Materials Testing 2.0 for Identifying the Orthotropic Stiffness Components of Cortical Bone

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Abstract. Modelling the mechanical response of human bone to predict fracture requires that the material properties are known accurately. Measuring the stiffness of cortical bone is challenging as it is heterogenous and anisotropic. Traditional approaches based on simple uniaxial tests (Materials Testing 1.0, MT1.0) require the assumption that the properties are homogeneous and that the orthotropy axis is aligned with the bone leading to large scatter in measured stiffness in the literature. In this work we develop a novel Materials Testing 2.0 approach for extracting all orthotropic stiffness components of a cortical bone sample in a single test using Digital Image Correlation (DIC) combined with the Virtual Fields Method (VFM).

Introduction

The material properties of human bone are required to create accurate computational models to predict fracture under diseased conditions (*e.g.*, osteoporosis) or to aid in the design of protective equipment (*e.g.*, ballistic armour or sports equipment). Human cortical bone is a complex heterogeneous and anisotropic material, so it is difficult to accurately measure the stiffness using traditional uniaxial tests (MT1.0). When using the MT1.0 approach small bone specimens must be sectioned, and it needs to be assumed that the properties are homogenous and that the axis of orthotropy is aligned with the long axis of the bone. There is considerable scatter in the stiffness data for bone in the literature [1,2], especially for Poisson's ratio which varies between 0.1 and 0.5. While more scatter than an engineering material is expected due to the biological nature of bone it is not clear how much of this scatter is true heterogeneity and how much is a result of testing artefacts and assumptions. New Materials Testing 2.0 (MT2.0) approaches that combine heterogenous strain fields with full-field measurements and inverse identification [3,4] are a promising alternative to traditional MT1.0 tests for bone as they allow for the extraction of multiple material parameters per test and do not require strong assumptions on the alignment of the orthotropy axis. In this work we design a new MT2.0 configuration that can identify all four stiffness components of cortical bone in a single test using digital image correlation (DIC) combined with the virtual fields method (VFM).

Method and Experimental Setup

Ten femoral and tibial cortical bone samples were sectioned from two elderly female donors (ethics reference: 19/YH/0184) using a bandsaw for bulk cuts with the final geometry being machined using a bench top mini mill while irrigating with Phosphate Buffered Saline (PBS), see Fig.1 (a). The specimen geometry was limited based on the cortical bone shaft geometry (80 x 15 x 2 mm, aligned to the bone long axis).

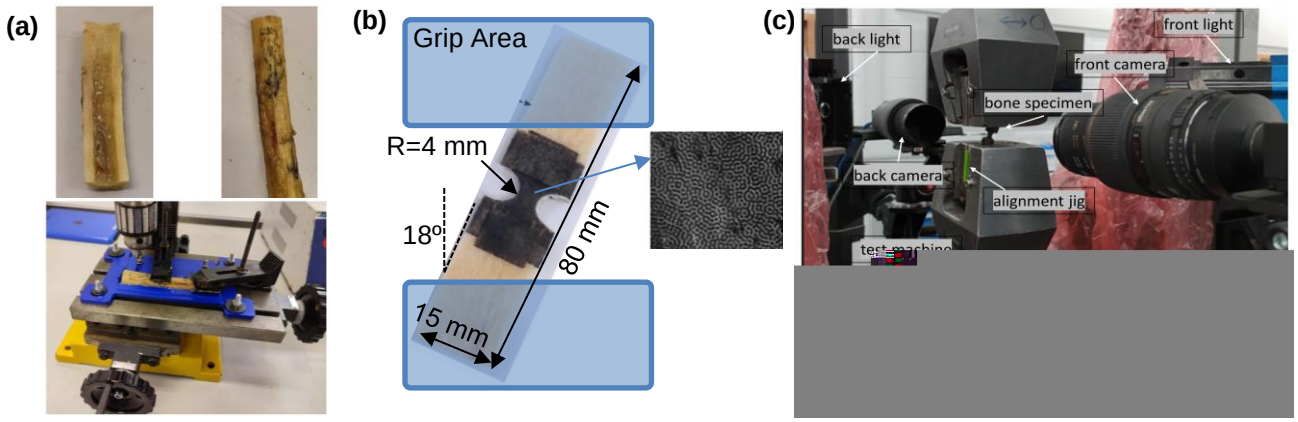

Figure 1: (a) Cortical bone cross section and machining process with the mini mill. (b) Test configuration, sample geometry and speckle pattern. (c) Test machine and DIC setup.

The designed test configuration was a deep notched off-axis test mounted directly into the widest grips of the test machine (50 mm) using a 3D printed alignment jig, see Fig 1 (b) and (c). Speckle patterns of between 20 and 40 µm were transferred onto the samples using a stamp and the ink from a permanent marker. The samples were loaded in displacement control until 400 N which was reached (based on the linear region before failure from trial tests) and then unloaded. Each sample was tested repeatedly to assess repeatability and different speckle patterns. Back-to-back 2D DIC was used to extract the displacement and strain fields with

the parameters in Tab. 1. The strain fields were averaged back-to-back after rotating and interpolating the back camera data onto the same coordinate system as the front camera. Piecewise special optimised virtual fields were used to identify the orthotropic stiffness components using a custom in-house Matlab code with a virtual mesh of 6x6 elements.

Table 1: DIC parameters

Software	MatchID	**Interpolation function**	Bicubic spline
Method	2D DIC back-to-back	**Correlation criterion**	ZNSSD
Camera resolution	5320x4600 px, 16 bit	**Prefiltering**	Gaussian (kernel = 5px)
Pixel to mm	~0.004 mm	**Strain window**	61 data points
Average speckle size	11 px	**Virtual strain gauge**	151 px
Subset size	31 px	**Strain interpolation**	Bilinear quadrilateral
Step size	2 px	**Strain tensor**	Hencky
Shape function	Quadratic		

Results and Discussion

The stiffnesses identified for all samples are shown in Fig. 2. The stiffness values and errors bars in this figure are the result of a thorough uncertainty quantification simulation for each specimen that accounted for individual speckle pattern quality and the specific boundary conditions applied to each sample. These simulations were realised by combining a finite element model of the test with the image deformation tool in MatchID. The results are consistent between donors and different bones. Given the donor age these results agree well with the average values presented in the literature with low variability in the identified parameters, especially Poisson's ratio (see the right hand axis of Fig 2 (c).

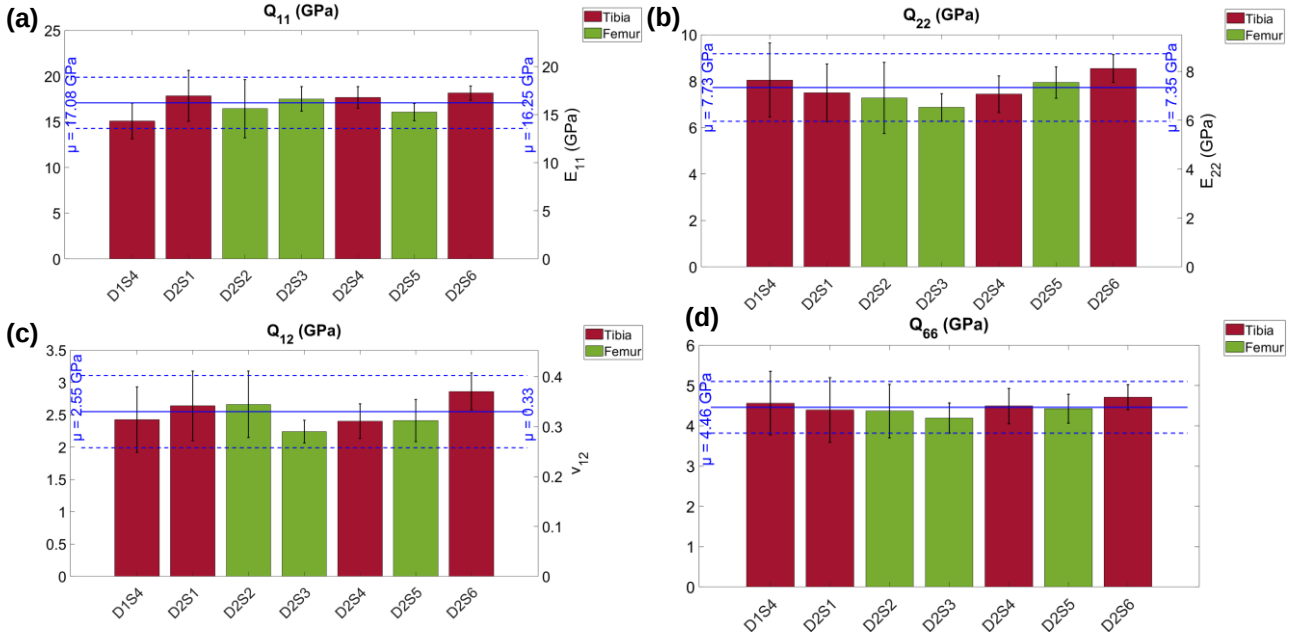

Figure 2: Average stiffness identification results for all samples. The error bars for each specimen are the combined result of multiple tests and uncertainty quantification simulations using synthetic image deformation.

Conclusion

In this work we have developed and demonstrated the use of a novel MT2.0 method for extracting all four stiffness components of cortical bone in a single test. The test configuration we designed is an 18º off-axis test on a notched sample mounted in a standard tensile machine with 50 mm wide grips. The specimen geometry respected the machining constraints on cortical bone and was able to extract all stiffness components with low variability. Uncertainty quantification simulations were performed for each individual sample allowing the systematic errors to be corrected and the random error to be quantified.

References

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