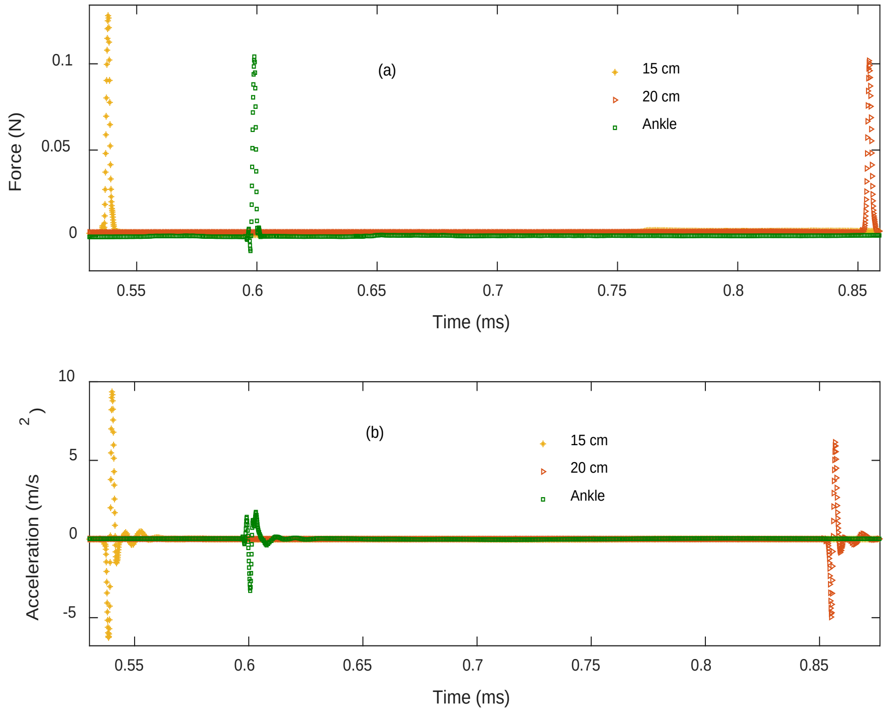

Figure 1: (a) Input force applied to human tibia by an impact hammer, (b) Responses detected by an accelerometer.

A transfer function method based on Laplace transforms is used to analyse detected the bone responses in details and to extract acoustical and structural parameters of the bone. Detected signals in the time domain were denoised before they were converted into the frequency domain using a Fast Fourier Transform (FFT). Frequency dependent transfer function of the system is the ratio of the response of the system to the force applied to the system. Frequency domain transmission function curves of the tibia are given in Figure 2. When the distance between the accelerometer and the impact hammer is increased, the amount of structural borne acoustic energy transmitted through the bone mostly reduces throughout the frequency range, and it causes the natural frequency of the bone to shift from higher frequency to a lower frequency.

The soft-tissue surrounding the bone tibia attenuates vibrational force, absorbs sound energy, and behaves as a wave guide allowing the vibration borne sound waves to propagate through it. The attenuation of acoustic energy travelling through bone may be due to the distance between input and outputs, marrow in the bone, muscles, soft tissue surrounding it, and changes in bone diameter along the tibia surface. As it can be seen from Figure 2, only the fundamental resonance frequency of the bending vibration was determined from the measured transfer function curve of the human tibia. The second and third resonance frequencies, mentioned in previous works carried out on dry human bone and dog femora [10-11], were not observed on human bone despite repeating the same measurements several times. Dry bones behave like a porous rigid beam and allows the most of structural borne vibrational energy to be transmitted through its structure. This is most likely due to the lack of any marrow, soft tissue and muscles to absorb sound waves and dampen the structural borne vibration.

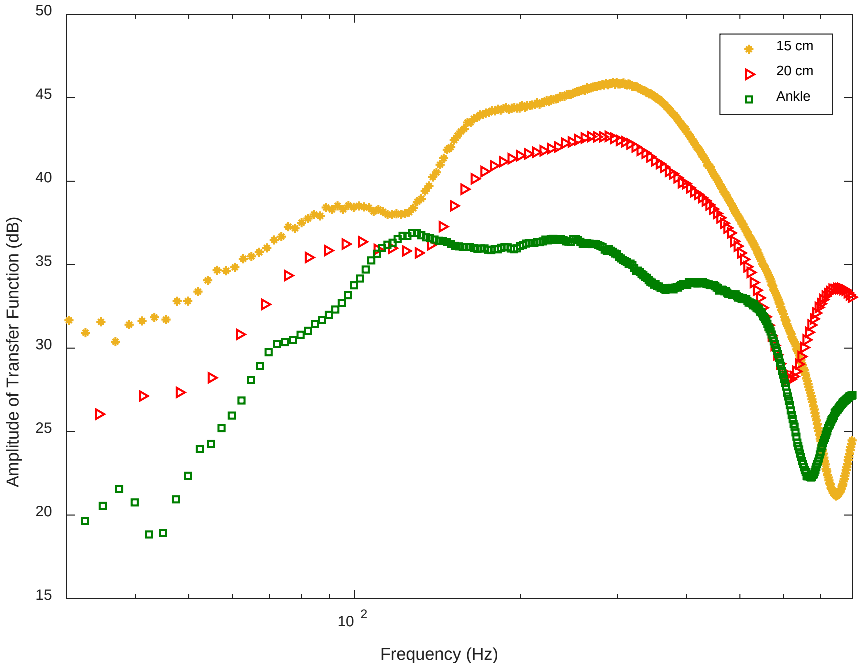

Figure 2: Transfer functions versus frequency for human tibia.

Measurements were carried out on sawbones with and without perforations. The aim of these measurements on sawbones was to determine the resonance frequencies from transfer function curve and to see if second and third resonance frequencies, mentioned in previous works carried out on dry human bone and dog femora [10-11], were observed in their transfer function response. Sawbone (replica bone) made of solid rigid polyurethane foam does not replicate the structure of human bone. But its materials properties are in the range of human cancellous bone. The density of sawbone is 1.64 g/cc, with a strength of 106 MPa, and a length of 40.5 cm. Initial measurements were carried out on the sawbone without perforating it. Indeed, fundamental, second and third resonance frequencies were observed from the frequency dependent function given by dashed line in Figure 3. Measurements were repeated on the perforated sample, initially with 20 holes of 2 mm diameter, and then with 40 holes of 2 mm diameter. The distance between impact hammer and accelerometer was 20 cm. Increasing the perforation ratio of sawbones slightly amplified the amplitude of transfer function at mid-range frequencies while shifting the resonance frequencies to lower values.

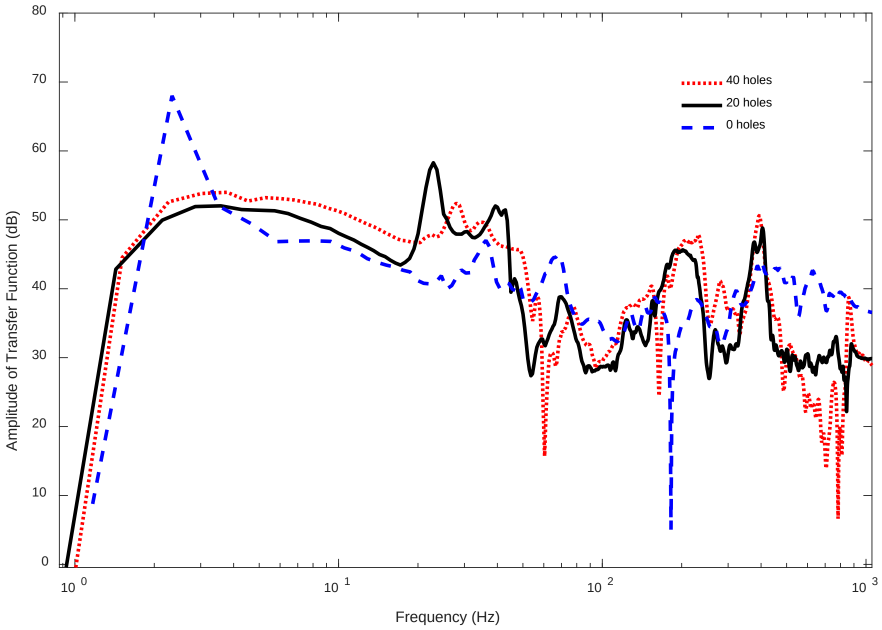

Figure 3: Frequency dependent function of replica bones (sawbones) with and without perforations.

3 MODAL ANALYSIS

3.1 Damping coefficient

The transfer function method was used to determine the damped natural frequencies, damping ratios, and mode shapes corresponding to all resonant peaks observed in Figures 2. A MATLAB syntax was used to find peak amplitude of the transfer function. The damping ratio [12] was found using the equation below;

$$\xi = \frac{f_2 - f_1}{2f_n} \tag{1}$$

where the points $f_1$and f_2, where the amplification factor falls to $\frac{|H(if_n)|}{\sqrt{2}}$, are called half-power points because the power absorbed by the damper (soft tissue, muscles, and bone), responding harmonically at a given frequency, is proportional to the square of the amplitude.

The difference between the frequencies associated with the half-power points is called the *bandwidth* of the system, and satisfies the relation [12],

$$|H(if_1)| = |H(if_2)| = \frac{|H(if_n)|}{\sqrt{2}} \tag{2}$$

The damping ratio corresponding to peak amplitude of transfer function in Figure 4 with resonant frequency f_n denotes the modal damping ratio ξ. The amplitude of transfer function for the response detected at 20 cm is 42.69 dB at resonant frequency, f_n = 288.5 Hz. The power absorbed by the visoelastic system at half-power points is 3 dB less than the peak amplitude of the system at resoance frequency.

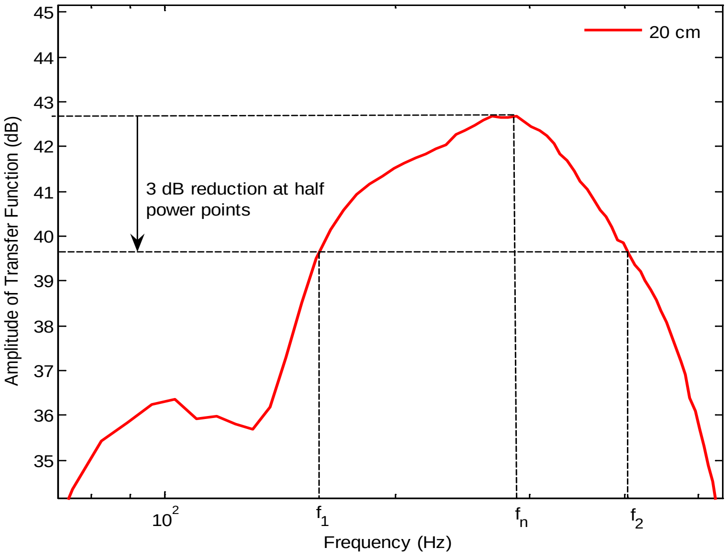

Figure 4: The amplitude of tranfer function response of the tibia bone detected at 20 cm.

3.2 Loss factor

The loss factor (or loss coefficient) was originally developed as a measure of intrinsic damping of viscoelastic structures. It is the energy loss per radian to the energy associated to the vibration. The loss factor of the bone system [12] is defined with respect to steady-state oscillation as follow;

$$\eta = \frac{E/2\pi}{W} \tag{3}$$

where E is the energy dissipated per cycle of a vibration at frequency f_n and equals to $\pi\omega_n cX^2$ where c is the damping coefficient of the system, ω_n is the undamped radian natural frequency of the system given by $2\pi f_n$, and W is the total energy of the system and it equals to $\frac{1}{2}m\omega_n^2 X^2$.

The loss factor is related to damping ratio [13] as;

$$\eta = \frac{\pi\omega_n cX^2 /2\pi}{\frac{1}{2}m\omega_n^2 X^2} = 2\xi \tag{4}$$

The damping capacity ψ is the ratio of the energy dissipated per cycle to the energy present in the system, and given [13] by;

$$\psi = \frac{E}{W} = 4\pi\xi \tag{5}$$

4 ANALYSIS

The parameters of human tibia and replica bone (sawbone) were determined using frequency response signals. Increasing the distance between the impact hammer and accelerometer caused slight changes in the bone parameters as shown in Table 1. More acoustic energy was absorbed by the bone system when the structural borne sound waves propagated though the bone. The resonance frequency of the bone was shifted to lower frequency. Damping capacity of the system was reduced because of the changes in damping coefficient and loss factor. The resonance frequency determined from transfer function at 15 cm and 20 cm distances from the accelerometer were found to be equal to 294.44 Hz and 288.5 Hz respectively. Frequencies

(f_1 and f_2) at half-power points are 155.37 Hz and 401.33 Hz for response at 15 cm, and 159.82 Hz and 402.62 Hz for response at 20 cm respectively. The reason for these changes in bone parameters could be attributed to the presence of soft tissue attenuating and damping sound waves propagating along the surface of bone tibia. The porous structure of the bone filled with marrow can be another reason for the attenuation of acoustic waves travelling through the bone. This reveals anisotropy in elasticity in human tibia.

Table 1: Bone tibia parameters deduced from transfer function method.

Parameters	**Human male bone**		**Replica bone**
	15 cm	**20 cm**	**20 cm**
The peak response	45.92 dB	42.69 dB	68 dB
Resonance frequency (f_n)	294.44 Hz	288.5 Hz	2.34 Hz
Damping coefficient (ξ)	0.418	0.421	0.37
Loss factor (η)	0.836	0.842	0.74
Damping capacity (ψ)	5.25	5.3	4.65

5 CONCLUSION

An investigation was carried out on human bone in-vivo to detect the variation of sound propagation in the bone using structural borne acoustic wave technique. The tibia of a human subject was used for vibro-acoustics measurements to determine acoustical and mechanical parameters of it. The acoustics wave technique was used to deduce acoustical properties of bone from frequency depend transfer function of the system while a viscoelastic bone system is modelled and used to estimate mechanical properties of the bone. The resonances (second and third resonance frequencies) observed in measurements undertaken on dry bones and sawbones were not seen in frequency dependent transfer function of human bone surrounded with soft tissue and muscles except for fundamental natural frequency. Structural behaviour of the bone is described in terms of its anisotropic elasticity which is mostly depend on the complex stiffness. The real part of the complex elasticity determines bone system's acoustic energy storage capability and its imaginary part indicates its energy dissipation capability. The acoustic energy storage capability of the bone is found to be less than the energy dissipation capability of the bone.

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