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DEVELOPMENT OF TESTING EQUIPMENT FOR MEASURING MECHANICAL PROPERTIES OF CANCELLOUS BONE

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Summary: *The article reports on development of experimental procedures used for evaluation of mechanical properties of cancellous bone using small samples of cylindrical shape. Both the compressive and tensile specimens are tested while for the strain measurement an optical method utilizing CCD camera of high resolution is used. The procedure is used to assess the relationship between the apparent density of the cancellous bone in Hounsfield units obtained from computer tomography scans and viscoelastic material properties used in finite element modeling of whole bones.*

1 Introduction

For the purpose of patient-specific finite element models of whole bones a better knowledge of the relationship between the mechanical properties of cancellous bone and its apparent density is required. Apparent density is mass per unit bulk volume of the porous bone tissue and can be retrieved from the computer tomography scans. This enables us to reconstruct the bone geometry and assign the material properties in correlation with the apparent density of the respective tissue. It has been reported that both the Young's modulus and strength of cancellous bone depends not only on apparent density and strain rate [J.C. Rice et al., 1988], but also on anatomic site [E. F. Morgan and T. M. Keaveny, 2001]. Using mechanical tests of both the whole bones and small samples of bone tissue we want to evaluate the reliability of patient-specific FE models to predict the whole bone fracture.

2 Methods

Every tested bone is first scanned using Somatom Plus CT scanner. Small cylindrical specimens for compressive testing of 10 mm in diameter and the same height are drilled out using a slow-rotation micro-drill cooled with water and cut using a low-speed, water-cooled saw. The

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ends of the specimen are then machined using wet sand-paper with the specimen fixed in a special device ensuring that the ends remain perfectly parallel. The surface of the specimen is then examined microscopically to identify possible cracks caused by machining. The tensile specimens are only 5 mm in diameter and $20 - 40$ mm in length. Their ends are fixed in metal tubes using either cyanoacrylate adhesive or two-component epoxy. Mechanical properties of bone depend significantly upon the storage and handling procedures used after the removal of the tissue and kept during the specimen preparation and mechanical testing. Immediately after the removal the specimens are wrapped into a towel impregnated with saline solution and put into a freezer at -20^oC. During all stages of sample preparation the bone tissue is kept hydrated in saline solution.

Figure 1: *Compressive and tensile specimens*

The reproducibility of the first test cycle is not particularly good without a procedure known as preconditioning of the bone samples. The reasons for this phenomenon can be divided into two parts. The first reason are the viscoelastic material properties of the cancellous bone itself and the second one is the smoothing of small irregularities of the surfaces of the samples during the first part of the loading. A steady state is usually reached somewhere between the first five to twenty loading cycles. We define the end of the preconditioning as a point where the starting strain is within a certain limit from the end strain of the previous preconditioning cycle.
It has been shown that for the compressive testing of these small bone specimens there is a great effect of friction between the bone sample and the compressive platens. To minimize this effect a thin film of oil is put between the platens and the sample to prevent the underestimation of Young's modulus caused by the damage artifact (structural end phenomenon associated with cut surfaces [T. M. Keaveny et al., 1993]).
Since the cancellous bone has viscoelastic material properties, all the results of testing are time-dependent and the strain rate and testing frequency have to be carefully fixed. For studies of normal bone activity the strain rate can be considered within the physiological range. We assume the strain rate to be between $0.002 - 0.01/s$, it means between $0.2 - 1\%\,\varepsilon/s$.
The specimens are fixed in Instron 4301 testing machine capable of fine strain-rate adjustment. The strain values are measured using a CCD camera VDS CCD-1300F and computed using

an optical identification method. The camera is able to process 25 images per second enabling determination of viscoelastic properties of the cancellous bone. The experimental set-up is shown in Fig. 2.

Figure 2: *Experimental set-up*

3 Results and conclusions

For the construction of finite element models of whole bones material properties based on apparent density values of individual elements appears to be the most suitable procedure to account for individual variations in bone structural properties. It has been shown that for small ranges of strain rate the material properties of cancellous bone are proportional to the apparent density of bone tissue and the strain rate to the power of 0.06 [J.C. Rice et al., 1988]. However, viscoelastic properties of cancellous bone with a correlation to apparent density for higher values of strain rate have not been described up to now. No correlation with bone density has been shown for tensile or torsional strength of cancellous bone or Poisson's ratio.
As an example of experimental results we present a strain-stress diagram for one tensile specimen (Fig. 3). The preconditioning of the specimen consisted of ten cycles with the fixed strain limit of 0.6%. Immediately after the last cycle of the preconditioning the specimen was fully loaded up to the break. The figure also presents a detailed view of the extensometer attached to another specimen. The extensometric measurement served as a validation of the strains

calculated from the optical identification method. The specimen was first fully preconditioned thus enabling repetitive cyclic loading without change in strains for both methods.

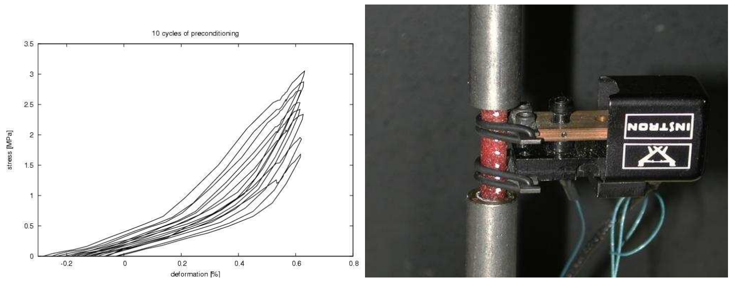

Figure 3: *Preconditioning and a detailed view of extensometer attached to the tensile specimen*

Using the described method we are able to assess the material properties of cancellous bone in relationship with the apparent density in Hounsfield units for both in compression and tension. This procedure will be used to validate finite element models of whole bones used in our computational analyzes.

Testing procedure for measurement of material properties of cancellous bone has been proposed. Complete stress–strain behavior for several bone samples and different strain rates has been evaluated both for the compressive and tensile tests. However it should be stated that for evaluation of more accurate relationship between apparent density and mechanical properties of cancellous bone statistically important number of tests still has to be done.

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