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Anisotropic Poisson's ratio and compression modulus of cortical bone determined by speckle interferometry

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Abstract

Young's modulus and Poisson's ratios of 6 mm-sized cubes of equine cortical bone were measured in compression using a micro-mechanical loading device. Surface displacements were determined by electronic speckle pattern-correlation interferometry. This method allows for non-destructive testing of very small samples in water. Analyses of standard materials showed that the method is accurate and precise for determining both Young's modulus and Poisson's ratio. Material properties were determined concurrently in three orthogonal anatomic directions (axial, radial and transverse). Young's modulus values were found to be anisotropic and consistent with values of equine cortical bone reported in the literature. Poisson's ratios were also found to be anisotropic, but lower than those previously reported. Poisson's ratios for the radial–transverse and transverse–radial directions were 0.15 ± 0.02, for the axial–transverse and axial–radial directions 0.19 ± 0.04, and for the transverse–axial and radial–axial direction 0.09 ± 0.02 (mean $\pm$ SD). Cubes located only millimetres apart had significantly different elastic properties, showing that significant spatial variation occurs in equine cortical bone.

Keywords: Bone; Mechanical properties; Interferometry; Poisson's ratio; ESPI

1. Introduction

Cortical bone is anisotropic, with the elastic modulus in the axial direction being significantly higher than in the transverse and radial directions (Reilly and Burstein, 1975, Taylor et al., 2002, Dong and Guo, 2004, Iyo et al., 2004). In fact the mechanical properties of bone are affected by many aspects of its complex structure (Weiner and Wagner, 1998), and in particular by the mineral content (Currey, 2002).

Few studies have attempted to correlate structure with function at the micron to millimeter meso-scale (Zysset et al., 1999, Liu et al., 1999, Turner et al., 1999, 2000; Hengsberger et al., 2003; Enstrom, et al., 2001). Since many structural differences between (and even within) various types of cortical bone are found at that length scale, the study of the mechanical properties using millimeter-sized samples is of great importance. However testing such samples is complicated, posing many technical challenges. Various experimental methods have been reported for determining the elastic properties of cortical bone, with sample sizes ranging from several centimetres (Reilly et al., 1974, Reilly and Burstein, 1975) to single osteons with dimensions of hundreds of micrometres (Ascenzi and Bonucci, 1968). Most methods were based on loading relatively bulky bone samples in material testing machines, and recording load–displacement curves for loads such as tension,

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compression, torsion and bending. In tension and compression experiments, the slope of the stress–strain curve within the elastic region was used to estimate the Young's modulus of the bone. Most tests are performed by applying a controlled deformation rate, and often progress continuously until failure. Such experiments are usually used to also provide information regarding the yield point (the point at which the behaviour of the sample ceases to be linearly elastic), load and work to failure and ultimate strain. However, since these tests are destructive, often only one estimate of modulus can be obtained from each sample, thus experimental precision cannot be determined. Furthermore, since the use of large and bulky samples is required, local micro-scale variations are ignored.

Several non-destructive methods are widely used for obtaining mechanical properties of small samples. Micro- and nano-indentation have been used to measure the hardness and elastic constants of cortical bone at the micro-structural level (Weiner et al., 1997, Rho et al., 1997, Zysset et al., 1999, Silva et al., 2004, Hengsberger et al., 2003; Bensamoun et al., 2004). These methods allow estimation of hardness and Young's modulus from contact stiffness between the indenter tip and the sample. They require a highly polished sample surface, and the calculation assumes knowledge of the Poisson's ratios of the sample. When used to measure the elastic modulus of anisotropic materials such as bone, the modulus derived from the method is an average of the anisotropic constants biased towards the modulus of the direction of testing (Rho et al., 1997). Another approach is based on the measurement of the speed at which sound travels through bone (Yoon and Katz, 1976a,b, Ashman et al., 1987, Rho et al., 1993). Although these methods are non-destructive, they are also indirect, and rely on the application of theories of composite materials to the measurements in order to obtain estimates of the elastic constants.

Few studies describe experimental determination of Poisson's ratios of cortical bone. Reilly and Burstein (1975) assumed transverse isotropy of fibrolamellar bone, and used extensometers to measure strains in two orthogonal directions concurrently. They found Poisson's ratio values which ranged between 0.29 and 0.63. Ashman et al. (1984) reported on the use of an ultrasonic continuous wave technique, and found Poisson's ratio values which ranged between 0.27 and 0.45. Pithioux et al. (2002) also used an ultrasonic method, and found Poisson's ratios between 0.12 and 0.29. Despite this wide range of reported values (0.12–0.63), many studies, especially finite element analyses, often use values in the much narrower range of 0.28–0.33.

Optical metrology techniques allow non-contact measurement of displacements on surfaces of samples subjected to static or dynamic mechanical loading. Electronic speckle pattern-correlation interferometry (ESPI) (Jones and Wykes, 1989, Rastogi, 2001) has recently been used to determine sub-micron surface displacements on the surface of millimetre-sized tooth dentin samples loaded elastically in compression (Zaslansky et al., 2005). Displacements are directly determined from variations of laser light reflected from samples immersed in water. Using this technique, it is possible to perform quantitative analysis of strain on compressed samples of mineralized biological tissues such as bone and dentin, by loading them in a high-precision micro-mechanical loading device. Such measurements can be performed without damaging the sample and hence anisotropic Young's moduli and Poisson's ratios can be determined from multiple measurements of each sample.

We report on measurements performed using a commercial ESPI system (Q300—Ettemeyer, Ulm, Germany) which has been combined with a custom-built loading device allowing non-destructive compression tests of small cubes of cortical bone in three orthogonal directions. Our set-up allows the measurement of in-plane and out-of-plane deformation fields on surfaces of very small samples. Due to the high sensitivity of our system, experiments can be conducted non-destructively by repeatedly loading the sample within its elastic region. Measurements may be performed on wet samples, thus satisfying a basic requirement for the study of biological specimens. Measurements by this technique require load to be applied in small increments, since large deformations cause optical decorrelation that renders the measurements invalid.

While the ESPI technique allows for the determination of the elastic constants from the traditional stress–strain curve, as is common in classical mechanical testing methods, it also allows for the use of a compliance-based method ('Estimated best E' from Zaslansky et al., 2005). The compliance method is based on the principle that each incremental loading step within the elastic region can be considered as an independent experiment in which the strain field created within the sample and the incremental load causing it are determined. Thus, the compliance of the sample is determined repetitively and non-destructively.

An interesting feature of the ESPI method is its inherent ability to *concurrently* measure strain along two orthogonal directions on the sample surface. This allows the derivation of Poisson's ratios from the same experimental data on exactly the same sample under identical loading conditions. For each incremental loading step, in addition to the axial strain of the sample, the lateral strain is also determined. The negative ratio of the latter to the former can be used to estimate Poisson's ratio. Since these loading steps can be repeated at the discretion of the investigator, the