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Apparent Young's modulus of human radius using inverse finite-element method

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Abstract

The ability to assess the elastic and failure properties of cortical bone at the radial diaphysis has a clinical importance. A new generation of quantitative ultrasound (QUS) devices and peripheral quantitative computed tomography (p-QCT) has been developed to assess non-invasively bone material and structural properties at the distal radius. This anatomical site is characterized by a thin cortical thickness that complicates traditional mechanical testing methods on specimens. Until now, mechanical properties of cortical bone at distal radius (e.g., elastic modulus, yield stress and strain) remain rarely studied probably due to experimental difficulties. The present study introduces an inverse finite-element method strategy to measure the elastic modulus and yield properties of human cortical specimens of the radial diaphysis. Twenty millimeter-thick portions of diaphysis were cut from 40 human radii (ages 45–90) for biomechanical test. Subsequently the same portion was modeled in order to obtain a specimen-specific three dimensional finite-element model (3D-FEM). Longitudinal elastic constants at the apparent level and stress characterizations were performed by coupling mechanical parameters with isotropic linear-elastic simulations. The results indicated that the mean apparent Young's modulus for radial cortical bone was 16 GPa (SD 1.8) and the yield stress was 153 MPa (SD 33). Breaking load was 12,946 N (SD 3644), cortical thickness 2.9 mm (SD 0.6), structural effective strain at the yield ($\varepsilon_y = 0.0097$) and failure ($\varepsilon_u = 0.0154$) load were also calculated. The 3D-FEM strategy described here may help to investigate bone mechanical properties when some difficulties arise from machining mechanical sample.

Keywords: Cortical bone; Breaking load; Compression; Biomechanics; Strain

1. Introduction

Osteoporotic fractures of the radius represent an early predictive sign of future fractures at other sites such as the proximal femur or the spine and the assessment of bone radial properties could be a promising diagnostic evaluation to predict fracture risk and to initiate or evaluate therapeutic actions (Cuddihy et al., 1999, 2002; Klotzbuecher et al., 2000; Haentjens et al., 2003, 2004). In the last two decades several studies on ultradistal radius and mid-shaft have been performed using biomechanical tests, but their efforts were limited to the assessment of the ultimate load. An extensive review has been reported (Eckstein et al., 2004).

With the advent of a new generation of quantitative ultrasound (QUS) devices measuring the speed of sound at the distal radius (Barkmann et al., 2000; Muller et al., 2003; Bossy et al., 2004a, b; Hudelmaier et al., 2004), a parameter sensitive to porosity and materials properties (Bossy et al., 2004b; Raum et al., 2005), it became necessary to evaluate not only the ultimate load at the radial diaphysis but also the elastic properties at the structural (apparent) level such as the Young's modulus in order to gain a better insight into the relation between QUS measurements and elastic and yield properties.

To the authors' knowledge, no published data related to apparent Young's modulus of cortical bone at the radius were found in the literature. This is probably due to the

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difficulty of cutting test samples from radial diaphysis for mechanical testing.

Apparent Young's modulus assessed by biomechanical testing at the midshaft of long bone, mainly the femur, with a large number of specimens (regularly shaped reduced section or cubic samples) varies between 8 and 22.8 GPa (Table 1) in longitudinal direction (Reilly et al., 1974; Reilly and Burstein, 1975; Keller, 1994; Kaneko et al., 2003; Bayraktar et al., 2004; Dong and Guo, 2004). The apparent Young's modulus of a macroscopic sample is evaluated based on both the intrinsic anisotropic elastic properties of the bone extracellular matrix and the porosity due to lacunae, vascular canals and resorption cavities (Hengsberger et al., 2003).

Techniques relying on Scanning Acoustic Microscopy (SAM) and nanoindentation accurately characterize the intrinsic mechanical properties of bone tissue down to the lamellar level and provide values in the range of 13 GPa in the transverse direction, 20–30 GPa along the bone axis from acoustic techniques (Turner et al., 1999; Raum et al., 2006) and 16–23 GPa from nanoindentation (Turner et al., 1999; Zysset et al., 1999). These techniques could be helpful for an accurate characterization of bone tissue properties. This remain true when cortical thickness is less than that required for testing samples machining, but the techniques do not take into account porosity. Moreover, they are extremely sensitive to the region where the test is carried out (Zysset et al., 1999), due to their high resolution from a few μm for SAM (Raum et al., 2004) down to 1 μm for latest indenter (Turner et al., 1999). It may be possible to infer the apparent Young's modulus from such measurements performed at the microscopic level. However, the main limitation of this approach lies in the homogenization assumption required to evaluate the structural properties of the material. This assumption may not be valid for orthotropic and non-homogeneous material like bone. In a recent validation study (Hengsberger et al., 2003), it was shown how the indentation modulus could be related to apparent Young's modulus but the complexity of these techniques and the equipment cost limit their use.

The aim of this study was to estimate the apparent Young's modulus and tissue equivalent stresses using an inverse numerical technique relying on specimen-specific 3D finite-element models (FEMs) and biomechanical experiments.

2. Materials and methods

Forty excised human radii with soft tissue removed were used in this study. The sample population includes 15 female and 24 male donors (mean age 73 ± 10 years old; range, 45–90 years old). Sex and age were not known for one donor. The samples were removed from fresh cadavers and were kept frozen at a temperature of −20 °C before use. Thawing was requested before computed tomography (CT) measurements but was kept to a minimum. Ethics approval for collection samples was granted at Human Ethics Committee of the Institute of Anatomy at the University René Descartes (Paris, France). The tissue donors or their legal guardians provided informed written consent.

2.1. Multislice CT

CT-images were performed with a four-line, state-of-the-art CT scanner ('Volume Zoom'; Siemens, Erlangen, Germany) perpendicular to the bone axis (collimation: 2 × 0.5 mm; voltage: 120 kV; tube current: 160 mA s). Samples were immersed in water during acquisition to reduce beam-hardening effects.

A series of 500 μm-thick slices were measured with a step of 200 μm between adjacent slices in order to get a 3D reconstruction of the samples geometry. The images were reconstructed with an overlap (bone convolution kernel B70s). The field of view was $50 \times 50\,\text{mm}^2$ with a 512 × 512 pixel matrix giving an in-plane pixel size of 98 μm. (Fig. 1a). This resolution ignores vascular and lacunar porosity.

Table 1
A comparison of longitudinal elastic modulus at the apparent (E^{app}) and tissue (E^{tissue}) level and other biomechanical properties of human cortical bone reported in the literature

References	Test method	Spec/ind (donors)	Mean age	Sex	$\dot{\varepsilon}$ (s^{-1})	ε_u	E^{app} (GPa)	E^{tissue} (GPa)	S_y (MPa)	S_u (MPa)
Reilly et al. (1974)	C	196 (19)	53.2	—	0.05	0.018	17.1	—	—	193
Reilly and Burstein (1975)	C	4 (4)	55.5	3M, 1F	0.05	0.018	17.0	—	—	205
Keller (1994)	C[a]	297 (2)	56.5	2M	0.01	—	8-20	—	—	60–180
Louis et al. (1995)[c]	C[b]	33 (33)	74	33F	0.01	0.032[c]	—	—	—	109
Turner et al. (1999)	NI[d]	60 (1)	65	M	—	—	—	23.4	—	—
	SAM	3 (1)	65	M	—	—	—	20.5	—	—
Zysset et al. (1999)	NI	N/A (8)	75.3	4M, 4F	—	—	—	20.1	—	—
Kaneko et al. (2003)	C	16 (2)	78	M	0.001	0.012	23	—	153	162
Bayraktar et al. (2004)	T	74 (34)	71.8	22M, 12F	0.002	—	17.8	19.9[e]	108	—
Dong and Guo (2004)	T	18 (3)	56	1M, 2F	0.1	—	16.6	—	—	—
Raum et al. (2005)	SAM	485 (10)	75.9	8M, 2F	—	—	—	27.9	—	—

Spec/ind, number of specimens (or indentation for nanoindentation test method) and donors; $\dot{\varepsilon}$, strain rate; ε_u, ultimate strain; S_y, yield stress; S_u, ultimate stress; C, compressive test and T, tensile test (all these studies were carried out with machined reduced-section testing samples at the femur unless otherwise stated); F, female; M, male; NI, nanoindentation; SAM, scanning acoustic microscopy.

[a]Machined cubic samples.
[b]Cylinder of radial diaphysis.
[c]Ultimate effective strain.
[d]Specimens were dehydrated.
[e]Cortical tissue elastic modulus calculated from the modulus-porosity regression.