Changes in Elastic Modulus During Cyclic Loading Measured Using Ultrasound – Implications for Fragility Fracture Detection

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Introduction: Nondestructive ultrasound testing has been applied to bone in order to improve predictions of fragility 1-3. When ultrasound propagates through thin shells such as bone cortices, multiple guided wave modes (termed lamb waves), are generated that propagate through the cortical bone. Because of the complexity in isolating these multiple guided wave modes, typical application of ultrasonic methods utilize the measurement of the first arrival speed of sound (FASS) through the specimen as a predictor of overall health, including bone mineral density and risk of fracture 2. Yet, the FASS is dependent on a variety of factors including the diameter of the bone, angle of incidence, mineral density, and the ultrasound carrier frequency. The susceptibility of the FASS to so many variables makes it difficult to get a clear indication of the bone health. In this study, we present a novel ultrasound based means of detecting the extent of damage in bone. Note: in this study, damage is defined as change in modulus (instantaneous elastic or secant modulus). The proposed technique relies on measuring speed of sound during cyclic loading. The hypothesis to be tested is that changes in instantaneous modulus (damaged bone has a non-linear stress-strain behavior with constantly varying modulus during the loading cycle) are correlated to changes in ultrasound velocities.

Theory: Current ultrasonic methods treat the elastic/young modulus as a static variable through which speed of sound properties are determined. Yet, a change in modulus, as happens with cumulative damage, will cause a partial change in the FASS. The speed of sound (V) through the bone will be proportional to elastic modulus (E) and bone density (p) according to:

\[ V = \sqrt{\frac{E}{p}} \]  

(1)

Note that regardless of the type of guided wave used for damage detection, the speed of sound will be an integral part of the FASS.

Methods: Frozen Bovine femur specimens from a local slaughterhouse (Moyer Packing Co, Mopac, PA) were ground to dumbbell shaped specimens with a uniform gage length of (length x width x thickness of 40x5x2mm). Care was taken during the cutting, milling, and grinding operations to keep the specimen wet at all times during testing. Tensile fatigue tests were conducted at 4Hz, 2MPa to 80MPa, sinusoidal waveform, on an electromechanical testing machine while measuring displacements (Instron Model 1371). Load-displacement data were recorded at 1kHz. From the recorded load-displacement curves, instantaneous elastic modulus (instantaneous slopes) and secant modulus (line connecting peak and minimum load-displacement data) were calculated assuming a gage length between grips was 40mm and measured cross-sectional dimensions. Secant modulus for each cycle was measured from peak loads and peak deformations. Changes in secant modulus were used to determine parameters of damage, 'D'.

\[ D = 1 - \frac{E}{E_0} \]  

(2)

where E is the secant modulus of the current loading cycle, while E_0 is the secant modulus determined from the first loading cycle.

Two ultrasound transducers (paired 1MHz Panametrics transducers, one pulser and another receiver at 45° to the bone length) were pulsed at 1kHz repetition using a Panametrics pulser/receiver (5072PR) (n = 3 samples). The data was recorded using an oscilloscope (Agilent, 1GHz) that was configured to record data at different times along the loading cycle. Custom programs were written in JAVA to obtain wave velocities at different times during loading using first arriving signals. Distances to the bone from the pulser and from the bone to the receiver were subtracted to obtain propagation velocities.

Changes in ultrasound velocities during the beginning of different cycles were subsequently correlated with damage (using Eq. 2). Within loading cycles, changes in ultrasound velocities were also correlated with changes in elastic modulus during load-unload cycle.

Results: Changes in secant modulus were observed to be correlated to changes in squared velocities according to equation 1 (R^2 = 1.0; p < 0.001). Note that secant moduli means that measurements were made at different loading cycles. Similarly, changes in velocities within a loading cycle were correlated to changes in instantaneous moduli (p < 0.001 at each damage level). At the three damage levels shown, there were increased changes to velocities as well as changes in elastic modulus. In all cases, changes in instantaneous moduli were correlated to changes in elastic modulus values.

Discussion: Our results support the hypothesis that changes in instantaneous modulus during loading are correlated to ultrasound velocities. This suggests that it is possible to evaluate damage accumulation of bone independent of prior measurements (measurements at low load serve as baseline values and any variation from these values is indicative of damage).

There is considerable disagreement over whether damage accumulation in bone (as measured by changes in elastic modulus) contributes towards fragility fractures. In vitro tests of machined samples of bone are not useful in detecting damage because controlled experiments indicate that damage appears to repair itself (and is not reflected in initial elastic modulus measurements), after damaged bones were stored in an unloaded situation 3. In other words, even if mechanical tests of damaged bone were done in vitro, it would not be possible to evaluate whether the in vivo properties of bone had been affected. As a result, techniques that are capable of assessing bone mechanical integrity in a load bearing situation in vivo need to be developed. Future developments of the proposed technique will enable the development of an useful clinical tool that will enable us to investigate the role of damaged bone in contributing towards fragility fractures.

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