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New microscale constitutive model of human trabecular bone based on depth sensing indentation technique

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ABSTRACT

A new constitutive model for human trabecular bone is presented in the present study. As the model is based on indentation tests performed on single trabeculae it is formulated in a microscale. The constitutive law takes into account non-linear viscoelasticity of the tissue. The elastic response is described by the hyperelastic Mooney-Rivlin model while the viscoelastic effects are considered by means of the hereditary integral in which stress depends on both time and strain. The material constants in the constitutive equation are identified on the basis of the stress relaxation tests and the indentation tests using curve-fitting procedure. The constitutive model is implemented into finite element package Abaqus® by means of UMAT subroutine. The curve-fitting error is low and the viscoelastic behaviour of the tissue predicted by the proposed constitutive model corresponds well to the realistic response of the trabecular bone.

1. Introduction

Bone tissue, in general, has been investigated for decades. Recently it has become one of the most studied biomedical materials. The reason of the interest in bone tissue research is related to medical problems of the skeletal system. The demographic aging and hectic way of living are origins of bone diseases, such as osteoporosis, Paget's disease, fibrous dysplasia, bone cancer, post-implantation bone fractures, etc. Some of those diseases are treated pharmacologically. However, in some cases surgical procedures can be used. Such procedures usually consist in application of prosthetic implants, injectable materials or scaffolds for tissue engineering (White and Rushbrook, 2013; Kim et al., 2017; Tanner, 2012; Murray et al., 2008; Segredo-Morales et al., 2018; Patricio et al., 2014). The study presented in this paper concentrates on formulation of a new microscale constitutive model for human trabecular bone based on depth sensing indentation technique. Such a constitutive law can be used to numerically model bone behaviour by means of a constitutive law and to perform finite element analyses. Those analyses can be an important tool for prediction all or some of the bone-related disorders and for better understanding of the relationship between bone and implanted foreign bodies.

From morphological point of view bone exhibits two types of anatomical structure, i.e. cortical (compact) bone and trabecular (cancellous) bone. In the microscopic scale an osteon is the basic unit of the cortical bone and a trabecula is that of the cancellous bone. Both osteons and trabeculae consist of collagen fibres, which are reinforced with calcium phosphates particles. In the macroscopic scale bone can be regarded as a kind of a composite consisting of osteons/trabeculae and body fluid. Thus, phenomenological constitutive models of bone formulated in the macroscale, however valuable, are not accurate enough.

The material properties of bone in the microstructural level have been investigated for years. The studies include both individal osteons (Ascenzi and Bonucci, 1968; Ascenzi et al., 1990) and single trabeculae (Townsend and Rose, 1975; Mente and Lewis, 1989). Also a considerable amount of research has been focused on formulation of constitutive models for bone tissue. However, the investigations aiming at development of a constitutive equation for bone, including trabecular tissue, have not been accomplished.

As for cortical bone, different approaches have been adopted in bone constitutive phenomenological modelling, i.e. non-linear viscoelasticiy (Pawlikowski and Barcz, 2016), visco-elasto-plasticity (Natali et al., 2008), viscoplasticity (Johnson et al., 2010) or damage propagation (Garcia et al., 2009).

Similar effects have been taken into account in modelling of trabecular bone tissue. Niebur et al. (2000) proposed a bilinear asymmetric elastic constitutive model. They assumed that the yield strain for trabecular bone is the same as that of cortical tissue. The yield criterion was defined by the magnitudes of maximal and minimal principal strains. In order to identify the yield properties the authors performed a series of non-linear finite element analyses. They stated that their

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models can be utilised to predict the bone tissue behaviour at destructive mechanical tests of real bone specimens. A similar approach was presented in (Verhulp et al., 2008a) where the authors used micro-FE models of bovine trabecular bone specimens to calibrate the parameters of the isotropic plasticity model based on Hill's yield function. Models, which assume plastic behaviour of trabecular bone, have been also proposed by other groups, see e.g. (Stölken and Kinney, 2003; van Rietbergen et al., 2000; Verhulp et al., 2008b; Phillips et al., 2006).

In the recent years new constitutive models for trabecular bone have been presented. Those models, which are briefly detailed below, represent different phenomenological approaches and take into account at a macroscale other mechanical effects that the bone tissue is characterised by, i.e. anisotropy, failure at tension and compression, viscoelasticity, viscoplasticity. As it was mentioned earlier, trabecular bone consists of a net of spur-like trabeculae. Thus, it may be regarded as a lattice-like structure. One of the ways to describe the mechanical behaviour of such materials is to apply the homogenisation approach, which has been already implemented in various structures, see e.g. (dell'Isola et al., 2016; Alibert and Della Corte, 2015; Placidi and Dhaba, 2015; Dos Reis and Ganghoffer, 2012; Turco et al., 2016). The homogenisation method is a mathematical technique to formulate an equivalent model of continuous medium behaviour for discrete structures. The method consists in parameterisation of the microscopic mathematical formulation for discrete structures by means of a scale parameter defined as the ratio of the basic cell's length to the macroscopic characteristic length of the lattice structure (lattice length). The homogenisation method was involved to formulate a micropolar anisotropic constitutive model for trabecular bone (Goda et al., 2012). The authors considered trabecular bone as a cellular solid modelled by means of two-dimensional (2D) lattices of articulated Timoshenko beams. They derived relationships for the effective mechanical properties of the bone tissue. As the basic unit cell a hexagonal lattice was considered to prototype the topology of trabecular bone. Both axial and shear effects were taken into account. The model was implemented to 2D numerical simulation of uniaxial tension applied on a 1 by 1 mm bone specimen with a crack in the middle. The geometrical parameters and mechanical properties of the unit cells were taken from the studies of other authors.

Kefalas and Eftaxiopoulos (2012) proposed a probabilistic constitutive model for trabecular bone. They assumed that failure of trabeculae under compression and tension can be expressed by a normal probability density function. This is achieved by defining the material stiffness as the Gaussian function with respect to strain. A series of uniaxial tension and compression tests was performed on bovine trabecular bone samples. The experimental results were used to identify the material parameters of the constitutive model, which is able to capture the process of bone damage under tension and compression. The model, thus, covers large strain behaviour of the spongy bone.

The newest constitutive model for trabecular bone was presented in (Lee et al., 2017). The authors introduced a model that combines viscoelastic and viscoplastic effects. This allowed them to capture characteristic bone behaviour under compressive load, i.e. softening beyond the yield point, plateau and hardening. The material parameters in the proposed model were calibrated using the results from compression tests performed on bovine bone specimens. It is worth mentioning that such a model have been already utilised to express the behaviour of glassy polymers (Frank and Brockman, 2001).

In the present study a completely different approach is introduced. The constitutive model is formulated for human trabecular bone tissue. It is based on nanoindentation tests performed on single trabeculae. The model covers non-linear viscoelastic behaviour of cancellous bone, i.e. it simulates the tissue response to indentation load and unload cycle (hysteresis loop) and stress relaxation effects. In addition, the model was implemented in a commercial finite element method (FEM) software. The material parameters were identified by fitting the results of indentation finite element analyses (FEA) to the experimental results.

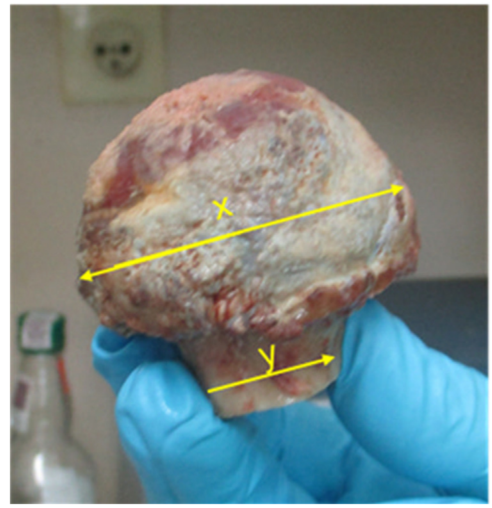

Fig. 1. Femoral heads harvested during a surgery of hip joint implantation: main dimensions x = Ø 50 mm; y = Ø 28 mm.

2. Materials and methods

2.1. Preparation of trabecular bone samples

The human trabecular bone samples were extracted from femoral heads of four patients during surgeries of hip joint implantation (Fig. 1). Two of the patients were relatively young, i.e. 56 and 62 years old, and two of them older, i.e. 72 and 83 years old. After extraction the heads were kept in 95% alcohol in temperature 4 °C. The cubic samples, whose dimensions were 25 × 25 × 20 mm (Fig. 2), were cut out of the heads with a saw blade. The following parameters of the cutting process were applied: i) saw blade shaft speed n = 3300 rpm, ii) saw blade feed p = 0.170 mm/s, iii) blade appropriate to cut materials of hardness 70–400 HV. The cubic samples were stored in the same conditions.

2.2. DSI tests

The depth sensing nanoindentation (DSI) method has proved to be a very useful technique to study mechanical properties of such biomedical materials as cortical bone and canellous bone. It can be also successfully utilised in formulation of a constitutive equation for trabecular bone at a microscopic level.

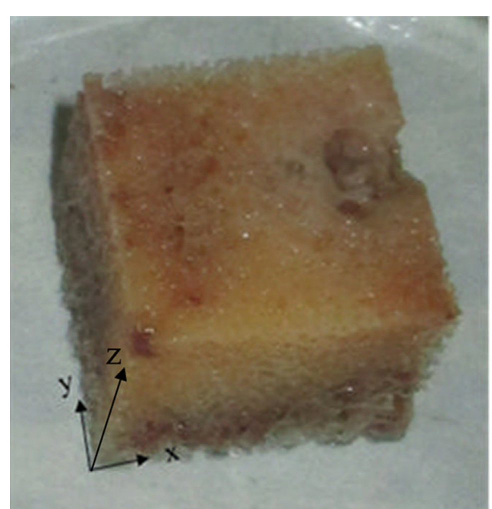

Fig. 2. Trabecular bone sample extracted from femoral head (dimensions: 25 × 25 × 20 mm).