ON THE DETECTION OF BONE CRACKS BY SHOCK WAVE PROPAGATION
عن اكتشاف شروخ العظام بواسطة انتشار الموجة الصدمية

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ملخص: البحث المعملى الحالى يهدف الى الوصول لتقييم موضوعى بالنسبة لتماسك العظام فى حالة وجود شرخ سطحى بها. ويقدم البحث طريقة ميسرة - عملية وغير جراحية لاكتشاف شروخ العظام ومتابعة سرعة التآم الشروخ. وهذه الطريقة تعتمد على دراسة انتشار موجة صدمية فى العظم فى وجود شرخ صناعى متزايد الأبعاد ومقارنته بالعظم السليم. وقد توصلت الدراسة الى أن هناك علاقات ايجابية بين الأبعاد النسبية للشرخ وكل من ترددات الرنين - معامل الانتقال الموجى وسرعة الموجة وزمن الانتقال خلال الشرخ والانتقالية.

ABSTRACT

The present experimental work aims to give an objective assessment for the integrity of bone due to crack existence. A simple, non-invasive and practical method for detection of bone cracks and monitoring the healing progress of bone fractures was presented. The technique used is based on monitoring shock wave propagation in a long bone with a progressively increasing defect in the bony cortex. Significant relationships were found between the relative size of the bone discontinuity and the resonance frequencies, the transmission coefficient, the wave velocity, the transit time across the fracture and the transmissibility.

INTRODUCTION

Assessment of the integrity of bone in-vivo and the degree of fracture healing are essential elements for a patient. Surgeons need to be ascertain of the crack existence, its position and its dimensions to decide upon the best method for remedy or surgical operation. In addition, they need to ascertain the state of healing before the patient is allowed to bear weight partially and for deciding the optimum duration of the period of immobilization. If the patient is immobilized too long, this may produce reduced range of motion and it also increases the cost of medical care. On the other hand, too early resumption of activity may produce refracture or delay of healing. This clearly shows the necessity of the development of objective means of measuring the cracks and the state of union of healing fractures.

At present, manual and radiographic examinations are the most common clinical methods in the management of bone-fractured patients. However, for many applications these methods suffer from low sensitivity. For example, less than 30 % bone mineral loss is generally not detectable by radiography, thus making it difficult to diagnose the early stages of osteoporosis. In addition, minute cracks can not be distinguished by radiography. Moreover, interpretation of radiologic images is subjective in nature and it varies with the clinical judgment of the physician.

During the last 30 years, many investigators have attempted to develop new diagnostic techniques for detecting bone-cracks and judging fracture healing. Mechanical impedance, natural frequency, stress wave propagation and ultrasonic measurements are some of the techniques which have been attempted by different investigators. Although these techniques could be used experimentally to determine the integrity of bone in vivo but most of them are not practicable for widespread clinical use due to low reliability, complicated instrumentations or for being invasive in nature. Thus, for a successful clinical application, the technique should be non-invasive, reproduciable, inexpensive, simple to operate and painless in application. The technique that satisfies most of these criteria is the impact test in which an instrumented hammer is used to produce an impact on a long bone and the impact response is monitored by an accelerometer.

Vibration analysis as a technique to monitor the integrity of a bone has been investigated by several workers. Christensen et al. [1] and Cornelissen et al [2] described vibration analysis as a method to monitor fracture healing. Christensen et al. [3-4] used "Bone Resonance Analysis" (BRA) technique in which the lowest frequency of resonance of the healing fractured tibia was compared to the lowest resonance frequency of the intact tibia as an index for fracture healing. They also investigated the validity of the left-right leg comparison and observed no significant difference between the resonant frequency of the left and right leg in over 50 normal persons. They also studied the influences of soft tissues, joints and fibula upon the vibration of human tibia [5]. They found that the mass of muscles and tissues have an influence on vibration amplitudes while the influences of skin and joints were small. Van der Perre and Cornelissen [6] proposed "MADAMS" (Modal Analysis Dynamic Anatomic Modelling for Stability) as a procedure for the analysis and interpretation of bone vibration tests in which damped natural freqencies, damping ratios and mode shapes are determined at a number of points along the bone and mathematical models are used to correlate these parameters to the physical integrity of bone. Another technique was utilized by Fook et al [7] who determined the "Impulse Frequency Response" (IFR) to characterize the dynamic response of human tibia. The tibia was excited with hammer impact and the response was measured by an accelerometer. Collier et al. [8] presented a theoretical model to predict the tibia resonance frequencies using a homogeneous hollow beam with constant cross-section. They found a good correlation between the experimental transverse modes in the medial/lateral and posterior bone surfaces to those predicted by their model.

Stress wave propagation across a bony discontinuity was studied by Pelker and Saha [9] to simulate a healing fracture. They found statistical positive relations between the size of the discontinuity and the transmission coefficient, dispersion and transit time across the fracture. Moyle and Gavens [10] investigated the fracture properties of tibial bone experimentally. They noted that the fracture stress depends on the crack length and not on the crack tip radius of curvature. The influences of bone density, specimen thickness and crack velocity on longitudinal fracture were elaborated by Behiri and Bonfield [11]. They concluded that both the stress intensity factor (Kc) and the strain energy release rate (Gc) depend on the loading rate and resultant crack velocity. The increase in bone density resulted in an increase in Kc and Gc, while the specimen thickness had no effect on the fracture parameters. On the other hand, Moyle and Bowden [12] found that the work of fracture was independent of the degree of bone mineralization while it increased with increasing osteon fractional area.

MATERIALS AND METHODS

Bovine tibial bones were obtained and examined visually in order to be free from any surface fractures or craks. The bones were wrapped in saline solution soaked paper towels and freezed at -20 °c until tested. This method of storage has been proved to preserve their biomechanical and biophysical properties without any significant changes [13-14]. At the time of testing, bones were thawed to room temperature while being kept moist in saline solution. Tested bone was suspended horizontally by light nylon wires in a free-free mode. After carrying the impact tests on the intact bone, the same bone was used to perform tests with artificial surface cracks. These cracks were in the mid-way between the impact position and the accelerometer measuring position. The artificial cracks or cuts were made progressively on the bone cortex using a hand-saw. Cuts of depths 0.5, 1, 3 and 4.5 mm with constant width of 1 mm were performed and cuts of 2 and 3 mm width with constant depth of 4.5 mm were also investigated. The artificial cut dimensions were measured using machinist's depth gauge and fillers. After each cut the compression impulse test was repeated four times and the output average for travelling wave characteristics was calculated.

In each test, a short duration (about 0.3 ms) transverse impact load of 10 N was applied at a predetermined point near the bone end shaft using an instrumented impact hammer. An accelerometer with relatively high sensitivity was cemented to the bone surface and was used to pick-up the output response. The output signals were analyzed with a HP 5451C Fourier Analyzer and then displayed on an oscilloscope and X-Y pen recorder. Fig. 1 demonstrates a view for the test-rig, tested bone and measuring equipment.

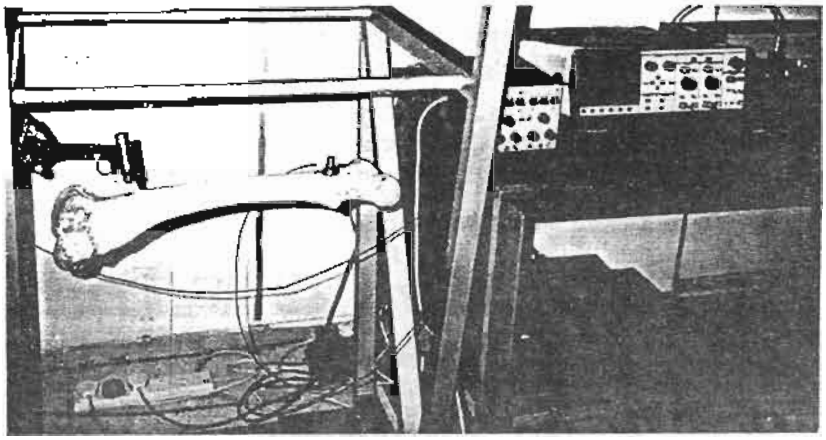

Fig. 1. View for the test-rig and measuring equipment

TEST RESULTS

An example for the mobility curves obtained for an intact bone and for a bone with an artificial surface cut are shown in Fig. 2. From the mobility curves, three resonance peaks could be observed.These frequencies are denoted F1, F2 and F3 respectively The variations of average frequencies with the crack dimensions, expressed in terms of depth and width dimensions of the artificial cuts are shown in Fig. 3. The figure indicates that as the bone discontinuity increased the frequencies also increased linearly, i.e. they are shifted to the right hand in the mobility curves.

The transmission coefficient is defined as the ratio of maximum pulse height after a given fracture cut in the bone surface to the maximum pulse height of the intact bone. Fig. 4 shows the variation of the transmission coefficient versus the crack dimensional parameters. As can be seen, the transmission coefficient decreases with the increase in the crack dimensions.

The time delay of the arrival of the vibration pulse due to the presence of the increasing fracture depth was measured from the obtained mobility curves. This was done by subtracting the transit time for the pulse to travel in the cut bone from the original transit time for the uncut bone. The results are plotted in Fig. 5 against the crack parameters. The solid line is the least squares fit of the resulted data. As can be seen, the delay time increases linearly with the increase in crack parameters.

The wave velocity of the impact was also calculated as the distance travelled by the wave between the position of hammering and the position of the accelerometer (180 mm), divided by the lag time. Fig. 6 illustrates the variation in wave velocity against the crack parameters. It can be seen that the wave velocity decreases as the crack dimensions increase.

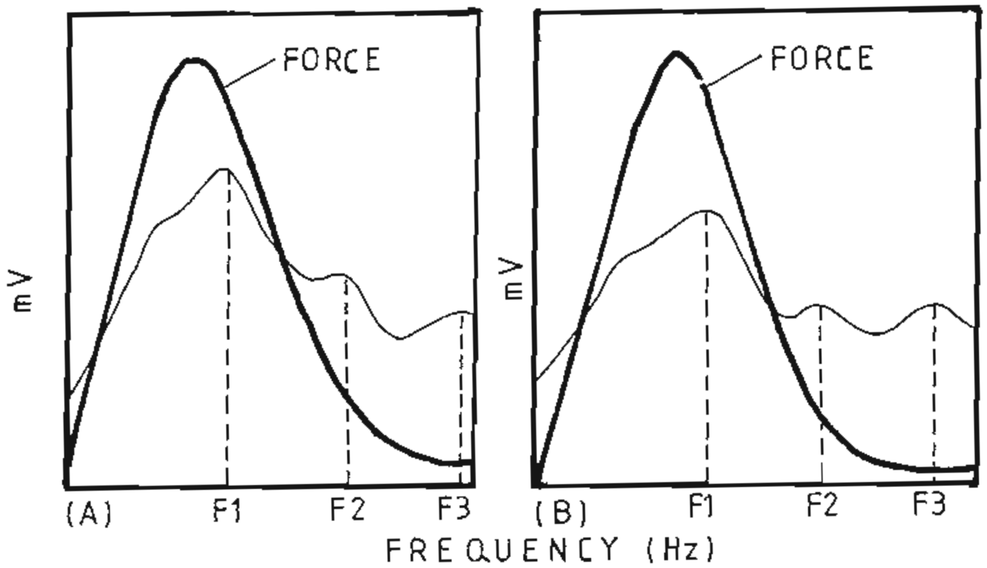

Fig. 2. Evaluation of the Mobility Curve for: (A) Intact Bone (B) Cut Bone.

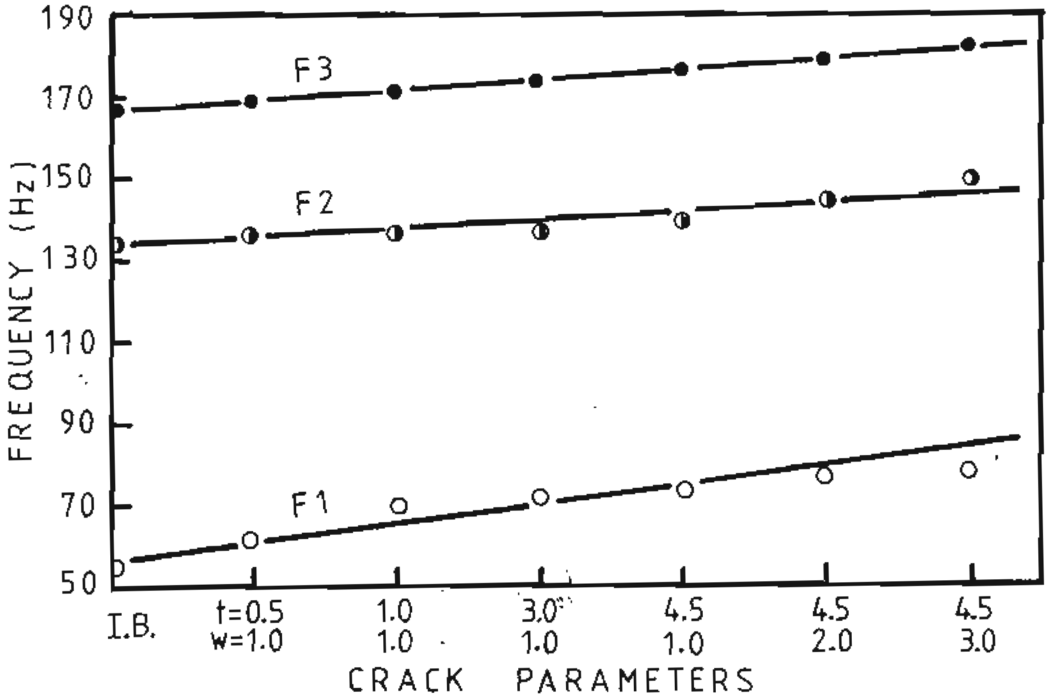

Fig. 3. The Variations in the Resonance Frequencies due to Gradual Weakening of the Tibia Bone (I.B. = Intact Bone, t = Thickness of cut in mm, w = Width of cut in mm).

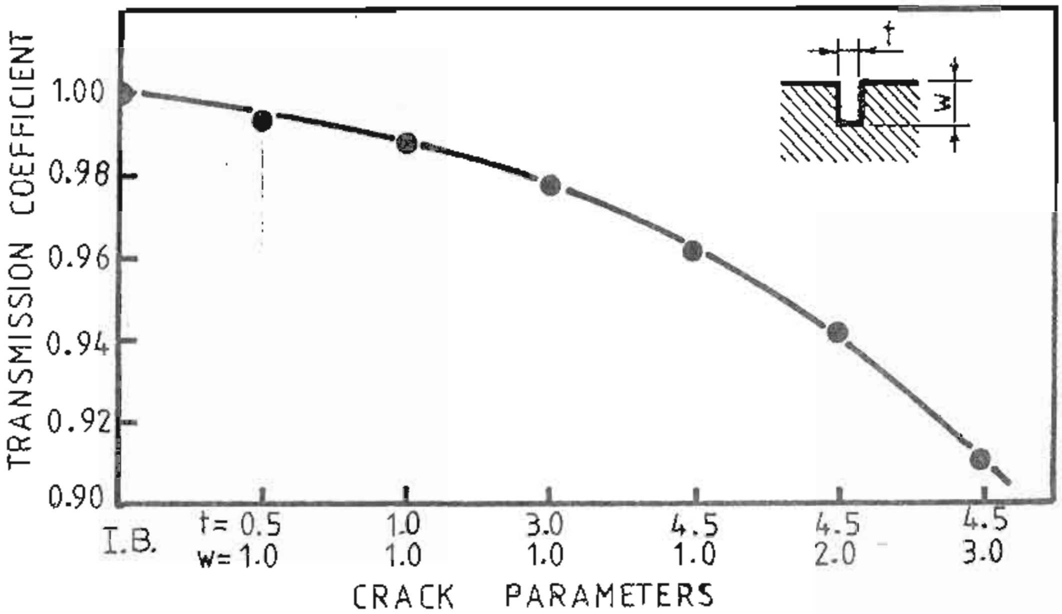

Fig. 4. The Variations in the Transmission Coefficient with Dimensional Gap Parameters. (I.B. = Intact Bone, t = Thickness of cut in mm, w = Width of cut in mm).

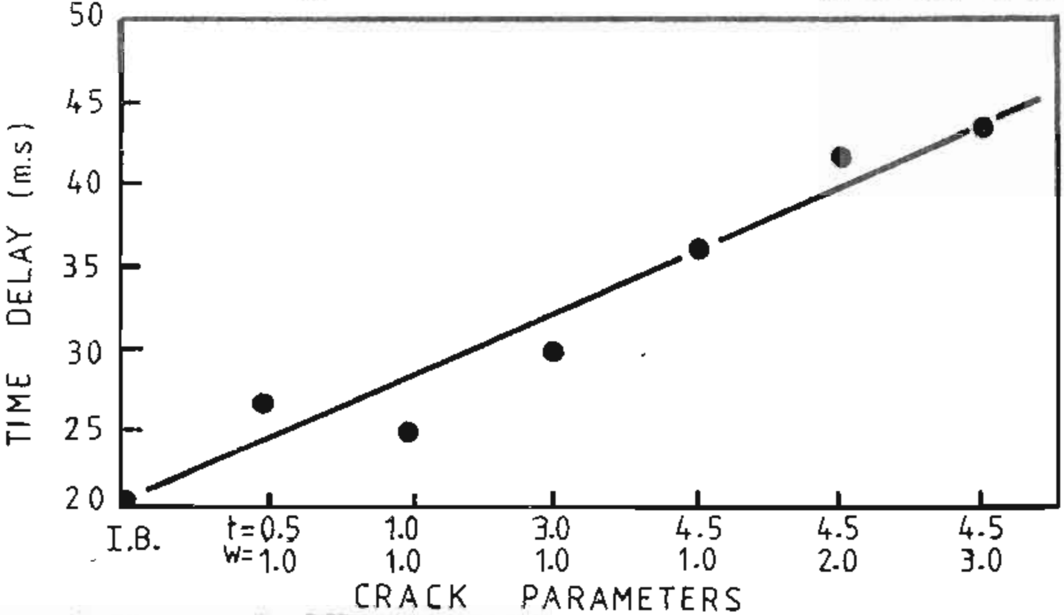

Fig. 5. Variations in Time Delay with Crack Parameters (I.B. = Intact Bone, t = Thickness of cut in mm, w = Width of cut in mm).

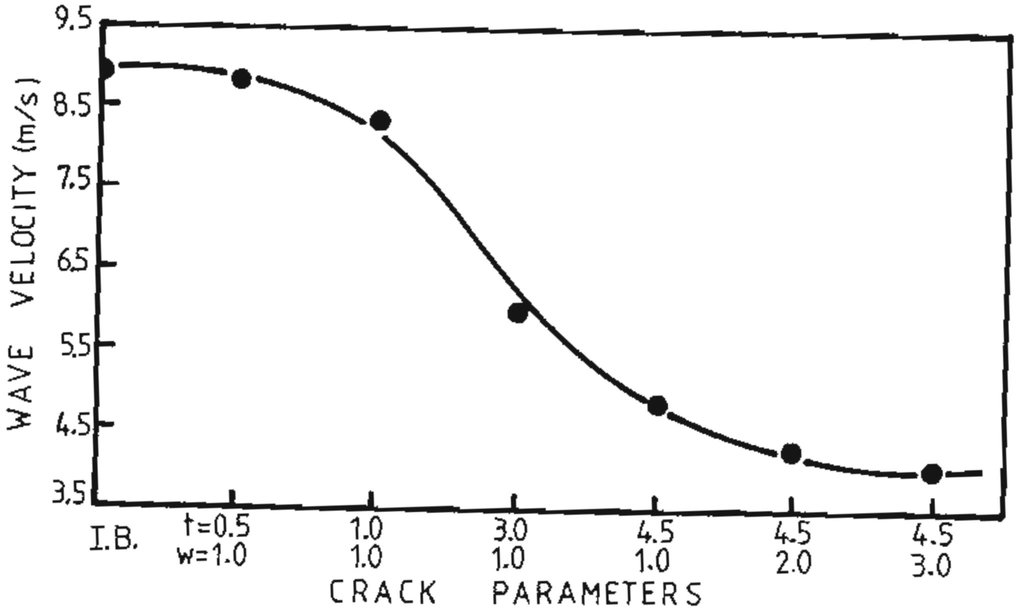

Fig. 6. Wave Velocity Versus Crack Dimensional Parameters (I.B. = Intact Bone, t = Thickness of cut in mm, w = Width of cut in mm).

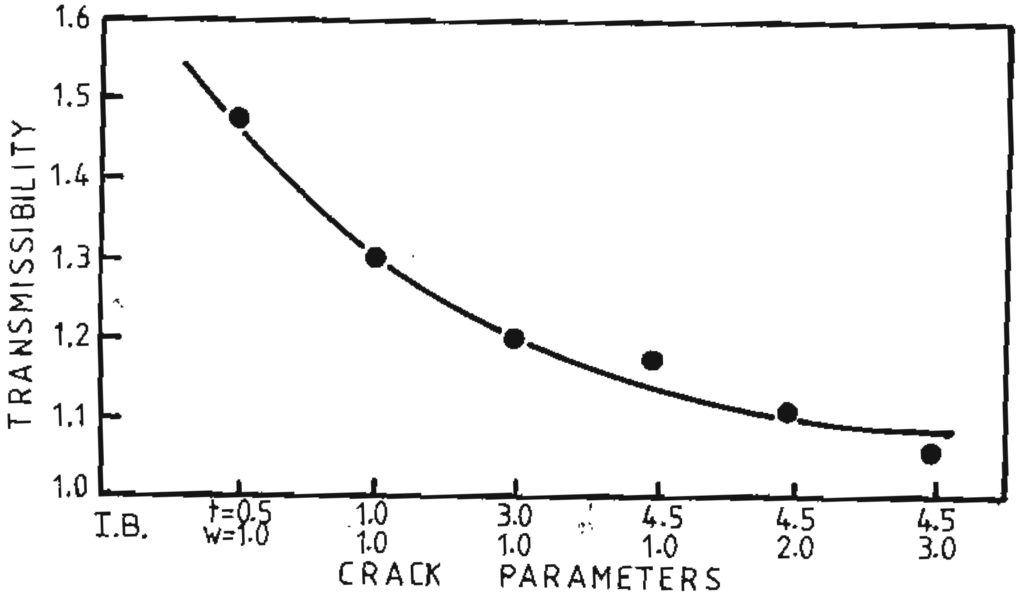

Fig. 7. Variations in Transmissibility with Bone-gap Dimensions (I.B. =Intact Bone, t =Thickness of cut in mm, w= Width of cut in mm).

According to vibration theories, the transmissibility is defined as the ratio between the transmitted force to the original applied force. The transmissibility of the tested bones was calculated by considering that for the compact solid bone the natural frequency is about 200 rad/s and the damping ratio is 0.3. Fig. 7 demonstrates the variation of the transmissibility versus the crack dimensions. As can be seen, the transmissibility decreased with the increase in gap parameters.

It is worth noting that experimental investigation for the influence of varying the crack angle direction with respect to the bone longitudinal axis has revealed that crack direction has no effect upon the wave travelled in bone either in magnitude or lag time compared with similar cut performed perpendicular to the bone axis.

DISCUSSION OF RESULTS

The impact experimental tests carried out in the present investigation is relatively simple to set-up and it would not cause unnecessary pain or inconvenience to the human subjects. Tests on large number of patients could be done in a short time. In addition, the data reduction is quite simple. The results obtained suggest that useful clinical informations could be reached by this impact test and thus it could potentially be used as a non-invasive diagnostic tool. Although the present work has been carried out on only solid bovine tibia bone but it is known that soft tissues covering the actual bone, fibula and joint do not result in fundamental changes in the vibrational behaviour of the bone. They hinders the exact interpretation of the vibration measurements of the bone but do not make them impossible. Comparative measurements such as fracture healing monitoring, where the opposite leg can be used as a reference, are within reach [5].

In the present study, intact and gradually weakened tibia bone were subject to impulse frequency response technique. Vibrations were generated by a hammer and picked-up by an accelerometer. The weakening of the bone cross-section is a rough simulation of crack existence and healing with callus formation. The fact that the same vibration mode shapes are found on healing and on weakened tibia indicates that the healing simulation used by weakening one cross-section is acceptable for this kind of research [2-8]. Mobility curves obtained in the present work have demonstrated three resonance peak frequencies: F1, F2 and F3, which increased with the increase in crack dimensions. When comparing an intact bone with a cut one, the frequencies in the cracked bone will be shifted to the right in the mobility curves. From these mobility curves, it was found that the transmission coefficient, the wave velocity and the transmissibility decreased with the increase in crack dimensions. An increased bone loss either due to age, osteoporosis or crack existence is reflected by the decreased wave velocity measured during the impact test.

It is worth noting that in order to ascertain whether the magnitude of the impact force could influence the velocity of wave propagation, impact forces of varying magnitudes ranging from 5 N to a maximum of 100 N were applied by the hammer in the present work. It was found that the transit time for the propagation of wave between the points of the impact and the pick-up was relatively constant over this entire range of hammer impact force. This suggests that the magnitude of impact force did not influence the velocity of wave propagation significantly. On the other hand, the lag time increased with the increase in crack dimensions as the discontinuity of bone cause an obstacle for the travelling wave causing more delay in time compared to the intact bone.

CONCLUSIONS

From the results obtained, the following conclusions can be drawn with reference to the intact bone :

1. The presence of a crack on the bone surface increases the resonance frequencies by about 25 %. Such increase is higher for low frequencies and lower for high frequencies.

2. The transmission coefficient decreases with the increase in crack dimensions. As the intact bone has a transmission coefficientof 1.0, the existance of crack can be predicted by the transmission coefficient if different than unity.

3. The lag time between the input signal and the picked-up response increases with the increase in crack dimensions.

4. The response wave velocity decreases with the increase in crack dimensions. Such decrease in velocity is sensitive to minute changes in bone discontinuity.

5. The transmissibility decreases with the increase in crack dimensional parameters.

6. The variation in crack direction with respect to the longitudinal bone axis has no effect upon the characteristics of the propagated wave in the bone.

7. The impact test method represents a simple and efficient non invasive mean for detection surface bone cracks by comparing the fractured leg with the non-fractured one in terms of lag time, resonance frequencies, transmission coefficient, wave velocity and transmissibility.

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