Wavelet transform based decomposition of ultrasound signals for cortical bone model evaluation

1st Laksis Dans
Institute of Electronics and Computer Science
Riga, Latvia
dans.laksis@edi.lv

2nd Aleksejs Tatarinovs
Institute of Electronics and Computer Science
Riga, Latvia
aleksejs.tatarinovs@edi.lv

3rd Kārlis Freivalds
Institute of Electronics and Computer Science
Riga, Latvia
karlis.freivalds@edi.lv

***Abstract*—With the global population aging, there is a growing demand for precise, cost-effective, and accessible methods to assess cortical bones for diagnosing degenerative bone conditions like osteoporosis. This article delves into innovative techniques for decomposing ultrasound signals to enhance current state-of-the-art methodologies. Our approach focuses on deriving quantitative parameters for evaluating bone model characteristics. Utilizing ultrasound scans of bone model surfaces, acquired signals undergo continuous wavelet transform. Subsequently, we extract two key parameters pertinent to bone models: cortical speed of sound and cumulative magnitude sum. Through this methodology, we aim to contribute to advancements in the assessment of cortical bone health.**

***Index Terms*—cortical bone models, continuous wavelet transform, cortical speed of sound, cumulative magnitude sum**

I. Introduction

Since the year 2000, bone fragility-related fractures have surged, with approximately 9 million cases annually [1]. As people age, the risk of bone degenerative diseases like osteoporosis increases. By 2050, the global population aged 60 and above is expected to reach 2.1 billion, compared to 901 million in 2015. Precise bone evaluation is crucial to meet this growing demand.

Current state-of-the-art techniques for osteoporosis diagnostics are dual-energy X-ray absorption (DXA) and quantitative computed tomography (QCT) [2]. With DXA and QCT methods it is possible to get 2D and 3D images of a bone respectively.

Both DXA and QCT methods employ ionizing radiation and are expensive since they require trained staff. Therefore, there is a need for a less harmful and cheaper way of diagnosing osteoporosis. More research is needed to better evaluate cortical bone states by employing ultrasound.

Over the last two decades, ultrasonic-guided waves have played a significant role in diagnostics. These methods often rely on frequency spectrum analysis to create dispersion graphs [3]. Unfortunately, despite their utility, the results have not yet proven satisfactory enough to replace established techniques like DXA and QCT.

Our objective is to enhance the precision of ultrasound evaluations of human cortical bone models by researching and improving ultrasound signal processing methods. By assessing the cortical bone model, we aim to model the progression of osteoporosis in real bones.

We are going to look at ways of processing ultrasound signals that have been transmitted through bone models. Since frequency spectrum analysis of ultrasound signals hasn't shown results good enough to advance the state-of-the-art, we will try a different approach to processing ultrasound signals. Specifically, we will look into how can wavelet transform be used to decompose ultrasound signals and lead to quantitative cortical bone model (BM) parameters: cortical thickness (CTh) and porosity thickness (PT) of the BM.

We show that both CTh and PT are related to the cortical speed of sound (cSOS). We also show that PT is related to the cumulative magnitude sum (CMS) parameter.

II. Methodology

The experiment centered around parallelepiped cortical BM, which included an additional layer of soft tissue (STL), effectively simulating human soft tissue, which can have a varying thickness. BM surfaces underwent scanning using a custom-developed device that transmitted ultrasound signals through them. The acquired signals were then leveraged for parameter extraction related to the characteristics of the BM.

A. Models of cortical bone and soft tissue

BM were made from polymethyl methacrylate (PMMA) due to its high speed of sound (2750 m/s), as indicated by [4], and its high hardness. Notably, PMMA has been previously employed as a cortical BM [5]. BM have a dense part consisting of PMMA and a porous part, where 20% of space is taken up by air since this is expected porosity for old people [6]. To simulate osteoporosis, we modified two parameters (CTh and PT). Details of the utilized BM are summarized in Table I. Developed BM can be seen in Figure 1.

TABLE I: Cortical bone model classification table

BM thickness, mm	2	3	4	5	6
Dense part:porous part ($mm : mm$)	2:0	3:0	4:0	5:0	6:0
	1:1	2:1	3:1	4:1	5:1
	0:2	1:2	2:2	3:2	4:2
		0:3	1:3	2:3	3:3
			0:4	1:4	2:4
				0:5	1:5
					0:6

To imitate human skin, we use an STL of turkey skin. There are three possible STL thicknesses: 0 mm, 2 mm, and 4 mm.

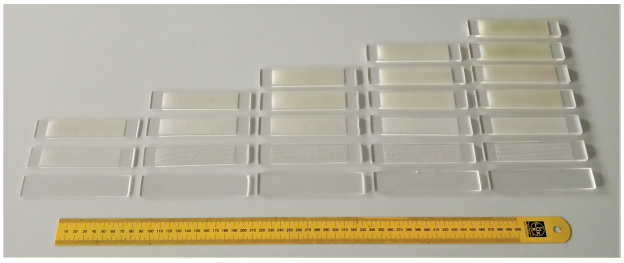

Fig. 1: BM samples.

B. Axial scanning device

BM surfaces were scanned using a custom-made surface scanner that employs the axial scanning (AS) principle when a transducer generates an ultrasound signal that is then received. AS can be implemented using either a single-channel or multi-channel approach. We opted for the multi-channel approach, as it is expected to provide more compelling information from the data [3]. Our multi-channel axial scanner consists of a stationary transducer and a receiver that is incrementally moved along the surface of the BM (see Figure 2). The initial and closest distance between the transducer and receiver is 20 mm, which is then progressively increased with a 3 mm step. As can be seen in Figure 2, the porous part of the BM is placed on the bottom side (further from the AS), since osteoporosis propagates from inside the bone [7].

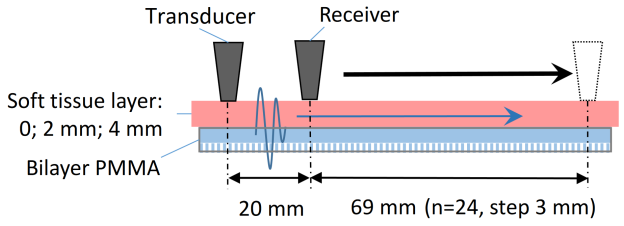

Fig. 2: Diagram of AS methodology.

Our custom-made AS can be seen in Figure 3. Control of the developed AS is done by a computer.

Ultrasound is generated and received using a lead zirconate titanate piezoelectric sensor. The discretization frequency employed was 30 MHz. We attempted to transmit a single transient frequency pulse (100 kHz and 300 kHz) through the bone model (BM). However, due to the various frequency

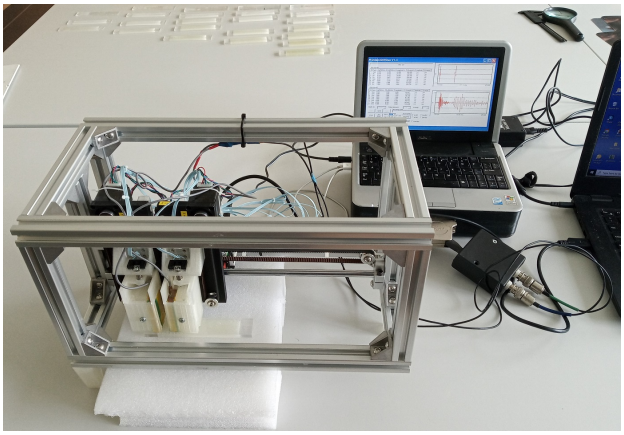

Fig. 3: Developed AS device.

resonances in the piezoelectric element, interference occurred. Consequently, we would need signal processing to extract the transmitted frequency. To analyze a broader bandwidth of frequencies, we chose to transmit a wide frequency range through the BM. To achieve this, we utilized a chirp signal with a frequency sweep ranging from 50 kHz to 500 kHz.

III. Signal Processing

Signal processing was carried out to obtain quantitative parameters associated with bone model (BM) thickness and the thickness of the porous portion. The initial step involved decomposing the ultrasound signal into various frequencies. The Continuous Wavelet Transform (CWT) stands out as one of the most effective methods for processing signals acquired from axial scanning (AS) when compared to techniques like the Short-Time Fourier Transform. This superiority is attributed to its anti-interference nature, as supported by research from Song and Feng [8]. Previously, CWT was chosen to extract a packet of guided waves at a selected frequency on a constant acoustic base and to follow its changes along the BM surface by Tatarinov et. al. [9]. Therefore, ultrasound signal decomposition was achieved by applying a CWT to the received signal at two different frequencies. Subsequently, we extracted two quantitative parameters from these transformed signals: cSOS and CMS. These parameters would then be linked to the BM CTh and PT.

A. Signal decomposition with wavelet transform

When faced with a decision among various wavelet types, we conducted a comparison of signal decomposition using different wavelets. Interestingly, our findings aligned with those observed in another article [10]: there was no significant difference. Consequently, the choice of wavelet did not appear to be critical. As a result, we proceeded with the gaus3 wavelet for further processing.

Given the diverse frequencies present in a chirp signal, we needed to select specific frequencies for further signal processing. After analyzing frequencies ranging from 50 kHz to 500 kHz, we observed two distinct patterns: one for lower

frequencies and another for higher-end frequencies (as shown in Figure 4). For each pattern, we opted to focus on a single frequency with the highest apparent amplitude. These selected frequencies are 60 kHz and 300 kHz. To perform the wavelet transform, we utilized the *pywt* library available in *Python*.

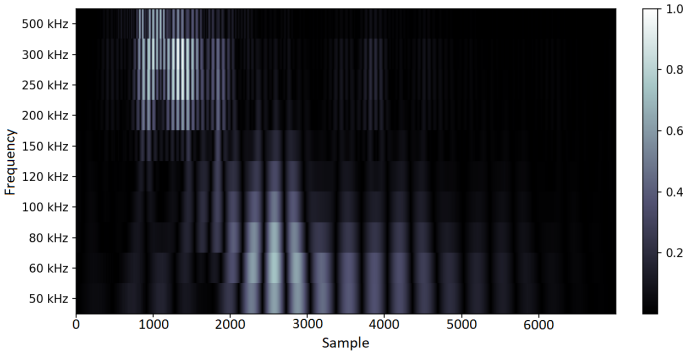

Fig. 4: Spectrogram of decomposed received chirp signal for BM with a CTh of 2 mm, no porosity, and without STL.

B. Guided waves

It is expected that guided waves will be present when ultrasound is transmitted through BM [11]. When guided waves propagate through a waveguide in the range from 0.25 to 2 MHz, it is possible to observe both symmetric and antisymmetric Lamb waves. Depending on the type, BM parameters will have different effects on wave speed. Specifically:

1) Antisymmetric Lamb wave speed is expected to increase as BM thickness and wave numbers increase.
2) Conversely, the symmetric Lamb wave speed is expected to decrease as modeled by Ezin et. al. [12].

C. Cortical speed of sound

Cortical speed of sound (cSOS) is associated with BM thickness [12], . cSOS will decrease as PT increases as seen as deduced by Chiba et. al. [13]. Consequently, we have chosen to calculate this parameter. The calculation of cSOS involves drawing a wave propagation line that illustrates how signals are received at various distances (see Figure 5). To compute cSOS, we will use formula 1:

$$cSOS = \frac{\Delta d}{\Delta t} \tag{1}$$

where Δd - the difference between the closest and farthest transducer-receiver positions and Δt - the time difference to receive the transducer signal when the transducer and receiver are at their closest and farthest positions.

The calculation of cSOS needed to be performed at both frequencies (60 and 300 kHz). This is because dispersion occurs when ultrasound travels through the BM.

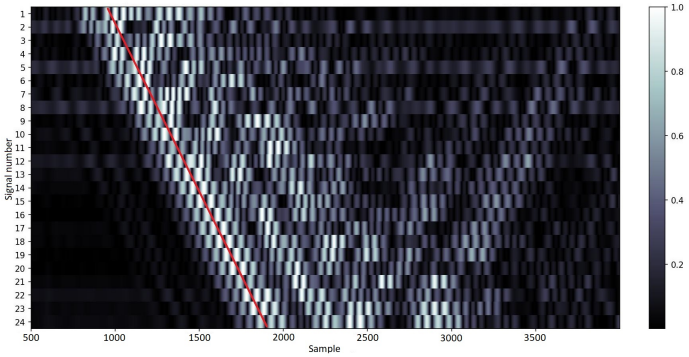

Fig. 5: Spatiotemporal image of BM with a CTh of 2 mm, no porosity, and STL of 2 mm. Used gaus3 wavelet with a 300 kHz frequency. The red line represents cSOS. Each signal is normalized to a range from 0 to 1, facilitating the identification of signal maximum and minimum values.

D. Cumulative Magnitude Sum

Given that both BM thickness and porosity thickness influence energy dissipation within them, we sought a quantitative parameter that would reflect these effects. Considering that received signal amplitudes are influenced by changes in BM parameters. We opted to calculate the cumulative magnitude sum (CMS) of all signals in a 2D matrix *X*, see formula 2:

$$\|X\|_1 \tag{2}$$

IV. Results

This section is split into two parts, one for each quantitative parameter (cSOS and CMS) and its relation to CTh and PT. We show the achieved results when signal decomposition is done only with a 60 kHz *gaus3* wavelet. Calculated cSOS values when signals were processed with 300 kHz wavelet had roughly 2-3 times higher values compared to when signals were processed with 60 kHz wavelet. We show those cSOS calculated after signal decomposition with 60 kHz wavelet since the relation to CTh and PT parameters were similar for both 60 and 300 kHz wavelets. CMS results acquired from decomposition with 300 kHz wavelet did not show a relation to BM neither CTh or PT, therefore they are not shown.

A. cSOS results

As BM CTh increases, so does cSOS, which can be seen in Figure 6. This follows the theory of guided waves described in [12]. Seeing that cSOS increases from 600 m/s to 1050 m/s, these are first-order antisymmetric Lamb waves, since symmetric Lamb waves have a higher cSOS and will decrease as CTh increases.

Figure 7 shows how PT affects cSOS. cSOS has a decreasing tendency when PT increases when CTh is bigger (4 mm, 5 mm, 6 mm). STL doesn't noticeably affect cSOS, based on Figures displaying cSOS values.

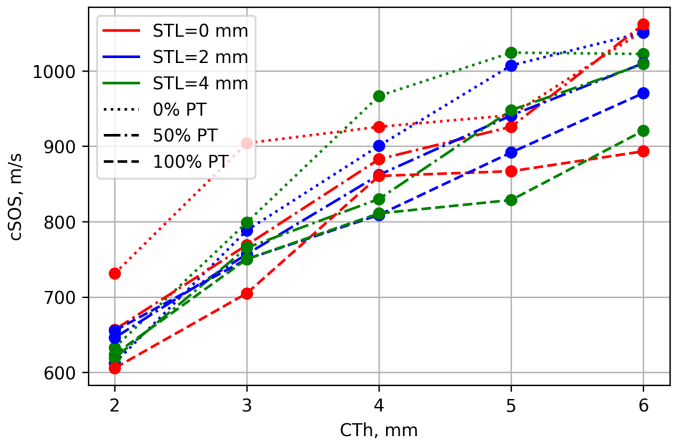

Fig. 6: cSOS with varying BM CTh. PT as a percentage of bone model thickness. The cSOS calculations were performed using a 60 kHz continuous wavelet transform (CWT) frequency.

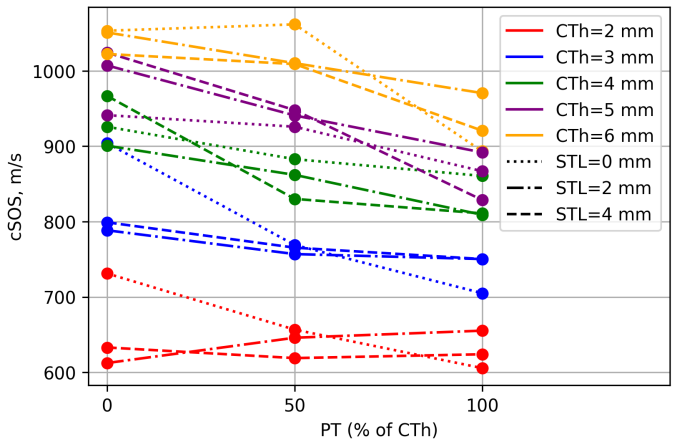

Fig. 7: cSOS in BM with varying PT, considering different STL thicknesses (0 mm, 2 mm and 4 mm). The cSOS calculations were performed using a 60 kHz continuous wavelet transform (CWT) frequency.

B. CMS results

CMS dependency on CTh is illustrated in Figure 8. The thickness of STL has a noticeable effect on CMS - with an additional 2 mm of STL layer, it decreases by around 25×10^6. Changes in CMS values are more gradual for higher STL thicknesses.

CMS results for the highest CTh values (5 mm and 6 mm) were irregular. They neither decreased nor increased, but they seemed too noisy to extract a connection between BM parameters and CMS. Therefore, in Figure 9 CMS results are shown for BM with CTh of 2 mm, 3 mm, 4 mm. In Figure 9 we see that increased PT leads to a lower CMS value.

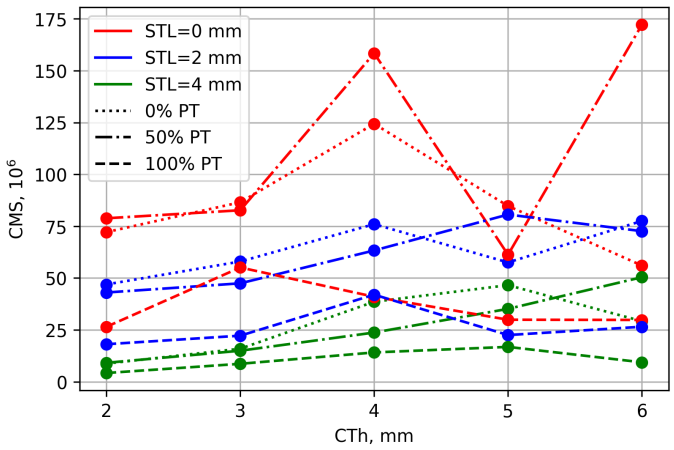

Fig. 8: CMS when signals are processed with 60 kHz wavelet. PT as a percentage of bone model thickness.

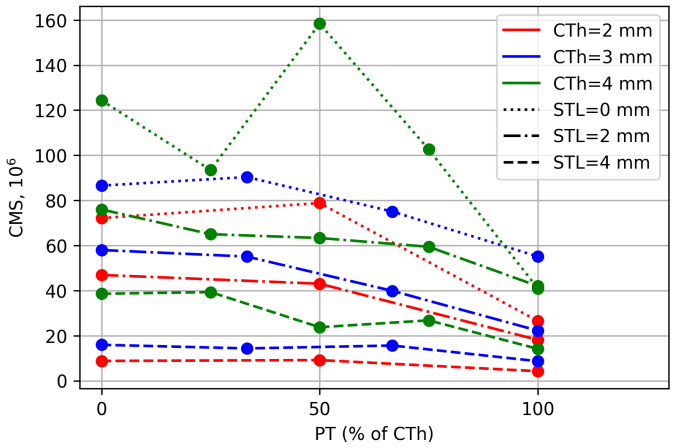

Fig. 9: CMS when signals are processed with 60 kHz wavelet. STL thicknesses = 0 mm, 2 mm, 4 mm.

V. Conclusion

Ultrasound signal decomposition with CWT is a promising way of acquiring BM parameters to evaluate bone models. When decomposing our PMMA cortical BM, there were two different patterns of how signals propagate in BM at frequencies from 50 to 500 kHz. Acquired parameters (cSOS and CMS) are related to both CTh and PT. The next research step involves validating the proposed approach using real human subjects with normal and osteoporotic bone conditions. To achieve this, we will assess cortical porosity and thickness in representative cohorts through DXA and ultrasound scanning. Subsequently, we can validate the results by comparing DXA measurements with ultrasonic data.

VI. Acknowledgements

The study was supported by the research project of the Latvian Council of Science lzp-2021/1-0290 “Comprehensive assessment of the condition of bone and muscle tissues using quantitative ultrasound” (BoMUS).

REFERENCES

[1] Cyrus Cooper and Serge Livio Ferrari. Iof compendium of osteoporosis. *Nyon: International Osteoporosis Foundation (IOF)*, page 60, 2017.

[2] Q. Grimal and P. Laugier. Quantitative ultrasound assessment of cortical bone properties beyond bone mineral density. *IRBM*, 40(1):16–24, 2019.

[3] Tho Tran, Feng He, Zhenggang Zhang, Mauricio Sacchi, Dean Ta, and Lawrence Le. Single versus multi-channel dispersion analysis of ultrasonic guided waves propagating in long bones. *Ultrasonic Imaging*, 43:016173462110066, 04 2021.

[4] J.E. Carlson, J. van Deventer, A. Scolan, and C. Carlander. Frequency and temperature dependence of acoustic properties of polymers used in pulse-echo systems. In *IEEE Symposium on Ultrasonics, 2003*, volume 1, pages 885–888 Vol.1, 2003.

[5] Huong Minh, Juan Du, and Kay Raum. Estimation of thickness and speed of sound in cortical bone using multifocus pulse-echo ultrasound. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, PP:1–1, 10 2019.

[6] Qingwen Ni, J King, and Xiaodu Wang. The characterization of human compact bone structure changes by low-field nuclear magnetic resonance. *Measurement Science and Technology*, 15:58, 10 2003.

[7] Bjørnerem Åshild. The clinical contribution of cortical porosity to fragility fractures. *Bonekey Rep.*, 5:846, Oct 2016.

[8] Yongxian Song and Juanli Ma Yuan Feng. The bone density detection based on dsp and wavelet transform. *Procedia Engineering*, 15:2211–2216, 2011. CEIS 2011.

[9] Alexey Tatarinov, Armen Sarvazyan, Gisela Beller, and Dieter Felsenberg. Comparative examination of human proximal tibiae in vitro by ultrasonic guided waves and pqct. *Ultrasound in Medicine & Biology*, 37(11):1791–1801, 2011.

[10] Stefanie Dencks, Reinhard Barkmann, Frederic Padilla, Guillaume Haiat, Pascal Laugier, and Claus Glüer. Wavelet-based signal processing of in vitro ultrasonic measurements at the proximal femur. *Ultrasound in medicine & biology*, 33:970–80, 06 2007.

[11] Pascal Laugier and Guillaume Haiat. *Introduction to the Physics of Ultrasound*, pages 29–45. 11 2010.

[12] Hamdi Ezzin, Mohammad Arefi, Bin Wang, and Zhenghua Qian. Multiple crossing points of lamb wave propagating in a magneto-electro-elastic composite plate. *Archive of Applied Mechanics*, 91, 06 2021.

[13] Chiba K., Suetoshi R., and Cretin D. Development of a qus device to evaluate deterioration of cortical bone: Verification by hr-pqct and measurements in healthy individuals and dialysis patients. *J Clin Densitom*, 24(1):94–105, 2020.