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Research paper

Are tensile and compressive Young's moduli of compact bone different?

Meir M. Barak[a], *John D. Currey*[b], *Steve Weiner*[a], *Ron Shahar*[c,*]

[a] *Department of Structural Biology, Weizmann Institute of Science, Israel*
[b] *Department of Biology, University of York, UK*
[c] *Koret School of Veterinary Medicine, The Hebrew University of Jerusalem, Israel*

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ABSTRACT

This study examines the question of whether the stiffness (Young's modulus) of secondary osteonal cortical bone is different in compression and tension. Electronic speckle pattern interferometry (ESPI) is used to measure concurrently the compressive and tensile strains in cortical bone beams tested in bending. ESPI is a non-contact method of measuring surface deformations over the entire region of interest of a specimen, tested wet. The measured strain distributions across the beam, and the determination of the location of the neutral axis, demonstrate in a statistically-robust way that the tensile Young's modulus is slightly (6%), but significantly greater than that of the compressive Young's modulus. It is also shown that within a relatively small bone specimen there are considerable variations in the modulus, presumably caused by structural inhomogeneities.

1. Introduction

Tissue engineering is a fast-growing field attracting much attention in recent years. This field deals with bioactive materials, and combines aspects of cell biology, engineering, material science and surgery to develop new functional tissues. Engineered bone tissue is used to repair segmental defects, and restore mechanical function (Liebschner, 2004). It is therefore evaluated in terms of its biomechanical properties, in particular its material stiffness (Young's modulus). Clearly, a thorough knowledge of the mechanical properties of natural bone is required for it to be successfully tissue-engineered. Furthermore, for many other practical purposes – such as producing finite element models of bones and bone-implant systems – a good estimate of the modulus of the material is needed, and in particular it is important to know whether the modulus is different in different loading modes. We address this question. We note that although the stiffness of any material is a function of interatomic attraction/repulsion forces, cortical bone is heterogeneous so that relating its stiffness to interatomic events would be extremely difficult. Like other researchers, we therefore use the term 'Young's modulus' to denote the slope of the linear portion of the relationship between stress and strain.

It is generally accepted that the Young's modulus of compact bone is not different in tension and compression

* *Corresponding address:* Koret School of Veterinary Medicine, The Hebrew University of Jerusalem, PO Box 12, Rehovot, 76100, Israel. Tel.: +972 8 9489756; fax: +972 8 9467940.
E-mail address: shahar@agri.huji.ac.il (R. Shahar).

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(Reilly et al., 1974; Yeni et al., 2004). This aspect of bone material behaviour has been claimed to occur both in trabecular bone (Keaveny et al., 1994; Rohl et al., 1991) and compact bone (Reilly et al., 1974; Yeni et al., 2004). However, there is no *a priori* reason why a complex, lamellar, porous structure like compact bone should have the same modulus in tension and compression (Yamada et al., 2006; Yeni et al., 2004; Yu et al., 2005). For example, the compressive strength of bone is much higher than its tensile strength (Currey, 2002). Should a difference be found, the structural reasons for this difference will need to be elucidated.

The determination of the relationship between tensile and compressive moduli of bone is difficult; one can either test different specimens in tension and compression – in which case comparisons are of questionable validity – or the same specimen is loaded sequentially in the two different modes, which is technically challenging. Beam bending produces areas of tension concurrently within the same specimen. However, the determination of the tensile and compressive moduli would require multiple strain measurements at high spatial resolution, which is impractical when using strain gauges.

ESPI (electronic speckle pattern interferometry) is an optical metrology non-contact technique which measures whole surface displacement and produces strain maps. It has been shown by (Zaslansky et al., 2005) to be an extremely precise and accurate method for the mechanical testing of wet bone and dentine samples. In the present study ESPI is used to determine whole surface strain maps in bone specimens loaded in four-point bending. The specimens are completely immersed in water during testing, and are therefore in a uniform environment that approximates their physiological state. The signal-to-noise ratio is rather low (Zaslansky et al., 2005, 2006), but the method produces many data points, so the noisiness of the data can be taken care of by statistical methods. These features were used here to simultaneously determine with great precision and accuracy the axial tensile and compressive strains through the thickness of the same bone specimen. The following section describes the theory upon which the calculations are made.

2. Theory

The whole-surface deformation maps of beams of cortical bone loaded in four-point bending can be used to determine strain as a function of depth through the thickness of the specimen. In all that follows the specimens were loaded well within their elastic range, and never came anywhere near their yield point. Beam bending theory shows that in a beam made of homogeneous material, strain should vary linearly with distance from the neutral axis. Differences in modulus through the specimen will not change this linear behaviour or cause a change in the slope of the strain-versus-position curve. Any differences in modulus will produce differences in the stress as a function of depth, but the stress cannot be measured directly. A distribution of the strain as a function of depth should, therefore, be linear irrespective of the differences in modulus throughout the specimen. However, the location of the neutral axis (position of zero strain) could change if the specimen has different moduli in the two loading modes.

There are two potential causes of differences in Young's modulus in different parts of a bending specimen. One possible cause, named here 'intrinsic', is due to the fact that the tensile and compressive moduli of bone may be inherently different. The other cause, named here 'inhomogeneity' is due to the fact that the specimen may not be homogeneous: some parts of the specimen may have a higher modulus than other parts, because, for example, of differences in the extent of mineralization, structural differences and variations in porosity.

Throughout the following discussion the beams shall be loaded so that their upper part is in compression. Consider a beam-shaped specimen with a rectangular cross-section, with no inhomogeneity or intrinsic differences in modulus, that is loaded in four-point bending. The region of interest, in which displacements and strains are determined, is limited to between the inner loading points. In this region the specimen is loaded in pure bending, with no shear to complicate matters. What should be the relationship between the strain in the specimen and the depth of the specimen? The strain should vary linearly with depth, and be zero at half the depth of the specimen.

Now suppose that the specimen is homogeneous, but there are intrinsic differences in Young's modulus, and that Young's modulus in compression is greater than Young's modulus in tension. The strain will still vary linearly with depth, but the neutral axis will not be at half the depth of the specimen, but some distance towards the upper, compression, side of the specimen. This is because the neutral axis is necessarily within the stiffer side of a beam. This can be visualised by considering a beam, half of whose depth is steel and half is foam rubber. The foam rubber will have almost no effect on the stiffness of the whole beam, and the neutral axis of the whole beam will be nearly in the middle of the steel rather than at half the depth of the specimen. With the set-up used in this study (and supposing the Young's modulus to be greater in compression than in tension) the neutral axis will be shifted towards the upper side of the specimen. If this homogeneous specimen is reloaded after being rotated by 180° (so that the previously compressive side is now in tension), the neutral axis will again be shifted towards the upper side of the specimen.

Suppose, on the other hand, that there is no intrinsic difference in modulus, but that the specimen is inhomogeneous, so that one side is stiffer than the other side. The neutral axis will always be displaced towards the stiffer side; if it were towards the upper side in one orientation, then if the specimen were rotated by 180 degrees, the neutral axis would be shifted towards the lower side.

Inhomogeneity differences in modulus were not the primary concern of this study (though they were found to be rather large even within relatively small samples, and shall thus be reported). However, they can mask intrinsic differences, therefore they must be considered when calculating the effect of purely intrinsic differences. This objective was achieved by testing the specimen in one orientation, then reversing the orientation, allowing us to