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Abstract. New modern additive technologies and reverse engineering are becoming available, especially in medical applications. The paper presents possible ways of using additive technologies in the scope of increasing the level of training of medical specialists in everyday clinical practice and in the selection of the appropriate scenario before real surgery. Descriptions of projects implemented with surgeons whose effect is to achieve aforementioned goals have been presented. The concepts are known as new solutions, but their further development may lead to the extension of the scope of application of these techniques in medicine, among others in relation to other disciplines.

1. Introduction

Implementations of traditional design and manufacturing of artificial organs for the needs of daily clinical practice have limitations, e.g. slow preparation, long-lasting production and personalization of products. Traditional training based on the anatomy of human corpses showing the natural variability of anatomy has limitations resulting from the education of medical specialists. The paper proposes solutions using modern technologies: 3D printing and reverse engineering [1–6]. Thanks to the use of new technologies, it is possible to increase the level of traditional teaching due to lower costs, scalability, diagnostics and teaching based on objects, covering the entire age range, gender. Additionally, they can be used all over the world [7, 8]. There are many initiatives to use modern 3D printing technologies in a variety of medical applications [9]. They concern the use of 3D geometry obtained from the patient for the purpose of editing and production of selected organs [2–5, 7, 8, 10–12]. Technologies are widely recognized as new and complementary, but they can also support current applications of medicine in everyday clinical practice. They can also form the basis of a new family of commercial techniques that optimize 3D technologies for 3D printing in a fully functional clinical solution. The paper presents original concepts of designing and manufacturing artificial organs in close cooperation with the medical community.

1.1. 3D techniques in clinical applications

Current medical applications of 3D techniques include many areas, including:

- learning, including adapted anatomical models, individual and team training in medical simulation centers,

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- research on, for example, modelling and testing of bones or soft tissues,
- 2D or 3D diagnostics (CT, MRI, clinical motion analysis, etc.) – 2D images can be converted into 3D images,
- 3D scanning (including quick face/head scans and quick scan of the whole body),
- 3D printing in surgery, drug manufacturing and rehabilitation engineering,
- reverse engineering (digitalization of real objects, partly for the purposes of replication),
- additive production, which allows for geometric flexibility of printed products (e.g. implants) and adaptation to individual needs.

Traditional design and production of personalized therapeutic solutions can be changed thanks to the implementation of computer design (CAD), rapid prototyping (RP) and computer-aided production (CAM) of physical models and even final products directly from 3D computer data. The combination of different methods and techniques (e.g. in the reverse engineering) allows to significantly shorten the path between measurements, in particular the patient, and ready-to-use personalized equipment. Expensive, high-end 3D technologies are now being replaced by many commercial technologies that have proven to be significantly cheaper, offering the same quality, geometric accuracy and shape changeability. Each 3D copy reflects the same original (or modified by the therapist / manufacturer) data – for example, there is no plastic form or element damaged irreversibly in the production process. Modification of geometrical parameters and material characteristics of the model or end product is possible at almost every stage of production. In selected cases where more specialized knowledge and experience is required, rapid prototyping can only be seen as a faster alternative to modern approaches. Another problem is the use of appropriate materials in special cases – there is a need to develop novel 3D printing materials, dedicated to medical applications (e.g. in anti-allergic, waterproof, unstable, etc.). Despite the efforts of scientists, traditional natural materials (wood, leather, metals) can be difficult to replace and it will be necessary to incorporate these materials.

2. Materials and methods

Own research carried out in inter-university cooperation is concentrated in three main areas:

- development of the concept and implementation of an innovative method of producing artificial organs,
- construction of the Bydgoszcz repository of 3D images for the needs of reverse engineering and medical simulation,
- innovative applications of 3D printing in the broadly understood assistive technology (AT), including the construction and construction of medical exoskeletons and active orthoses based on elements made using 3D printing.

Currently, these studies have been conducted at the Institute of Applied Mechanics and Computer Science of the Kazimierz Wielki University independently or in cooperation with the Department of Physiotherapy, Collegium Medicum of the Nicolaus Copernicus University in Bydgoszcz and the Neurocognitive Laboratory of the Interdisciplinary Center of Modern Technologies (LNK ICNT) of the Nicolaus Copernicus University in Toruń.

The subject of the project Development of the concept and implementation of the innovative method of producing artificial organs, based on anatomical features of the patient was to develop the concept and implement an innovative method of producing artificial organs that will ultimately be used to build mechatronic trainers. Thanks to simulators, it will be possible to carry out surgical training procedures while maintaining conditions close to real conditions during urological operations. For this purpose, methods in the field of reverse 3D engineering and specialist methods in the field of medical diagnostics were used.

The range of works includes the development of appropriate materials imitating the physical and mechanical properties of organs and obtaining data on 3D organ geometry, based on, among others, CT scans and magnetic resonance data (also based on patient data), intended for their production, data processing (clouds points) about the object and creation of an optimization algorithm regarding the final geometric model, adaptation of 3D printing technology to ensure the expected geometric accuracy, material modifications in 3D printing, determination and testing of physical and mechanical properties of these organs, 3D printing of artificial organs corresponding to properties real organs, verification, from the medical side, of created models. The planned result of this work is the development of technology for the production of artificial organs that will be used in ongoing training and workshops.

An innovative method of producing artificial organs based on anatomical features of the patient was used to build mechatronic trainers, enabling the implementation of advanced research, operations, training and workshops e.g. in the field of urological surgery.

Acquisition of 3D organ geometry data is based, among others, on the basis for CT scans and magnetic resonance data.

As part of this work, the focus was on the following stages:

- data processing (point clouds) about the object and creation of an optimization algorithm regarding the final geometric model,
- adaptation of 3D printing technology to ensure the expected geometric accuracy,
- material modifications in the field of 3D printing,
- determination and testing of detailed physical properties and mechanical ones of these organs,
- production (in the conditions of additive technologies – 3D printing) of artificial organs,
- corresponding to the properties of real organs,
- verification, from the medical side, of prototypes (models) created.

3. Results and discussion

Artificial organs created on the basis of individual patient data resulting from CT scans and magnetic resonance data allowed for the introduction of attractive and unique training that are necessary for the continuous training of specialists. These organs imitate research material, and training and workshops using such artificial organs are unique, and this is due to the fact that not only theoretical knowledge is enriched, but also, above all, practical knowledge.

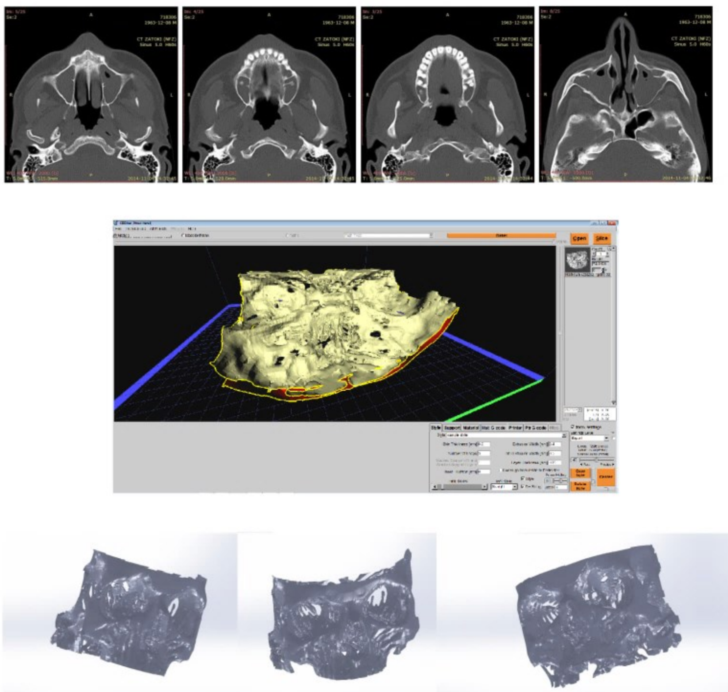

Figure 1. The formation a digital model in the repository (variant-own study).

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This is more important because the gap between theory and practice can still exist, regardless of the number of scientific ventures in which the specialist physician participates. Hence, training and practical workshops are very important in an area where efficiency in practice is at least as important as theoretical knowledge. Indirect recipients will be all patients, because increasing the knowledge and experience of doctors contributes to quick and more effective diagnostics and to proper treatment without complications [3, 4]. Similar work was carried out together with a team of laryngologists to create a model of a patient's skull with faithful representation of complicated sinus shapes (figure 1).

Data for work (MRI and CT) were prepared as files in the Dicom standard. Magnetic resonance imaging (MRI) uses electromagnetic radiation produced by radio waves that are harmless to the body, whereas in computerized tomography (CT), the energy carrier is X waves or X-rays, which too often or too large doses can lead to DNA damage. A number of applications were used to process data (graphical raster images), and then create 3D objects and edit them, and proprietary sub-applications were implemented. One of the programs used during the project was Simpleware ScanIP. It is a software for the visualization and processing of 3D images. ScanIP provides a development environment for comprehensive 3D image data processing (MRI, CT, micro-CT, FIB-SEM, etc.). The software offers advanced tools for visualization, analysis, segmentation and image quantification. The ScanIP application contains a number of functions for exporting surface / mesh models from data segments for CAD and 3D printing. Additional modules were used to export CAE mesh, image data and CAD data integration, NURBS export and calculation of effective material properties during scanning. A series of works have been carried out to improve the manual segmentation of low-contrast medical data using a multi-layered surface grid, and then to generate STL files.

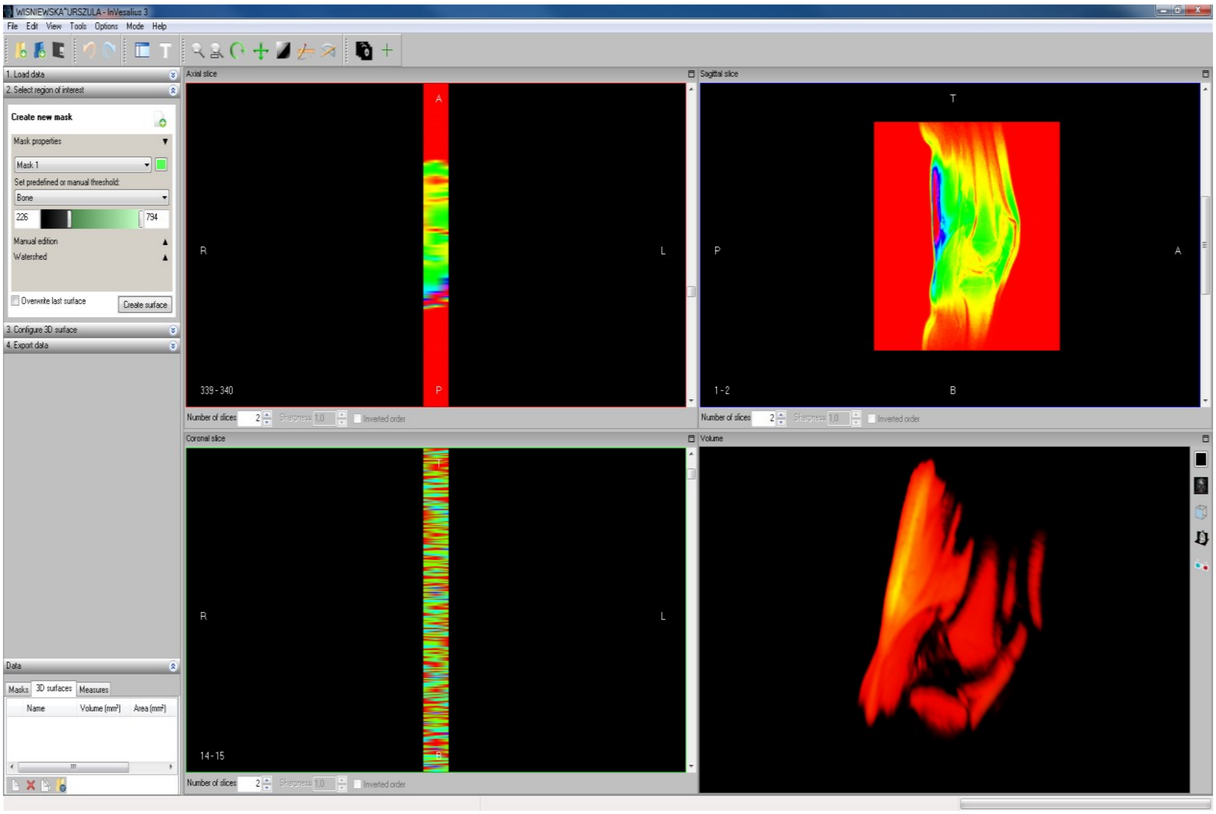

Figure 2. Invesalius screen view with a knee accident.

In order to assess the suitability of available 3D applications for the work, the models *.stl were imported and edited in the following programs: InVesalius 3.1, ScanIP, MeshLab, Netfabb Basic, Blender and SolidWorks. After analyzing the data obtained from the scans, the method (MRI) turned out to be more useful in research. The (CT) method focuses on the precise analysis of tissues in terms of higher density than bone tissue. This is due to the use of X-rays. X-rays represent a larger spectrum of densities, although smaller densities are more difficult to reproduce and are much closer together, e.g. in an 8-bit data structure obtained from scanning. The method (MRI), due to magnetic resonance imaging, better illustrates soft tissues containing more atoms, such as iron, etc. which aggregations (agglomerations) are very well recognized in this method. The method (MRI) thanks to this, has a much larger spectrum density selection range when scanning soft tissues, in this case the threshold is much easier. The data obtained in this way were processed in the InVesalius 3.1 application to create permanent objects, and then edited (figure 2).

During the tests, data obtained from patients with and without contrast were used. Contrast proved to be very useful from the point of view of 3D analysis, provided it was applied directly to the analyzed organ in the case of 3D scanning. The 3D scanning process is not understood in this case as a direct recognition of the structure and is a series of treatments that allow obtaining data analogous to 3D scanning, which are the basis for creating a stereophotographic structure. In this approach, it is the basic 3D geometry in further procedures enabling the creation of a replica of organs. In order to obtain and correctly interpret the data, it was necessary to consult CT and MRI specialists on average once every two weeks.

The main standard used while working with medical installations was the DICOM standard. This standard is treated as a medical standard and contains a number of additional information about the patient's condition, however, for the purposes of the project, the focus was only on geometric data obtained in the form of cross-sections, which were later changed into three multidimensional matrices. Data obtained in other standards, including JPG, BMP and STL directly from the scanning machine software or indirectly, can also be used in the implementation of the project. Data from the above-mentioned standards must be interpreted as 3D matrix data. The effect of these works are spatial objects presented in various applications.

Mimics application was also used, which enabled importing from DICOM and other files (JPEG, TIFF, BMP, X-ray) graphics necessary for creating and editing 3D-standard files and for creating necessary FEM simulations and preparation for printing in 3D standard printing. In the environment of 3D application users, the Blender application is very often used. It is available free and has open image modeling and rendering software and three-dimensional animations with an unconventional user interface. In own work, the application was used to create and later edit various 3D graphic standards, such as: meshes, NURBS surfaces, Bézier curves, meta objects, vector fonts (TrueType, Post Script, OpenType). The application has also been used for "net sculpting", catmull-clark division, Boolean functions for grids, grid editing based on vertices, edges and polygons (polygons), Python scripting, which allows you to add new editing tools, BMesh – system, which allows you to create and edit walls with a very complicated structure – for example, about a dozen or so edges. The implementation of these applications and their own modifications led to the creation of files sent directly to the 3D printer. Printouts were made, successfully completed, selected organ geometries that will be used to make the mold for a model made of material resembling the structure and properties of the source organs.

The process of preparing such type of medical organs is complicated and takes place in several stages, using various 3D printing methods, and the final result depends on the software used and the user's skills. The MeshLab and GOM Inspect application analyzed the deviations of the STL file for 3D printing from the grid model with DICOM. Flat masks have been identified that allow the separation of zones that mark bones from soft tissues. This was achieved by determining the range of gray threshold values. After applying the masks and extracting specific areas and creating a three-dimensional surface model, it was exported to the STL file. At this stage it was possible to further process the obtained web form, which still contained many errors and could not be the basis for 3D printing. In order to clean and repair the mesh model, applications were used: MeshLab and GOM Inspect. Based on them, errors in the geometry of the mesh were removed: artefacts and errors created during the conversion of a series of DICOM images into a spatial grid model. Fragments of the grid lost at the stage of converting DICOM images into a grid model and during its correction were supplemented with the free version of the GOM Inspect program. One of the successful attempts to cooperate in the field of scanning and 3D printing were breast models for women after mastectomy (figure 3).

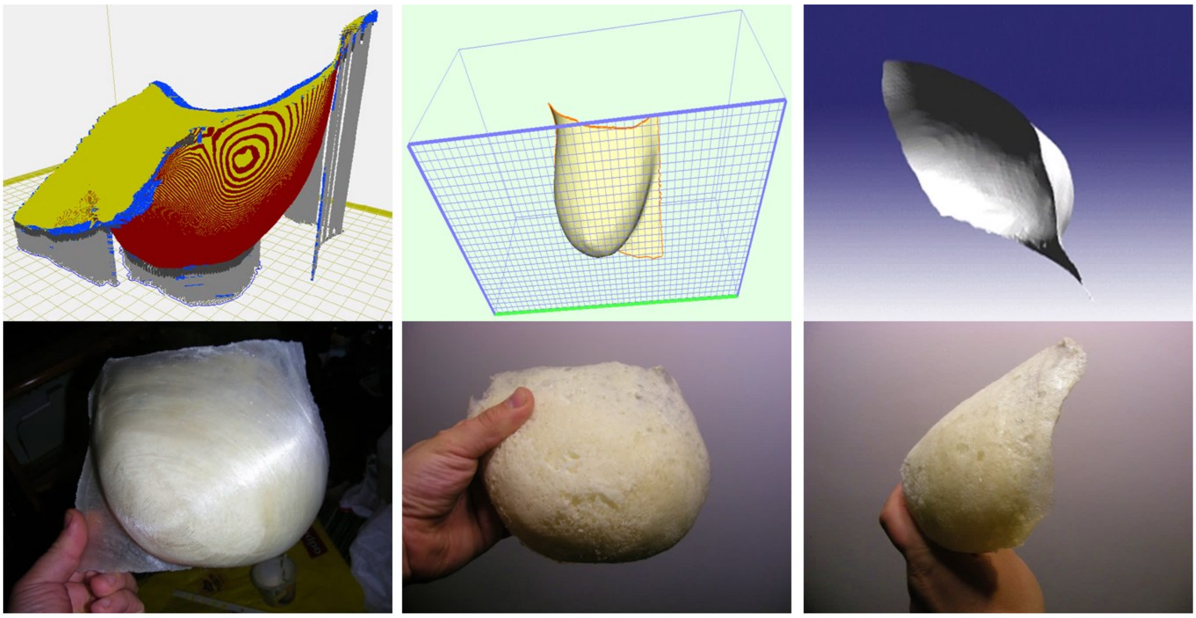

Figure 3. Preparation of 3D data for printing in FDM technology.

Based on the survey rated the usefulness of applications for creating and editing 3D objects in order to create artificial organs. Table 1 presents the results of usability analysis of selected applications for 3D modeling on a 1–10 scale.

Table 1. Formatting sections, subsections and subsubsections.

No.	Application name	Ease of use Dicom	Dicom - point cloud	Compilation time	Friendly interface	Overall rating
1	InVesalius 3.1	7	10	5	8	30
2	ScanIP	4	8	6	7	25
3	MeshLab	5	5	6	6	22
4	Blender	4	3	4	4	15
5	SolidWorks	8	-	7	7	22

For the efficient editing process and preparation of an object for 3D printing, it is necessary to use several applications, but the use of InVesalius 3.1 seems to be the most important. The next step was to adapt the 3D printing technology to ensure the expected geometric accuracy. For economic reasons, the use of FDM and SLA printing technologies has been proposed. FDM technology uses thermoplastic material, which is brought to the plastic state by means of a thin stream in subsequent layers of the object. The work involved a Multitool Gaja 3D printer. SLA technology uses acrylic resin and point laser beam. The work involved a Nobel 1.0 printer. PolyJet 3D printing technology (OBJET 30 pro) was not used due to the high cost of the material (acrylic resin). All mentioned 3D printing

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technologies (FDM, SLA, PolyJet) are in possession of the Laboratory of Technical and Medical Prototyping located at the Institute of Applied Mechanics.

4. Conclusion

The existing 3D printing capabilities in medical applications for the design and production of artificial organs for training purposes are not fully utilized. Despite the initial phase of development, these technologies may introduce significant changes additionally in the area of personalized therapies or rehabilitation supplies. The current situation requires targeted research involving interdisciplinary teams of scientists and clinicians. Completely forward-looking challenges are: multi-element products printed from materials with different properties using the so-called multi-material 3D printers enabling printing of electronic devices impossible to be implemented by traditional methods or multicomponent medicines, 3D printing technologies with programmed response to factors such as time lapse, light, humidity level, temperature, etc., printing of intelligent materials, printing of personalized food, enabling the optimization of the diet of ill people or athletes (see ultrasonic agglomeration to 3-D print small snack-type items for printing pizzas or casseroles). Rapid development in this area may stimulate further areas of research, which will increase the chances of commercial success of 3D printing and its optimal use in the future.

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