AN INVESTIGATION OF RELATIONSHIP BETWEEN BONE VIBRATION FREQUENCY AND ITS MASS-VOLUME RATIO

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ABSTRACT

The correlation between turkey bones' mass/volume ratios and the magnitude and frequency of the largest peak in their vibration frequency spectra was studied. A computer controlled small hammer was used to induce bone vibrations. The study indicated a correlation of 0.87 between the magnitude of the largest peak and mass/volume ratio. The relationship between the frequency of the largest peak in the frequency spectra of the vibration responses and mass/volume ratio was best represented by a second order polynomial while the relationship between the magnitude of the largest peak and mass/volume ratio was best represented by a first order polynomial.

Index Terms—*Bone vibration spectral analysis, bone mass/volume ratio analysis, osteoporosis*

1. INTRODUCTION

Vibration analysis is a well-established, non-invasive technique in monitoring system properties [1]. This analysis technique also has several applications in the medical field. In the last few decades a number of studies have been carried out involving vibration analysis as a diagnostic and treatment tool, for example in orthopaedics [2]. The first time that vibration analysis was used to examine bone properties was in 1932, when Lippmann [3] applied oscillatory percussion across fractures of the humerus, femur and clavicle using his finger. He recorded the resulting responses via a stethoscope and compared the results. He concluded that the pitch and quality of responses differ because of free vibration of separate fragments and this could be used to distinguish between a completely healed fracture and an incomplete one. Since then, the efficacy of vibration analysis to assess the mechanical properties of bone has been investigated in a number of studies.

In 1976, Markery and Jurist [4] evaluated tibial fracture healing using an oscillator-amplifier combination. They analysed the ratios of resonant frequency of a fractured tibia of one patient to that of the intact one. The study showed a noticeable difference between the resonant frequencies of the two bones. In 1990, Nikiforidis et al [5] investigated the vibration analysis of fracture healing in vitro and in vivo human tibia. They used an electromagnetic shaker with a variable frequency range of 20 to 1500 Hz as an excitation source. Lateral and axial vibrations were detected by an accelerometer fixed to the tibia. Their results indicated that the amplitude of the vibration response spectrum of the fractured tibia was less than that of the intact tibia. In addition, the resonant frequency of the response spectrum was lower in the fractured tibia than the intact one. In contrast, Nakatsuchi et al [6] and Gabrielli et al [7] in two separate in vitro studies showed that frequency responses of fractured specimens were significantly higher than that of intact ones. Investigation of the elastic wave propagation on two groups of 78 year old women with different bone mineral density (BMD) showed that the velocities of bending waves depend on the bone density and cross-sectional area [8]. Bediz et al [9] investigated the mechanical properties of human tibia using vibration analysis, both in vivo and in vitro. They investigated the relationship between the obtained structural dynamic properties and the corresponding bone mineral density values measured by dual energy x-ray absorptiometry (DXA). Their study indicated that the natural frequency of the tibia decreased with decreasing BMD with a weak correlation. They concluded that this weak correlation was not sufficient to use as a diagnostic tool for osteoporosis. Osteoporosis is a condition where BMD is abnormally low, thereby weakening the bones and making them more susceptible to fractures [10]. The most commonly used method to detect osteoporosis is DXA. However, this method has its limitations since the BMD assessed with this method is not predictive of bone fracture risk [11-12]. Therefore there is a need for alternative bone strength assessment techniques [13-14]. Although vibration has been studied in the assessment of bone physical properties [2], its applicability for assessing BMD has not yet been established.

In order to investigate bone vibration as a tool for assessing BMD, we initially carried out an in vitro study based on turkey legs and we found that soft tissues (muscle and skin) surrounding the bone reduced the bone vibration amplitude and frequency [15]. We also found that bone vibration frequency changed depending on its mass/volume ratio. The current study builds on the results from our previous study [15] and in a novel way analyses sections of the vibration signal in order to determine the manner in which the parameters of their frequency spectra relate to bone's mass/volume ratio.

2. METHODOLOGY

2.1. Signal Acquisition

Eight fresh turkey legs were used for this study. Each leg was processed by first removing its soft tissues (skin and muscle). The resulting tibiotarsus was cut using an electric saw (model: Socomec Snc, SN600) to produce a 12 cm diaphyseal section (i.e. the bone shaft). The bone marrow was removed using a water jet. The bones were then dried at 25 ^oC for one week. The bones' mass/volume ratios (ρ) were then determined. Each bone's volume was obtained by determining the amount of water it displaced (in cm^3) once placed in an accuratly caliberated laboratory test tube. Its mass was measured using a very sensitive weighting scale (model type: Mettler Toledo, AT261DeltaRange, accuracy = 0.1 mg). The bone was held in a vice attached to one end. Vibration was induced using a small electrical hammer, controlled by a computer. The computer allowed the number of impacts and the time duration of the impacts to be set. An integrated spring in the hammer mechanism allowed the magnitude of the delivered impact to be controlled. This set-up ensured that the tests were consistent for all bones. The impact point was chosen to be at 4 cm from the top of the bone. The induced bone vibration responses were detected using a CM-01B vibration sensor, placed at 5 cm from the top of the bone. CM-01B is a light-weight sensor with a high sensitivity (typical value 40 V/mm) designed to pick up sound and vibration signals, while minimizing external acoustic noise.

The vibration signal was amplified using an instrumentation amplifier with a gain of 5 and low pass filtered using a 4^{th} order Sallen-Key, cutoff frequency of 2 kHz. The filter's cutoff frequency corresponded to the vibration sensor's maximum operating frequency of 2 kHz. LabVIEW and a National Instrument data acquisition system (i.e. myDAQ) were used to digitally record and store the responses. The myDAQ device has a 16- bit analogue to digital converter. The signal sample rate was 150,000 samples per second and 20 recordings each of 1s duration were obtained for each bone to examine consistency.

2.2. Signal Processing Operations

2.2.1 Processing of complete signal

The bone vibration signals showed oscillations for no more than 40 ms. Therefore, only the first 40 ms of the signal was considered. The 20 signal responses for each bone were processed by performing the following operations - the signals were windowed using Tukey window function [16] to reduce spectral leakage when performing Fourier transform in a later stage. This window was chosen as it allows flatness of its top to be adjusted. The flatness parameter was chosen to minimise the alteration of the desired part of the signal when the window was applied. The value selected for this parameter was 0.1. The windowed signals were averaged and then fast Fourier transformed (FFT) to obtain magnitude frequency spectrum. The magnitude frequency spectrum was examined for its dominant (i.e. largest) peak. The spectra however had multiple peaks and so to determine which peak to select the procedure described below was followed.

The vibration signals for the 8 bones showed distinct differences in oscillation rate of their first 5 ms section as compared with their remaining section. The first 5 ms section had a significantly higher oscillation rate. The signal oscillation during this section is possibly a result of the hammer's interaction with the bone during impact, while the remaining section relates to the hammer having recoiled. Therefore, the first 5 ms section and the remaining section were processed separately.

2.2.2 Separate processing of the first 5 ms (Section 1) and remaining part of the signal (Section 2)

The two selected sections of the averaged signal (i.e. sections 1 and 2) needed to be windowed prior to their spectral analysis (to reduce spectral leakage). As both sections had short duration, to reduce their distortion by windowing, their front and tail ends were equally extended by repeating their first (for front end) and last (for tail end) values till the complete section length was equal to the nearest 2^n samples (for FFT operation the length needs to contain 2^n samples, where n is an integer number). Each section was then windowed with the Tukey function. The flatness parameter of the window was set to 0.3. This value produced a window that tapered the signal edges, and preserved the desired part of the signal. FFT was performed on each windowed section and their frequency magnitude spectra were obtained.

2.2.3 Correlation Analysis

Results (outlined in the next section), indicate that lowpass filtering of the bone vibration signals (that contains both Sections 1 and 2) with cutoff frequency of 750 Hz, and analysing their frequency spectra provided the most suitable route to determining the correlation between the bones' mass/volume ratios and the information from their frequency spectra. For this purpose each windowed vibration signal was lowpass filtered with a 7^{th} order Butterworth filter. By attaching them end to end, the 20 filtered signals for each bone were abutted. This longer length signal reduced spectral line separation by a factor of 20, thus allowing an improved determination of frequency components. The magnitude frequency spectra of the resulting signals were obtained and the magnitude and frequency of their highest peak was correlated with the bones’ mass/volume ratio.

3. RESULTS AND DISCUSSIONS

A typical averaged bone vibration signal and its magnitude frequency spectrum are shown in Figure 1.

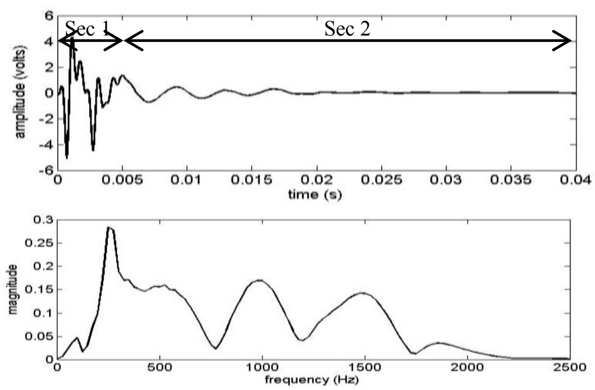

Fig 1. Typical averaged bone vibration signal (top) and its magnitude frequency spectrum (bottom).

The tail-end part of the signal not shown in the figure did not have significant oscillation and so was not analysed. The frequency spectrum had multiple peaks. Considering the frequency spectrum, it was not possible to determine which peak had the most relevant information. In order to deal with this issue, the frequency spectra of the Sections 1 and 2 (shown in Figure 2) were considered separately.

The spectrum for Section 1 had muliple peaks highlighting its more complex nature as the hammer interacted with the bone during its impact. The spectrum for Section 2 has a single dominant peak characterizing bone vibration, after the hammer recoiled.

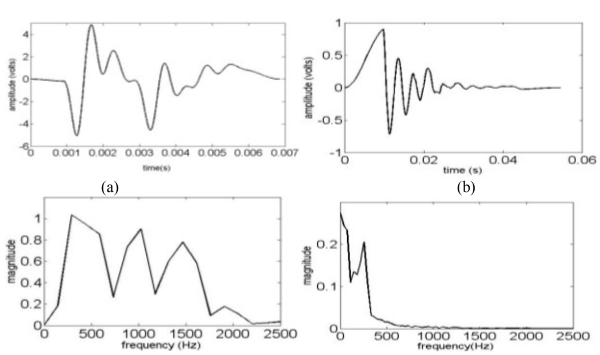

Fig 2. Section 1 (a) and section 2 (b) of the vibration signal and their corresponding magnitude frequency spectra (c) and (d).

Section 1 had frequency components up to 2 kHz (i.e. the limit of the vibration sensor), while Section 2 did not have significant components above 750 Hz. In order to investigate the frequency components above and below 750 Hz, the 20 bone vibration signals (for all 8 bones) were separately filtered with lowpass and highpass 7^{th}-order Butterworth filters, cutoff frequency 750 Hz. Examples of the resulting low pass and highpass filtered signals are shown in Figure 3.

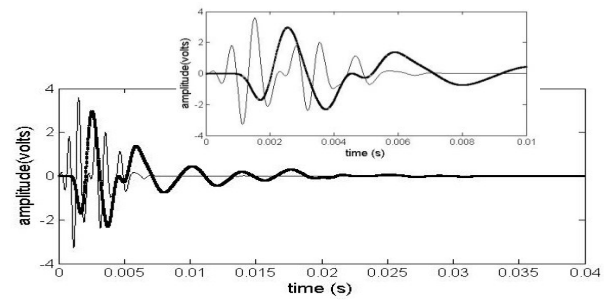

Fig 3. Averaged vibration signal filtered using a lowpass (darker waveform) and highpass (lighter waveform) filter. The inset on the top shows the zoomed first 10 ms sections of the two signals.

A comparison of the lowpass and highpass filtered signals indicated that the lower frequency signal is delayed by about 1 ms in relation to the higher frequency signal. As both were filtered using a 7^{th} order Butterworth filter, the delay difference is not due to filtering process. It was concluded that the delay was due to bone vibrating with a delay, once it was impacted with the hammer. This relates to our initial observation that Section 1 is the result of the hammer’s interaction with the bone during impact, while during Section 2 the hammer has recoiled and so bone vibrates without the hammer’s interference. For this reason, the remaining analysis was only based on the lowpass filtered signal.

Figure 4 shows a typical abutted low frequency signal and its corresponding magnitude frequency spectrum.

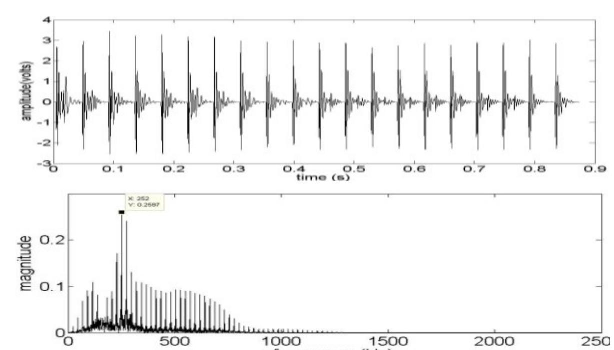

Fig 4. Abutted signal obtained from the lowpass filterd part of the signal (top) and its corresponding magnitude frequency spectrum (bottom).

The magnitude and frequency of the largest peak in the abutted signals' frequency spectra were identified. The resulting data are summarised in Table I together with the relevant bones' mass/volume ratios.

TABLE I
RESULTS SUMMARY

Bone Label	Frequency (Hz)	Magnitude	Bone mass (g)	Bone volume (cm^3)	Bone mass/volume ratio (g/cm^3)
T1	137	0.0329	18.59	11.5	1.62
T2	320	0.0324	20.02	11.5	1.74
T3	297	0.0975	15.09	8.5	1.77
T4	229	0.1282	17.57	10.5	1.67
T5	252	0.1326	16.09	9.5	1.69
T6	2252	0.2597	19.74	12.5	1.58
T7	274	0.0427	16.57	9.0	1.84
T8	252	0.2094	16.76	10.0	1.68
Average	251.6	0.1169	17.55	10.37	1.70
Standard deviation	54.6	0.0840	1.65	1.29	0.08

Figure 5 shows the relationship between the frequency of the largest peak in the lowpass filtered bones' vibration frequency spectra and the bones' mass/volume ratio using first and second order polynomials. Higher order polynomials were not used because they went through all data points causing over fitting. The data point associated with bone 6 (T6, mass/volume ratio= 1.58 g/cm^3) has been left out of the plot as its value was very far from the remaining data points. The reason for this bone behaving differently from the rest requires further studies.

R squared (shown on the graph) is a coefficient between 0 and 1. It indicates the closeness of the polynomial to the data points. When this value is equal to 1, the points fit on the graph without any deviation. For first order polynomial, R provides the correlation coefficient between two variables.

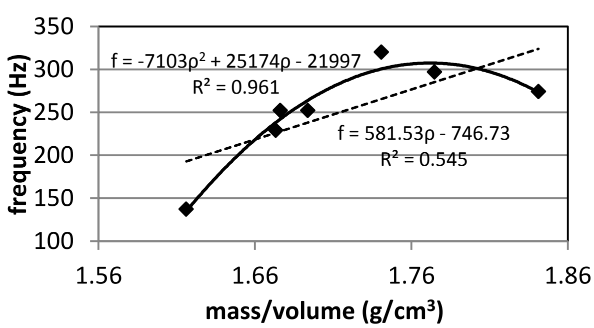

Fig 5. Plot of the frequency of the largst peak in the lowpass filtered bones' vibration frequency spectra agaist their mass/volume ratios using first (dashed line) and second (solid line) order polynomials.

The results from Figure 5 indicate that an increase in bone mass/volume ratio causes an increase in the bone's vibration frequency. The second order polynomial fitted the data points much better (R^2= 0.961) than the first order polynomial (R^2=0.545). The second order polynomial showed that as mass/volume increased, the bone vibration frequency initially increased and then from about 1.74 g/cm^3 it fell.

Figure 6 shows a plot representing the relationship between magnitude of the largst peak in the lowpass filtered bones' vibration frequency spectra and their mass/volume ratios using first order polynomial. The data point associated with bone 1 (T1, mass/volume ratio= 1.62 g/cm^3) was left out in this plot as its value was very far from the remaining data points. The value of R^2 for this plot was 0.75. This corresponds to a correlation coefficient of 0.87. This is much higher than the value obtained when frequency of the largest peak was plotted against mass/volume ratio.

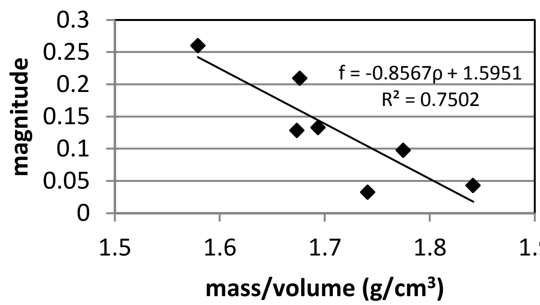

Fig 6. Plot showing the relationship between magnitude of the largst peak in the bones' vibration frequency spectra and their mass/volume ratios using first order polynomial.

The spectral analysis of the bone vibration signal indicated that both frequency and magnitude of the highest peak in lowpass filtered bone vibration signals were related to the bones' mass/volume ratios. However, the relationship for vibration frequency was more complex and was best described by a second order polynomial.

4. CONCLUSION

The study indicates that a number of relationships exist between turkey bone mass/volume ratio and its vibration frequency response. The magnitude of the highest peak in the frequency spectrum of the bone vibration response was linearly related to the bone's mass/ volume ratio (correlation coefficient = 0.87). However, the relationship between the frequency of the highest peak in the bone's vibration frequency spectrum and the bone's mass/volume ratio was best represented by a second order polynomial.

Future studies will involve investigating bone vibration responses in human subjects to assess their bone mineral density (BMD) in vivo and relating the findings to the BMD obtained from dual energy x-ray absorptiometry (DXA).

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