BIOCYBERNETICS AND BIOMEDICAL ENGINEERING XXX (2017) XXX–XXX

Available online at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/bbe

Original Research Article

Stress–strain characteristic of human trabecular bone based on depth sensing indentation measurements

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A R T I C L E I N F O

Article history:
Received 4 July 2016
Accepted 11 January 2017
Available online xxx

Keywords:
Nanoindentation
Constitutive relation
Trabecular structure

A B S T R A C T

In the paper a relation between stress and strain for trabecular bone is presented. The relation is based on the results of depth sensing indentation (DSI) tests which were performed with a spherical indenter. The DSI technique allowed also to determine three measures of hardness, i.e. Martens hardness (H_M), nanohardness (H_{IT}), Vickers hardness (H_V) and Young modulus E_{IT} of the trabecular bone tissue. The bone samples were harvested from human femoral heads during orthopaedical procedures of hip joint implantation.

In the research the Hertzian approach is undertaken. The constitutive relation is then formulated in the elastic domain. The values of hardness and the Young modulus obtained from the DSI tests are in good agreement with those found in literature. The stress–strain relation is formulated to implement it in the future in finite element analyses of trabecular bone. Such simulations allow to take into account the microstructural mechanical properties of the trabecular tissue as well as remodelling phenomenon. This will make it possible to analyse the stress and strain states in bone for engineering and medical purposes.

1. Introduction

The primary aim of the paper is to elaborate a method of constitutive model formulation for human trabecular bone. The formulation is based on nanoindentation tests carried out on samples of trabecular tissue extracted from human femoral heads. Another goal of the research is also to determine material properties of the tissue, such as elastic modulus, hardness, and its ability to harden in the deformation process. The approach proposed by Olivier-Pharr is adapted in the study.

Nanoindentation or depth-sensing indentation (DSI) technique has proven to be very useful to measure mechanical properties of various tissues at a micro-scale. Bone tissue is one of the most commonly tested tissue by means of DSI. Localised tests on bone samples are carried out to compare the mechanical properties of lamellar and interlamellar

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http://dx.doi.org/10.1016/j.bbe.2017.01.002

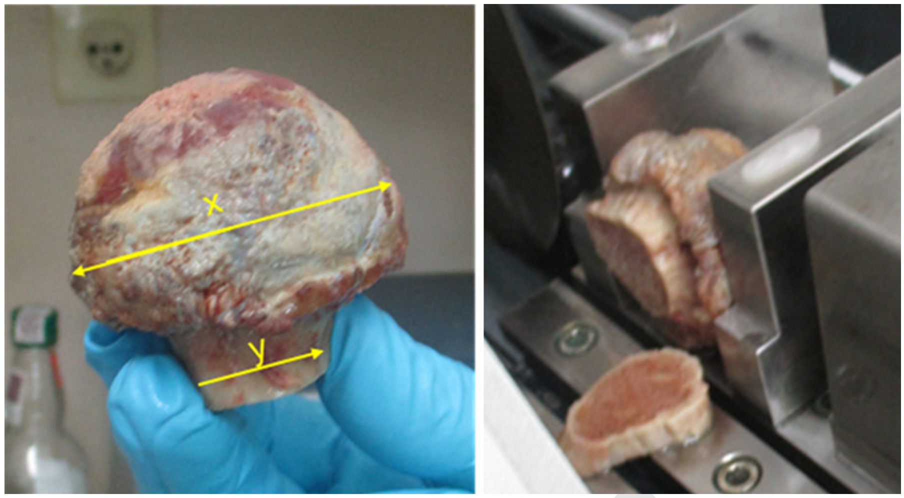

Fig. 1 – Femoral heads harvested during a surgery of hip joint implantation: main dimensions x = Ø50 mm; y = Ø28 mm (left); preparation to the cutting process (right).

bone [1–3], osteonal bone [4] as well as compact and cancellous bone [5,6].

Nanoindentation technique can be also used to determine properties of bone in the case of various diseases. Albert et al. measured bone elastic modulus and hardness by nanoindentation on samples harvested during routine surgeries from patients suffering from osteogenesis imperfecta [7]. They tested specimens taken from various sites of femur and tibia. The values of the Young modulus they obtained were approx. from 14 to 18 GPa, whereas those of hardness from approx. 0.5 to 0.65 GPa. The authors studied two types of osteogenesis imperfecta severity and concluded that there were no significant differences in the obtained values between the two types. Their findings confirmed the earlier research of Fan et al. who tried to adopt the nanoindentation technique to distinguish a clinical type of osteogenesis imperfecta [8]. They found that there is no significant relationship between nanoindentation measurements (elastic modulus and hardness) and osteogenesis imperfecta clinical types.

Mechanical properties of bone have been studied at a micro- or nano-scale by means of nanoindentation technique for at least two decades (see e.g. [9,10]). Recently similar studies have been carried out with an attempt to determine viscoelastic properties of bone tissue [11,12].

In the present paper the nanoindentation technique is used to determine constitutive relation at a nanoscale for human trabecular bone. The bone samples were harvested in cooperation with Military Institute of Medicine, Warsaw, Poland, from femoral heads during surgery of artificial hip joint implantation. It is assumed here that bone indicates elasto-plastic properties.

2. Materials and methods

2.1. *Preparation of samples for nanoindentation tests*

The process of the preparation of the samples was conducted in the laboratory at the Institute of Precision Mechanics. We obtained 25 femoral heads (Fig. 1) which were kept in 95% alcohol in temperature 4 °C. The cubic samples cut out of the head were stored in the same conditions. The dimensions of the specimens were 25 mm × 25 mm × 20 mm (Fig. 2).

The sign of each sample consisted of the number of the sample, the age of the patient, the sex of the patients, the type of tissue (cortical, trabecular), the month and the year of extraction. After the tests the samples were disposed in the Military Institute of Medicine, Warsaw, Poland.

The main parameters of the cutting process were as follows:

- saw blade shaft speed, n = 3300 rpm,
- saw blade feed, p = 0.170 mm/s,
- blade appropriate to cut materials of hardness 70–400 HV.

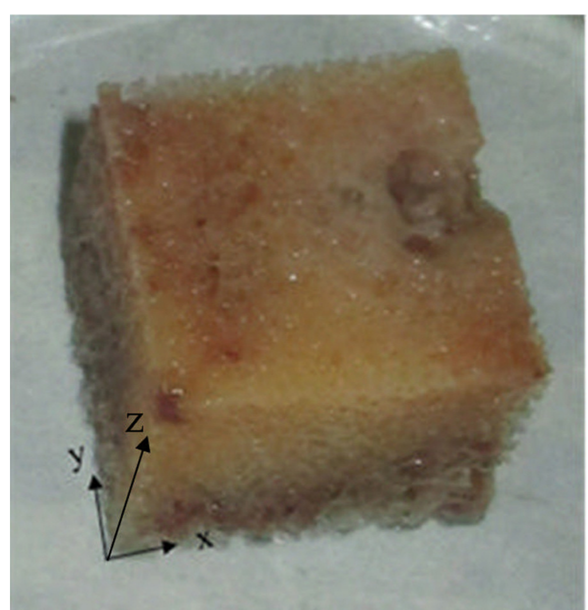

Fig. 2 – Cubic trabecular bone sample cut from femoral head (dimensions: 25 mm × 25 mm × 20 mm).

Please cite this article in press as: Pawlikowski M, et al. Stress–strain characteristic of human trabecular bone based on depth sensing indentation measurements. Biocybern Biomed Eng (2017), http://dx.doi.org/10.1016/j.bbe.2017.01.002