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Clinical Application of Solid Model Based on Trabecular Tibia Bone CT Images Created by 3D Printer

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Objectives: The aim of this work is to use a 3D solid model to predict the mechanical loads of human bone fracture risk associated with bone disease conditions according to biomechanical engineering parameters. **Methods:** We used special image processing tools for image segmentation and three-dimensional (3D) reconstruction to generate meshes, which are necessary for the production of a solid model with a 3D printer from computed tomography (CT) images of the human tibia's trabecular and cortical bones. We examined the defects of the mechanism for the tibia's trabecular bones. **Results:** Image processing tools and segmentation techniques were used to analyze bone structures and produce a solid model with a 3D printer. **Conclusions:** These days, bio-imaging (CT and magnetic resonance imaging) devices are able to display and reconstruct 3D anatomical details, and diagnostics are becoming increasingly vital to the quality of patient treatment planning and clinical treatment. Furthermore, radiographic images are being used to study biomechanical systems with several aims, namely, to describe and simulate the mechanical behavior of certain anatomical systems, to analyze pathological bone conditions, to study tissues structure and properties, and to create a solid model using a 3D printer to support surgical planning and reduce experimental costs. These days, research using image processing tools and segmentation techniques to analyze bone structures to produce a solid model with a 3D printer is rapidly becoming very important.

Keywords: 3D Printer, Computed Tomography, Computer-Aided Design, Computer-Assisted, Image Processing, Prototype

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I. Introduction

Current bio-imaging devices are able to display and reconstruct three-dimensional (3D) anatomical details, and diagnostics are becoming increasingly vital to the quality of patient treatment planning and clinical treatment [1,2]. It is important to know that radiographic images obtained by techniques, such as computed tomography (CT) and magnetic resonance imaging, can be converted to 3D files and produce a 3D solid model with a 3D printer [3]. Radiographic images and image processing tools are being used for the segmentation and reconstruction of tissue images in 3D to determine bone and muscle characteristics [4]. However,

the results are not satisfactory when the focus is on the stress and strain distributions near boundaries [5]. Generally, the finite-element method is used to compensate the defects [6].

Today, radiographic images are being used to study biomechanical systems with several aims, namely, to describe and simulate the mechanical behavior of certain anatomical systems, to analyze pathological bone conditions, to study tissues structure and tissues properties, and to create a solid model using a 3D printer to support surgical planning and reduce experimental costs [7].

The rapid prototyping process known as 3D printing is expanding rapidly in clinical application; it provides novel possibilities and potentials for modeling, simulation and analysis of the human body [8]. There have already been attempts to use this novel technology in various fields of clinical applications. For example, in the fields of orthopedics and oral and maxillofacial surgery, it has been used in designing implant prosthetics and tissues. Moreover, it can be used in planning surgeries, to investigate possibilities, and improve accuracy before surgery [9]. Especially in the dental field, 3D printing is actively used to design implants and crowns. In addition, 3D printing can be used in a special way to facilitate facial reconstruction [10].

The use of 3D-printed solid models has many benefits in clinical fields, including determining whether a specific surgical procedure is too risky to perform for an individual patient, implant prosthetics designing, and medical research (too costly for *in vivo* experiments), thus improve surgical accuracy. It can also be useful for educational programs, such as medical student education and training to aid understanding of complex anatomical structures [11,12].

Various 3D printing methods have been developed to build 3D structural models, such as stereolithography, fused-deposition modeling, selective-laser sintering, selective-laser melting, electronic-beam melting, and laminated-object manufacturing [13]. The 3D printer (ProJet 3510 HD; 3D Systems Inc., Rock Hill, SC, USA) is owned by the National Cancer Center using the stereolithography printing method. This method is the oldest and has a wide range of application. The whole process consists of the sequential printing of layers, which is similar to the functioning of the traditional inkjet printer. However, the printer differs from the conventional printer in that it produces 3D solid objects layer-by-layer [14]. The 3D printer first follows the instructions of computer-aided design (CAD) to build the foundation of an object, while the printer-head moves along the X, Y-planes and along the Z-plane to build the object's vertical layers [15]. It can build almost any shape defined in a CAD file and can use various types of materials and forms, such as plastics,
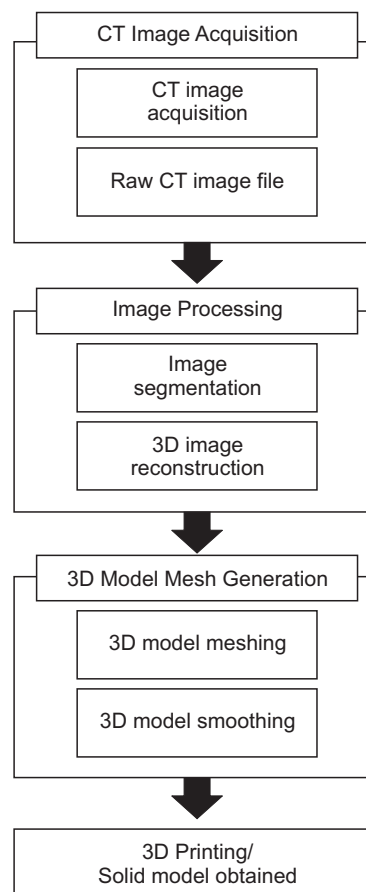

Figure 1. Process from image acquisition to the production of a 3D solid object. CT: computed tomography.

rubber, gypsum, metals powders, liquids and solid which can be selected depending on the object's intended use [16,17].

In this study, we used special image processing tools for image segmentation and 3D reconstruction to generate meshes necessary for production of solid objects with a 3D printer from CT images of the human tibia's trabecular and cortical bones (Figure 1).

II. Case Description

1. CT Images Acquisition
To acquire cadaver tibia CT images, the CT conditions were the following: 293 × 293 × 100 μm voxel size (virtually degraded resolution), temporal bone protocol, 120 kVp, 300 mAs, 150 mm field of view, 12 mm away from distal (Figure 2A).

2. Image Segmentation and 3D Image Reconstruction
Image segmentation was applied to the acquired cadaver tibia CT images using Analyze ver. 11.0 (Biomedical Imaging Resource at Mayo Clinic, Rochester, MN, USA). Various
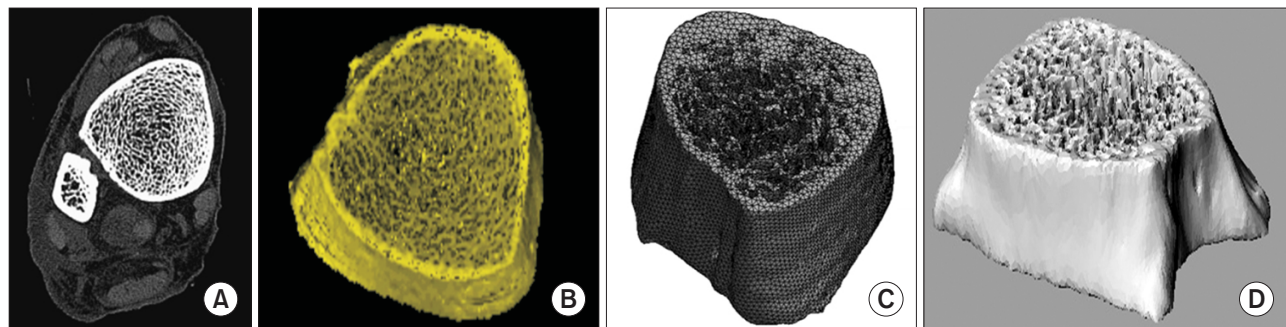
Figure 2. Process from computed tomography (CT) image acquisition to the production of a 3D file, comprising four major steps: image is acquired from CT and raw CT data image is achieved, image segmentation is performed in image post-processing and a 3D file is reconstructed, a 3D structural computer-aided design (CAD) mesh file is constructed, smoothing method is applied to the irregular surface. (A) Raw CT image, (B) image segmentation, (C) 3D model meshing, and (D) 3D model smoothing.
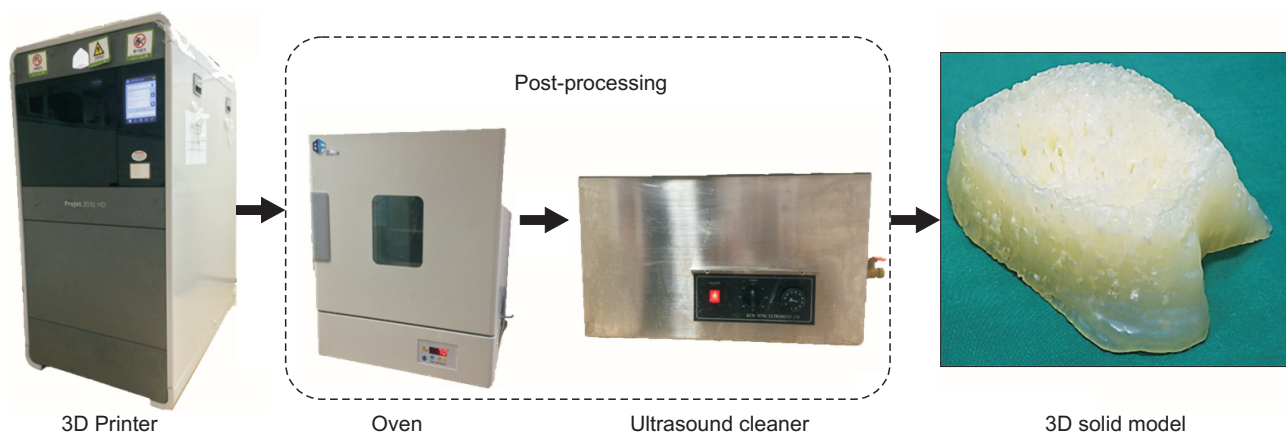

Figure 3. Process to produce a 3D solid model.

regions window levels/ widths (contrast) were applied to establish a clear separation between the cortical bone and the trabecular bone. The set up image segmentation was performed with a contrast region on 300/2000 for visualization, which was shown by yellow coloring on the trabecula bone region for clear separation during 3D reconstruction. Also, automatic detection of each region was performed, and then manual segmentation was performed as needed. The segmented images were accumulated layer-by-layer following the Z-plane and reconstructed as a 3D image (Figure 2B and C).

3. 3D Model Mesh Generation

The 3D reconstruct file formats were transformed to surface tessellation language (STL) to composed 3D meshes. The STL file format is accepted in 3D printer software and is widely and commonly used for many 3D processes. The 3D mesh model format constructed only surfaces; the surface format was composed of only 3D images and it was rough and irregular. In this case, an additional mesh method was

required to overcome inside defect errors. Another mesh method was required for mesh repair because mesh defects had occurred on the irregular surface in the process of connecting between the complex 3D model and meshes. Furthermore, an additional smoothing method is required if the model has excessive meshes that are detected as defect elements in 3D printing. In this case, due to the characteristics of ICEM ver. 14.0 software (ANSYS Inc., Canonsburg, PA, USA), the in and out surfaces of the meshes consisted of curves and points. The meshes were composed of hexagonal and triangular surface meshes, and homogeneous meshes could only transfer a limit quantity (less than 40 million of meshes) of the whole model's meshes. Furthermore, additional composited model smoothing was performed with the Taubin mesh smoothing method (Figure 2D).

4. 3D Printing and 3D Solid Object Post-processing

The 3D printing method is used to produce a 3D solid object with 3D CAD format files (STL). The STL format file is transferred to the 3D printer. Before printing a 3D model

from an STL file, the file must be examined for manifold errors, sue to such errors, surfaces do not connect each other or there are gaps in the model. It takes varying amounts of time depending on the size of the object, its resolution, and the material used. In this study, the 3D printer (ProJet 3510 HD, 3D Systems Inc.) produced the object layer-by-layer with part and support materials. The part material used the VisiJet M3 Crystal (3D Systems Inc.), which is composed of urethane acrylate oligomers and tough plastic and translucent materials. The material was designed for durability and reliability for functional testing and rapid tooling applications. The support material, VisiJet S300 (3D Systems Inc.) is based on hydroxylated wax and is used for support during the processing.

Post-processing procedure of 3D printed object: the support was removed from the 3D solid object using an oven and ultrasound cleaner. The support material was made from wax, which was easily removed by the application of heat (60°C) without affecting the object, and to remove the support from the more delicate surfaces, manual hand work is sometimes necessary (Figure 3).

III. Discussion

These days, research regarding the use of image processing tools and segmentation techniques to analyze bone structures to produce a solid model with a 3D printer is rapidly becoming increasingly important. The aim of this work was to use a 3D solid model to predict the mechanical loads of human bone fracture risk for bone disease conditions using biomechanical engineering parameters. The 3D printing technique has potential for use in a variety of clinical applications, such as analyzing human anatomical structure, implant design, medical research, as well as surgical planning and training. However, 3D printing is not used often in clinical practice yet because of its limitations.

The limited choice of materials is an issue in the clinical field. It is imperfect represented by using polymers, rubber, gypsum, and metal for human body tissues. To build an object, two kinds of materials are required for both the support and part materials. A support material is needed to build the object which uses the part material. However, the materials are expensive to build objects for only research purposes so, user should be sure to check the file before produce a 3D solid model. The software is difficult to use by people who are not experts; it is difficult to learn, and it takes time to become an expert user. Furthermore, the process of creating a 3D file has not been fully automated before 3D printing, and they the software is still expensive. Even expensive software

does not include a fully automated program from start to end to obtain a 3D file. The limitations are producing a small version of large structure or dividing the whole model into smaller parts which can be combined after printing. Normally, a 3D printer only prints models of certain sizes with certain levels of complexity, and it usually takes a long time to obtain a solid model, depending on its size. Commonly, 3D printers use polymer or a polymer mix with rubber for the material, and these are not strong enough to build joint implant prosthetics or dental implants. They could break or crack because they are too weak.

The potential and benefits of 3D printing have already has been demonstrated in several studies in various fields. Clinical research has conducted on the development of artificial organs, prosthetics, and tissues using a 3D printer. Models can be produced by 3D printing that are suitable to use for the education of medical student, surgical planning, and to help patients understand surgical procedures. The additional cost of 3D printing might be compensated by reducing operating time and achieving higher success rates for surgical procedure. However, it is still has not been approved to use 3D printers to produce clinical support devices, and applications of artificial medical tissues are limited and still in an early stage of research. Furthermore, 3D printers can only print model of certain sizes and certain levels of complexity. Also, the use of part and support materials depends on a model's size and the structures which lie within time and cost spent as 3D solid object. The clinical application of 3D printing is technically in an early stage. In the near future, it will have enormous potential for expanded utilization and the development of new applications in the fields of individual patient care as well as academic and research activities.

The study here is different in terms of aims and impacts on medical applications. However, it is common in the methodological approach that is use of 3D printer based on medical image processing techniques with the goal of improving clinical processes.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgments

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