Initial study of A-Mode ultrasound spectroscopy through mechanical wave scattering phenomenon for measuring 3D-printed bone model density

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Abstract—In Indonesia, the prevalence of osteoporosis is high. Given the economic burden it may impose on the population, this condition must be taken seriously. Dual-energy X-ray absorptiometry is the gold standard for diagnosing osteoporosis (DEXA). However, due to its high cost, non-portability, and radiation risk, DEXA cannot be applied to large populations. An alternative method for evaluating bone quality is ultrasound. It is more affordable, portable, and has no radiation risk. In this preliminary study, an A-mode ultrasound spectroscopy prototype for assessing the density of a 3D-printed bone model is designed. A single-element transducer (Transmit-Tx/Receive-Rx), a reconfigurable and modular FPGA-based ultrasound beamformer system, and a Raspberry Pi 3 are the system's control units. The raw radio frequency (RF) signal is acquired from three variations of density of the 3D-printed bone model, i.e., 100%, 60%, and 40%, to represent normal bone, osteopenia, and osteoporosis. The designed prototype can adequately characterize the mechanical wave scattering pattern of the 3D-printed bone model indicated by the increased tendency in the maximum amplitude when the density of the bone model is increasing. The tendency is the opposite for delay time and Power Spectral Density (PSD). These three signal parameters are potential candidate parameters to represent bone density. For future work, the selected candidate parameters can later be used as reference values while adding a significant data so that a machine learning method can be employed to extract representative features of bone density level, i.e., normal bone, osteopenia, and osteoporosis.

Keywords—Osteoporosis, bone model, 3D printing, ultrasound spectroscopy, A-mode, mechanical wave scattering.

I. Introduction

OSTEOPOROSIS is a bone disease that causes low bone density and degradation of the structure of its microarchitecture, [1]. This condition requires immediate attention because it can result in bone fractures, disability, and even death. The economic burden incurred is also not insignificant because of the long-time treatment and many medical expenses required, [2]. According to WHO data from 2012, osteoporosis ranks second after heart disease, [3]. Furthermore, per statistics from the Ministry of Health of the Republic of Indonesia in 2015, osteoporosis affected 19.7% of the total population, [4].

Dual-energy X-ray absorptiometry (DEXA) is the current international gold standard for diagnosing osteoporosis. However, DEXA cannot be applied to large populations due to the high cost and non-portability of the equipment, as well as the risk of radiation/ionization exposure, especially with certain patients such as pregnant women, [5], [6]. Another method, i.e., ultrasonography (USG), has begun to be accepted as an alternative method for evaluating bone quality in populations at risk of osteoporosis, [7], [8], [9], [10], because it is much more

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affordable, portable, and has no radiation risk. In previous studies, [7], [8], [9], [10], many researchers have developed a quantitative ultrasound method for the bone data measured directly from the patients, e.g., calcaneal and vertebral bone. However, this method does not yet have a standard measurement parameter for bone quality like DEXA because of the various types and quality of USG devices. The lack of a universal standard is still a barrier to making USG the primary diagnostic tool for bone density despite the many potentials and advantages mentioned previously.

Thus, it is necessary to carry out sufficient data testing to determine the standard reference value. Sampling representative ultrasound scanning data from patients requires a tremendous number of measurements. In this initial study, we offer a solution by taking an approach, i.e., modeling bones with 3D printing. With current 3D printing technology, it is possible to make bone models with various shapes, sizes, and porosities that are close to the actual conditions of human bones, [11].

One of the focuses of this initial study is to develop representative bone models for normal, osteopenia, and osteoporosis conditions. In addition to that, this study also aims to explore and investigate representative candidate parameters for bone density extracted from A-mode ultrasonic spectroscopy data from the 3D bone models. Furthermore, the selected candidate parameters can later be used as reference values while adding significant data so that a machine learning method can be employed to extract representative features of bone density level. Concerning the high prevalence of undetected osteoporosis in the population, this method can be a promising affordable screening method for many populations for potential risk of osteoporosis.

II. METHODOLOGY

A. 3D-printed Bone Model

3D printing technology is an additive manufacturing process, i.e., by gradually adding/combining layers of material, in contrast with conventional methods carried out by removing material by cutting or drilling. This technology has advantages in speed, design freedom, manufacturing cost, and prototyping that are not feasible to be accomplished with traditional methods, [12].

We used the most popular 3D printing technique, i.e., Fused Deposition Modeling (FDM). The FDM method usually uses a thermoplastic material as a filament or coil. The thermoplastic materials commonly used are polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), and nylon. With the FDM method, 3-dimensional objects are created by synchronizing between the two following processes:

1. The filament is fed into heating nozzles with the controlled extrusion speed,
2. The machine shifts the nozzle in relation to the platform where the object is formed.

By synchronizing these two processes, the material will be added layer by layer onto the object platform until a 3D object is formed according to the design.

To create a 3D model of human bones, a precise 3D geometry design is needed to approach the actual conditions of human bones. For bone model density testing, the bone model must have representative porosity. The bone model's porosity level is determined not only by the input design and 3D printer control~~,~~ but also by the type of filament material. These 3D bone models are printed with PLA material.

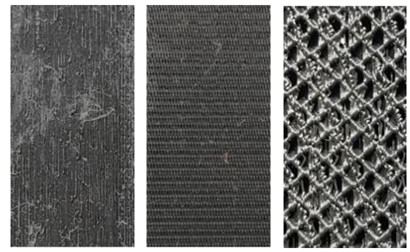

Fig.1. The 3D bone model representing normal bone (left: density of 100%), osteopenia (middle: density of 60%), and osteoporosis (right: density of 40%)

Considering the positioning of the ultrasound transducer on the testing object, in this initial work, we only focused on the porosity condition of the bone model, not the shape. The shape is a simple cuboid with a 15cm × 7cm × 2.5cm dimension. The porosity is set with input density values of 100% (representing normal bone), 60% (representing osteopenia), and 40 % (representing osteoporosis). The 3D-printed bone models are shown in Fig.1.

B. Amplitude Mode (A-Mode) Ultrasound Spectroscopy

The A-mode ultrasound spectroscopy has been used for non-destructive testing (NDT) of various materials, e.g., metal, plastic, and soft tissue. In clinical applications, this method is used for measuring the deformation of muscle, [13], and orthopedic surgery, [14]. The A-mode ultrasound spectroscopy system proposed in this research is specifically designed to evaluate the acoustic characteristics of the 3D bone model.

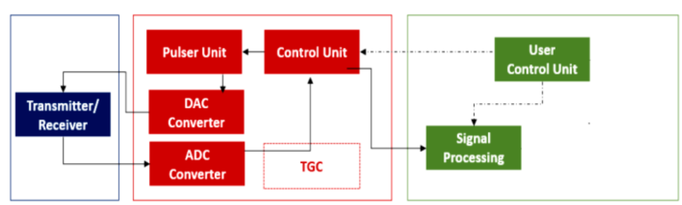

Fig.2. Block diagram of A-mode ultrasound spectroscopy

This ultrasonic spectroscopy system consists of three main components, i.e., the ultrasonic system (red), transducer (dark blue), and computer (green), as shown in Fig.2. The ultrasonic system consists of a pulser unit, control unit, DAC and ADC converter, and time gain compensation (TGC). In this system, the transducer is a single transducer used alternately as a transmitter and receiver. The computer is used as a user-control unit and signal processor.

The ultrasonic system is implemented with a reconfigurable and modular FPGA-based ultrasound beamformer system (un0rick open hardware board), [15], [16], [17], and a Raspberry Pi 3 as a control unit, as shown in Fig.3.

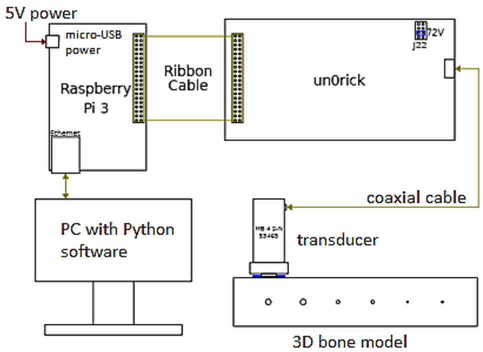

Fig.3. A-mode ultrasound spectroscopy architecture

The information displayed in the amplitude mode (A-mode) is two-dimensional. The x-axis represents the transmission depth of the ultrasonic wave, and the y-axis represents the amplitude of the reflection echo. The time needed for the wave to travel from the transducer (transmit) until received back by the transducer (receiver) is known as the time of flight (ToF). The A-Mode is the fundamental mode of ultrasonic spectroscopy representing the information of the ultrasonic wave propagation through the medium.

C. Experiment Setting

The experiments were conducted by sampling the raw radio frequency (RF) signal for each A-mode scan line representing the 3D bone model acoustic scattering pressure field. The beamforming effect is excluded from the experiment.

Three 3D bone models with a density of 100%, 60%, and 40% were tested using a single-element transducer (Sonatest IMR3750, Milton Keynes, UK) with a frequency of 5 MHz (±10 %) and a crystal diameter of 6.35 mm. The space between the transducer's face and the object was filled with ultrasonic couplant (standard clinical USG gel) to prevent mismatching of acoustic impedance. The transmit frequency is set at the optimal value of 1.87 MHz by applying the input signal from the pulser to the transducer.

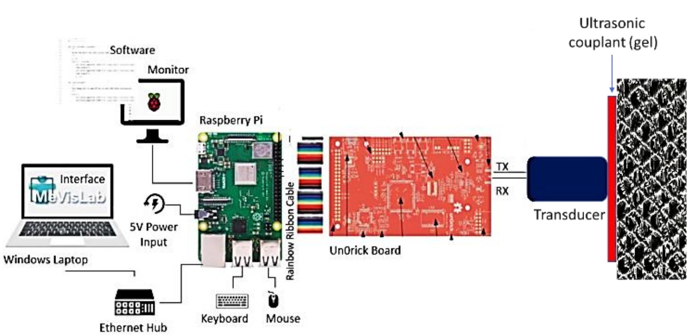

Fig.4. Experiment configuration

The raw RF signal acquired by the transducer is sampled and recorded by a computer laptop for further processing. The experimental configuration is shown in Fig.4.

The data acquisition was performed with a single firing of ultrasonic waves for 200 microseconds, and then the reflection waves were recorded as A-mode raw data. The experimental setting is shown in Fig.5.

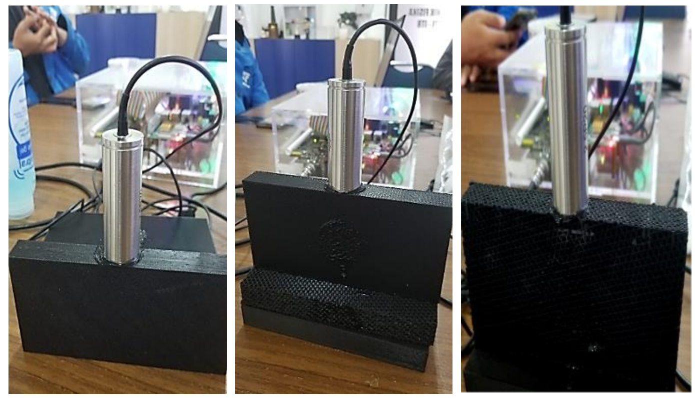

Fig.5. Experiment setting: the density of 100% (left), density of 60% (middle), and density of 40% (right).

D. Signal Processing

The signal processing is performed in the time and frequency domain. The raw RF signal is represented by the modulated signal on each scan line obtained by the single-element transducer, [18], as described in (1).

$$x(t) = A(t)\cos[2\pi f_C t + \varphi(t)] \tag{1}$$

$A(t)$ is a superposition of the 3D bone model's phases and scattering reflection amplitude, f_C is the center frequency, and $\varphi(t)$ is the phase function.

Raw RF signal $x(t)$ is further processed in the frequency domain as the Power Spectral Density (PSD) as described in (2).

$$PSD(f_k) = \frac{1}{P}\sum_{p=0}^{P-1} \tilde{P}_{xx}^{(p)}(f_k) \tag{2}$$

f_k is the sampling frequency in the k domain, P is the total segment of the data, and $\tilde{P}_{xx}^{(p)}$ is the estimated PSD for each segment. The formulation has been described in detail in [19]. The information on the energy content of the signal in its frequency spectrum can be used to determine the level of reflection echo as a function of the object's density.

III. Result and Discussion

A. Data Analysis: Signal Processing in Time Domain

The measurement results show that the amplitude level of raw data is 2 Volts for 100% density, 0.5 Volts for 60% density, and 0.45 Volts for 40% density. The maximum peaks of the envelope signals are achieved at a delay time of 6.25 microseconds for 100% density, 8.33 microseconds for 60% density, and 10.76 microseconds for 40% density. The plot of the signals in the time domain is shown in Fig.6.

The maximum amplitude indicates a pattern that can represent the density of the 3D-printed bone model. The sample with a density of 100% shows the highest maximum amplitude compared to the other lower-density samples because the strongest reflection is produced by the medium with the highest density. The maximum amplitude decreases when the density of the medium decreases because the wave hits a target farther away from the transducer before being reflected in the transducer. When it passes through space within the medium, the energy of the reflected wave attenuated significantly due to the distance and the dispersed nature of the ultrasound wave in the air because of the mismatching of the acoustic impedance between the solid medium and the air.

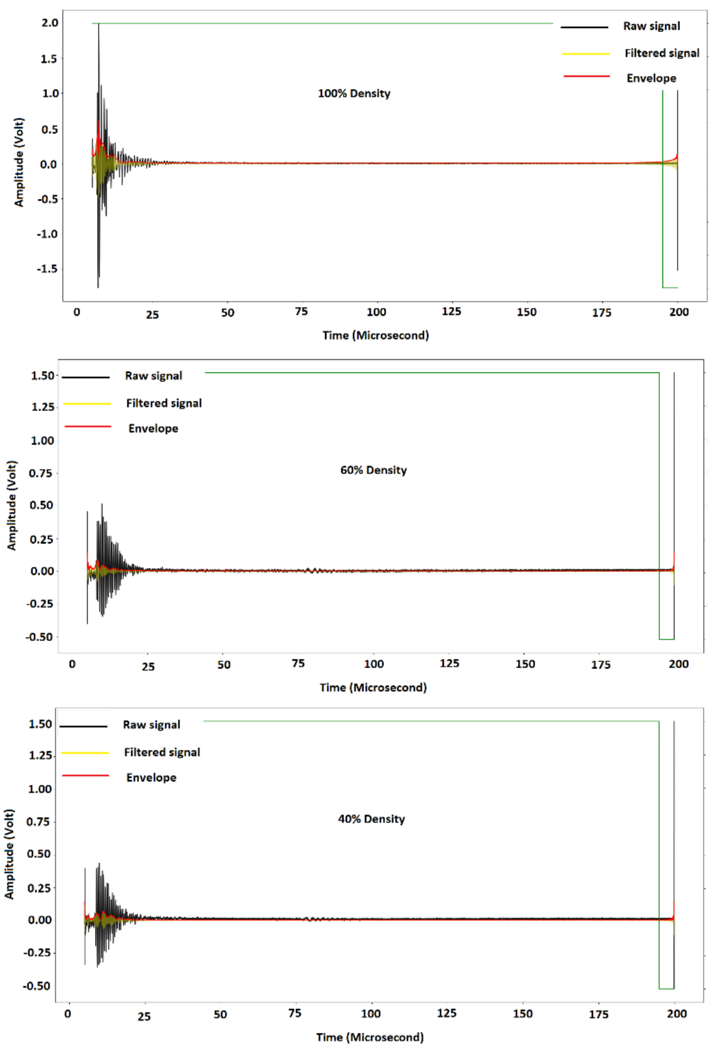

Fig.6. Plot of data in the time domain: raw signal, filtered signal, and envelope signal from measurements with a density of 100% (top); 60% (middle); and 40% (bottom)

A similar pattern is observed from the parameter of delay time. In a medium with a higher density, the transducer will receive the reflection back faster (as indicated by a shorter delay time) than in a medium with a lower density.

The decreasing pattern of the maximum amplitude agrees with the decreasing density value of the 3D bone model. In contrast, the increasing pattern of the delay time follows the decreasing density value of the 3D bone model. These results indicate that the parameters in the time domain, i.e., the maximum amplitude and the delay time, are potential candidate parameters for bone density.

B. Data Analysis: Signal Processing in Frequency Domain

The measurement data are also processed in the frequency domain, i.e., Power Spectral Density (PSD). The results indicate that the PSD shows a pattern corresponding to the trend of differences in the density level of the bone model, i.e., high-density bone model samples show lower PSD peaks compared to the lower-density bone models.

All the PSD peaks are present in almost the same frequency spectrum region, i.e., around 3 Hz. These results show that the power of the ultrasonic reflected waves from a high-density bone model is smaller than that from a lower-density bone model. These results also indicate that the parameter in the frequency domain, i.e., the PSD is a potential candidate parameter to be used as the bone density parameter. The plot of the PSD in the frequency domain is shown in Fig.7.

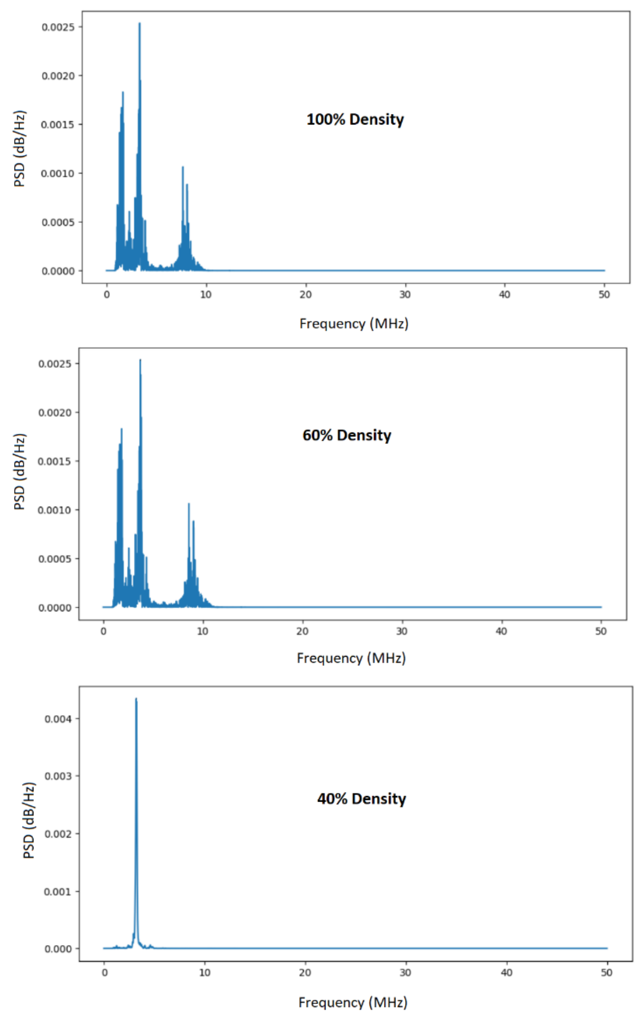

Fig.7. Plot of PSD in the frequency domain from measurements with a density of 100%; 60%; and 40%

IV. Conclusion

The lack of a universal standard like DEXA is still a barrier to making USG the primary diagnostic tool for bone density despite the many potentials and advantages compared to DEXA, i.e., much more affordable, portable, and no radiation risk, so that it can be used for screening the prevalence of osteoporosis for many populations. Thus, it is necessary to carry out sufficient data testing to determine the standard reference value.

This initial study aims to explore and investigate representative candidate parameters for bone density extracted from A-mode ultrasonic spectroscopy data from the 3D bone models, i.e., 100%, 60%, and 40% to represent normal bone, osteopenia, and osteoporosis.

The designed prototype of an FPGA-based ultrasound beamformer system for A-mode ultrasound spectroscopy can characterize the mechanical wave scattering pattern of the 3D-printed bone model properly. It is indicated that when the density of the bone model increases, so does the tendency in signal parameters, i.e., the maximum amplitude because the wave hits a target farther away from the transducer before being reflected to the transducer. When it passes through space within the medium, the energy of the reflected wave attenuated significantly due to the distance and the dispersed nature of the ultrasound wave in the air because of the mismatching of the acoustic impedance between the solid medium and the air.

The tendency is the opposite for the delay time because the transducer will receive the reflection back faster than from a medium with a lower-_density. The power of the ultrasonic reflected waves from a high-density bone model is smaller than that from a lower density bone model indicated with lower Spectral Density (PSD). These three signal parameters, i.e., the maximum amplitude, delay time, and PSD, are potential candidate parameters for representing bone density.

Furthermore, the selected candidate parameters can later be used as reference values while adding significant data so that a machine learning method can be employed to extract representative features of bone density level. Concerning the high prevalence of undetected osteoporosis in the population, this method can be a promising affordable screening method for many populations for potential risk of osteoporosis. These results can also be used to develop a multimodality affordable measurement system of bone density by adding other supportive measurement parameters, e.g., electrical impedance spectroscopy.

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

Hesty Susanti conducted the data analysis and wrote the manuscript. The 3D bone model was designed and printed by Husneni Mukhtar and Willy Anugrah Cahyadi. Suprijanto organized and executed the experiments.

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Conflict of Interest

The authors have no conflict of interest to declare.