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

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Introduction

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)
- porosity thickness (PT) of the BM.

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 quantitative parameter extraction related to the characteristics of the BM.

Bone model parameter extraction

Axial scanning device

BM surfaces were scanned using a custom-made surface scanner (see Figure 1) that employs the axial scanning (AS) principle when a transducer generates an ultrasound signal that is then received.

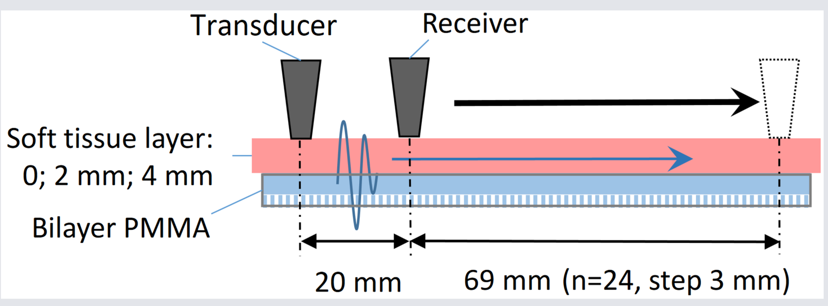

Figure 1: Diagram of AS methodology

CWT application

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 [1].

cSOS and CMS parameters

The calculation of Cortical speed of sound (cSOS) involves drawing a wave propagation line that illustrates how signals are received at various distances (see Figure 2). To compute cSOS, we will use formula 1:

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

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.

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:

$$CMS = \|X\|_1$$

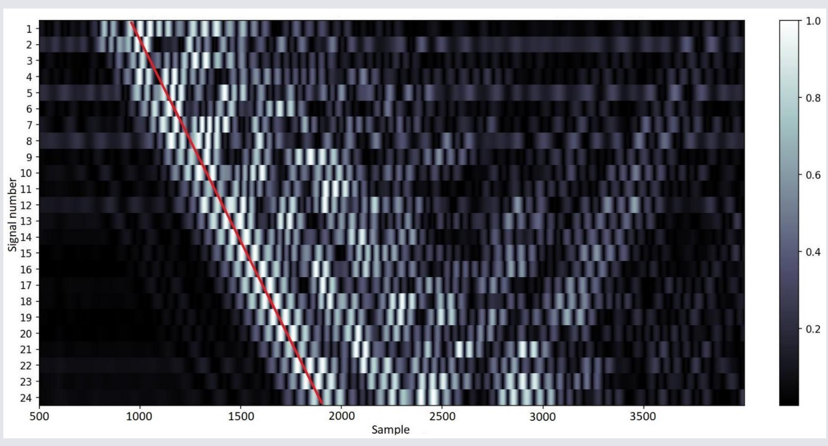

Figure 2: Spatiotemporal image of BM with a CTh of 2 mm, no porosity, and STL of 2 mm. Used gaus3 wavelet with a 300 kHz frequency. The red line represents cSOS. Each signal is normalized to a range from 0 to 1, facilitating the identification of signal maximum and minimum values.

Results

cSOS results

As BM CTh increases, so does cSOS, which can be seen in Figure 3. This follows the theory of guided waves described in [2]. Figure 4 shows how PT affects cSOS. cSOS has a decreasing tendency when PT increases when CTh is bigger (4, 5, 6 mm).

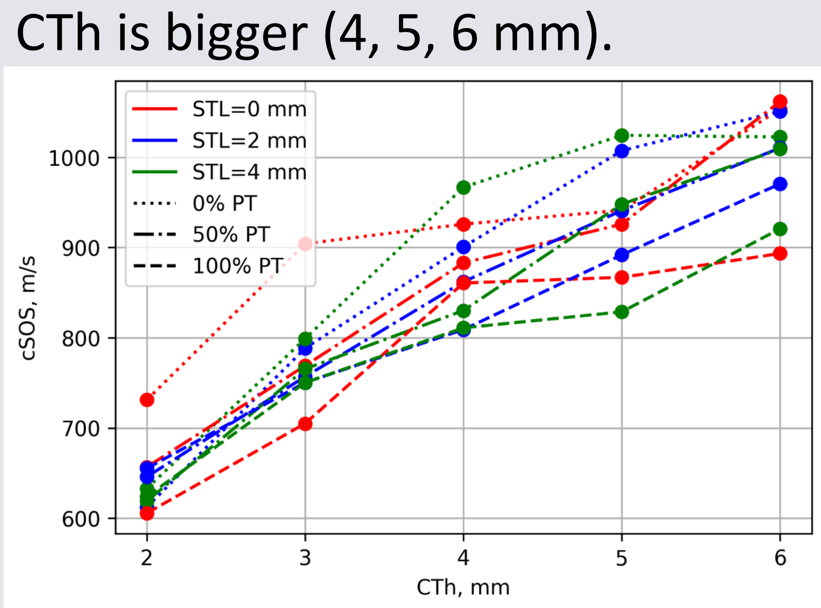

Figure 3: cSOS with varying BM CTh. PT as a percentage of bone model thickness. The cSOS calculations were performed using a 60 kHz continuous wavelet transform (CWT) frequency

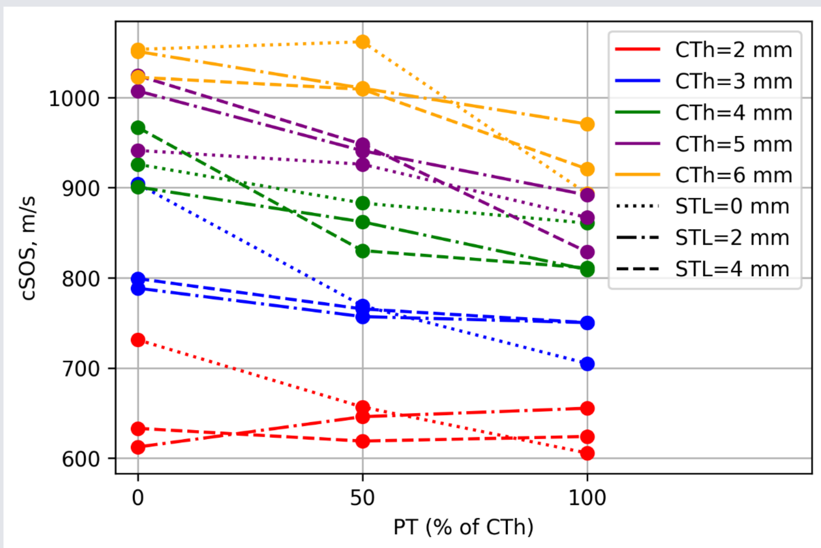

Figure 4: cSOS in BM with varying PT, considering different STL thicknesses (0 mm, 2 mm and 4 mm). The cSOS calculations were performed using a 60 kHz CWT frequency.

CMS results

CMS dependency on CTh is illustrated in Figure 5. Changes in CMS values are more gradual for higher STL thicknesses. CMS results for the highest CTh values were irregular. Therefore, in Figure 6 CMS results are shown for BM with CTh of 2, 3, 4 mm. In Figure 6 we see that increased PT leads to a lower CMS value.

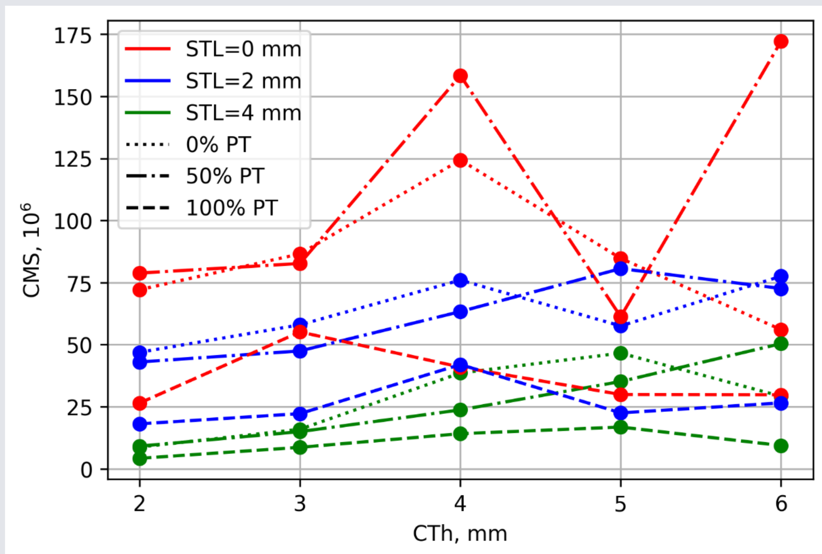

Figure 5: CMS when signals are processed with 60 kHz wavelet. PT as a percentage of bone model thickness.

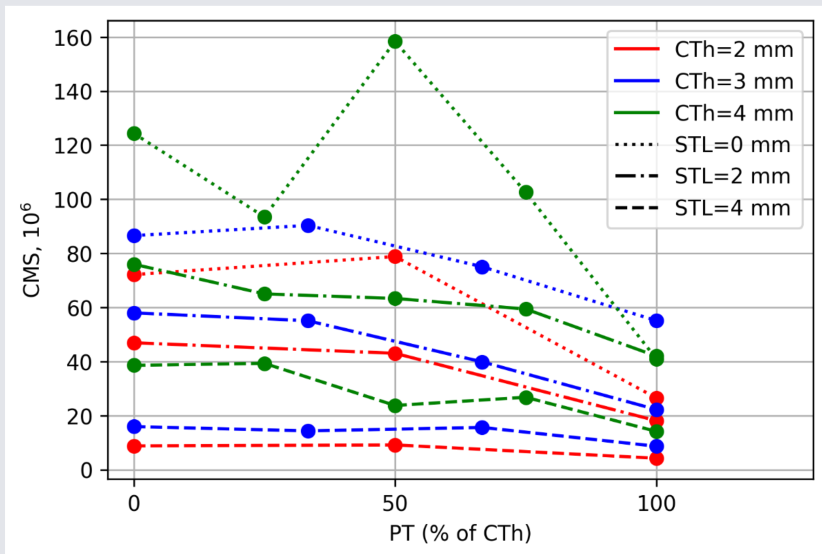

Figure 6: CMS when signals are processed with 60 kHz wavelet. Soft tissue layer (STL) thicknesses = 0 mm, 2 mm, 4 mm.

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.

Acknowledgements

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2. Hamdi Ezzin, Mohammad Arefi, Bin Wang, and Zhenghua Qian. Multiple crossing points of lamb wave propagating in a magneto-electroelastic composite plate. Archive of Applied Mechanics, 91, 06 2021.