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Creation of Patient-Specific Bone Densitometry Models from 3D Imaging Data

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Abstract

Low bone density is a condition involving trabecular bone that leads to fractures. In an effort to increase compliance of patients with low bone density to their clinical treatments, patient-specific three-dimensional models were created so that patients can better visualize their level of bone deterioration. This research focuses on the process of converting these bone scans to 3D models through additive manufacturing. The bone densitometry imaging techniques that were chosen were computed tomography (CT) and micro computed tomography (microCT). CT and microCT both produce 3D images of bone; however, microCT provides a higher-resolution image detailing the inner structure of bone. Two contrasting scans were used in this research. The first was a CT image of a healthy iliac bone. The second was a microCT scan of a 61-year-old male with bone density indicating osteoporosis. These images were converted through MIMICS (Materialise Interactive Medical Image Control System) and MAGICs (Medical Applications Graphic Image Compression), both medical imaging software, to STL files that were able to be fabricated. The models were printed using a Selective Laser Sintering (SLS) machine, which captured the complex geometry of trabecular bone. The 3D models of bone densitometry resulting from this research provide individuals with the status of their bone health in a compelling manner so they can take proper measures to follow through with the doctor's advice or prescription.

Keywords: bone density, osteoporosis, patient compliance, densitometry, image processing software, rapid prototyping

1. Background

1.1. Introduction

Patient compliance is lacking in the treatment of low bone density, so it would be of great potential value for patients to see a physical model of their bone density in comparison to healthy bone density. In order for patients to comprehend their skeletal health, models are needed to recreate their specific bone density. Once they grasp the

magnitude of the problem, they can proceed with the necessary precautions to prevent a fracture. In this research, two different bone types were modeled: one healthy bone and one with osteoporosis.

1.2. Bone Density

Bone density is often referred to as bone mineral density, which differs from the conventional definition of density (mass per volume). Bone mineral density (BMD) is the amount of mineral matter per segment of bone. BMD is the areal mineral density based on two-dimensional images and it is measured in terms of grams per centimeter squared. It is represented clinically using what is called the z-score and the t-score. The z-score is the number of standard deviations away from the average BMD for the patient's specific age, gender, and ethnicity. The t-score is the number of standard deviations away from a healthy 30-year-old's BMD of the same gender and ethnicity as the patient. These scores are used to assess the patient's bone density and classify their condition.[4]

The structure of bone is comprised of two main components – cortical bone and trabecular bone. Cortical bone is often referred to as compact bone because of its high density. It is on the exterior of bone and gives bone its solid appearance. Trabecular bone, often referred to as spongy bone, is more porous than cortical bone. This allows for blood vessels and marrow to fill these holes. The bone models produced in this research portray the internal structure of trabecular bone. Trabecular bone shows the health of the bone density most clearly.

1.3. Osteoporosis

Osteoporosis is a condition in which bone density is abnormally low (see Figure 1). Osteoporosis occurs when the bone fails to produce enough new bone, when too much original bone is absorbed by the body, or both cases. In the bone, there are two cells that contribute to bone density – osteoblasts, which build new bone, and osteoclasts, which consume old bone. In healthy bones, remodeling occurs when osteoclasts eradicate the old bone and osteoblasts refill the holes at the same rate with new bone. But in bones with osteoporosis, this process is disrupted in a way that the bone begins to deplete. Either osteoblasts fail to regenerate the bone tissue or osteoclasts absorb too much bone.[2]

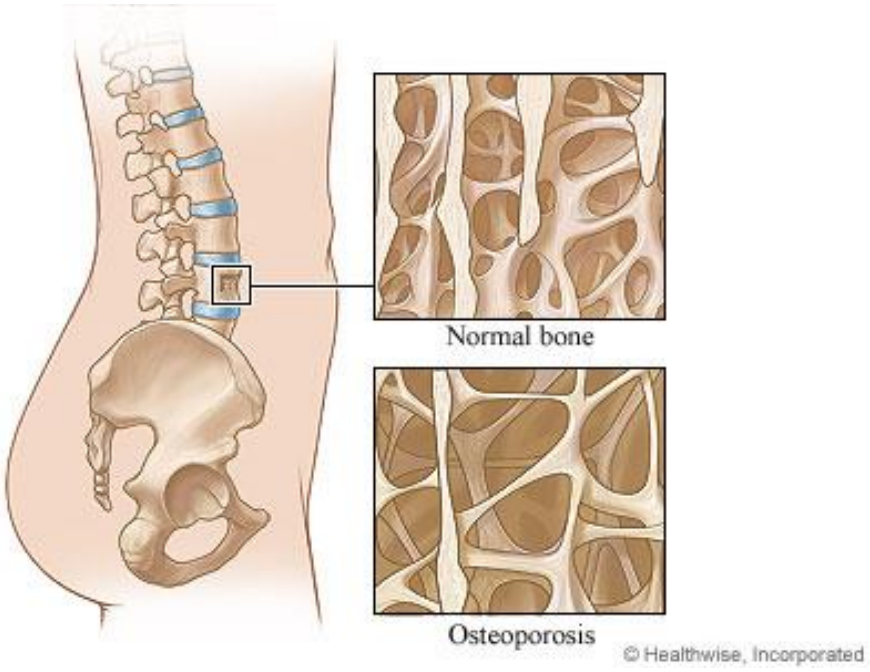

Figure 1. Normal bone vs osteoporotic bone[2]

Osteoporosis is a degenerative disease that occurs as people age. As bones age, they become more porous and susceptible to fracture. Because of this, elderly people are more likely to be diagnosed with osteoporosis. Women

are more prone to this disease than men and deficiencies in calcium or vitamin D can lead to osteoporosis. Since the bone is weak and porous with the onset of osteoporosis, it often leads to fractures. Fractures commonly occur in the proximal femur. These fractures are especially harmful to a person's health and often lead to death within a year after injury. It is imperative to prevent this by monitoring and treating one's low bone density.[8]

As previously discussed, the t-score and z-score are used to quantify osteoporosis. A t-score of -1.0 or higher (meaning the patient's bone density is no more than 1 standard deviation below the healthy bone) is classified as healthy and -2.5 or lower is classified as osteoporosis. A t-score between -1.0 and -2.5 is known as osteopenia. Osteopenia is the precursor to osteoporosis.[4]

A variety of treatments exist for increasing low bone density. Because bone formation relies on calcium, calcium supplements or foods rich in calcium are recommended to patients with osteoporosis. Also, calcium uptake is regulated by vitamin D, so these supplements are also recommended. In addition to supplements, drugs are prescribed that inhibit the work of osteoclasts. As osteoclasts are diminished, bone growth can continue.

2. Methodology

2.1. Densitometry

Bone densitometry, or the measurement of bone density, is crucial to this research. Many different methods of bone densitometry were studied to determine which was the best choice for this research. It was known that it would be necessary for the scanning technique to be capable of producing three-dimensional images, so all two-dimensional methods were eliminated. The optimal densitometry methods were computed tomography (CT) and micro computed tomography (microCT). Both of these techniques are three-dimensional, yet microCT provides a higher-resolution image than CT.

However, both of these methods operate in a similar manner. A CT or microCT scanner emits a series of X-ray beams throughout the body, which is filtered to narrow the energy spectrum (see Figure 2). The scanner is able to reconstruct a three-dimensional image after many two-dimensional X-ray images are taken around an axis of rotation. It captures the region of interest (in this case, the hip bone) in a series of volumetric slices that a computer comprises. A complete CT scan includes a set of projections of under different rotations of the specimen.[3]

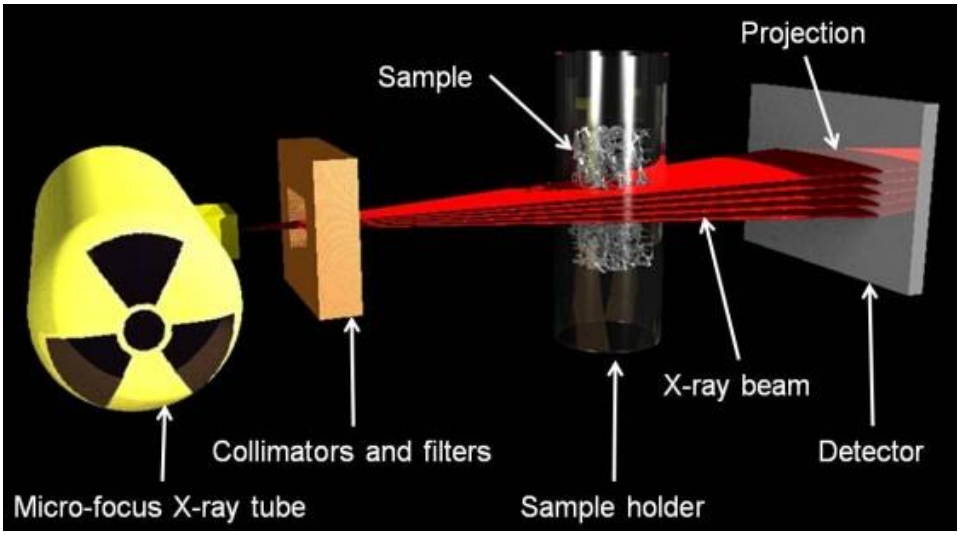

Figure 2. Main components of a CT or microCT scanner[3]

In this research, both CT and microCT images from de-identified patients were used. The CT image was of a healthy iliac bone in DICOM file format. The microCT image belonged to a de-identified 61-year-old male whose bone was clearly deteriorating and was obtained in STL form with a resolution of19.5 μm. Although the resolutions between the CT and the microCT scans were dissimilar, they were able to be manipulated and scaled in medical

imaging programs to both clearly and accurately portray the inner bone structure in a way that permits communication of bone density to the patient.

2.2. Image Processing Software

In order to convert the images to three-dimensional models, image processing software was needed. These programs converted the files that were received into file formats that were recognizable by the rapid prototyping machines. The machines can only utilize STL files, so each image needed to be in this form. Two types of image processing software were used in this research. The first was MIMICs (Materialise Interactive Medical Image Control System). Since the osteoporosis image was already in STL file format, it did not need to be manipulated in MIMICs. It was imported directly into MAGICS (Medical Applications Graphic Image Compression), the second image processing program used in this research. The image was viewed in MAGICS and sent to the 3D printer (see Figure 5).

The DICOM file of the CT scan required significant processing. Because it was a different resolution than the other file, it needed to be manipulated in a way that showed the inner structure of the trabecular bone to the same extent that the microCT images did. When it was placed into MIMICS, only the inner region of the bone was selected and the cortical bone was excluded. If the cortical bone were to be included, patients would not be able to see the inner structure of the bone (see Figure 3). The DICOM image was reviewed multiple times with the thresholding tool in MIMICS to ensure that only the inner trabecular bone was selected. This file was then imported into MAGICS (see Figure 4). In MAGICS, a cube was extracted from the entire iliac bone to show a greater magnification of the bone density. The final STL file before it was sent to the 3D printer is shown in Figure 5.

Next, it was ensured that each image was to scale. The healthy bone scan was scaled to the osteoporosis image, since the latter was already in the format to be sent to the printer. A scaling factor was applied to the resulting healthy bone image. The ultimate conversion is 3.9 mm of anatomical bone density is proportional to 2 inches of the physical three-dimensional model. The files that were sent to the 3D printer are visible in Figures 5 and 6.

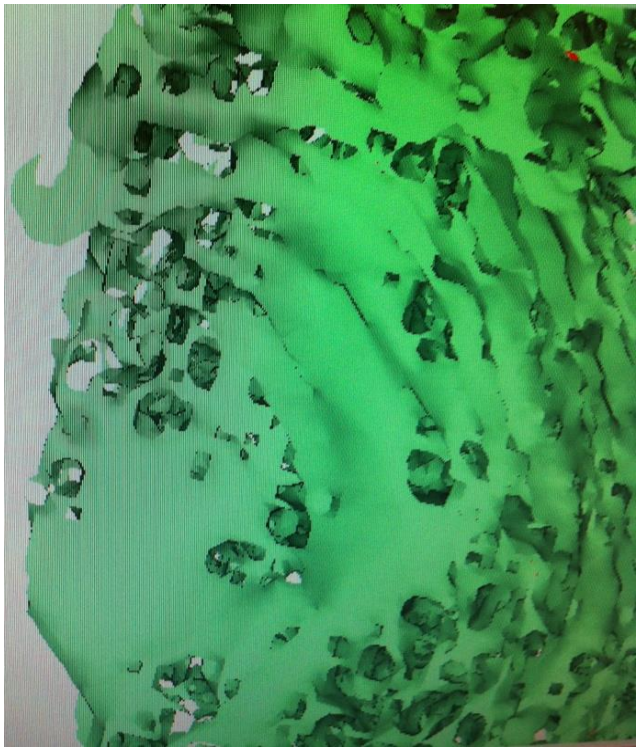

Figure 3. Preliminary healthy bone in MIMICS

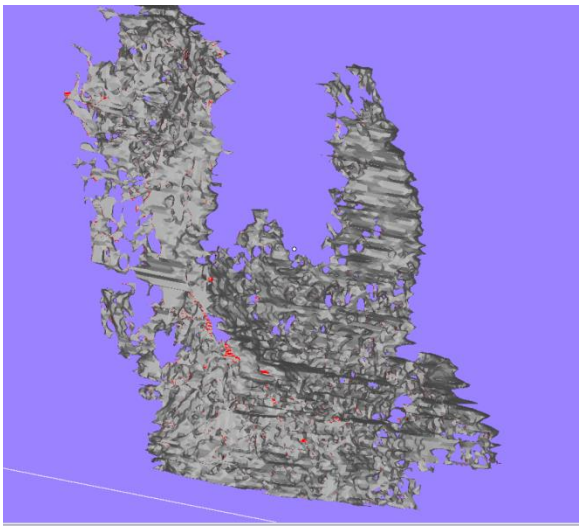

Figure 4. Selected inner region of healthy bone, pre-cut

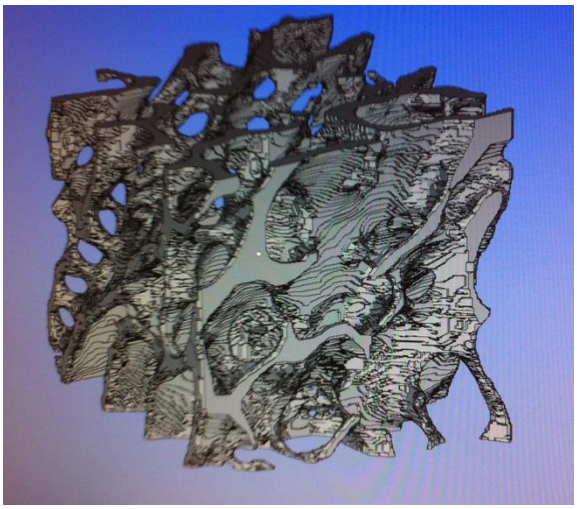

Figure 5. Osteoporosis image

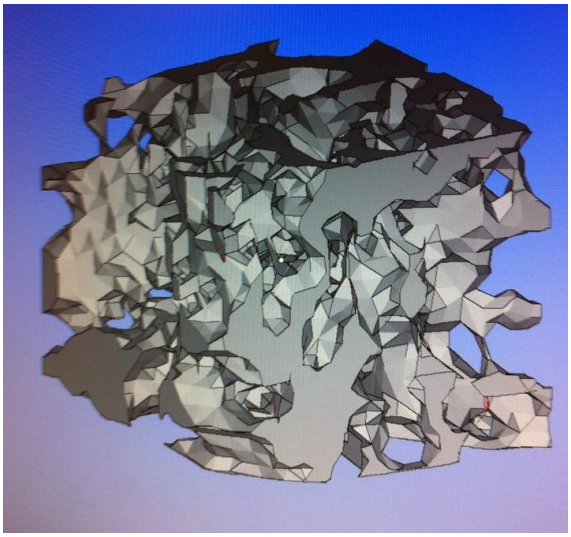

Figure 6. Healthy bone image

2.3. Rapid Prototyping

Rapid prototyping was the technology chosen for this research because it can produce parts quickly and readily. It is essential to have a technology that can rapidly manufacture the bone density models in a medical setting. The rapid prototyping device that was chosen was the Selective Laser Sintering (SLS) machine, Sinterstation 2500plus. Selective laser sintering uses a carbon dioxide laser to fuse powder together layer by layer (see Figure 7). It fuses this powder by scanning cross-sections on the surface of the powder bed generated from an STL file provided. The SLS machine was chosen to produce the bone density models because it does not require supports, which allows for more complex geometries.

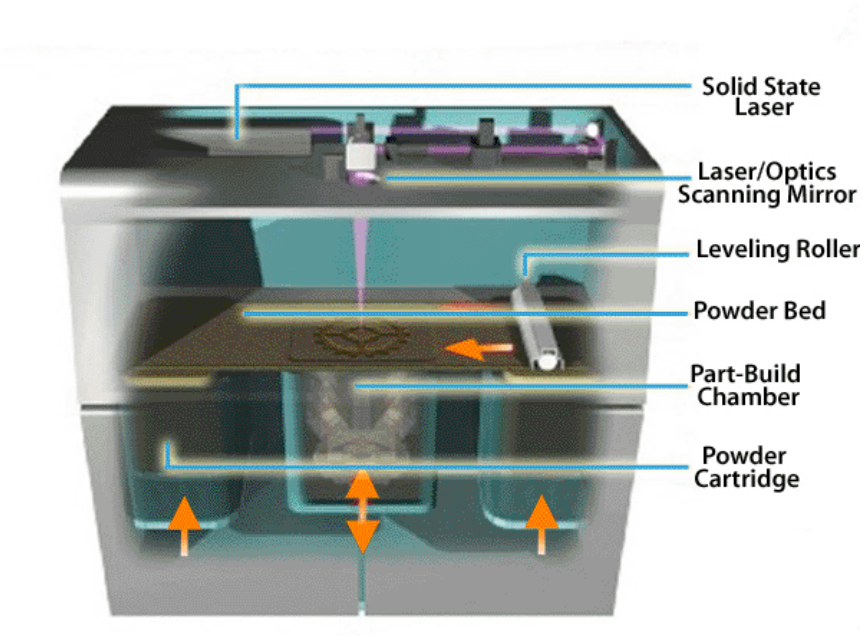

Figure 7. SLS machine diagram[13]

4. Results

The DICOM image file was successfully converted in MIMICS to an STL file, and both STL files were sent to the SLS machine to be fabricated. The models clearly indicate the varying levels of bone density, with the healthy bone appearing to be denser than the osteoporotic bone. The resulting SLS models were minimally affected by the difference in resolution between the CT and microCT scans. These scans were scaled appropriately to each other in order to avoid misleading bone densities.

In addition to qualitatively assessing the bone density models (see Figures 8 and 9), quantitative analysis in MAGICs proved these expected densities: the healthy model was about 3 times as dense as the osteoporotic model. The finished models were evaluated by an endocrinologist, who stated that they would be a useful tool for portraying bone density and potentially increasing patient compliance.[7]

Figure 8. Healthy bone density model

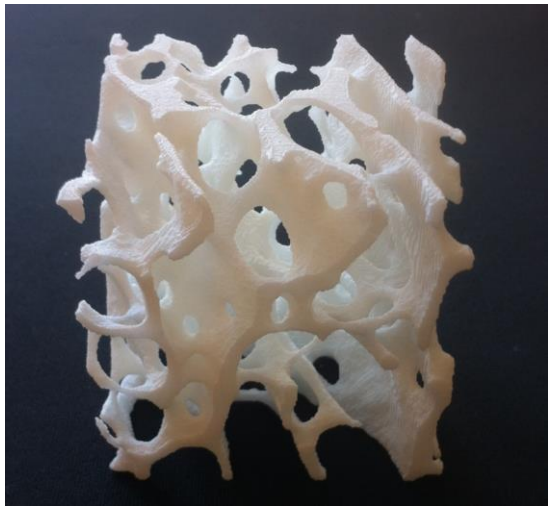

Figure 9. Osteoporosis model

5. Conclusion

The purpose of this research was twofold, with both purposes being strongly correlated. The first was to create a methodology for converting bone scans to physical three-dimensional models in a medical setting. For example, when a patient undergoes a bone scan at the hospital, they can readily have a model of their bone density available. A crucial part of this methodology is to be able to create these models from a variety of file formats, which is why this research examines the input of two different formats. This research proves that it is applicable in a medical situation to create a model of a patient's bone density from DICOM and STL files. Most CT and microCT scans will fall into these format categories, so this method can be easily reproduced at a medical office. The second purpose of this project, which stems from the first, is to increase patient compliance to follow their prescribed treatment. The models created in this research are an effective tool for doing so because they portray bone density in a way that two-dimensional images cannot.

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7. References

1. "Micro-Computed Tomography Core," Hospital for Special Surgery. N.p., n.d. Web. 12 June 2012. http://www.hss.edu/research-micro-computed-tomography.asp.
2. "Healthy Bone versus Bone Weakened by Osteoporosis," WebMD. WebMD, n.d. Web. 10 June 2012. http://www.webmd.com/osteoporosis/healthy-bone-versus-bone-weakened-by-osteoporosis.
3. "Micro-Computed Tomography," B-cube AG, Switzerland. N.p., n.d. Web. 13 June 2012. http://www.b-cube.ch/index.php?option=com_content.
4. Ott, Susan. "Bone Density." Bone Densitometry. N.p., n.d. Web. 10 June 2012. http://courses.washington.edu/bonephys/opbmd.html.
5. L. Wang and others, "Targeted overexpression of G protein-coupled receptor kinase-2 in osteoblasts promotes bone loss," American Journal of Physiology 826, no. 4 (2004): 834.
6. University of Brussels, "Bone and Joint CT-Scan Data," Laboratory of Human Anatomy and Embryology, http://isbweb.org/data/vsj/.
7. Interview with endocrinologist, Dr. Kim LaMack, Wheaton Franciscan Healthcare, June 14, 2012.
8. Guglielmi, G., and TF Lang. "Quantitative Computed Tomography." National Center for Biotechnology Information. U.S. National Library of Medicine, n.d. Web. 10 June 2012. http://www.ncbi.nlm.nih.gov/pubmed/12541199.
9. MacMillan, Amanda. "For Older Women, Year following Hip Fracture Can Be Especially Deadly - CNN.com." CNN. Cable News Network, 26 Sept. 2011. Web. 25 June 2012. http://www.cnn.com/2011/09/26/health/older-women-hip-fracture/index.html.
10. The Biomedical Research Community, "X-ray MicroCT Scans of Human Bone Biopsies," Biomedtown, https://www.biomedtown.org/biomed_town/LHDL/Reception/datarepository/repositories/BelRepWikiPages/XRayMicroCTScansOfHumanBoneBiopsies/.

11. Monson, Kristi, and Arthur Schoenstadt. "Osteoporosis Statistics You Need to Know." Osteoporosis Statistics. N.p., 25 Feb. 2011. Web. 17 July 2012. http://osteoporosis.emedtv.com/osteoporosis/osteoporosis-statistics.html.
12. "MicroCT." University of Southern Denmark, 15 Nov. 2010. Web. 14 June 2012. http://www.sdu.dk/en/Om_SDU/Institutter_centre/Klinisk_institut/Forskning/Forskningsenheder/Ortopaedkirurgi/Forskningsomraader/Eksperimentel+forskning/MicroCT.
13. "Services and Capabilities LaserSintering.com - Selective Laser Sintering, Rapid Prototyping, Rapid MFG." Lasersintering.com. N.p., n.d. Web. 14 July 2012. http://www.lasersintering.com/sls-information.php.
14. K. O'Neil and others, "Micro-computed tomography assessment of the progression of fracture healing in mice," Bone 1357, no. 6 (2012): 1367.