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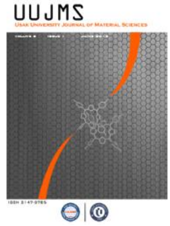

Research article

3D Bio-Cad modeling of human mandible and fabrication by rapid-prototyping technology

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Abstract

The purpose of this study is to prepare a model of the human mandible in accordance with anatomical structure and fabricated by rapid-prototyping (RP) technology. In this study, a computed tomographic (CT) scan of a dentate mandible was obtained with a 0.3 mm voxel resolution with capability to export to DICOM format. The data were cleaned; edited and separated 'mask' generated for cortical bone, cancellous bone, and teeth using Mimics 10.01 and Geomagic 11.0 software. The data were imported to Solidworks from Geomagic and converted to the solid model and fabricated by 3D rapid-prototyping technique. The mandible structure was divided into layers and then an average Young's modulus value was calculated for each layer of cortical bone and cancellous bone using the basis of CT density as in previously published protocols. In this study, the procedure of obtaining bio-CAD model of mandible methodology has nine phases: computed tomography (CT), 2D segmentation, calculating 3D object from scanned data, reverse engineering interface, point cloud data processing, surface reconstruction, solid model reconstruction, obtaining bio-CAD model, and fabricating the model using RP technology. The average Young's Modulus value of cortical bone and cancellous bone was calculated 30100.88 MPa, and 685.42 MPa, respectively. As a result, according to expert review, examination of the anatomical structure, and literature survey, we concluded that the development of 3D human mandible model can be used to conduct research on human mandible.

Keywords: *3D modeling of human mandible, rapid-prototyping, material modeling, reverse engineering*

1. Introduction

Bio-modeling describes the ability to replicate the morphology of a biological structure. Numerical (computer) and physical model are important tools for engineers, scientists, and experts in any filed to help understand physical phenomena, to analyze physical objects and systems, as well as to perform design. Physical models range from simple

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bone models mounted on a testing jig to more complex Bio-models rendered in solid form that can be produced by engineering technologies such as rapid prototyping technologies, which replicate the morphology of the bone structure [1,2].

Computer modeling has revolutionized almost all areas of engineering and science over the last 30 years. In addition, new and efficient production process, based around rapid prototyping (RP) technologies, is currently revolutionizing the generation of physical models [2]. In recent years, the advances in computing technologies and production processes, both terms of hardware and software have led to the using of Computer Aided Design (CAD) in biomedical engineering that is a technological field, which includes medicine engineering, tissue engineering, genetic technology, medical treatment engineering [3], in applications, ranging from clinical medicine, and customized medical implant to tissue engineering [4].

The integration of CAD and medical technology, in other words, the modeling of human body parts in a CAD based virtual environment is called as bio-CAD modeling. Bio-CAD includes regenerative medicine engineering, computer-aided surgery, structural modeling of tissue and tissue informatics, design of orthopedic devices and implants, design of tissue scaffolds, reverse engineering (RE) and 3D reconstruction, heterogeneous tissue modeling, and solid freeform fabrication or bio-manufacturing [3,4].

The mandible is one of the bones most susceptible to trauma in the facial region due to its more projected position in the facial skeleton [5]. The biomechanical behavior of the mandible is very important in various clinical situations. The biomechanical and physical behaviors of mandibles have been investigated by different approaches; experimental approach and Finite Element Analysis approach. The important disadvantage of the experiments using strain gauges or holographic interferometry is the inability to determine strains at defined positions within the specimen. Additionally, research in biomechanics by these methods is limited to surface deformations and neither stresses nor dislocations can be measured. On the other hand, FEA approach requires exact knowledge of the material parameters as well as the geometry of the mandible under investigation [6]. Given a high correlation between the FEA and the experiment, various data within the specimen can be visualized using the FE calculation. In order to obtain a more accurate result from FEA, the human mandible must be designed in accordance with the anatomical structure.

A non-invasive procedure to quantify morphometric data of the body is achieved by 3D computed tomography (CT) that is the key tool for viewing the internal structure of the human body [3]. After obtaining the geometric information, Hounsfield units (HU) are measured. The data can be transformed into bone density values and thereby correlate with Young's modulus. Following this procedure a 3D CT of one specimen provides both geometric parameters and material properties at the same time [6]. All reconstructed 3D solid models can be converted to Rapid Prototyping (RP) physical models and Virtual Reality Modeling Language (VRML) format for visualization [3].

It is difficult to fabricate the human mandible using standard manufacturing technology, because it has complex shapes of geometry and material features. Recent advances in material engineering and manufacturing technologies have brought enormous innovation opportunities in product development. Various methods have been proposed to form 3D objects by decomposition material layer by layer on a substrate [7]. Rapid prototyping that was developed in 1980's [8], technology is one of the newest methods used in this field. Rapid prototyping (RP) technology that uses additive manufacturing technology to accurately reconstruct physical object [8], otherwise known as solid freeform fabrication (SFF) or layer manufacturing technology (LMT), represents a range of systems which can fabricate 3D structures from a computer-aided system in a matter of hours. A common feature of these RP systems is that they all apply additive methods in the fabrication process, that is, they build a part, prototype, or tool in a gradual, controlled way by layering down material, point by point, then layer by layer, until the part is completed. Additive methods of fabrication are necessary because of the part's complexity [9].

The aim of this study was to apply the methodologies of obtaining the 3D modeling of human mandible in accordance with the anatomical structure, calculate the material properties form CT data, and fabricate by using rapid prototyping technology.

2. Materials and methods

In this study, according to the procedure previously reported by Sun *et al*., an image based bio-CAD modeling process, which involves following three major steps: (1) non-invasive image acquisition, (2) imaging process and three dimensional reconstructions (3DR) to form voxel-based volumetric image representation, and (3) construction of CAD-based model, was used [4]. Furthermore, the obtained bio-CAD model was fabricated using rapid prototyping technology. An overall procedure of the imaged based Bio-CAD modeling was illustrated in Fig. 1.

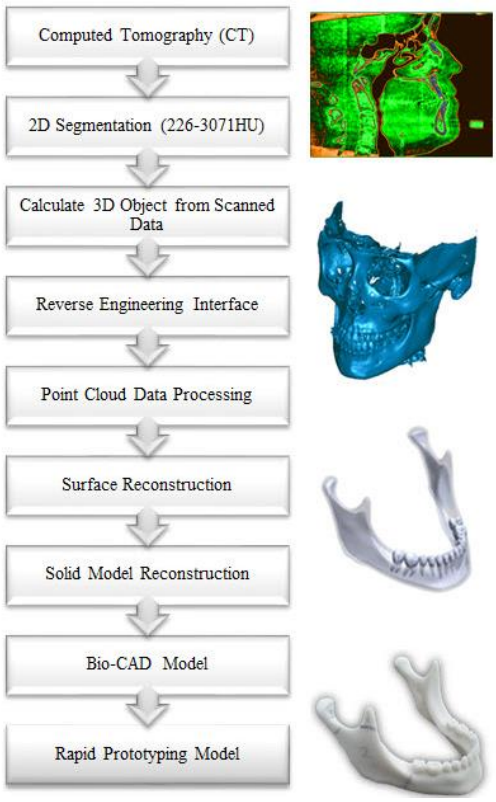

Fig. 1 Process definition to arrive rapid prototyping model from CT data

2.1. Data Acquisition

A computed tomographic (CT) scan of a dentate patient's mandible was obtained using iCAT tomography (Imaging Sciences International, Inc., Hatfield, PA) scanner with a 0.3 mm voxel resolution with capability to export to DICOM format.

2.2. Medical Image Processing

All data from the CT were imported to a visualization module using a graphics program called Mimics (Materialise, Leuven, Belgium). To reduce the time needed for point cloud processing in reverse engineering software, the data was segmented by 226 to 3071 HU values and created 3D object from the scanned data as shown Fig. 2.

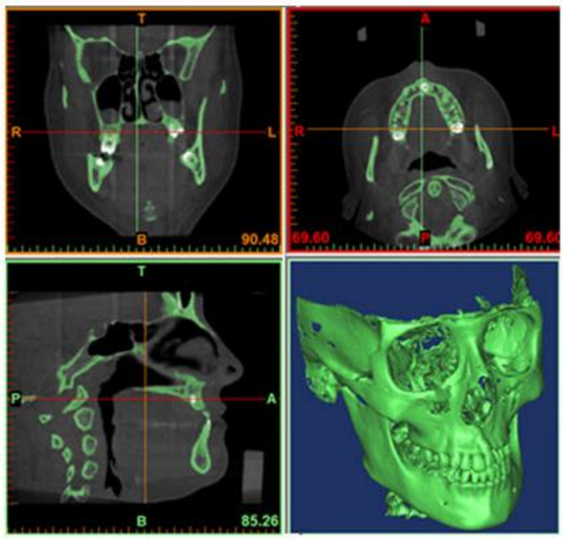

Fig. 2 The view of scanned data and segmented by using HU units

The reverse engineering interface approach used a 3D voxel model created from the segmentation. The 3D voxel model was converted to point cloud data form and the points were loaded into the reverse engineering software (Geomagic 11.0) to create the surface model of human mandible.

2.3. Point Cloud Data Processing and Surface Reconstruction in Reverse Engineering Software

The point cloud data segmented mandible and teeth from skull. The data of mandible are cleaned and arranged. Different type of errors, non-manifold edges, self-intersection, small component, spikes, etc., in the data was corrected. After the operations, the point cloud data of mandible were divided in cortical and cancellous region according to an expert opinion.

Then, the data were triangulated to form a faced model. The number of triangles was 464000 elements. The faced model was further refined and enhanced to reduce the file sizes and unwanted features. The free form surfaces of NURBS (Non-Uniform Rational B-Spline) patched and used fit across the outer shape of the model. The NURBS surface is the most elastic method to represent surfaces in a model and it is commonly used in CAD systems [10]. The procedure of reconstruction face model of mandible and teeth is shown Figs. 3 and 4.

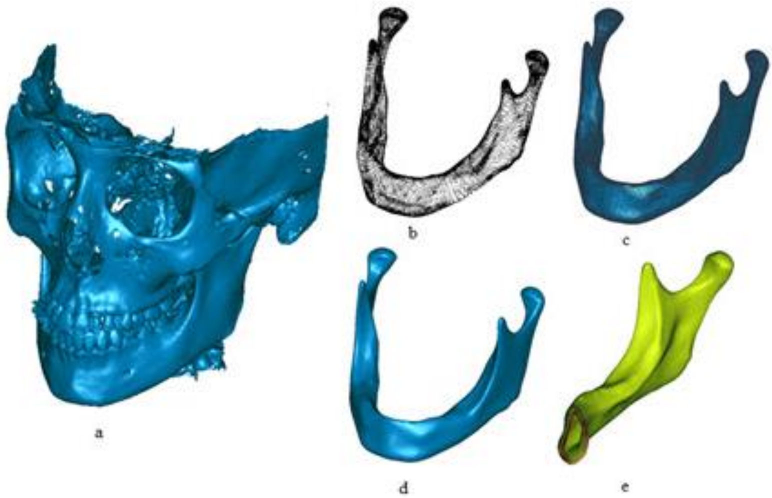

Fig. 3 Surface model construction of mandible steps of mandible using RE software (a) Point cloud data, (b) Point processing, (c) Triangulation, (d) Faced model, (e) Surface cleaning and NURBS fit (CAD)

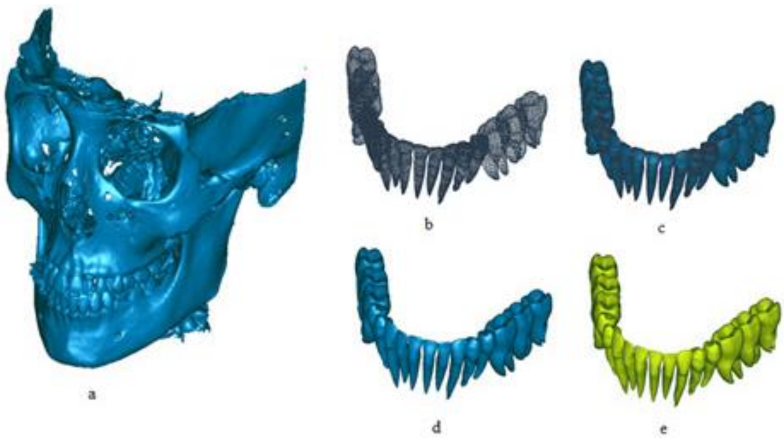

Fig. 4 Surface model constructions of teeth using RE software (a) Point cloud data, (b) Point processing, (c) Triangulation, (d) Faced model, (e) Surface cleaning and NURBS fit (CAD)

2.4. Solid Modeling of Mandible Using Computer Aided Design Software

The final surface model data were imported to computer aided design software (SolidWorks 2013) to create solid modeling of the mandible. The surface model converted to solid model using different operations and the solid model of total mandible was shown in Fig. 5, and the solid model of dentate mandible was shown in Fig. 6.

Fig. 5 The solid modeling of total mandible

Fig. 6 The solid modeling of dentate mandible

2.5. Fabrication the Prepared Solid Model of Mandible Using Rapid Prototyping Technology

The solid model data was fabricated using rapid prototyping technology (RP) for an expert assessment and to be used for future experimental studies. The prototyping model of dentate mandible was shown in Fig. 7.

Fig. 7 Rapid prototyping (RP) model of human mandible

2.6. Material Modeling of Human Mandible

The material properties of the mandible were obtained using Hounsfield units (HU) method. The electron density is obtained from the CT-scanner via so-called Hounsfield units (HU). These are defined as;

$$HU = 1000\left(\frac{\mu - \mu_{water}}{\mu_{water}}\right) \quad (1)$$

where μ referred to the linear attenuation coefficient for the respective material compared with water. The linear attenuation coefficient depends on parameters such as electron density, atomic number and the beam quality of the CT-scanner. In the implementation of the Hounsfield scale in this study the Hounsfield scale stretches between HU=226 and 3071 and is shown in Fig. 8.

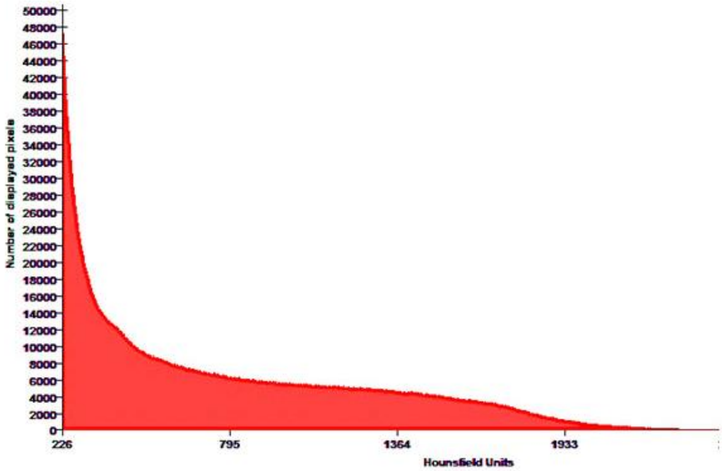

Fig. 8 Radio density expressed in Hounsfield Units

The CT segmentation of mandible was achieved by the homogenization technique, the mandible structure was divided into layers and then average CT# for each layer found. Each layer thickness was about 5mm and an average CT# number was obtained for each layer. Then, the density was obtained using the Eqs. 2 and 4. This density can in turn be then related to *E* using Eqs. 3 and 5 [4].

For CT#<816,

$$\rho = 1.9\times10^{-3}\mathrm{CT} + 0.105 \quad (2)$$

$$E = 0.06 + 0.9\rho^{2} \quad (3)$$

For CT#>816,

$$\rho = 7.69\times10^{-4}\mathrm{CT} + 1.028 \quad (4)$$

$$E = 0.09 + 0.9\rho^{7.4} \quad (5)$$

where; ρ is density, *E* is the Young modulus, CT is the Hounsfield Units. The view of segmentation of mandible and first layer (5 mm) HU ratio is shown in Fig. 9.

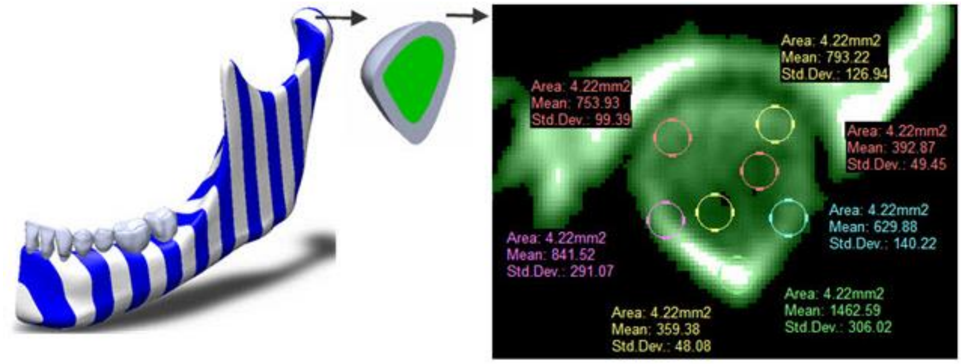

Fig. 9 The segmentation of mandible structure was divided into layers

3. Results

The mandibula was divided the cortical, cancellous, and tooth region according to expert opinion and literature survey. The view of divided region is shown in Fig. 10.

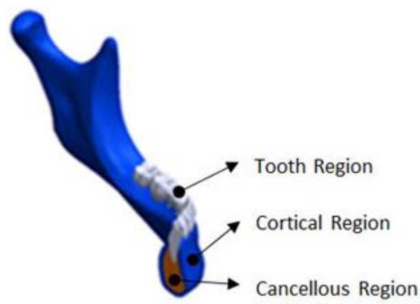

Fig. 10 Anatomical structure of human mandible

The HU was obtained using CT data in each layer as shown in Fig. 11. The graph shows that the HU value of cortical bone is higher than cancellous bone as consistent with the literature survey.

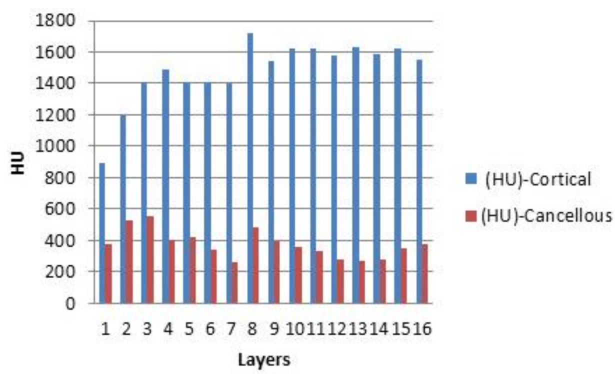

Fig. 11 Hounsfield units of cortical and cancellous regions

The density value of cortical and cancellous bone was calculated using Eqs. 2 and 4 as shown in Fig. 12.

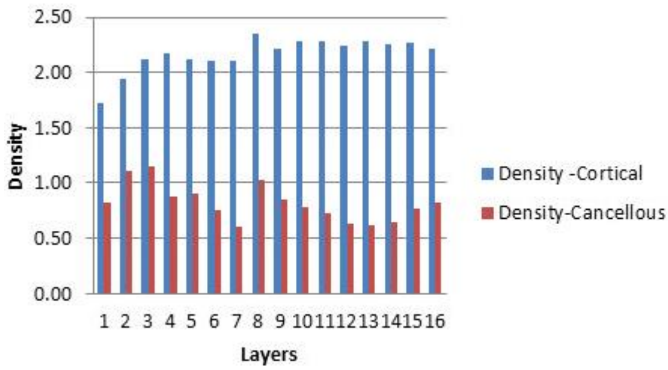

Fig. 12 Density value of cortical and cancellous regions

The young modulus of cortical and cancellous bone was calculated using Eqs. 3 and 5 and shown in Fig. 13.

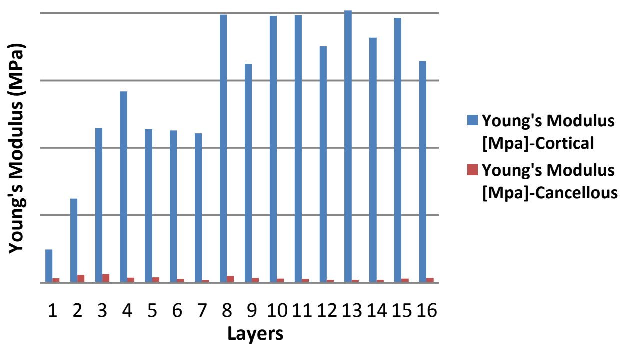

Fig. 13 Young modulus of cortical and cancellous regions

When we examine the results, the young modulus of cortical and cancellous bone has different value. The average value of the results is shown in Table 1.

Table 1
The average value of HU, density, and young modulus of cortical and cancellous bone

	HU	Density [g/cu cm]	Young Modulus [Mpa]
Cortical Bone	1480.31	2.17	30100.88
Cancellous Bone	375.19	0.82	685.42

The Young Modulus and Poisson's ratio are required for FEA simulation to obtain mechanical behavior of mandible under load. The young modulus can be calculated using different equation. In the literature, the young modulus of cortical bone ranges between 13-39 GPa [5,11,12], and the young modulus of cancellous bone ranges between 500 and 1500 MPa [12]. The situation shows that the obtained values of young modulus for cortical and cancellous bone are available value and can be used as mechanical properties for FEA simulation. The Poisson's ratio is 0.3 in all studies on mandibula in the literature.

4. Discussion

The mandible is more susceptible to trauma compared to other body parts due to its localization and anatomy. This situation leads to studies on the mandible. The studies focus on the development of new fixation systems for fixating fractures, improving dental implants, and evaluating mechanical behavior of mandible. In these studies, experimental and numerical approaches have been used. Experimental studies are very hard to conduct due to the difficulty in obtaining fresh bone or creating an imitation. Furthermore, the experimental procedure takes a long time and is not cost-effective. Due to this situation, the studies on mandible have tended to study on numerical simulation that FEA is commonly uses. In the FEA simulation, the CAD modeling of mandible in accordance with the anatomical structure and mechanical properties (young modulus and Poisson's ratio) are very important and affect the result of simulation. Construction the bio-CAD modeling of mandible is very difficult and requires experience because of the mandible has a very complex shape and structure.

A number of methodologies were developed to obtain bio-CAD modeling of mandible. The imaged based bio-CAD modeling process that was reported by W., SUN *et al.* was used in our study. The steps of this method are: (1) obtaining CT data, (2) Medical image processing, (3) Point cloud data processing, (4) Surface reconstruction, (5) Solid modeling (6) Fabrication, and (7) obtaining the mechanical properties of human mandible. After the steps, the developed bio-CAD model in accordance with the anatomical structure (cortical region, cancellous region, tooth, material properties, *etc.*) was examined by an expert and concluded that the bio-CAD model and RP model can be used for FEA simulation or Experimental Approach. The described procedure is a successful method to obtain a highly detailed bio-CAD model of mandible.

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References

1. Wong RCW, Tideman T, Merkx MAW, Jansen J, Goh SM, and Liao K. Review of biomechanical models used in studying the biomechanics of reconstructed mandibles. International Association of Oral and Maxillofacial Surgeons, 2011; 40: 393 – 400.
2. Lohfeld S, Barron V, and Mchugh PE. Biomodels of Bone: A Review. Annals of Biomedical Engineering, 2005; 33(10): 1295 – 1311.
3. Wang CS, Wang WHA, and Lin MC. STL rapid prototyping bio-CAD model for CT medical image segmentation. Computer in Industry, 2010; 60: 187 – 197.
4. Sun W, Starly B, Nam J, and Darling A. Bio-CAD modeling and its applications in computer-aided tissue engineering. Computer-Aided Design, 2005; 37: 1097 – 1114.
5. Bezerro TP, Silva Jnior FI, Scarparo HC, Costa FWG, and Studart-Soares EC. Do erupted third molars weaken the mandibular angle after trauma to the chin region? A 3D finite element study. International Journal of Oral&Maxillofacial Surgery, 2012; 42(4): 474 – 480.
6. Vollmer D, Meyer U, Joos U, Vegh A, and Piffko J. Experimental and finite element study of a human mandible. Journal of Cranio-Maxillofacial Surgery, 2000; 28: 91 – 96.

7. Liew CL, Leong KF, Chua CK, and Du Z. Dual material rapid prototyping techniques for the development of biomedical devices. Part 1: Space creation. The International Journal of Advanced Manufacturing Technology, 2001; 18: 717 – 723.
8. Bagaria V, Deshpande S, and Rasalkar DD. Use of rapid prototyping and three-dimensional reconstruction modeling in the management of complex fractures. European Journal of Radiology, 2011; 80: 814 – 820.
9. Ma D, Lin F, and Chua K. Rapid prototyping applications in medicine, Part 1: NURBS-based volume modeling. The International Journal of Advanced Manufacturing Technology, 2001; 18: 103 – 117.
10. Dobrzanski LA and Reimann L. Digitization procedure of creating 3D model of dental bridgework reconstruction. Journal of Achievements in Materials and Manufacturing Engineering, 2012; 55(2): 469 – 476.
11. Aquilina P, Chamoli U, Parr WCH, and Clausen PD. Finite element analysis of three patterns of internal fixation of fractures of the mandibular condyle. British Journal of Oral and Maxillofacial Surgery, 2012; 51(4): 326 – 331.
12. Kimura A, Nagasao T, Kaneko T, Miyamoto J, and Hakajima T. A comparative study of most suitable miniplate fixation for mandibular symphysis fracture using a finite element model. The Keio Journal of Medicine, 2006; 55: 1 – 8.