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The Influence of the Layer Thickness Change on the Accuracy of the Zygomatic Bone Geometry Manufactured Using the FDM Technology †

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Abstract: Due to the unique geometry of the models of anatomical structures, manufacturing them using subtractive methods is difficult or often impossible. This situation makes the additive processes an ideal alternative for manufacturing this model type. Many factors during 3D printing affect the accuracy of the model geometry. The most important are the type of technology used, the finishing treatment, the material used, the print layer's selected thickness, and the object's orientation in the 3D printer space. The manuscript determined the impact of changing the layer thickness on the zygomatic bone geometry accuracy. The manufacturing process was carried out on a Fortus 360-mc 3D printer. Physical models of the zygomatic bone were made of ABS material using four-layer thicknesses: 0.127 mm, 0.178 mm, 0.254 mm, and 0.330 mm. The MCA-II measuring arm with an MMD × 100 laser head system was used to assess the accuracy of the model geometry. Statistical parameters and histograms presented the accuracy analysis. The obtained results showed a gradual deterioration in the accuracy of the model geometry representation with the increase of the print layer thickness. However, all the models manufactured are within the accuracy of ± 0.25 mm geometry, acceptable to surgeons.

Keywords: accuracy; additive manufacturing; zygomatic bone; reverse engineering; laser triangulation; layer thickness; FDM technology

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1. Introduction

The increasing pace of life and the development of means of transport result in increased susceptibility to injuries. One of the leading positions among them is fractures of the middle level of the facial skull, including mainly the zygomatic bone [1,2]. The zygomatic bone plays an essential role in maintaining the aesthetic and functional balance of the middle level of the face. Fractures of the orbit account for 40% of craniofacial injuries. Their number increases every year. The most common causes of orbital injuries are road accidents, beatings, sports-related injuries, and accidents from heights [3,4]. The bottom wall is the most frequently fractured of the four walls that make up the eye socket. Orbital injuries can lead to permanent facial deformities and visual impairment. Therefore, it is crucial to make a correct diagnosis and therapeutic decision. Craniofacial injuries with damage to the foreheads require interdisciplinary consultations and supplies with the participation of ophthalmologists, otolaryngologists, maxillary surgeons, plastic surgeons, neurosis, and radiologists [2,3]. Hence, efforts are made to constantly improve diagnostic and therapeutic methods in dealing with fractures and recreating this area's aesthetic and functional balance. Therefore, a rapid increase in the use of reconstructed and additively manufactured anatomical structures in planning reconstruction procedures within the craniofacial area has been observed recently [5,6]. The most commonly manufactured models are used as surgical templates or implants in the cranial [7,8], mandible [9,10], and zygomatic bone areas [2,3].

Each stage of creating a model of the bone structure affects the accuracy of the model geometry reconstruction. At the data acquisition stage, it is necessary to properly select the system and measurement parameters, as they ultimately affect the quality of the obtained diagnostic data [11–13]. The data processing stage is mainly related to choosing an appropriate segmentation method that separates the selected bone structure from the rest of the data [14–16]. Volumetric data can be visualized into a three-dimensional model using direct and indirect methods. Unfortunately, these methods have their drawbacks. The geometry reconstructed by these methods requires additional editing, which most often consists of inverting normal vectors and removing gaps between surfaces. The stage of manufacturing the model using additive techniques also influences the dimensional and geometric accuracy of the obtained models [14]. Currently, there is a wide variety of devices and methods of shaping models based on additive methods. The differences in their functioning occur mainly in the process of subsequent hardening layers and the type of material used. Despite the variety and availability of many methods, none dominate in medical applications [5,17], mainly due to the different properties of the materials used and the requirements for ready-made models. In the case of additive methods, the recommended accuracy of manufacturing models of anatomical structures should be within ±0.25 mm [18,19]. To achieve such precision, particular attention should be paid to, e.g., proper orientation of the object in the 3D printer space, the model material selection, and the print layer's thickness.

Modeling and manufacturing a model of the bone structure with specific accuracy to perform a surgical procedure is not a simple task. This is especially true of the craniofacial area, which consists of bone tissues with very complex geometry. Appropriate knowledge and skills in medicine and technical sciences are needed, allowing the full use of currently available tools in the processes related to the reconstruction of the craniofacial areas. This aspect is crucial because manufacturing a model of the bone structure, surgical template, or implant with the assumed accuracy can significantly increase the precision and shorten the time of the operation, reduce blood loss during the procedure and minimize the occurrence of intraoperative complications. Therefore, it is necessary to conduct a wide range of tests to determine the impact of selected parameters on final models' dimensional and geometric accuracy. In the case of the presented article, the focus was on assessing the effect of changing the layer thickness of the 3D printer on the accuracy of the zygomatic bone geometry.

2. Materials and Methods

The research was performed on Digital Imaging and Communications in Medicine (DICOM) data. They were obtained on the Somatom Sensation Open 40 scanner installed in the Regional Clinical Hospital No. 1 at the Frederic Chopin in Rzeszow, with the scanning protocol for orbital studies (Table 1).

Table 1. The scanning protocol.

Name of a Parameter	Value of a Parameter
Tube voltage	120 kV
Tube current-time product	115 mAs
Acquisition	40 × 0.6 mm
Slice collimation	0.6 mm
Kernel	H60s
Matrix size	512 × 512
Pixel size	0.4 mm × 0.4 mm
Slice thickness	1.5 mm

The obtained data were characterized by a pixel size of 0.4 mm × 0.4 mm and a layer thickness of 1.5 mm. The loaded images were subjected to interpolation and filtration in the Amira software. As a result of the performed actions, a better quality of DICOM data was obtained by increasing the spatial and contrast resolution. Based on the prepared data, the value of 230 HU was selected as the value of the lower segmentation threshold. The segmentation process was carried out for him using the region growing method. It belongs to the area method group, which consists of selecting pixels of a similar shade and classifying them into one group defining a given tissue. The Marching Cubes (MC) method was used to visualize the zygomatic bone model [20]. As a result, the generated model was saved to the Standard Tessellation Language (STL) file (Figure 1a). Physical models of the zygomatic bone were made on a Fortus 360 3D printer using ABS-M30 material. Four-layer thicknesses were used for printing the models: 0.127 mm, 0.178 mm, 0.254 mm, and 0.330 mm (Figure 1b). To ensure the repeatability of the manufacturing process, each model made was placed and oriented in the same place in the 3D printer's working space (the bottom surface of the orbit is oriented parallel to the axis Z of the 3D printer). This was to ensure that the orbital bone area was manufactured as accurately as possible. This is because titanium plates will be manually bent to these surfaces [3,5]. The measuring process of the zygomatic bone models was performed using the MCA-II measuring arm with an MMD × 100 laser head system (Figure 1c).

(**a**) (**b**) (**c**)

Figure 1. The procedure applied in the research process: (**a**) The reconstruction process of the zygomatic bone geometry; (**b**) The manufacturing process using the FDM technology; (**c**) The measuring process using a measuring arm and laser head.

Optical measurements using MMD × 100 are based on the laser triangulation method. In laser-based triangulation systems, a narrow band of light projected onto a 3D surface produces a line of illumination that will appear distorted from an observation perspective other than that of the projector [21]. Analysis of the shape of these line images can then be used to achieve an accurate geometric reconstruction of the object's surface shape. Before starting, the measurement system was checked. The coordinated measuring arm's point repeatability and volumetric length accuracy were tested according to the ASME B89.4.22 standard [22]. The accuracy of the laser head MMD × 100 and the measuring arm system was also tested on a flat plane. Table 2 presents parameters obtained while testing the system. In addition, the table shows the accuracy of the arm and laser head performed on the zygomatic bone model manufactured using Computerized Numerical Control (CNC) technology [23]. For this model, a bimodal distribution of the deviations was recognized.

Table 2. The parameters obtained during testing the system.

Acceptance Test	Measured Value/Maximum Permission Error (2σ)
Effective diameter test	±0.004 mm/±0.008 mm
Single point articulation test	±0.022 mm/±0.024 mm
Volumetric performance test	±0.032 mm/±0.035 mm
	Maximum deviation (2σ)
Laser head test (flat plate)	±0.020 mm
Arm with a laser head (flat plane test)	±0.030 mm
Arm with a laser head (CNC zygomatic bone model test)	±0.060 mm

The measuring process of the four zygomatic bone models manufacturing using Fused Deposition Modeling (FDM) technology was carried out under repeatability conditions to minimize measurement errors. The resolution of obtained data was 0.01 mm. The maximum repeatability error of the measurement procedure was 0.008 mm. Scanned geometries of the zygomatic bone models were compared with the geometry reconstructed from DICOM data. The fitting process was carried out using the best-fit algorithm. A Best Fit alignment is an iterative process using the condition of minimizing the square of the distance between the nominal and measured data to converge on a solution. Adjustment of point clouds using the best-fit in this paper was carried out to an accuracy of 0.001 mm. This minimal improvement parameter represents the criteria used to determine when the best fit alignment is achieved. If the movement required during any iteration is more significant than this value, further iterations will continue until the action is less than the specified value. The process of the inspection was made in GOM Inspect software. Evaluation of the quality of manufacturing geometry was carried out using conventional measurements describing the structure of the community. In this situation, mean deviation, standard deviation (S.D), and the data distribution were considered.

3. Results and Discussion

Evaluation of the quality of manufacturing zygomatic bone geometry was carried out using mean deviation, standard deviation, and the data distribution. Standard deviations of analyzed models range from 0.134 mm (layer thickness −0.127 mm) to 0.172 mm (layer thickness −0.330 mm). These values confirmed that the model manufactured using the thinnest layer generated more precise results than the other models (Table 3).

Table 3. Mean and standard deviation.

Type of the Model	Mean Deviation	Standard Deviation (S.D)
Model—layer thickness 0.127 mm	0.030 mm	0.134 mm
Model—layer thickness 0.178 mm	0.044 mm	0.143 mm
Model—layer thickness 0.254 mm	0.021 mm	0.163 mm
Model—layer thickness 0.330 mm	0.033 mm	0.172 mm

Figure 2 presents the deviations maps. The model manufactured with an applied layer thickness of 0.330 mm generates much higher deviations in the center of the orbit area than the other model. Maximum deviations in this area are +0.06 mm and +0.46 mm. In the edge of this region, observed deviations in the range from −0.16 mm to −0.5 mm. In the model manufactured with an applied layer thickness of 0.254 mm, the major errors range from +0.05 mm to +0.32 mm. At the edge of the orbit, the area observed deviations from −0.24 mm to −0.4 mm. For the model manufactured with an applied layer thickness of 0.178 mm, maximum deviations are +0.19 mm and −0.04 mm. The major error for this model is from −0.16 mm to −0.38 mm in the edge of the orbit area. The model manufactured with an applied layer thickness of 0.127 mm presents the best results from all analyzed models. In the orbit's center area deviations range from +0.03 mm to +0.13 mm. On edge from −0.22 mm to −0.30 mm. The negative deviations occurring at the edge of the orbit may result from the fact in this region of the support material formed during 3D printing.

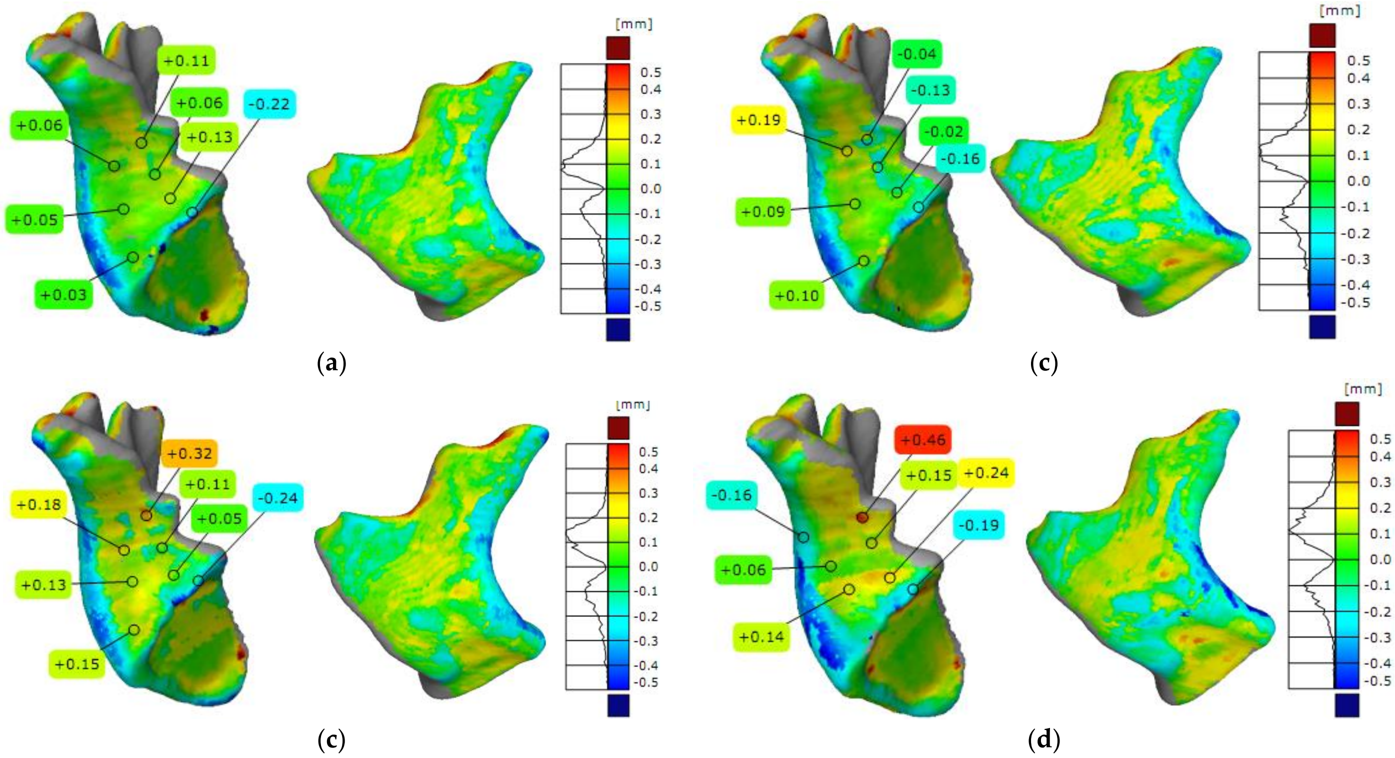

Figure 2. The results of the accuracy of manufacturing zygomatic bone geometry: (**a**) Model manufactured with an applied layer thickness of 0.127 mm; (**b**) Model manufactured with an applied layer thickness of 0.178 mm; (**c**) Model manufactured with an applied layer thickness of 0.254 mm; (**d**) Model manufactured with an applied layer thickness 0.330 mm.

For all models, a bimodal distribution of the deviations could be recognized. In this situation, the value of mean deviation is not cognitive. Each original distribution was separated into two distributions to evaluate these parts using the peak fit function available in OriginPro. The mean value and the standard deviation of the components are presented in Table 4. For all models, it can be observed that one mean value of feature distributions is positive and the second is negative, and the modes are close to symmetrical to 0. It can be assumed that the observed bimodal distributions are composed of positive and negative deviations distributions. That implicates low and similar values of mean deviation when the distributions are evaluated as unimodal. Analyzed results presented in Figure 2 only in the area of the orbit. The most deviations are in tolerance ± 0.13 mm, which is confirmed by the results given by Hanssen [24]. The occurrence of the bimodal distribution is very interesting because the currently presented manuscript did not observe distribution like that in manufacturing medical models using Fortus 360-mc [21]. This situation probably influences a measuring procedure.

Table 4. Statistics of components evaluated bimodal distributions.

Type of the Model	Mean 1	S.D. 1	Mean 2	S.D. 2
Model—layer thickness 0.127 mm	−0.079 mm	0.061 mm	0.101 mm	0.074 mm
Model—layer thickness 0.178 mm	−0.082 mm	0.068 mm	0.119 mm	0.079 mm
Model—layer thickness 0.254 mm	−0.084 mm	0.065 mm	0.108 mm	0.080 mm
Model—layer thickness 0.330 mm	−0.096 mm	0.071 mm	0.115 mm	0.082 mm

4. Conclusions

The development of imaging, reconstruction, and manufacturing bio-medical geometry is an excellent advancement in the medical field because it reduces the rate of medical misdiagnosis of illnesses. FDM technology is the most widely used additive technique in manufacturing medical replicas. Many factors influence the accuracy of medical models manufactured using FDM technology. These results indicate that changes in the layer thickness of the 3D printer Fortus 360-mc affect the accuracy of manufacturing of zygomatic bone geometry and, more critically, the orbital wall. The presented research is a starting point for further studies, presenting more extensive research related to assessing the accuracy of preparation of models of anatomical structures, surgical templates, and implants within the middle level of a craniofacial area.

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