Journal of Biomechanics 45 (2012) 1790–1795

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Prediction of trabecular bone principal structural orientation using quantitative ultrasound scanning

Liangjun Lin, Jiqi Cheng, Wei Lin, Yi-Xian Qin*

Orthopaedic Bioengineering Research Laboratory, Department of Biomedical Engineering, Stony Brook University, Stony Brook, NY, USA

ARTICLE INFO

Article history:
Accepted 13 April 2012

Keywords:
Quantitative ultrasound
Non-invasive measurement
Anisotropic structure
Trabecular bone
Ultrasound attenuation
Fast wave velocity

ABSTRACT

Bone has the ability to adapt its structure in response to the mechanical environment as defined as Wolff's Law. The alignment of trabecular structure is intended to adapt to the particular mechanical milieu applied to it. Due to the absence of normal mechanical loading, it will be extremely important to assess the anisotropic deterioration of bone during the extreme conditions, i.e., long term space mission and disease orientated disuse, to predict risk of fractures. The propagation of ultrasound wave in trabecular bone is substantially influenced by the anisotropy of the trabecular structure. Previous studies have shown that both ultrasound velocity and amplitude is dependent on the incident angle of the ultrasound signal into the bone sample. In this work, seven bovine trabecular bone balls were used for rotational ultrasound measurement around three anatomical axes to elucidate the ability of ultrasound to identify trabecular orientation. Both ultrasound attenuation (ATT) and fast wave velocity (UV) were used to calculate the principal orientation of the trabecular bone. By comparing to the mean intercept length (MIL) tensor obtained from μCT, the angle difference of the prediction by UV was 4.45°, while it resulted in 11.67° angle difference between direction predicted by μCT and the prediction by ATT. This result demonstrates the ability of ultrasound as a non-invasive measurement tool for the principal structural orientation of the trabecular bone.

1. Introduction

According to Wolff's law, bone has the ability to adapt its structure in response to the mechanical environment, and the alignment of trabecula is heavily influenced by the stress applied to it (Martin et al., 1998). This internal structural anisotropy of trabecular bone substantially affects its mechanical properties in different orientations, and the anisotropic deterioration of the trabecular structure increases the risk of fracture. Therefore, simply measuring the "quantity" of bone such as bone mineral density (BMD) by using dual-energy x-ray absorptiometry (DXA) is not sufficient to fully characterize the "quality" of bone. Since being introduced by Langton et al., quantitative ultrasound (QUS) has been widely used for bone health status assessment (Ashman et al., 1987; Cardoso et al., 2003; Gluer, 1997; Kaufman et al., 2007; Lin et al., 2006; Nicholson et al., 1994; Njeh et al., 1997; Qin et al., 2007). Compared to the current gold standard, DXA, QUS has the advantages such as safe, low cost, portable, radiation-free and easy to operate. As ultrasound wave propagates through bone, both the velocity and the amplitude of the wave are modified. This modification can provide useful information of the mechanical properties of bone, i.e., the elastic modulus (Njeh et al., 1999).

For the past few years, many researchers have been investigating extensively on the interaction between ultrasound wave propagation and the anisotropic structure of trabecular bone. Cardoso and Cowin (Cardoso and Cowin, 2011, 2012; Cowin and Cardoso, 2011) studied the relation between fabric tensor—a measurement of the degree of anisotropy of the trabecular bone—and the wave propagation equations in anisotropic porous media. An angle-dependent model to the classic Biot's theory (Biot, 1956a, b) to predict the ultrasound velocity in an anisotropic trabecular bone model was also introduced (Lee et al., 2007). Mizuno et al. reported in vitro studies on the different effects of the structural anisotropy of trabecular bone on the velocity of the fast wave and slow wave components of the broadband ultrasound signal (Mizuno et al., 2009; Mizuno et al., 2008; Mizuno et al., 2010). Hosokawa and Otani (1998) investigated the same subject, and later on computational simulation work was also reported by Hosokawa (2011). Han and Rho (1998) reported that a combination of BMD and elastic anisotropy of the bone resulted in an enhanced correlation with broadband ultrasound attenuation, a spectrum of ultrasound attenuation in frequency domain.

Although those investigations mentioned above have shown how ultrasound wave propagation in trabecular bone is influenced by the anisotropic structural property of trabecular bone in

* Correspondence to: Department of Biomedical Engineering, Stony Brook University, Bioengineering Building, Room 215, Stony Brook, NY 11794-5281, USA. Tel.: +1 631 632 1481; fax: +1 631 632 8577.
E-mail address: Yi-Xian.Qin@sunysb.edu (Y.-X. Qin).

0021-9290/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2012.04.022

both computation simulations and in vitro experiments, some basic and fundamental questions remained unanswered: if ultrasound wave can be used to characterize the anisotropy of the porous structure of trabecular bone, can we use quantitative ultrasound to predict such principal alignment of trabecula, and to what degree? Which quantitative ultrasound parameter has the better ability to provide information to characterize the anisotropy of the trabecular structure? The objective of this study is to employ quantitative ultrasound to non-invasively predict the principal structural orientation of trabecular bones, and use the longest vector of mean intercept length (MIL) tensor, the current gold standard, to validate the accuracy of such prediction.

2. Materials and methods

2.1. 3-D volumetric trabecular sample preparation

Seven trabecular bone cylinders (∅ 38.1 mm) were cut from distal bovine femurs using cylindrical cutting bit. Then seven trabecular bone balls (∅ 25.4 mm) were machined from the bone cylinders using lathe machine. Anatomical orientations were first marked on the surface of the cylinder. Then half of the bone ball was machined, and the orientation markers were extended to the newly machined semi-spherical surface before the other half of the bone ball was machined. Anatomical poles were marked on the surfaces of the bone balls to indicate the three principal anatomical orientations—anterior–posterior (AP), medial–lateral (ML) and proximal–distal (PD). The marrow inside the trabeculae was flushed out using dental water-pick. For preservation, the bone balls were wrapped in gauze soaked with saline and 70% ethanol "half-and-half" solution and stored in 4 °C refrigerator. Before quantitative ultrasound measurement, the bone balls were put into a vacuum chamber for 3 h to remove the air bubbles trapped among the trabeculae.

2.2. Quantitative ultrasound measurement

Quantitative ultrasound measurement was performed by using a scanning confocal acoustic diagnostic navigation (SCAN) system (Xia et al., 2007), consisted of a computer-controlled 2-dimensional scanner unit and a pair of focused transducers (V302-SU-F2.00IN, Olympus NDT Inc., Waltham, MA) with a center frequency of 1 MHz. The diameter of the transducers is 25.4 mm, and the confocal length of the transducers is 50.8 mm. Therefore, the transducers were coaxially installed 101.6 mm away from each other, aligned with the center of the bone ball which was placed in a rotation stage at the midpoint of the two transducers. The rotation stage consisted of a holder for the bone ball and a base with angular calibration (Fig. 1). For ultrasound measurement, ultrasonic pulses transmitted through the center of the bone ball, and the bone ball was rotated 10° around the long axis of the rotation stage between every two scans. For every bone ball, ultrasound measurement was performed around all three anatomical axes, resulting 36 scans around each axis and 108 scans in total for each trabecular bone ball. Because of the shape of the bone ball sample, for each measurement in different scanning angles of a bone ball, the distance that ultrasound wave traveled in the bone sample should be the same. Therefore, the difference of amplitude and signal arrival time among the received signals in different scanning angles of a bone ball was induced by the anisotropic material property. The ultrasound results were then processed and visualized in a custom written MATLAB program. For each measurement, ultrasound attenuation and velocity were calculated using the classic substitution method (Langton et al., 1984). Based on the previous work showing that the speed of fast wave is more related with the change of the incident angle than the speed of slow wave, and that the amplitude of both the fast wave and slow wave are influenced by the incident angle (Hosokawa and Otani, 1998; Mizuno et al., 2010), the fast wave of the ultrasound pulse was chosen for the velocity calculation via the following equation:

$$c_b = \frac{c_w d}{d - c_w \Delta t} \tag{1}$$

here c_b is the ultrasound velocity in the bone sample, c_w is the ultrasound velocity in the water, d is the diameter of the bone ball, and Δt is the phase difference of the same signal landmark of the reference signal and the sample signal. In this study, 1480 m/s was used for the velocity of ultrasound in water (Langton et al., 1990).

2.3. μCT scanning and imaging

μCT with a resolution of 18 μm was performed on each trabecular bone ball by using a *μCT 40* system (SCANCO Medical AG, Brüttisellen, Switzerland). In order to eliminate the influence from the surface condition induced by the machining of the bone ball, a cubic volume (15 × 15 × 15 mm^3) of trabecular bone in the center of the bone ball was used for evaluation. The longest vector of the MIL tensor **H** was obtained from the μCT system. Currently, MIL is the gold standard of quantifying the structural anisotropy (Whitehouse, 1974). When straight lines in

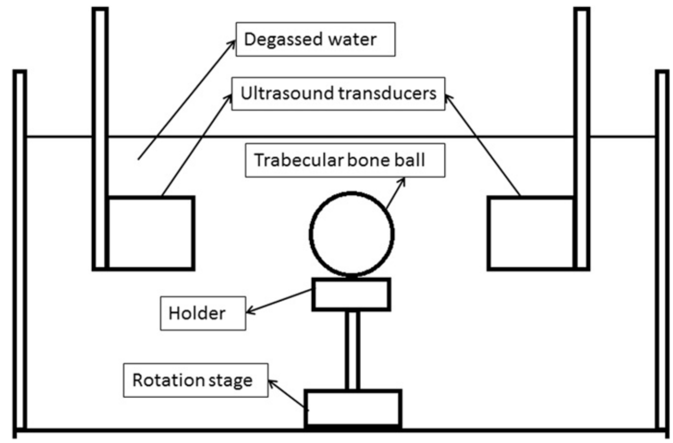

Fig. 1. Schematic representation of the ultrasound measurement experiment set up. A trabecular bone ball is placed onto a holder with a rotation stage. The stage was placed in a water tank filled with degassed water. Two ultrasound transducers used for the measurement were placed on both sides of the bone ball, with the bone ball at the confocal point. The ultrasound signal was transmitted from one of the transducers and received by the other one after propagating through the bone ball sample and the water between the sample and transducers.

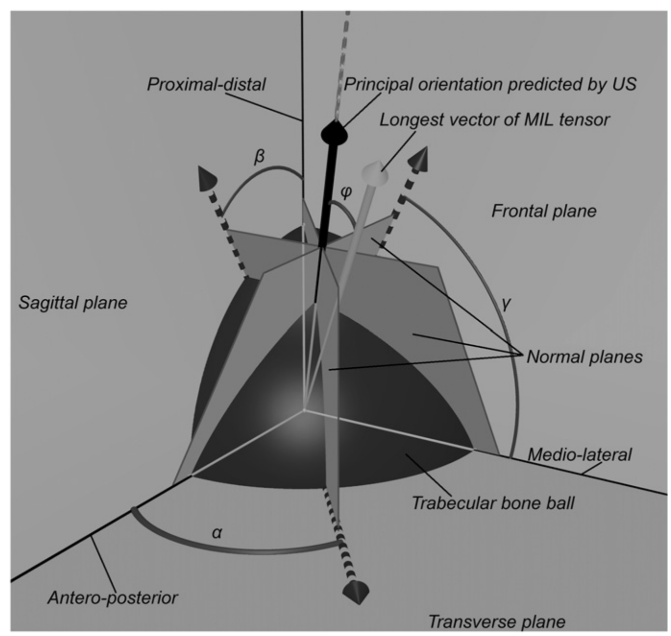

Fig. 2. The trabecular bone ball (dark sphere) was placed in a Cartesian coordinates system defined by the orthogonal anatomical planes (frontal, sagittal and transverse planes) with the center of the ball placed at the origin of the coordinates. Based on the rotational ultrasound measurement around three anatomical axes, the angles α, β and γ were determined. These are the angles in which the ultrasound measurements obtained peak values. According to these angles, three vectors (dash arrows) on the corresponding orthogonal anatomical planes were determined, i.e., the vector on the transverse plane is determined by the ultrasound measurements around proximal–distal axis. Along the direction of each of these three vectors, a plane was defined normal to the corresponding anatomical plane. These normal planes (gray planes) intersect at one line (dash line). The normal vectors of these normal planes were used to define the intersection line using Eqs. (3) and (4). A vector (dark arrow) along the direction of that intersection line is defined as the principal orientation predicted by ultrasound, and the angle difference φ compared to the longest vector of MIL tensor (light arrow) was calculated using Eq. (5).