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Fatigue evaluation of long cortical bone using ultrasonic guided waves

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ABSTRACT

Bone fatigue fracture is a progressive disease due to stress concentration. This study aims to evaluate the long bone fatigue damage using the ultrasonic guided waves. Two-dimensional finite-difference time-domain method was employed to simulate the ultrasonic guided wave propagation in the long bone under different elastic modulus. The experiment was conducted on a 3.8 mm-thick bovine bone plate. The phase velocities of two fundamental guided modes, A1 and S1, were measured by using the axial transmission technique. Simulation shows that the phase velocities of guided modes A1 and S1 decrease with the increasing of the fatigue damage. After 20,000 cycles of fatigue loading on the bone plate, the average phase velocities of A1 and S1 modes were 6.6% and 5.3% respectively, lower than those of the intact bone. The study suggests that ultrasonic guided waves can be potentially used to evaluate the fatigue damage in long bones.

1. Introduction

When long cortical bone suffers long-term, repeated and continuous stress, fatigue occurs and accumulates, finally leading to the strength degradation and bone fracture. Fatigue damage has become a main potential threat of bone fracture among the people who undertake long-term weight training, such as soldiers, athletes and gymnasts (Rue et al., 2004). It has been demonstrated that the fatigue damage is highly related to the structure destruction and function deterioration of bone tissue (Buettmann and Silva, 2016; Turnbull et al., 2011). Progressive reduction of elastic modulus can thus be employed to be an indicator of bone degradation. Conventional radiography, *e.g.*, dual X-ray absorptiometry (DXA), which has been established as a reliable means of measuring bone density, is one of the most common methods to evaluate bone fatigue damage (Njeh, 1999). Quantitative ultrasound technique has some advantages of non-ionizing radiation, portability and low cost, which holds a promise to become a viable alternative for radiography (Berger et al., 2007). Furthermore, the propagation characteristics of ultrasonic waves in bone are also related to the material quality, such as the porosity, density, and elasticity, which has been extensively studied for evaluating the quality of human bone (Laugier and Haïat, 2011).

Nonlinear ultrasonic techniques can be used to quantitatively assess material degradation prior to the micro-crack formation. The resonant frequency shift measured by nonlinear resonant spectroscopy has been proposed to assess the progressively-induced micro-damage in bovine bone samples (Muller et al., 2005b, 2008). Time-of-flight modulation measurements have been applied to assess nonlinear parameters in trabecular bone and provide a nonlinear signature for elastic modulus variations (Renaud et al., 2008). Nonlinear ultrasonic guided waves have been proposed for assessing the accumulated damage in waveguide (Deng and Pei, 2007; Deng, 2008). Long cortical bone is a plate-like waveguide supporting guided wave propagation (Moilanen, 2008). When the phase-velocity matching condition is satisfied, *i.e.*, at a certain frequency, the phase velocities between the fundamental guided mode and the double-frequency guided mode are the same, the second harmonic signals of guided waves can be observed (Zhang et al., 2014).

In the past decades, axial transmission method has been developed for long bone evaluation (Muller et al., 2005a; Le et al., 2010; Minonzio et al., 2015; Protopappas et al., 2007; Raum et al., 2014; Tran et al., 2013). Ultrasonic signals measured by using the axial transmission technique have two distinct contributions, *i.e.*, the first arriving signal (FAS) and a slower energetic component

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(Laugier and Haïat, 2011). FAS velocity highly depends on the ratio of longitudinal wavelength to the cortical thickness. When cortical thickness is larger than the wavelength, FAS corresponds to a lateral wave propagating along the bone parallel to the soft-tissue/bone interface (Bossy et al., 2004a); on the contrary, when cortical thickness is smaller than the wavelength, the FAS velocity is usually smaller than that of the lateral waves and could be explained by using the theory of ultrasonic guided waves (Nicholson et al. 2002; Muller et al., 2005a). It has been found that the FAS can characterize cortical bone properties, such as thickness (Bossy et al., 2002, 2004a; Moilanen et al., 2004), bone mineral density (Bossy et al., 2004b; Muller et al., 2005a), and porosity (Bossy et al., 2004b; Raum et al., 2005). In addition, FAS is one of the useful indicators for monitoring fracture healing of long cortical bone (Dodd et al., 2008; Machado et al., 2010; Protopappas et al., 2008).

In vitro axial transmission measurements operating at different bandwidth have been compared using fresh human radii (Muller et al., 2005a). The results have demonstrated that different velocities of ultrasonic signals provide different information about bone properties, thus increasing the diagnostic feasibility towards clinical application. Recently, multi-frequency axial transmission bone ultrasonometer has been developed, which extracts a plurality of ultrasonic parameters with differential sensitivity to the cortical thickness and intracortical porosity (Tatarinov et al., 2014).

Since the guided waves propagate throughout the entire cortical layer, it has an enhanced sensitivity to characterize both the periosteal and endosteal region of the cortical bone (Moilanen, 2008; Protopappas et al., 2008; Tatarinov et al., 2005). It has been demonstrated that velocities of the guided modes are able to reflect structural changes in the cortex (Lee and Yoon, 2004, 2012; Moilanen et al., 2006, 2007; Tatarinov et al., 2005). Other studies have addressed the significant correlation between the velocity of A0 mode and human radius bone thickness (Moilanen et al., 2006; Muller et al., 2005a, 2005b; Nicholson et al, 2002). A most recent study also demonstrated the sensitivity of the fundamental guided mode, A0, to cortical thickness and suggested A0 is an optimal mode for extracting bone properties (Tran et al, 2018). Current progress has illustrated that after solving an inverse problem, the difference between the extracted and theoretical multimode dispersion curves can be minimized to further predict the cortical thickness (Moilanen et al., 2006; Kilappa et al., 2013), stiffness (Bochud et al., 2017; Lefebvre et al., 2002), porosity (Foiret et al., 2014; Vallet et al., 2016) and bone mineral density (Lee and Yoon, 2012) etc. However, ultrasonic guided waves based long bone fatigue evaluation has not been reported yet.

The present study aims to investigate the feasibility of using the ultrasonic guided waves to monitor and evaluate progressive fatigue damage of long bone. The two-dimensional finite-difference time-domain (2D-FDTD) simulation is applied to analyze phase velocity variation with the elastic modulus. An *in vitro* experiment is carried out by repeating the process of fatigue loading test and ultrasonic measurement. The discussion of the impact of bone fatigue damage on the phase velocity of guided waves is followed.

2. Theory and methods

Guided waves propagating in a solid plate (or layer) are known as Lamb waves, which are vibrations with the traction-free boundary conditions. They can be generally grouped as symmetric and antisymmetric modes according to the different vibration features, governed by the Rayleigh-Lamb frequency equations (Rose, 2004):

$$(k^2 - q^2)^2 \tan\left(\frac{qh}{2}\right) + 4k^2 pq \tan\left(\frac{ph}{2}\right) = 0 \tag{1a}$$

$$(k^2 - q^2)^2 \tan\left(\frac{ph}{2}\right) + 4k^2 pq \tan\left(\frac{qh}{2}\right) = 0 \tag{1b}$$

where h is the thickness of the isotropic plate, k is the angular wavenumber and numerically equal to $\frac{\omega}{C_p}$, C_p is the phase velocity of the Lamb modes, and ω is the angular frequency. The coefficients p and q are given by:

$$p^2 = \frac{\omega^2}{C_L^2}, \quad q^2 = \frac{\omega^2}{C_T^2} \tag{2}$$

C_L and C_T are the longitudinal and shear wave velocities,

$$C_L = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{E}{\rho}\frac{(1-\nu)}{(1+\nu)(1-2\nu)}} \tag{3}$$

$$C_T = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{\rho}\frac{1}{2(1+\nu)}} \tag{4}$$

where E and ν are the Young's modulus and Poisson's ratio, λ and μ are the Lamé first and second constants, respectively, and ρ is the density.

The dispersion curves in this study were calculated by using the software Disperse (NDT Lab, Imperial College, London, UK).

3. Simulations

The numerical simulation of the axial transmission ultrasound in the long bone is performed using 2D-FDTD method. By converting the differential equation of wave motion into a difference equation, the numerical solution of the wave field component in the time and space domains can be solved. We use a custom-made FDTD code which has been validated in our previous studies (Liu et al., 2014a, 2014b; Xu et al., 2014a).

The bone plate model (Fig. 1) is 200-mm long and 3.8-mm thick. A free boundary condition is applied on upper and lower surfaces. Absorbing boundaries are arranged at both ends of the plate model to avoid the reflection. An emitter and 60 receivers are arranged in contact with the bone surface. According to the Snell's law, the incident angle θ is

$$\theta = \sin^{-1}\left(\frac{C_w}{C_p}\right) \tag{5}$$

where the longitudinal wave velocity in the Plexiglas wedge C_w is 2700 m/s (Nguyen et al., 2014; Ta et al., 2009). C_p is phase velocity of the mode of interest. When the incident angle is 45°, the fundamental A1 and S1 modes can be mainly excited at 0.5 MHz. The receiving signals are recorded from 60 mm to 180 mm with a spacing interval of 2 mm. The excitation is a 3-cycle Gaussian-enveloped sinusoid signal with center frequency of 0.5 MHz and −3 dB bandwidth from 0.37 MHz to 0.63 MHz. The temporal discretization in the simulation is 31.5 ns and the spatial grid size is 50 μm.

As shown in Table 1, the elastic modulus loss was used to model the progressive fatigue damage in the simulation. The bone elastic modulus E was set as 100%, 98%, 96%, 94%, 92%, and 90% of the initial theoretical elastic modulus, respectively. The initial theoretical modulus is obtained from (Luo et al., 1999; Gheduzzi et al., 2009). We assume that the Poisson's ratio ν and density ρ of the bone material are constant. Accordingly, the Lamé constants λ and μ were calculated using Poisson's ratio ν and varied elastic modulus E. The longitudinal wave velocity C_T and shear bulk wave velocity C_L were computed using Eqs. (3) and (4). So the temporal waveforms under different elastic modulus can be obtained.

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