HENRYK OLSZEWSKI*, WIKTORIA WOJNICZ*, EDMUND WITTBRODT *

METHOD OF SKELETAL SYSTEM MODELLING

An original method of skeletal system modelling is presented in detail. Using DICOM images obtained from CT and PET tests, shell models of nine bones were created (humerus, radius, ulna, scapula, clavicle, femur, tibia, fibula, pelvis). Two methods of bone behaviour are also proposed, the first method treating the bone as a solid structure and the second method treating the bone as a complex porous structure. The behaviour of model parts is numerically examined by using the finite element method.

1. Introduction

Modelling the movements of upper and lower human limbs requires creating the musculo-skeletal system model. Each part of this system is a complex structure, and its behaviour is modelled by taking into account physiological laws. To examine the behaviour of a complex model structure, one should determine input and output data and their cause-and-effect relationships. Determining the relationships in a real living body is difficult because the medical testing cannot be fully intrusive. That is why the behaviour of skeletal and muscular structures is examined using mathematical modelling and numerical simulations. Such methods take into account non-linear physical cause-and-effect relationships, non-homogenous mechanical properties and the complex geometry of component structures. Mathematical models often use the principles of mechanics, multibody dynamics and finite element method (FEM) [1,2,3].

From the physiological point of view, the bone is a system that continually adapts its construction and density to transfer external load. This assures that the bone will not be damaged under influence of this external

---

* *Gdansk University of Technology, Faculty of Mechanical Engineering, Gdansk, Poland; E-mail: holszews@pg.gda.pl; wiktoria.wojnicz@pg.gda.pl; e.wittbrodt@pg.gda.pl*

load. Every long bone (which includes those in the upper and lower limbs) comprises two different tissues: the cortical bone and trabecular (cancellous or 'spongy') bone [3]. These two types have different mechanical properties and micro constructions [3,4]. Their connections create a complex and light construction to transfer large external loads.

Today two problems remain unsolved in mechanobiology. The first concerns determining the cause-and-effect relationships between the influence of mechanical force and the activity of osteoclasts and osteoblasts, i.e. in what way external loads are sensed in the bone structure and how this translates into structural and material adaptation of the cortical and trabecular tissues [3]. The second problem concerns the lifelong renewal and repair process of bone tissues. In order to describe this phenomenon, models of bone modelling and remodelling should be created.

This paper presents an original method of skeletal system modelling. The behaviour of model parts is numerically simulated by using the finite element method. The proposed modelling method allows us to solve the above-mentioned mechanobiological problems.

2. Method

The graphical scheme of the procedures used in modelling method is presented in Fig. 1A. All steps and methods are described below.
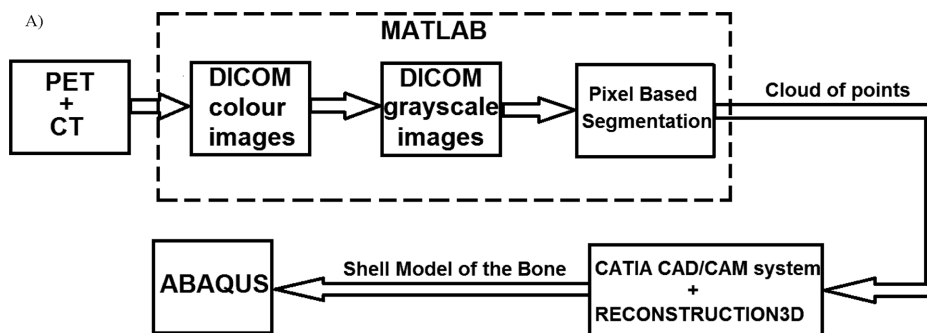

Fig. 1A). The graphical scheme of modelling

Bone models were created using DICOM format medical images obtained from Positron Emission Tomography (PET) and Computed Tomography (CT) performed at the Oncology Center in Bydgoszcz. The PET and CT tests were conducted simultaneously using the same testing machine. This allowed for the simultaneously location of soft tissues (PET) and hard tissues (CT) [5]. Thus series of medical colour images were obtained at 3.0 mm intervals along the body's vertical axis (Fig. 1B).
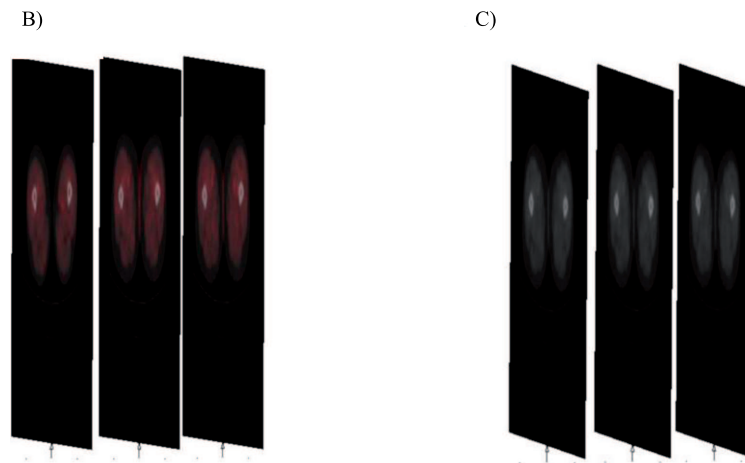
B)   C)

Fig. 1. Serials of medical images: B) colour images, C) grayscale images

In order to capture the bone contour (i.e. contour mapping), the colour images were converted into grayscale images using the MATLAB program (Fig. 1C). Using the Pixel Based Segmentation based on thresholding method, an interval of grayscale values was used to describe the external surface of the bone [5,6,7]. The lower and upper interval borders of thresholding were selected from an intensity histogram (Fig. 2). In this histogram the vertical axis describes the number of pixels and the horizontal axis the grayscale value (from black to white). The histogram shows how many pixels have the same grayscale value.

The bone contours were created by using all the grayscale images and detecting points that have grayscale values in the interval of external bone's surface. As an example, Fig. 3 shows the contours of right and left femurs.

Clouds of points were created by collecting all the contours of the image series. Each cloud of points profiles the external surface of a bone (Fig. 4). It is worth noticing that these clouds were enhanced by adding points interpolated between neighbouring images.

3D shell models of the bones (henceforth called 'shell models of bones') were created by using the CATIA CAD/CAM system and an original reconstruction algorithm. This algorithm named RECONSTRUCTION3D uses Delaunay triangulation and the sculpture process [8,9].

Delaunay triangulation allows us to obtain a convex hull (surface) model. The triangulation process involves dividing complex polihedrons into simplexes in such a way that two neighbouring simplexes have a common face, vertex or edge. This is achieved by building a sphere on the polihedron vertices. The RECONSTRUCTION3D program carries out the triangulation process in 3D by using the tetrahedron simplexes on the points of a given
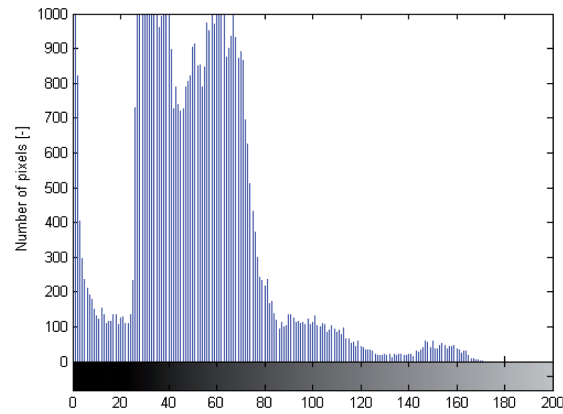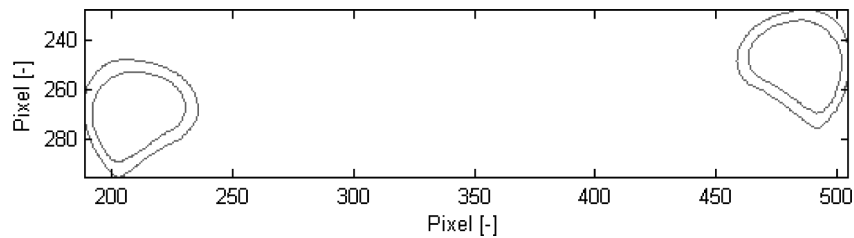
Fig. 2. Intensity histogram

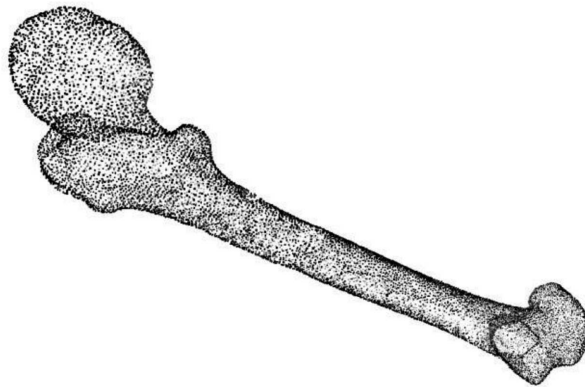Fig. 3. Contours of right and left femurs

Fig. 4. Cloud of points described an external surface of femur

cloud. The result of this process is a mesh of triangular elements, which provides the surface shape of the bone. The triangulation process involves a dual graph of Voronoi tessellation, which divides space into Voronoi cells [8]. If the created mesh is not convex, the recesses on the surface are filled by tetrahedrons. In this situation, these tetrahedrons are reduced during the sculpture process.

The process of sculpture is based on the Attene algorithm [10]. It smoothes and refines the mesh obtained from Delaunay triangulation to produce a very complex mesh that resembles a real bone surface. The Attene algorithm has three stages: limited sculpture, unlimited sculpture and sculpture with holes. This algorithm comprises the Euclidean Minimum Spanning Tree, Gabriel Graph and Extended Gabriel Graph.

3. Models

3.1 Shell models of bones

By applying the methods described above, shell models of bones in the upper and lower limbs were created. The skeletal model of a lower right limb is shown in Fig. 5. It is composed of the pelvis (Fig. 6), femur (Fig. 7), tibia (Fig. 8) and fibula (Fig. 9). Fig. 10 shows the contact surfaces of the right knee, Fig. 11 the right kneecap, Fig. 12 the hip joint and Fig. 13 the contact surface of the femur head.

The skeletal model of a left upper limb is shown in Fig. 14. It is composed of the humerus (Fig. 15), ulna (Fig. 16) and radius (Fig. 17). Fig. 18 shows elbow joint, Fig. 19 the glenohumeral joint, Fig. 20 the scapula and Fig. 21 the clavicle.

3.2 Numerical model of bone

Shell bone models can be used to model static and dynamic states of loading. However, there is a serious problem in determining the internal bone structure (i.e. the cortical and trabecular structure) [3,11]. DICOM images obtained from a living person do not allow us to accurately define cortical and trabecular areas. That is why two methods of bone behaviour modelling could be used: a) the first method treating the bone as a solid structure; b) the second method treating the bone as a complex porous structure. The first method is often used in numerical simulations [1,2]. However, this method can only be used in the primary stages because it does not take into account the fact that a bone is a non-homogenous, thin-walled structure. The second method requires creation of complex model by using specific mathematical and numerical methods. Nowadays, this second method is only used to simulate the remodelling process in the small trabecular part [2].
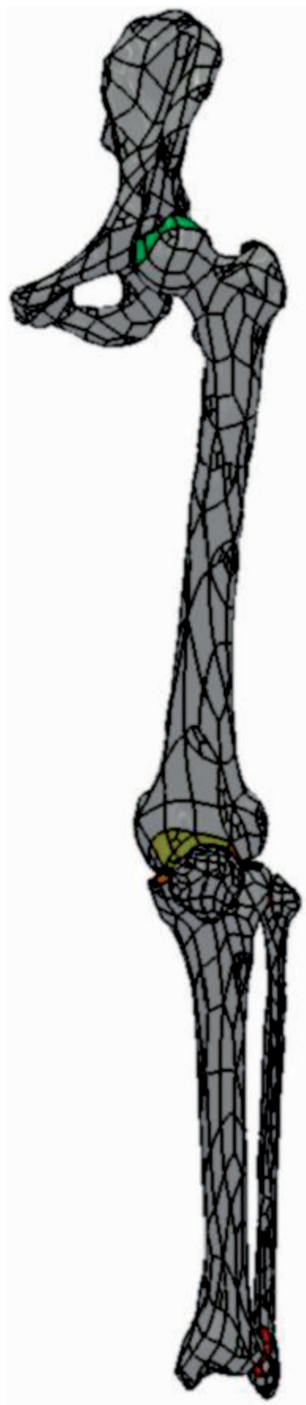
Fig. 5. Lower right limb

Fig. 6. Pelvis

Fig. 7. Femur

Fig. 8. Tibia

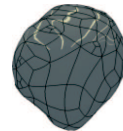Fig. 9. Fibula

Fig. 10. Contact surfaces of knee

Fig. 11. Kneecap
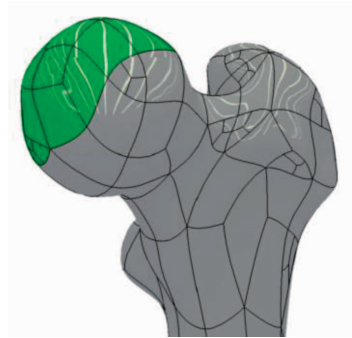
Fig. 12. Right hip joint

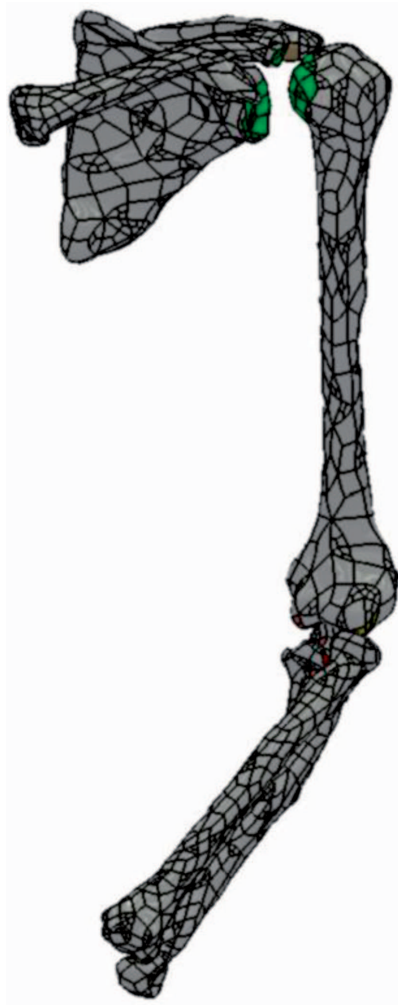Fig. 13. Contact surface of femur head

Fig. 15. Humerus

Fig. 16. Ulna

Fig. 17. Radius

Fig. 14. Upper left limb
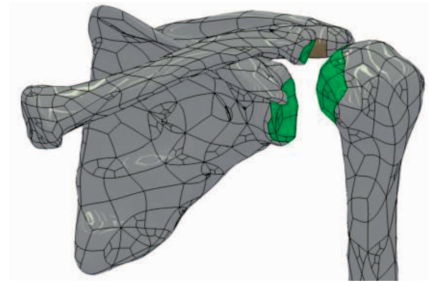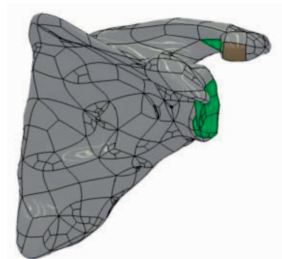
Fig. 18. Elbow

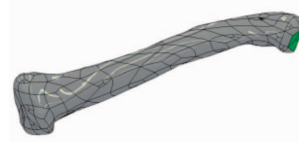Fig. 19. Glenohumeral

Fig. 20. Scapula model

Fig. 21. Clavicle model

3.2.1 Solid bone model

According to the first method of bone behaviour modelling, the solid bone model was obtained from transforming a part of a femur shell model into a solid model by using the ABAQUS program (Fig. 22A).
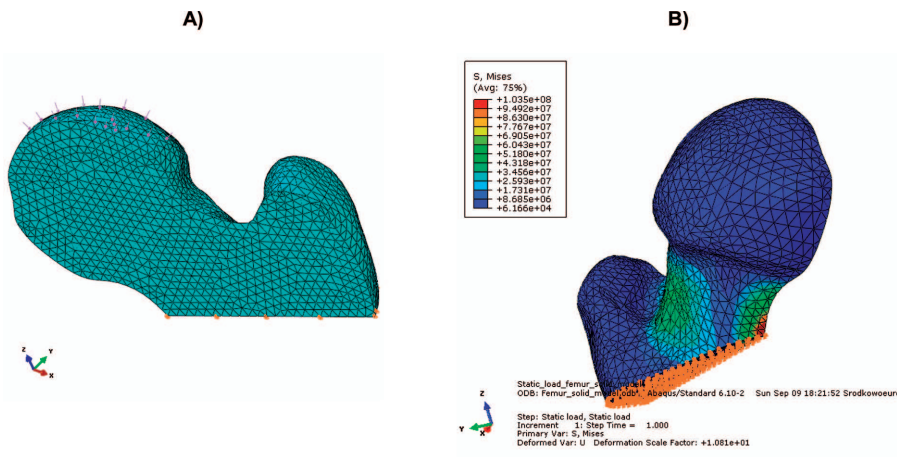

Fig. 22. Solid model of the femur: A) FEM model; B) FEM model results

The bone was treated as a homogeneous material described by Young's modulus E and Poisson's ratio v. The values of these coefficients were $E = 10$ GPa and $v = 0.25$ [1]. The lower FEM model part was fully pinned (boundary conditions), 5 MPa of pressure was applied to the upper part of the femoral head surface. The femur part was meshed by using 30831 linear tetrahedral elements of C3D4 type. The results of Mises stresses are presented in Fig. 22B. These results demonstrate that maximal stresses occur in the femur neck and the boundary points.

3.2.2 Model of trabecular structure

According to the second method of bone behaviour modelling, the trabecular structure model was created by comparing an extracted trabecular part [2] and a porous poly (L-lactic acid) scaffold's structure [12]. Using the ABAQUS program, we made the proposed model as a porous structure composed of connectors and struts (Fig. 23). The distance between repeated unloaded elements is called the trabecular unit dimension. According to [8], it equals 2.5 mm. The proposed model has an undeformed configuration, which can be used to simulate influence of the remodelling process.

Two modifications of the trabecular structure model were proposed. The first, called *A*-modification, is used to estimate the mechanical properties. The second, called *B*-modification, is used to fill out the trabecular bone in a physical bone model. It worth noting that *B*-modification with a 2.5 mm trabecular unit dimension is very difficult to model by using the FEM, as the model has many degrees of freedom requiring a very large computer capacity.
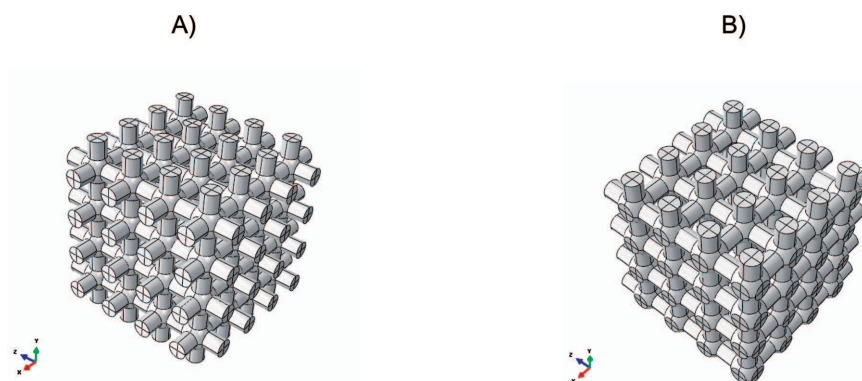
A)   B)

Fig. 23. Models of trabecular structure: A) A-modification, B) B-modification

Additionally, each modification was modelled as both a solid type (Fig. 24A, 25A) and a shell type (Fig. 24B, 25B). The solid type is a mesh of 27978 linear tetrahedral elements of C3D4H type. The shell type model is a thin-walled

structure with a mesh of 19904 quadratic triangular elements of STRI65 type. The numerical simulations were performed by applying different loading and boundary conditions. Analysing the results of these simulations, one can determine which type of trabecular structure model should be used to model the behaviour of a real trabecular structure in given conditions.
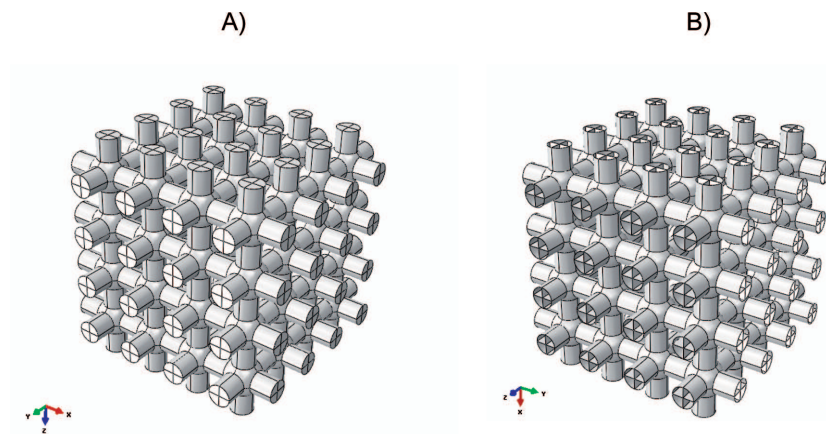

Fig. 24. Types of trabecular structure model: A) Solid type, B) Shell type
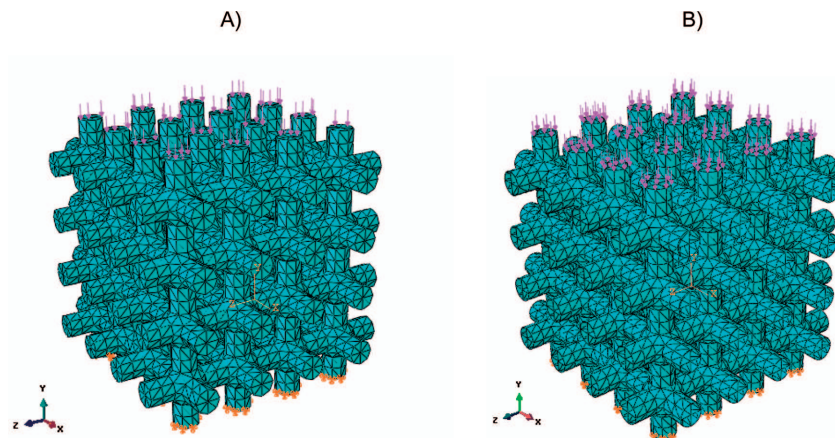

Fig. 25. FEM model of: A) Solid type, B) Shell type

4. Discussion

This paper has presented in detail an original method of skeletal system modelling. Parts of this model were created by using DICOM images from CT and PET tests. On the basis of these images, contour mapping models of upper and lower limb bones were obtained. Each contour mapping model

was transformed into a cloud of points model, which was next converted into a shell model. Here, nine shell models were made: of the humerus, radius, ulna, scapula, clavicle, femur, tibia, fibula and pelvis.

It is worth noting that CT and PET tests of a living person only provide us with data regarding the marrow cave and general construction of bones. However, these tests provide no information about the micro construction of trabecular and cortical bone parts. In some cases a biopsy can solve this problem, but this method is invasive and not always possible. The alternative is to apply a method of mathematical modelling and numerical simulations. In this paper, such methods have been presented. According to the first method, the bone was treated as a solid structure (by transforming a shell bone model into a solid model). This method does not take into account the bone's internal complex structure. According to the second method, a model of the bone's trabecular structure was created (p.3.2.2). Treating the bone as an isotropic material, numerical simulations of solid model and trabecular structure models were performed. Deciding which model best describes real bone behaviour requires numerous numerical simulations.

There are currently three approaches to the problem of bone modelling. The first involves reconfigurable models of regular trabecular structures (presented above) that take into account the remodelling and modelling processes occurring in a real bone. Applying numerical simulations, it is possible to show that a trabecular structure formed in accordance with the principal mechanical loading directions [13]. The second approach involves numerical simulations of a bone filled out with *B*-modification, which has a 2.5 mm trabecular unit dimension. Solving the numerical problem, it is possible to compare the results of the solid model and the porous models (either as a solid type structure or a shell type structure). On the basis of this comparison one can decide which structure is the more suitable to model long bone behaviour. The third approach involves creating a model of trabecular-cortical bone coupling. This approach can only be applied in the case of individual bones because the coupling is continually shaped to a given individual's ontogenesis.

Acknowledgment

REFERENCES

[1] Jaecques S.V.N., van Oosterwyck H., Muraru L., van Cleynenbreugel T., de Smet E., Wevers M., Naert I., vander Sloten J.: Individualised, micro CT-based finite element modelling as a tool for biomechanical analysis related to tissue engineering of bone. Biomaterials 25, 2004, pp. 1683-1696.

[2] Kadir M.R., Syahrom A., Öchsner A.: Finite element analysis of idealised unit cell cancellous structure based on morphological indices of cancellous bone. Med Biol Eng Comput 48, 2010, pp. 497-505.

[3] Ruimerman R.: Modelling and remodelling in bone tissue. PhD Thesis. Technische Universiteit Eindhoven, Eindhoven, 2005.

[4] Lievers W.B., Waldman S.D., Pilkey A.K.: Minimizing specimen length in elastic testing of end-constrained cancellous bone. Journal of the mechanical behavior of biomedical materials 3, 2010, pp.22-30.

[5] Bankman I.M.: Handbook of medical imaging. ACADEMIC PRESS, A Harcourt Science and Technology Company, 2000.

[6] Bovik A.: Handbook of image and video processing. ACADEMIC PRESS, A Harcourt Science and Technology Company, 2000.

[7] Nixon M.S., Aguado A.S.: Feature extraction and image processing. Newnes, 2002.

[8] Borouchaki H., Hecht F., Saltel E., George P.I.: Reasonably efficient Delaunay based mesh generator in 3 dimensions. INRIA. Domaine de Voluceau. Rocquencourt, BP 105, 78153 Le Chesnay Cedex, France, 2002.

[9] Hoppe H., DeRose T., Duchamp T., McDonald J., Stuetzle W.: Surface reconstruction from unorganized points. Computer Graphics (SIGGRAPH'92 Proceedings), 26(2): 71÷78, July 1992.

[10] Attene M., Spagnuolo M.: Automatic surface reconstruction from point sets in space. Instituto per 1a Matematica Applicata, Consiglio Nazionale delle Richerche, Genova, Italy, 2000.

[11] Carnelli D., Lucchini R., Ponzonu M., Contro R., Vena P.: Nanoindentation testing and finite element simulations of cortical bone allowing for anisotropic elastic and inelastic mechanical response. Journal of Biomechanics 44, 2011, pp. 1852-1858.

[12] Xiong Z., Yan Y., Zhang R., Sun L.: Fabrication of porous poly (L-lactic acid) scaffolds for bone tissue engineering via precis extrusion. Scripta Materialia 45, 2001, pp. 773-779.

[13] Tezuka K., Wada Y., Takahashi A.: Computer-simulated bone architecture in a simple bone-remodelling model based on a reaction-diffusion system. J Bone Miner Metab 23, 2005, pp. 1-7.

Metoda modelowania układu szkieletowego

S t r e s z c z e n i e

W artykule opisano autorską metodę modelowania układu szkieletowego. Stosując zdjęcia DICOM otrzymane z badania CT i PET, utworzono dziewięć modeli powłokowych kości (kości ramiennej, kości promieniowej, kości łokciowej, łopatki, obojczyka, kości udowej, kości piszczelowej, kości strzałkowej i miednicy). Zaproponowano dwie metody modelowania zachowania kości. Zgodnie z pierwszą metodą kość jest traktowana jako bryła jednorodna, zgodnie z drugą metodą – jako złożona struktura porowata. Zachowanie składowych części modelu zostało numerycznie przebadane, stosując metodę elementów skończonych.