

Technical note

Measurement of cancellous bone strain during mechanical tests
using a new extensometer deviceSteven Boyd ^{a, b}, Nigel Shrive ^{a, c}, Greg Wohl ^{a, b}, Ralph Müller ^f, Ron Zernicke ^{a, b, d, e, *}^a McCaig Centre for Joint Injury and Arthritis Research, University of Calgary, 2500 University Drive, N.W., Calgary, Alberta T2P 1N4, Canada^b Department of Mechanical and Manufacturing Engineering, University of Calgary, 2500 University Drive, N.W., Calgary, Alberta T2P 1N4, Canada^c Department of Civil Engineering, University of Calgary, 2500 University Drive, N.W., Calgary, Alberta T2P 1N4, Canada^d Department of Surgery, University of Calgary, 2500 University Drive, N.W., Calgary, Alberta T2P 1N4, Canada^e Faculty of Kinesiology, University of Calgary, 2500 University Drive, N.W., Calgary, Alberta T2P 1N4, Canada^f Orthopedic Biomechanics Laboratory, Beth Israel Deaconess Medical Center and Harvard Medical School, 330 Brookline Avenue, RN 115, Boston, MA 02215, USA

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Abstract

A device for measuring mid-substance strain in bone during uniaxial compression was developed with special attention to subsequent FE modelling. It is based on dual instrumented cantilever arms that measure the difference in tip-to-tip deflection. The so-called extensometer device was compared to two standard methods of measuring strain based on platen measurements. The extensometer device output was highly linear with tip deflection ($r^2 > 0.99$), and contact of the devices with the specimen was optimized by using an axial distribution of three devices fixed in a free-floating jig. Deflection of the extensometer arms was accurate to 4.8 μm , and precision was between 2–5 μm . Tests included measuring rubber test specimens and cylindrical cancellous bone cores extracted from canine femoral condyles. A trend of decreasing apparent modulus with decreasing strain rate was evident with the extensometer technique. Correlation between the extensometer method and the other two methods was $r^2 = 0.55$. The measure of mid-substance strain avoids non-linearities in the compression tests caused by early failure at the specimen ends, and the uniaxial testing conditions result in boundary conditions that are well suited for subsequent finite element analysis. © 2001 IPPEM. Published by Elsevier Science Ltd. All rights reserved.

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1. Introduction

Compression testing is a common experimental procedure for determining material properties of bone through determination of the stress–strain relation on regularly shaped specimens [1,2]. There are several factors to consider in the design of a compression testing protocol that affect accuracy and precision. Common sources of systematic error include *end* effects and *friction* effects [3]. End effects are due to the unsupported

free ends of the trabeculae at the edge of the excised testing specimen, and their premature failure leads to non-linear stress–strain curves and an under-estimation of the elastic modulus [4]. Friction effects are concerned with the constraints at the bone–platen interface. In a homogeneous continuum, the minimization of friction through lubrication leads to a uniaxial stress condition where strain is constant throughout the specimen. Alternatively, fully constraining the ends leads to a triaxial stress environment and a non-uniform strain distribution [5]. If cancellous bone is approximated as a continuum [6], then a uniaxial test will result in a uniform strain field that facilitates strain measurement, although some strain variability at individual trabeculae will still exist. Constraining the ends has the advantage of increasing strength and reducing end effects [7], but its disadvan-

* Corresponding author. Tel.: +1-403-220-2802; fax: +1-403-284-3553.

E-mail address: zernicke@ucalgary.ca (R. Zernicke).

tage is the over-estimation of elastic modulus and the non-uniform strain patterns throughout the specimen.

Mechanical testing techniques are useful for providing experimental data for input to large-scale high resolution finite element (FE) models [8]. Typically, the combined experimental and analytical approach involves a FE model that is based on the 3D micro-structure of the test specimen and simulates the experimental compression tests to elucidate tissue level material properties [9–11]. This approach can be expanded, for example, to develop large scale micro-structural FE models to investigate tissue-level stress–strain distributions in a whole joint [12]. Therefore, the influence of non-linear end effects and boundary conditions (i.e. friction effects) must be carefully considered in the experimental protocol. The boundary conditions must be well understood, and non-linearities avoided to facilitate subsequent simulation of experimental tests with a FE model.

Three general categories of techniques exist for measuring strain during compression testing. The simplest method uses crosshead displacement from the mechanical testing machine which includes errors caused by compliance of the load frame and the end effects. A clamp-to-clamp measure using a linear potentiometer between the two loading platens avoids the compliance issue, but still includes end effect errors. Adding brass end-caps fixed to the specimen can reduce the end effects [3], but has the disadvantage that test specimens must have sufficient excess length for embedding into the end-caps. This is not possible in cases where the cancellous region is small, or if it is bordered by non-cancellous tissue (i.e. immediately below an articular surface)—particularly if maintaining the recommended 2:1 specimen aspect ratio [13,14]. Optical methods can avoid end effects by tracking mid-axis markers, however high resolution optical equipment can be costly and post-processing time significant [15].

The purpose of this study is to introduce a new technique for mechanical testing of cancellous bone specimens that (i) have 2:1 aspect ratios due to physical constraints, (ii) avoid end effects, and (iii) are performed with boundary conditions suitable for subsequent FE modelling. The technique will be demonstrated on both a homogeneous rubber specimen and bone specimens, and the strain measurements from the new device are compared to established techniques of crosshead displacement and clamp-to-clamp measurements.

2. Methods

2.1. Extensometer device

Three extensometer devices were built to measure strain at the mid-substance during compression testing

from three sides simultaneously (Fig. 1). Each were comprised of two cantilever arms of thin spring steel (0.11 mm) that contact the bone during testing. Each of the arms were instrumented with two strain gauges (EA-06-125BT-120, Micro-measurements, Romulus, MI, USA) on opposing sides of the arm in a half-bridge configuration. Reinforcement of the arms beyond the gauges served as a stress raiser to ensure that deflection occurs at the strain gauges [16]. Strain was calculated as the difference in deflection between the arms [17,18]. The three extensometers were held in position by an aluminum retaining ring (Fig. 1b), and the entire unit was able to slide freely on three teflon set-screws sitting on the polished stainless steel base of the testing platen. Thus, contact was maintained between the extensometers and the specimen despite possible slight lateral shifts during compression because the extensometers and retaining ring could move as a unit with minimal sliding friction.

The clamp-to-clamp strain measurement utilized a linear potentiometer (LCP8-10, 1KO, ETI, Oceanside, CA, USA) fixed to the crosshead of the compression testing

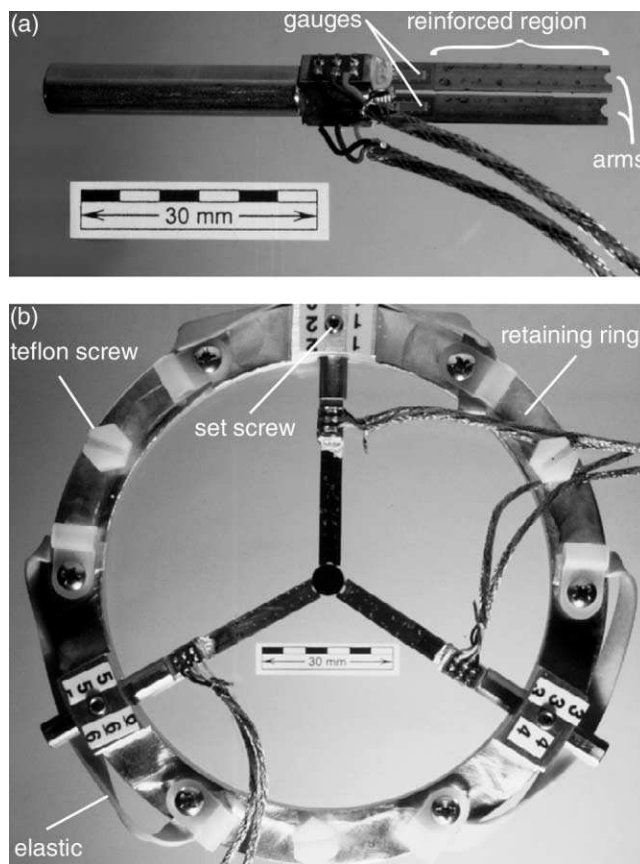


Fig. 1. (A) One of three extensometer devices built. The two arms are individually instrumented with strain gauges in a half-bridge configuration. (B) The retaining ring and the three extensometers in position to measure strain during a uniaxial compression test. A piece of rubber is in place (centre) of where a cylindrical bone specimen would be located. The retaining ring and the attached extensometers slide on the testing platen and can translate with the specimen if necessary.

system (Instron 1122, Canton, MA, USA). The crosshead displacement strain measurement was determined from the isokinetic crosshead velocity set on the Instron. The circuitry of the extensometer devices and the linear potentiometer were excited by precision amplifiers (Intertechnology Inc, Model 2310, Don Mills, ON, Canada). Output from these devices, and the Instron load cell, was collected on a data acquisition system (250 Hz) (CODAS, Dataq Instruments, Akron, OH).

The extensometer arms and the linear potentiometer were calibrated over a range of 0.5 mm prior to testing using a high precision measurement calliper (Mitutoyo, model 164-135, 0–50 mm range, 1 μ m resolution), and the linearity of each device was subsequently assessed.

2.2. Specimen preparation

A rubber test specimen (7.02 mm diameter, 10.80 mm length) was prepared to test the extensometer devices on a homogeneous substance. Bone cores (6.0 mm diameter) were excised from the medial and lateral condyles of the distal femur from dogs so that mechanical properties of the periarticular cancellous region could be investigated [19,20]. The bone cores were cut precisely into right-cylinders using a rotating diamond blade saw (Isomet Low Speed Saw, Buehler, Lake Bluff, IL) with the subchondral plate cut first (1–2 mm), then the trabecular bone cut to a length of 11 mm (Fig. 2). The exact initial length (L_0) was measured with callipers (Digimatic Calliper, Mitutoyo Corp, Japan). The aspect

ratio for our samples was 1.83:1 due to physical limitations of the femurs, and this aspect ratio is within acceptable limits (1.8:1) suggested for uniaxial compression testing [14]. Prior to each test, the position of the extensometer arms relative to the specimen were set by placing a calibration block under the bottom arm (3.02 mm) and another between the arms (4.91 mm). The arms were held in place temporarily by elastic bands providing a nominal axial load (approximately 1 N axial load), after which a set screw on the retaining ring was tightened to fix the extensometer position with respect to the ring, thus forming the extensometer–ring unit.

2.3. Testing protocol

Precision of the extensometer devices was assessed by evaluating device noise, and minimum detectable tip deflection. Accuracy was evaluated by comparing arm output against the Mitutoyo calliper over a range of 32 μ m (corresponding to 1.3% strain), and then additionally by ensuring that when the arms of an extensometer are deflected equally (i.e. displacement between the arms is fixed as a specimen is purely translated), the calculated strain output remains zero.

Repeatability was assessed by making three repeated measurements during non-destructive testing on the rubber specimen and the lateral bone specimens ($N=10$). These tests were done at different strain rates under the following conditions: 0.1/s, 0.01/s, and 0.001/s, 3 cycles each, 0.6% apparent strain. The order of the three

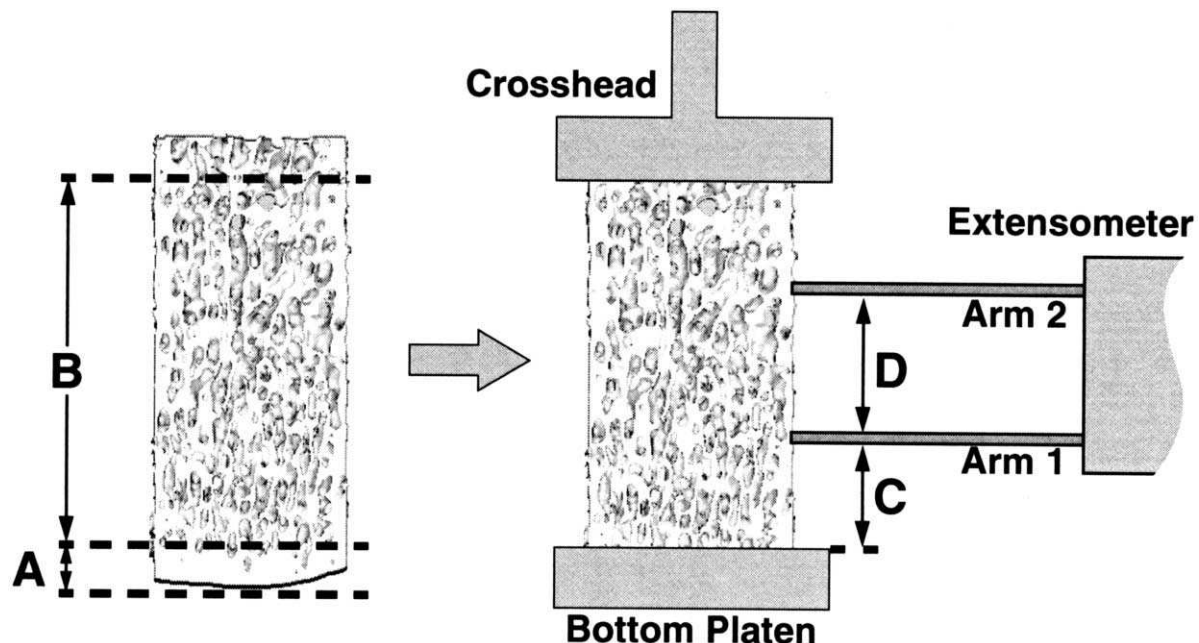


Fig. 2. A schematic illustrating the preparation of bone cores for compression testing. Using a diamond blade saw, cut 'A' location is determined from a micro-computed tomography (μ CT) scan and removes the subchondral cortical bone. Cut 'B' trims the cancellous specimen to 11 mm and the resulting cylindrical specimen is placed on the loading platen. Distances 'C', from the bottom platen to arm 1 of the extensometer, and 'D', from arm 1 to arm 2, are set with gauge blocks (3.02 mm and 4.91 mm, respectively). Thus, the position of the extensometer arms relative to the original μ CT scan is known and the specific region of the μ CT scan can be extracted for FE modelling based on compression test results.

applied strain rates was randomized, and a trend of decreased elastic modulus with decreased strain rate should be expected due to bone's viscous properties. The rubber specimen represents ideal testing conditions (a homogenous substance) while the bone represents a real experimental set-up. Thus, the components of repeatability due to the extensometers themselves can be separated from repeatability issues when testing inhomogeneous materials such as cancellous bone. Lubricant was applied between the specimens and the platen ends to reduce friction.

Lastly, compression to failure was performed on all of the bone specimens at a strain rate of 0.01/s with the lubricant at the ends. A comparison of the extensometer, clamp-to-clamp and crosshead displacement techniques will be presented for both destructive and non-destructive tests. Correlations were evaluated between the three measurement techniques.

The extensometer strain measure was based on averaging the three extensometers in the retaining ring. In cases of loss of contact, which was evident from the discontinuous or zero displacement output from a particular arm, the faulted extensometer was excluded. Data from all tests were smoothed by the generalized cross-validation method [21]. Stress was calculated by dividing the measured load cell force by specimen cross-sectional area. Engineering strain was calculated by dividing the measured strain by the original sample length: gauge distance (4.91 mm) for the extensometers and full length ($L_0 \approx 11$ mm) for clamp-to-clamp and crosshead displacement measures. Zero strain was defined at a 5 N pre-load. Elastic modulus was determined from the slope of the linear portion of the stress–strain curves.

3. Results

The calibration of each arm was highly linear ($R^2 > 0.99$ on 0.0–0.5 mm range). The precision of each device ranged from 2.1 to 4.7 μm standard deviation (SD), and the minimum detectable deflection was a 2.0 μm step. The accuracy over the 32 μm test range averaged 2.1 μm (minimum 0.5 μm , maximum 4.8 μm), which corresponds to 0.04% strain for the 4.91 mm inter-arm separation. The devices are also accurate over a larger range (0.2 mm), where the difference between two equally deflecting extensometer arms differed from zero at most by 2.0 μm .

A sample stress–strain result from a destructive test (Fig. 3) shows the curves from the extensometer devices, clamp-to-clamp measures, and the crosshead displacement measurements. The elastic modulus is estimated from the linear portion of these plots, and the estimated stiffness from the extensometer measures were consistently higher than the other two methods. A relation between strain rate and modulus is apparent with the

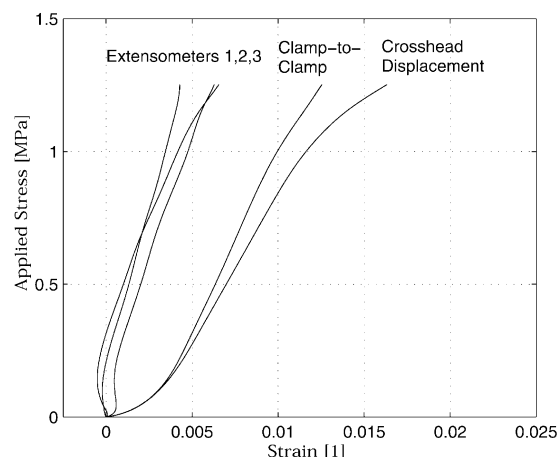


Fig. 3. Example stress–strain curves from each of the three extensometer devices, the clamp-to-clamp measurement, and the crosshead displacement measurement.

extensometer method where increased strain rate is related to increased effective stiffness (Fig. 4). This trend is less apparent with the clamp-to-clamp method and the crosshead displacement method.

The repeatability of the three strain measurement methods was nearly equal when testing the rubber specimen, but testing the bone specimens resulted in a higher SD for the extensometer than the other techniques (Table 1). The increased SD may partially result from a proportional relation with the increased elastic modulus measured by the extensometer, however the coefficient of variation should normalize for this effect, but is still slightly higher. Finally, the clamp-to-clamp and crosshead displacement measures correlated well, $r^2=0.98$, while the correlation between the extensometer and both other techniques was $r^2=0.55$.

4. Discussion

A new compression testing device based on extensometers was developed to determine strain during uniaxial testing by making mid-substance measures. This method has the advantage that the strain measurements avoid non-linearities caused by end effects, and can do so with specimens with aspect ratios of 2:1. The high correlation between the clamp-to-clamp and crosshead displacement measures ($r^2=0.98$) indicate high consistency between both techniques, but they both include end effects which explains the weaker correlation ($r^2=0.55$) with the extensometer technique.

The output from the extensometer arms was accurate with tip deflection, however reduction of the noise (~2–5 μm SD) would be beneficial as that limits the precision of the strain measurements. This noise accounts for 0.04% to 0.10% strain in this study (4.91 mm inter-arm extensometer setup). The noise was stationary and white,

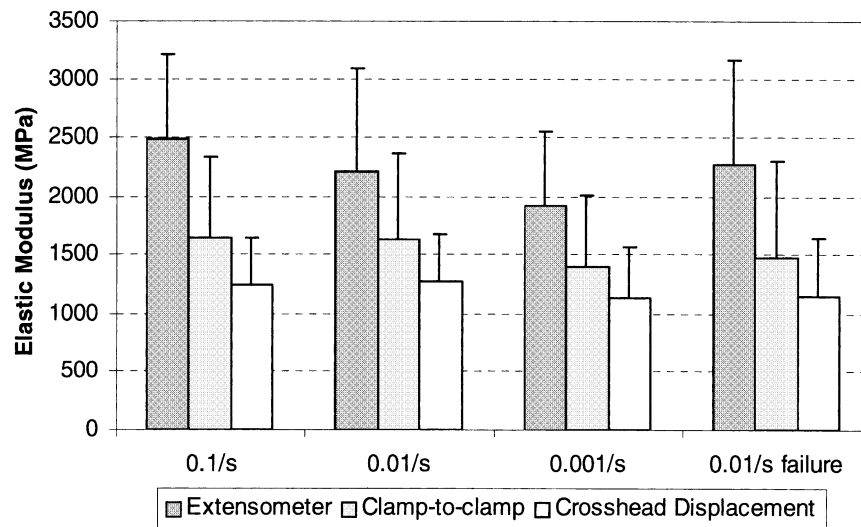


Fig. 4. Cancellous bone elastic modulus (mean and standard deviation) tested non-destructively at 0.1/s, 0.01/s, and 0.001/s strain rates, and then destructively tested at 0.01/s strain rate. The bar heights represent the mean elastic modulus, and standard deviation bars represent variation of elastic modulus between the different bone specimens. The effective stiffness of the bone specimen decreases with decreased strain rate, and this is evident from the extensometer measures, but less so from the other techniques. The increased stiffness measured with the extensometer measures is due to exclusion of end effects from the strain measurements.

Table 1

Repeated measures (SD) and coefficient of variation (COV) during non-destructive testing of cancellous bone samples ($N=10$) and a rubber specimen

	Cancellous bone		Rubber	
	SD (MPa)	COV (%)	SD (MPa)	COV (%)
Extensometer	7.59	6.16	0.016	1.77
Clamp-to-clamp	4.53	4.77	0.019	1.78
Crosshead displacement	2.92	3.83	0.018	1.72

and therefore it was well suited for smoothing [21]. But, in future designs, the signal-to-noise ratio and sensitivity could be improved either by designing shorter arm lengths relative to maximal tip deflection, performing the tests in an electrically shielded room, or by utilizing a full-bridge configuration.

Maintaining contact between the extensometers and the bone specimens during the tests was problematic as expected. The use of the retaining ring reduced this problem, but did not eliminate it completely. The mean trabecular thickness of these specimens was between 160 and 240 μm [19], and it is possible that part of the 110 μm thick tip on occasion was located over a void. The two points of contact where the semi-circle was cut in the arm tip (Fig. 1a) increased the chances that contact occurred. Nevertheless, an arm that has lost contact can be easily identified during the test (discontinuous or zero tip deflection) and the remaining extensometer devices provide the strain measurement. Future use of the extensometer devices should always incorporate a strategy to

maintain device contact with the specimen, such as the retaining ring used in this study, a flexible proving ring which has a mechanism to maintain a constant contact force [17], incorporating sliding extensometer arms, or another devised method.

The near vertical region of the extensometer curves reflect early failure at the bone specimen ends prior to substantial strain development in the mid-substance region (Fig. 3). At the onset of loading, this vertical region exhibits both small compressive and tensile strains, although compressive strain is measured in all three devices beyond this region. Similar patterns were observed for other bone specimens, but not in the rubber specimen. This pattern was not likely due to buckling of the extensometer arms caused by expansion of the specimen (an effect of the Poisson's ratio) because it was not evident in the rubber specimen tests where the rubber material had a high Poisson's ratio. The combination of early tensile and compressive strain suggests that some buckling of the bone specimen occurs at the onset of loading, perhaps due to inhomogeneity in the specimen or slight misalignment of the specimen with the platens. The average strain for the three extensometers is compressive and diverges from zero once the bone at the platens settle. The other techniques cannot reflect such effects as they measure displacement only between the clamps rather than from three sides.

The boundary conditions of the presented extensometer method are well suited for subsequent FE modelling. The location of the strain measurement on the specimen can be precisely controlled, and related back to the original μCT scan of the same specimen (Fig. 2). Thus, only mid-substance geometry (i.e. between the

extensometer arms) are needed as input to the FE model, and a reduction in model size is possible. The boundary conditions of the subsequent FE model should include a fixed displacement of the nodes at the cross-section boundary to apply axial strain, and free nodal displacements within the plane. These boundary conditions closely simulate uniaxial compression with zero bone-platen friction, and the reaction force of the FE model can be compared with the experimentally measured reaction force to determine cancellous bone properties such as tissue elastic modulus [11].

The important advantage to using the mid-substance strain measurement is that the end effects are not included with the 2:1 aspect ratio specimens, and these non-linear effects need not be taken into account in the FE model. Using brass end-caps also avoids non-linear end effects [1], but with the fixed end constraints at the end-caps, the non-uniform strain environment makes mid-substance surface strain measurements problematic as they do not necessarily represent strain throughout the specimen cross-section [5]. Thus, only a full sized FE model can confidently replicate the end-cap testing boundary conditions, and the FE model may be very large. The extensometer method assumes that the uniaxial compression results in uniform strain, and the strain measured at the surface represents the strain throughout the cross-section. Cancellous bone is not a homogeneous continuum, but when there are more than five trabeculae spanning the specimen cross-section it behaves approximately as a continuum [6], and the assumption is reasonable.

In conclusion, the extensometer device can be used to test bone specimens that due to physical constraints cannot fit the 4:1 aspect ratio criteria for using end-caps, while still avoiding non-linear end effects, and under boundary conditions that can be replicated in a FE model. The measure of the mid-substance strain reduces the necessary geometry in the FE model, and the ability to relate this region to original 3D μ CT data may make this approach useful for investigations into variability of tissue modulus, stresses and strain in age- and disease-related processes.

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