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Methods for designing and fabrication large-size medical models for orthopaedics

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Abstract. Computed tomography and rapid prototyping techniques can be used to construct and fabricate large size bone models for orthopaedics. Rapid Prototyping technology enables the fabrication of a true-to-scale bone joint model based on 3D virtual models, generated by segmenting patients' CT images. The model can be used to plan, to simulate, to assist prosthesis implantation for difficult cases of THR (Total Hip Replacements). The main restriction of implementing such models into medical practice is high cost of their production. Physical models of pelvic bones, were constructed on the basis of data collected during standard CT examinations. A method of development of a large-size model while fulfilling the requirement for reducing the price of model fabrication in the article was presented. The method can be used for fabrication the models with 3DP technique. This paper also discusses the issue of production costs when utilizing other RP techniques as well as their usefulness in practice.

Key words: Computed Tomography (CT), orthopaedic surgery, Computer Assisted Surgery (CAS), Rapid Prototyping (RP).

1. Introduction

Three-dimensional reconstructions of CT data are currently widely used in a variety of orthopaedic surgical applications. The reconstructions of bones based on CT images can be used to simulate and design complex orthopedic procedures [1]. In reconstructive surgery, 3D reconstructions may be used to identify and measure bony defects [2]. In osteotomy surgery, the medical RP model may be used to measure critical distances, angles and congruity of the joint surfaces. RP model of bone structures may be used in total joint replacement surgery to simulate the surgical treatment, to select the geometrically optimum standard implant, or to design a custom, individual endoprosthesis [3]. The meticulous preoperative planning is necessary due to a great aberration of the joint and in absence of normal anatomical landmarks. One of the problems related to disturbed anatomy structures of the hip joint affects the incompatibilities between standard implants and host bone. In some cases, customized prosthetic components may be an alternative. In these cases, the differences in the biomechanical behavior of custom implants compared to the standard components should be considered. The use of prototypes is helpful in the validation process of the optimal model of custom implant and in the preoperative planning of surgical interventions due to the possibility of simulation of the insertion of femoral component into the medullar canal [4].

Orthopaedic surgery can face challenges in presenting extensive injuries with multiple bone fragmentation, as well as in presenting bone deformities. Radiographs may provide inadequate information on the precise extent of bone defects. The 3D reconstructions from CT data offer better visualization but are not portable for consultation and medical guidance in the operating room [5]. A RP model manufactured from Computed Tomography data can offer better understanding of complex anatomical detail for doctors and patients.

Rapid Prototyping models can be integrated directly into non-industrial applications such as medicine, but the cost associated with medical model fabrication can be very significant [6]. It is essential for proper surgery planning to manufacture large-size models in 1:1 scale (Fig. 1). Comparing

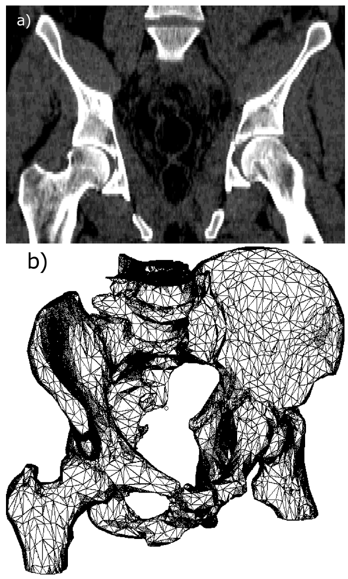

Fig. 1. Representation of medical data: a) DICOM view of pelvic area (CT examinations), b) 3D vector model of pelvic bones

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to the industrial applications, where the prototype's cost is a very small part of the final product's cost, in medicine the model is used for individual case [7]. As the result, the cost of the model's fabrication is simultaneously the total cost of the final product. This cost consists of two items: the price of the material and the operation time (device's amortization). Contrary to the most implantology applications, where models have slight dimensions and thus small fabrication costs, in orthopedic implementations most Rapid Prototyping techniques seem to be very expensive [8, 9].

2. Methods for developing the large-size medical objects

Based on research and consultations carried out by our orthopedic surgeons, the following recommendations are proposed for the preparation of medical models for reconstructive musculoskeletal surgery planning. It was assumed, that the costs of the chosen method for the large-size objects' modeling should not exceed the specified cost limit [10]. We conducted an investigation using the SLA and SLS models (Fig. 2), which confirmed the method's usefulness, however the areas of the prepared bone's fragments in examined cases were substantially reduced [10]. We found that the area's reduction significantly hinders the surgery's planning process. Both the SLS and SLA prepared models, have no references to the healthy bone fragments. Only the full-dimensioned model (Fig. 3), consists of both the healthy and also the damaged or affected bone fragments, which renders it suitable for the pre-surgery planning for reconstructive surgeries. The cost of this model's fabrication in 1:1 scale using RP techniques is much higher than assumed.

We propose a method for developing such a model with both the reduced amount of material needed for its production as well as a reduced device's operation time. During our research we noticed that for the purposes of surgery planning only some of the bones' fragments are used directly for mechanical processing (endoprosthesis placing, mounting etc.), The rest of the fragments deliver information about the bone's geometrical structure, which serves as the basis for choosing the tissue areas, for mounting and thus preparation of the whole surgery. This process is made in the relation to the healthy bones' fragments with proper geometric features. Taking into consideration the above observations, we accepted a new model for the development of orthopedic models: one that is divided into an "active part" as well as "shell fragments" (Fig. 4). The redistribution of the model into individual parts allows for the removal of the stored not solidified material from inside of the model's shelled areas.

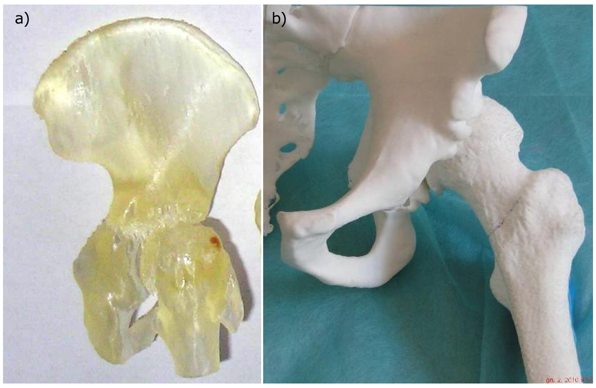

Fig. 2. Hip-joint medical models during pre-surgery planning in reconstructive surgery intervention: a) model made by SLA technique, b) model made by SLS technique

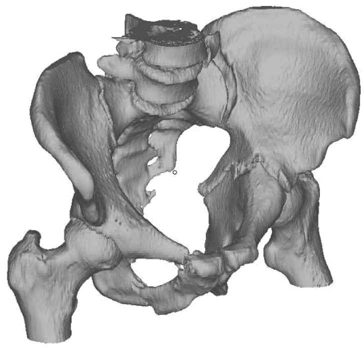

Fig. 3. STL model of pelvic bones generated on the base of CT examinations

a)

b)

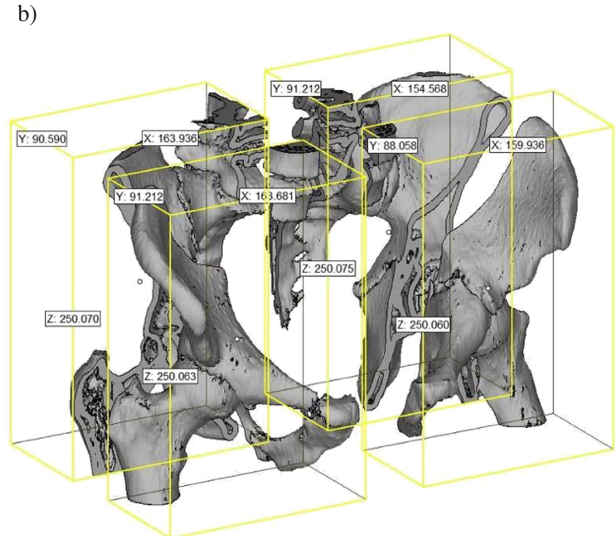

Fig. 4. Project of pelvic bones model performed with described method. a) fragment of shell region, b) juxtaposition picture of individual model's parts

It was assumed that the most effective method in respect of the costs would be the 3DP method using resinous infiltrator to increase the model's toughness. This method gives the possibility for easy removal of the powder from the inside of each model. After glueing all of the parts and saturating the model with resinous infiltrator, the material gains the final mechanical properties, which make it easy for mechanical processing while maintaining the required stiffness.

Alternatively to the division method, inspection openings created for the powder's removal were also trailed. However, this method was not very effective.

We found that the minimal thickness of shell thickness should be 4 mm. Using 3 mm thickness can lead to some technological difficulties with assembling the parts of the model (Fig. 5). Using the model with 4 mm thickness (Fig. 6), the volume of the reconstructed model was reduced from 1600 cm^3 to 441 cm^3. If 3 mm thickness was used, the volume would be reduced to 629 cm^3.

The development of the presented model requires consultation with the surgeon who is carrying out the planned surgery, to define the specific areas, which demand increased mechanical durability. Thanks to this method it is possible to reduce the cost of the model's fabrication and thereby to increase the utilization of the medical models in pre-surgery planning for reconstructive musculoskeletal surgery.

a)

b)

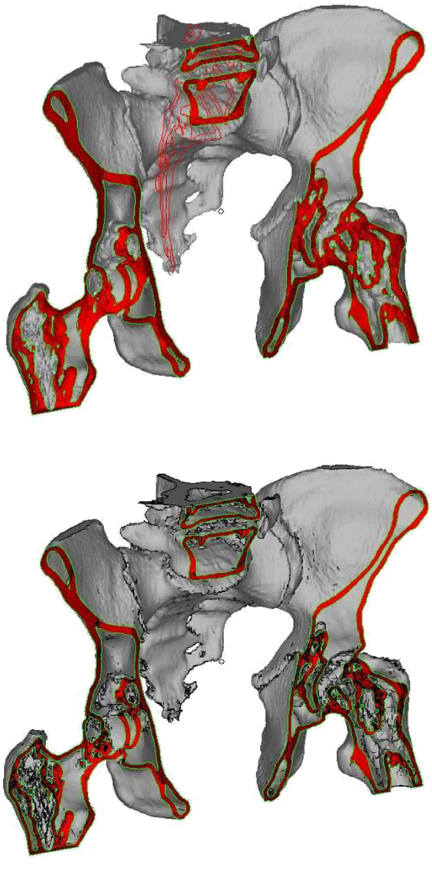

Fig. 5. Project of pelvic bones model. a) cross-section of 4 mm wall-thickness model, b) cross-section of 3 mm wall-thickness model

Fig. 6. Pelvic bones model made by 3DP technique – wall-thickness 4 mm

The development of RP "open source" type devices can lead to further decreasing the models' costs of fabrication. Implementation of devices: Fab@Home [11], MCOR Technologies – 3DPP (3D Paper Printing) [12], XYZPrinting Nobel 1 (SLA technology) [13] and other described in [14] requires performing the analysis of their usefulness for medical purposes. Figure 7 shows the physical model of pelvic bones made with MEM (Melted and Extruded Modeling) technique [15]. This technology utilizes thermoplastic materials (ABS, PLA). Despite the low costs of the model fabrication with this method, the substantial limitation is the difficulty of mechanical processing of this kind of material during pre-surgery planning.

Fig. 7. Pelvic bones model made by MEM technique

3. Summary

There are some technological determinants that should be considered in every design and manufacturing method. The main conditions are: precision of the chosen method, implemented materials and technological as well as dimensional limitations of chosen manufacturing method. It is especially important subject in term of medical models fabrication. The required precision of reproducing anatomical structures for orthopaedics should not be more than 0,5 mm for bone structures [8, 10]. In some clinical cases it can be desirable to fabricate a model with inner structures (spongy bone). The fabricated model, can be suitable for preoperative planning of surgical treatments for orthopaedics [3].

The most important aspect of the proposed method is reconstructing the precise images of patient's anatomic structures (Fig. 1). The data acquired from CT examinations are the main source of information for medical modeling. Precision of the CT data influences on quality of fabricated physical model [16–18]. It is important to set the lower possible thickness of the CT scanned layers and the distance between layers, than used in the standard CT imaging for orthopaedics (5 mm). The limitation of the method can be also image distortions, so called imaging artifacts. Their appearance in the CT images can limit, and in some cases even make impossible, the proper medical model's manufacturing. Artifacts can occur due to metal bone implants, solidifying screws and especially earlier mounted endoprosthesis. Figure 8 shows the surface model generated using CT examinations data of patient with artificial hip endoprosthesis. The visible artifacts make impossible precise hip-bone surface projection. When determining the usefulness of a model in pre-surgery planning, the decision should belong to the surgeon carrying out the procedure.

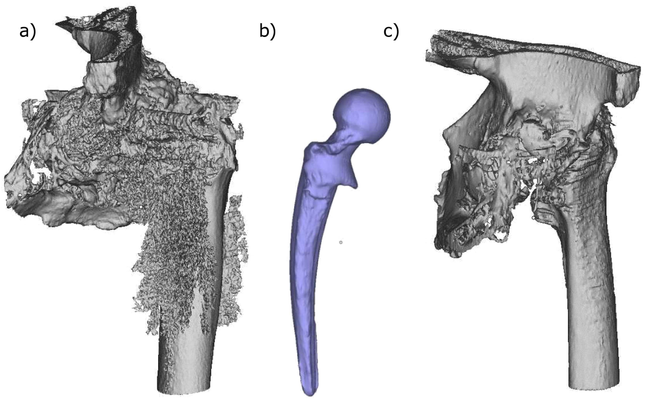

Fig. 8. Artifacts in 3D model: a) imaging artifacts caused directly by presence of endoprosthesis, b) 3D model of endoprosthesis (CT examination), c) model after digital "cleaning" – visible significant loss of information in the joint area - model in this examined case was considered as unhelpful for pre-surgery planning

The prepared models were applied in pre-surgery planning (Fig. 9) in orthopaedic reconstructive surgery (Fig. 10) at the Department of Trauma and Orthopaedic Surgery of MSW (Ministry of the Interior) Hospital in Cracow. In the qualitative assessment, the prepared models very well fitted to the examined anatomic objects.

This work is the continuation of the studies in bone and soft tissue modeling with implementation of modern imaging techniques and rapid prototyping methods. Techniques of Rapid Prototyping can be an effective tool for complex physical models fabrication and can improve the quality and make easier the surgery's planning process. The use of medical models can help to reduce the time of surgical treatment. The choice of Rapid Prototyping method allows for a significant reduction of the model's manufacturing costs. To achieve the assumed aim it is essential to solve many modeling and technological problems and it will be the topic of the future research.

Fig. 9. Pre-surgery planning

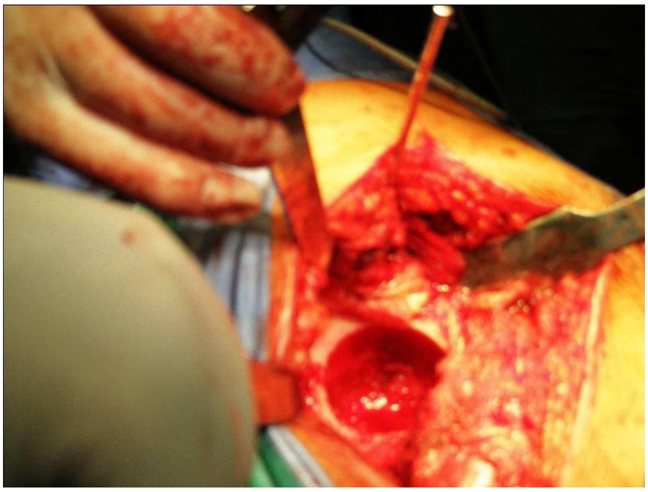

Fig. 10. Surgery treatment

4. Conclusions

1. The application of proposed methods improves the economical effectiveness of pre-surgery planning while using the RP models.
2. Precision of SLS technology is sufficient for fabrication medical models for needs of pre-surgery planning in reconstructive musculoskeletal surgery.
3. MEM technology allows for the lowest cost of model fabrication among the examined
4. With the use of the presented method of object designing, it is possible to manufacture a large-size medical model, in 1:1 scale, on RP machines with limited work platforms' dimensions.

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