Geometric accuracy of rapid prototyping technologies using laser scanner and coordinate measurement machine

A Dardzinska¹,² and K Fiedorczuk¹
¹Bialystok University of Technology, Institute of Biomedical Engineering, 15-351 Bialystok, Poland
Email: a.dardzinska@pb.edu.pl

Abstract. In this paper we present a prototyping method used in medical data. 3D printing technology is extremely important, especially in medical area. Using 3D printing in preoperative treatment planning seems to be a proper solution in personalized medicine, contributing to improving healthcare system quality. Medical measurements methods on living bones, with respect to their natural environment are still unknown, the basic research includes mainly the measurement of landmarks using a digital caliper, where the linear measurement is taken between the marked points. Another way is to use a coordinate measuring machine. Most often, the accuracy measurement methods are based on marking landmarks on the object, which are collected by a machine, and then performs coordinate measurements of points. In our research we focus not on individual points of the model but on the measurement of whole objects, we prepared materials, and printed the model in 3D technology in different technologies and on different devices: FDM, PJ, SLM. On the basis of our work we conclude there is no best RP technique for making medical models. Due to the criterion of model accuracy, PolyJet is one of the most suitable technologies for medical modelling. The CJP method is the most appropriate for the cost of making a model. Due to the type of material the FDM method is the most suitable for medical applications. 3D printing technologies provide physicians, engineers and scientists with the ability to create customized solutions for a variety of conditions.

1. Introduction
For several years there has been observable a dynamic development of rapid prototyping methods (RP) in medicine, based on 3D printing. Popularization of this method contributes to the development of technology and presentation of new materials, which affects the quality and usefulness of anatomical models. Increasingly, specialists use the possibility of designing and manufacturing individually tailored implants, prostheses and medical instruments.

3D printing technology in medicine is most often used in preoperative planning process. One of the advantages of planning is the possibility of more accurate preparation for a specialized doctor to a complicated operation and reduction of the risk factor of medical error. It should be emphasized that data obtained from subjective examinations may not be sufficient to get acquainted with a given pathology. Therefore, medical modeling is used, and it is based on creating 3D models from such examinations as: computed tomography (CT), magnetic resonance imaging (MRI) or 3D scanning. These devices are the main sources of data for the model.

The imaging data is saved in DICOM format, which makes it possible to create three-dimensional models of the patient's tissues, which are of interest to the physician. In such way, the assisted process of planning the surgery can help in the preliminary assessment of the case. It creates opportunities to
conduct virtual operations on generated 3D solids, practice appropriate operational techniques to increase precision and reduce the invasiveness of the procedure. The additional advantage of such technology is increasing patient’s awareness through the possibility of presenting the planned procedure in a visual way.

The first element of surgical procedure planning is image diagnostics. For the purpose of this article we will focus on hard tissues, therefore, the obtained diagnostic images have been analyzed using computed tomography.

Computed tomography (CT) is a method that uses X-rays (RTG) to image the body. The ability to penetrate the body enables the imaging of its interior, including soft tissues and bones. Moreover, the device's capabilities allow for selective imaging of certain tissues (e.g. bone only). Therefore, the CT examination is an important element in the diagnosis of fractures, especially multifracture and paraplegic fractures. The image obtained from the device is presented in Hounsfield grayscale (HU, Hounsfield Units). The progress of medical imaging technology allows for more and more accurate digital analysis of the examined object. The image created during the examination can then be computer processed to generate a 3D model of the studied organ (e.g. heart, bones). The method of obtaining the model will be presented later in the article.

In the area of three-dimensional printing, the development is taking place at an alarming rate, day by day. Every day there are new reports not only on the use of 3D printing, but also on the development of equipment and consumables. CAD models can be printed in 3D, what gives physical anatomical models of the patient. Often on the basis of medical data and the resulting medical models, the designer can individually adjust the implant, prosthesis or orthosis to the specific case. There are many spatial printing techniques such as stereolithography (SLA), fused deposition modeling (FDM), selective laser sintering (SLS), Selective laser melting (SLM), digital light processing (DLP), PolyJet, and ColorJet printing (CJP). They are characterized by the type of material used to make the model, working environment, layer thickness, price of equipment specializing in a given technology.

In our research we used printouts made in FDM, PolyJet, SLS, and CJP technologies.

2. Accuracy assessment and medical modeling – review of the literature
In the process of rapid prototyping we may come across a number of errors. These are inaccuracies related to data export, printing technique, material type, layer thickness and model setting on the working platform. In many publications, we can find information on errors in printing, most often anatomical ones. The devices that we can use to check the dimensional accuracy of an object are machines used in coordinate measuring technology and with laser/optical scanner measurements. The essence of coordinate measurements is to base the measurement procedures on the values of coordinates of specific points. During the measurement process, points are located, by means of which the machine determines the geometry of the object to be measured [1]. The laser scanner, on the other hand, bases its research on the location of markers applied to the object, recognizable for it in its own scanning system. The scanner automatically orienta points in space, giving the user a cloud of points of the object, which can be exported to the data format we are interested in.

Using 3D printing in preoperative treatment planning is a small step into the future of personalized medicine, contributing to improving healthcare system quality. There are no reports in the literature on medical measurements, on living bones with respect to their natural environment, and it is still not clear what order of magnitude of errors a doctor may expect when receiving "medical aids" in form of e.g. images.

In many reports, the inaccuracy of surface mapping is assessed. The basic research includes the measurement of landmarks using a digital caliper, as reported in [2]. Linear measurements were taken between the marked points. The activity was repeated 5 times. Choi J.-Y. compared the original skull with its reflection using RP [3], Silva [4] and Mannadhuachara [5] methods.

In the publications of Grzelak [6], Budzik [7], Joyce Van den Broeck [8], the examination of bone structure accuracy using a 3D optical scanner is discussed. In the case of Grzelak, the reference model was additionally scanned with an ATOS scanner in order to obtain a second model for comparison.
During the reconstruction of the human skeleton, the skull was also printed in FDM technology, the Budzik and the rest behaved similarly to verify the accuracy and precision of the models.

The second type of measurement is a method using a coordinate measuring machine. There is much more information on this subject in the literature. Primo [9], Ryniewicz [10], and Olszewski [11] searched for the value of inaccuracy in medical modeling, while Ibrahim [12], using a coordinate measuring machine, tried to assess the difference in the models coming from two different rapid prototyping techniques, SLS and PolyJet. Most often, the accuracy measurement methods are based on marking landmarks on the object, which are then collected by a machine that performs coordinate measurements of points.

In this study, we focus on the measurement of whole objects, not individual points of the model.

3. Materials and methods

3.1. Experiment design

The idea of the experiment is presented below (figure 1), in form of the flowchart. The whole procedure is explained below.

![Flowchart of the experiment](image)

**Figure 1.** Flowchart of the experiment.

3.1.1. Geometrical object. Two parts of the experiment were performed. The first part included the design of an analytically described, complex solid in SolidWorks software, 3D printing in various technologies, with different surface finish, materials and model arrangement on a work table, and accuracy testing of printed solids. Due to the CAD design there was no need to obtain the solid model in any other way.

3.1.2. Bone turkey. The second part was based on finding a suitable bone structure, computer tomography imaging (figure 2), segmentation of image data, 3D printing of bones in various technologies, preparation of animal bones (figure 3), which was chemically treated to avoid damage, and subsequent accuracy testing.
3.2. *Computed tomography data*

The first stage of the second part of the experiment was to place the prepared bone in a gantry CT scanner. In this case, it was a Toshiba Aquilion 16 model, which allows the object to be accurately reproduced by means of a 16-row detector system. The bone was stabilized by a plate made of PMMA, to which the object was attached. During the examination, the object was scanned with parameter settings: 120 kV lamp voltage, 60 mAs current-time load, 0.454 mm pixel size and 1 mm layer thickness were reconstructed using several standard filters. The results of the CT examination were files in DICOM format.

![Figure 2. Scan CT of turkey bone – CT machine and x-ray.](image)

The CT data of bone generated using Toshiba Aquilion with 0.5 mm slice thickness, 512x512 pixel resolutions. Voltage 120 KV, [mAs]: 60.00, size pixels: 0.454 mm, algorithm: FC12, number of scanned layers: 1661.

3.3. *Create 3D computer model - Segmentation/image processing*

3.3.1. *3D modeling bone model.* For the spatial reconstruction of the object one of the basic programs for visualization and segmentation of medical images Mimics 15.01.medical modeling software by "Materialize NV" was used. [13,14].
The series of images obtained from the CT scan were imported into the above program and the following steps were taken to obtain a 3D model:

Step 1. Import DICOM files to medical CAD software (figure 4)

![Sample DICOM files.](image)

**Figure 4.** Sample DICOM files.

Step 2. Mask preparation and calculation of 3D bone model (Hounsfield scale: 215 - 3071) (Figure 5)

![Segmentation of the bone.](image)

**Figure 5.** Segmentation of the bone.

Step 3. Separation of the bone (Figure 6)
Figure 6. Separation of the bone.

Step 4. Polyline tool – follow-up defects bone (figure 7)

Figure 7. Defects bone.

Step 5. Exported model as an STL file (figure 8)

Figure 8. STL file.

The saved bone mass in the form of a .STL file was repaired in Magics 20.04 using the Fix option.
3.4. 3D printing
The prepared solids (analytical as well as live bone) were loaded into the internal software of the 3D printer and printed using various methods. The first, the PJ method, is the advanced PolyJet technology represented by an Objet Connex 500 printer, which enables the production of high accuracy and surface quality details from a wide range of transparent or flexible surfaces. The second method, FDM - fused deposition modeling, Fortus 250mc allows to create models made of durable thermoplastic material - ABS. Thanks to the double nozzle it is possible to print with the use of soluble support material. SLS - Selective Laser Sintering, where the layers of powdered polymer are applied to the work table. In the next stage, it is melted selectively by a concentrated laser beam operating in a long infrared band. CJP - the process of creating models in Color Jet Printing technology is based on selective bonding of powder. SLM - Selective Laser Melting technology is the selective laser beam melting of metallic powders.

3.5. Measurements
There are many ways to measure the accuracy of a specific shape. One of them is computed tomography (CT) [15]. CT is a different device than standard measuring devices, because apart from the external dimensions of the tested object, it is possible to measure the internal structure of the object. Tomographs can be used both in industry, to assess the internal condition of the examined objects, without the need to destroy them, and in medicine [16]. Computed tomography makes it possible to penetrate deep into the internal structure of a device/tissue and determine its condition.

The second method is measurement by means of 3D scanners.

4. Results
4.1. 3D printing geometrical object results
Figure 9 presents the result of a 3D geometric object printout. The model has been printed in 3D technology in different technologies and on different devices: FDM, PJ, and SLM. The samples were printed in 3D with different finishes and printed with different sequences on the working platform. It shows the result of representing the global accuracy of the rapid prototyping models, and errors localization (figure 10).

![Figure 9. 3D prints and diagnostics geometrical structure with the Geomagic Systems.](image-url)
4.2. Bone results

Figure 11 shows the result of the 3D turkey bone printing. The model has been printed in 3D technology in different technologies and on different devices: FDM, PJ, SLS, and CJP. The models were printed in 3D format with different finishes and sequences on the work platform. And it shows the result of representing the global accuracy of rapid prototyping models. Figure 12 shows where these errors are located.

Figure 10. Diagnostics geometrical structure with the program.

Figure 11. 3D Print and diagnostics geometrical structure with the Geomagic Systems.
5. Conclusions

Application of reverse engineering allows one to obtain high accuracy of numerical models, in combination with RP technologies we are able to generate functional prototypes of all kinds of artificial limbs or implants, including cranial cavities. Supporting medicine with the use of RE and RP techniques has a significant impact on the efficiency of doctors' work. Using the above mentioned methods, it is possible to shorten the preoperative and operational time, significantly reduce the risk of complications during surgery and postoperative complications, which is also associated with lower costs.

The literature review shows methods for measuring accuracy that cannot be considered the best way to compare studies. The point inaccuracy methodology proposed in this study can only be helpful in future research to assess the accuracy of rapid 3D prototyping models.

There is no the best RP technique for making medical models. Every technology has its advantages and disadvantages. Due to the criterion of model accuracy, PolyJet is one of the most suitable technologies for medical modeling. However, the cost of making a model with this method is the highest. The CJP method is the most appropriate for the cost of making a model. The disadvantage of the method is that it is impossible to reproduce internal and very complex external structures.

Due to the type of material the FDM method is the most suitable for medical applications. The disadvantage of this method is the high cost of making the model, but smaller than PolyJet.

3D technology can help in the future: 3D visualization and model printing for a specific patient, preoperative planning, preparation of 3D models for anatomy and surgical templates for a specific patient to prepare the operation, printing of implants fitted to the patient. As a result of the literature it was found that there were no reports on medical measurements, on living bones taking into account their natural environment, and it was not clearly stated what order of magnitude of errors can be expected by a doctor receiving "medical aids".

3D printing technologies provide physicians, engineers and scientists with the ability to create customized solutions for a variety of conditions. They help to understand complex anatomy in education at all levels, but costs and working time are still too high to provide good quality.

The choice of reconstruction parameters is a very important issue in the process of tomography. This selection is a compromise between quality and speed of work. The number of X-rays is particularly
important in this respect. If it is too low, the image quality will be unsatisfactory, while too high will significantly prolong the process of data acquisition and reconstruction.

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