

Determination of tissue-level strains in trabecular structures with a 3-D digital image correlation technique

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DETERMINATION OF TISSUE-LEVEL STRAINS IN TRABECULAR STRUCTURES WITH A 3-D DIGITAL IMAGE CORRELATION TECHNIQUE

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Introduction

Osteoporosis is a common condition among elderly and postmenopausal women, leading to excessive loss of bone mass and degradation of the trabecular structure. As a result of this condition, the risk of bone fractures is increased. Fractures are initiated at the level of bone tissue, by failure of individual trabeculae. For a better understanding of failure behavior, the tissue properties and local stress/strain states must be investigated. Presently no experimental methods exist to measure strains at this level in-situ. As an alternative, micro-finite element (FE) techniques for the calculation of local strains in bone tissue can be used. However, these require assumptions about local tissue properties. In particular for large deformations, as they occur during bone failure, these mechanical properties are not well known.

In this study we explore a novel method for the measurement of strains in trabecular structures in-situ using an image correlation technique. With this technique, local strain conditions are calculated by comparing images of undeformed and deformed structures. The aim of this study was to establish the feasibility of this technique for 3-D structures when using high-resolution micro-computed tomography (CT) images and to determine the precision that can be achieved.

Materials and Methods

The 3-D digital image correlation technique we use is based on an earlier 2-D one [1] that calculates displacements from *subsets* of digital image pairs. To enable strain measurements in porous structures a number of additional steps were added. First, the trabecular structure is meshed with tetrahedral elements [2]. With the image correlation technique displacements are calculated in each of the element nodes. Secondly, a deformation tensor is estimated in the element centers from the surrounding displacement data [3]. Data is collected within a certain distance from the centers (*estimation radius*). Not only is the deformation tensor used to calculate the Green-Lagrange strain tensor, the tetrahedral elements are also deformed according to this tensor in order to visualize the deformed mesh.

The precision of the technique was studied on the basis of CT-images of an aluminum foam specimen (6101-T6, ERG Oakland, CA). A μ CT-40 and μ CT-80 scanner device (Scanco Medical AG, CH) were used to create image pairs with spatial resolutions of 12, 20 and 36 μ m. In a first study, the sample was scanned twice to test the reproducibility. In a second study, the effects of a rigid rotation of 8.5 degrees and different image resolutions were studied. In the final study, the sample was loaded to a continuum-level strain of 0.2 to create a deformed sample. Displacements and strains were calculated for various subset sizes and estimation radii.

Based on the reference and deformed states of the sample (Fig. 1) a single trabecula was selected for precision tests and strain measurements. This particular trabecula was selected for its moderate deformation, which ensures a successful correlation. Because the trabecula is visibly deformed, a visual validation between the CT-image of the deformed sample and the deformed mesh is also possible.

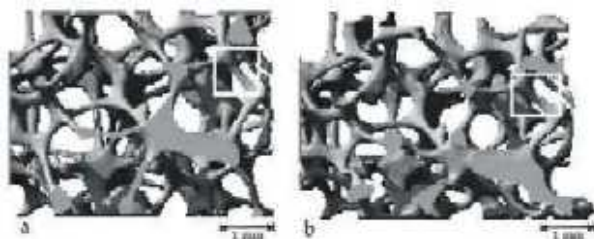


Fig.1. Rendered aluminum foam sample before (a) and after (b) the applied deformation. Digital image correlation is applied to the trabecula in the white box.

Results

Based on the precision tests, a typical value for the standard deviation in the displacement of 2 μ m for 36 μ m resolution images was determined. This value is not affected by rigid translations or rotations. Increasing the image resolution from 36 to 12 μ m did not result in significant improvements in the results. For the Green-Lagrange strain tensor components a typical standard deviation of 0.01 was achieved. This value strongly depends on subset size and estimation radius. Doubling the subset size or the estimation radius decreased this value by roughly 65 percent, but reduced the spatial resolution of the strain measurement.

The FE-mesh representation of the selected trabecula consists of 2130 nodes and 5752 elements. Analyzing the displacement and strain in this particular trabecula takes approximately 24 hours on an 800 MHz personal computer. The deformed trabecula (meshed and rendered) and calculated equivalent Green-Lagrange strain are shown in Fig. 2.

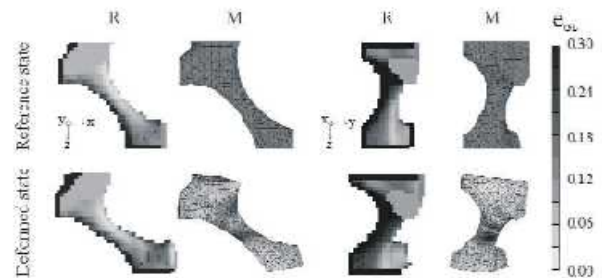


Fig. 2. Visual comparison between the deformed mesh (M) and the rendered (R) trabecula. The equivalent Green-Lagrange strain is shown in the deformed meshes.

Discussion

It is concluded that local strains in trabeculae in-situ can indeed be quantified with the 3-D digital image correlation technique. With a standard deviation for the strain measurement of 1%, the method is not suitable for the measurement of strains in the elastic range (where strains < 0.7%). It is precise enough, however, to measure local strains of several percent in magnitude, as they occur in bone tissue when a bone is loaded close to and beyond its yield load [4]. Hence, it is expected that this method can be used to improve our knowledge about the failure behavior of trabecular bone and trabecular bone tissue.

For practical reasons, we used an open-cell aluminum foam sample with a structure similar to low-density trabecular bone, rather than real bone, in this study. CT-images of aluminum show little variation in gray-values within the solid structure. This, in fact, complicates the correlation procedure. Hence, a more heterogeneous representation of the tissue, as expected for bone tissue, might lead to even better results.

Measurement of local strains with the techniques introduced here can also be of importance for the prediction of bone failure with micro-FE models. Non-linear FE-models, developed recently to simulate failure of trabecular bone [4] or aluminum foam [5], can now be validated on a local level.

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References: [1] Sutton et al., *Image Vision Comp* 4:168, 1986 [2] Frey et al., *Int J Num Methods Eng* 37:2735, 1994 [3] Peters, PhD thesis, Eindhoven University of Technology, 1987 [4] Niebur et al., *J Biomech* 33(12):1575, 2000 [5] Verhulp et al., *Comp Methods Biomech Biomed Eng* 4:8_3, 2003.