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Modeling and Validation of Rabbit Tibia Bone by Reverse Engineering

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Abstract - In the medical field, 3D modeling and prototyping of hard or soft tissues of living organisms provides great convenience for surgeons before the operation and during the simulation phase of the operation. In this study, 3D regular mesh and prototype models were created from normal CT data of the right tibia bone of a New Zealand albino rabbit and the errors occurring during this creation were compared. According to the results obtained, the lowest errors occurred in the TL dimension, while the largest errors occurred in the ITDD dimension. The measured error amounts vary between 0.8% and 7.2%. Considering these error margins compared to similar studies, it is seen that the modeling is quite normal and a satisfactory way to simulate surgeons has been created.

***Key Words*:** Rabbit Tibia, 3D Bone Modeling, Additive Manufacturing

1.INTRODUCTION

Reverse engineering (RE) is a systematic process of analyzing the functioning of an existing product or system in order to analyze, recreate and improve it. While this approach was initially widely used in areas such as the defense industry and the automotive industry, in recent years it has started to attract great interest in the medical sector. In the medical field, RE enables a better understanding and improvement of existing devices and systems, and even the creation of completely new, innovative solutions. The field of engineering is divided into two parts. The first is forward engineering. Forward engineering uses logical, mathematical and abstract concepts and translates them into physical and systematic products. RE, on the other hand, is based on the process of obtaining computer-aided design files from a physical and systematically manufactured product and ultimately creating a digital twin [1]. Modification of the existing product can be easily achieved by adding and subtracting the desired additions and subtractions on the digital twin. New technological developments in electronics and computer integration, computer graphics and virtual reality have improved the creation of computer-based representations of physical objects. There are a number of reasons that necessitate the use of RE. These include the fact that the manufacturer of a particular product is no longer available, the product is discontinued, original product documentation is not available, and a digital product is needed for quality control and product modifications [1–4].

Recently, the RE method has been in the center of attention in research and application areas for every sector with the developments in the field of Additive Manufacturing (AM). Thanks to AM technologies, physical objects of complex geometries can be produced directly with the help of computer-aided three-dimensional (3D) models. In this context, it may be difficult or not possible to create 3D models using AM techniques to produce objects with incomplete or non-existent designs. In this case, RE can produce AM files in a short time and provide great convenience to the user [5,6].

In this study, a 3D model of the rabbit tibia bone was created with the RE method, physically fabricated with AM technology and accuracy analysis was performed.

2. MATERIALS AND METHODS

RE method and the software used in this field are seen as an indispensable tool for recreating 3D models of mechanical or non-mechanical parts [7]. In order to create a 3D model of a part in a computer environment with the RE method, sometimes a simple detail of the part is considered sufficient, while sometimes even the finest detail images of the part are needed. If the parts to be imaged are convex, symmetrical and have repetitive surfaces, they are considered to be very suitable for the application of the RE method. On the contrary (concave, having negative surfaces, having complex structures, etc.) can be seen as a situation that complicates the application of the RE method [8]. The implementation of the RE method is realized by performing certain steps one after the other. In our study, we realized these steps as shown in Figure 1.

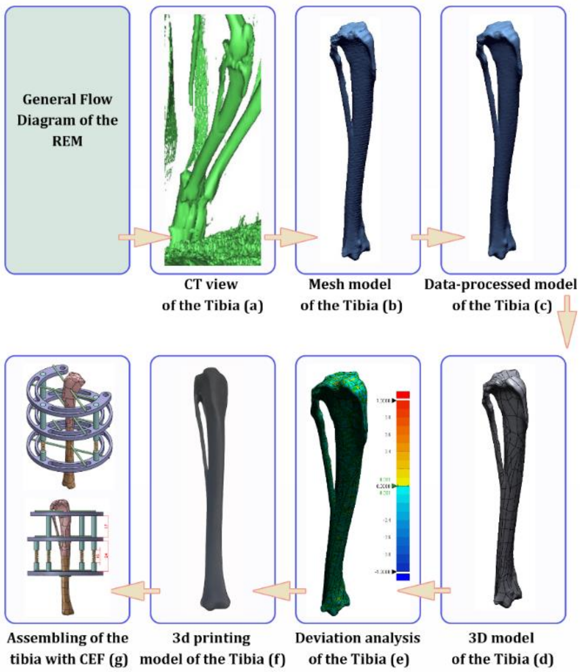

Figure 1. General flow diagram of the RE method

2.1 Processing of radiographic images of the tibia bone

The 3D modeling of the rabbit tibia bone was performed with the help of radiographic images obtained from a CT scanner (Figure 1a). The scan parameters applied in the CT device were determined as 0.4 mm slice spacing, 512x512 pixels and 610 slices [9]. The scan data were transferred to the Mimics (Materialise) program, where a 3D irregular mesh model was created by image processing (Figure 1b). In this process, the Hounsfield Unit (HU) value was determined as +589 and +2185 from the image processing threshold parameters. In order to eliminate the geometric deficiencies of the 3D irregular mesh model of the tibia bone, mesh optimization process was needed and the quality of the mesh model was improved in Geomagic Design x (3D Systems, Inc.) program.

2.2 Processing data of the tibia bone

The data processing process in Geomagic Design x program was done with the help of certain stages. These steps are Heal mesh, Global remesh, Decimate, Fill holes, Enhance shape, Edit boundaries and Optimize mesh. Mesh quality was improved by applying these steps respectively. These steps were performed to correct and improve the negative mesh structures that occurred in the previous process (Processing of Radiographic Images) (Figure 1c).

2.3 Deviation analysis of the tibia bone

A certain amount of error is realized between the 3D regular mesh structure created from radiographic images of the tibia bone and the 3D solid model. According to this margin of error, the idea of how accurate the process is is revealed. In our study, we set a value of ±0.1 for the tolerance of the deviation analysis we performed (Figure 1e). This tolerance value also shows the visibility of the error margin on the model.

2.4 3D printed model of the tibia bone

The prototype of the tibia bone was realized with the SLA (Stereolithography) method, one of the AM methods. The slicing program used for printing was Anycubic Photon Workshop and the material was ABS (Acrylonitrile Butadiene Styrene). Printing parameters were 0.05 mm layer thickness, 2 s normal exposure time, 23 s bottom exposure time and 2 mm/s Z lift speed. The tibia bone created with these data is shown in Figure 1f.

2.5 Mounting of the tibia bone with CEF (Circular External Fixator)

In the field of orthopedics, surgeons can simulate the operation to be performed by creating 3D models of bones before the operation [10,11]. For this simulation, desired 3D model structures can be created by making additions or subtractions on the previously created bones (Figure 1g). In Figure 1g, the rabbit femur bone was fractured in the transverse plane from the diaphyseal region and the two fracture segments were fixed with the CEF system.

2.6 Geometric description of the tibia bone

A number of measurements determined on the rabbit tibia are important for defining the morphology of the bone. Therefore, these measurements ensure the structural integrity of the bone. The measurements can be listed as follows [12];

- Tibial length (TL) = The length of the tibia
- Tibial proximal width (TPW) = The maximum distance at the proximal articular surface
- Tibial distal width (TDW) = The maximum distance across the tibial malleolus in the transversal plane
- Tibial diaphysis diameter (TDD) = Transverse diaphysis diameter at the middle of the tibia
- Internal tibial diaphysis diameter (ITDD) = Transverse diameter of the medullary cavity at the middle of the tibia
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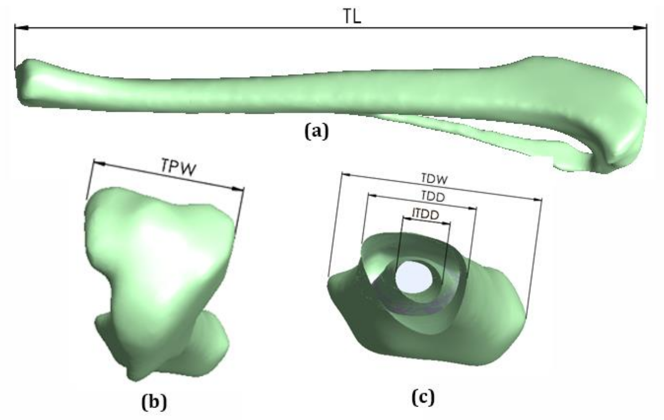

Figure 2. Geometric dimensions of rabbit tibia bone

3. RESULTS AND DISCUSSION

In this study, a 3D model was created from CT images of the tibia bone of a New Zealand albino rabbit and prototyped using the SLA method. With this study, geometric losses on the tibia bone were calculated from CT data until the prototype stage. These defects can be localized on the bone or spread throughout the part. In the process from CT data to prototype production, geometric losses occur four times on the model.

- The first loss occurs at the transition from position a to position b in Figure 1. Here, a 3D irregular mesh model is created by processing CT data with image processing method using Mimics program. During the transformation from radiographic images to the 3D mesh model, both program and operator errors are combined to create an equivalent error. The percentages of similarity of the models according to these error amounts are given in Table 1. On the tibia bone, the smallest error was 0.32% in the TL dimension and the largest error was 4.79% in the ITDD dimension.

- The second loss occurs at the transition from b to c in Figure 1. Here, there is a transition from an irregular mesh structure to a more regular mesh structure with data editing operations. These operations were performed with Geomagic Design x program. When the amount of similarity between the models obtained here is evaluated, the smallest amount of error occurred in TL (0.47%) and the largest amount of error occurred in TDD (4.96%).

- The third loss occurs during the transition from c to d in figure 1. Here there is a transition from 3d regular mesh model to 3d solid model. Since the tibia bone structure has an irregular superficial form, it is modeled as organic. Looking at the error values obtained in Table 1, it is seen that the smallest error amount is -0.15% in the TDD dimension and the largest error amount is -1.03% in the ITDD dimension.

- The fourth loss occurs during the transition from c to f in figure 1. Here the prototype model is created from a 3D regular mesh model. During this process, both device (3d printer) and operator errors occur. The smallest error is 0.22% for TPW and the largest error is 0.99% for TDW.

Table 1. 3D irregular mesh model, 3D regular mesh model, 3D solid model and Prototype model deviations with CT

Dimension Name	CT m. (mm)	3D irregular mesh model m. (mm)	3D regular mesh model m. (mm)	3D solid model m. (mm)	Prototype model m. (mm)	CT & 3D irregular mesh model deviation (%)	3D irregular mesh model & 3D regular mesh model deviation (%)	3D regular mesh model & 3D solid model deviation (%)	3D regular mesh model & Prototype deviation (%)
TL	92.42	92.12	91.68	91.71	91.35	0.32	0.47	-0.03	0.35
TPW	14.24	13.85	13.52	13.46	13.49	2.73	2.38	0.44	0.22
TDW	12.63	12.25	12.10	12.06	11.98	3.00	1.22	0.33	0.99
TDD	6.93	6.85	6.51	6.52	6.49	1.15	4.96	-0.15	0.30
ITDD	3.13	2.98	2.91	2.94	2.92	4.79	2.34	-1.03	-0.34

*m. is called measurement

The error margins in the four stages from CT data to the prototype stage are shown in the table above. Looking at the values in Table 1, it is seen that some error amounts are marked with a “-” sign. This is due to the fact that the output value is greater than the subtraction. The error margins in Table 1 show the evaluation of each stage compared to the previous stage. In addition to the importance of this evaluation, the margins of error between the final 3D solid model and the prototype model formed from the CT data are also important. Table 2 shows these data.

Table 2. 3D regular mesh model and Prototype model deviations with CT

Dimension Name	CT m. (mm)	3D regular mesh model m. (mm)	Prototype model m. (mm)	CT & 3D regular mesh model (%)	CT & Prototype Model (%)
TL	92.42	91.68	91.35	0.80	1.15
TPW	14.24	13.52	13.49	5.05	5.26
TDW	12.63	12.10	11.98	4.19	5.14
TDD	6.93	6.51	6.49	6.06	6.34
ITDD	3.13	2.91	2.92	7.02	6.70

*m. is called measurement

Looking at the data in Table 2, it is seen that the smallest margin of error during the conversion from CT data to 3D regular mesh model or prototype model is in the TL dimension and the largest margin of error is in the ITDD dimension. When the TL dimension is excluded from the evaluation, it is seen that the error rates vary between 4% and 7% in the light of the other dimensions.

4. CONCLUSIONS

In this study, a 3D regular mesh model was created from CT radiographic images of a New Zealand albino rabbit and then a 3D solid model and prototype model were developed. At this stage, the accuracy of the measurements during the transitions was over 92.98%. In addition, the error margins that occurred during these creation and development stages were analyzed in detail. When these values are examined, the reasons for the amount of errors;

- Algorithms used in the content of the programs used
- Errors of operators during the use of programs
- Measurement errors that may occur during measurement
- Disruptions in the additive manufacturing process
- During this procedure, it can be listed as procedures performed by people who are not experts in their field.

For better results of the study, micro CTs [12] with better resolution can be preferred instead of regular CT. In addition, more reliable results can be obtained by eliminating the above-mentioned reasons for the amount of error.

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