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METHOD FOR CREATING A DIGITAL ATLAS OF 3D MODELS OF HUMAN ANATOMY FOR PROSTHETICS

А. Волков, С. Антощук. **Метод створення цифрового атласу 3D-моделей анатомії людини для протезування**. Сучасні методи 3D-моделювання та комп'ютерної графіки відіграють ключову роль у медицині, зокрема у створенні персоналізованих протезів та імплантатів. Використання технології 3D-сканування дозволяє спеціалістам з високою точністю оцінювати ступінь пошкоджень людського тіла та створювати деталізовані цифрові моделі уражених ділянок. Це відкриває нові перспективи у діагностиці, хірургічному плануванні та виробництві індивідуальних протезів і імплантатів. Застосування 3D-реконструкції дає змогу лікарям проєктувати медичні пристрої, які ідеально відтворюють анатомічні структури конкретного пацієнта. Впровадження таких методів дозволяє обирати оптимальні варіанти терапії, прискорюючи відновлення хворих та підвищуючи ефективність лікувального процесу. На сьогодні існує безліч цифрових атласів тіла людини, проте більшість з них не спеціалізовані для завдань протезування, що ускладнює процес реконструкції кінцівок з урахуванням індивідуальних анатомічних особливостей пацієнтів. Метою роботи є розробка методики створення цифрового атласу 3D-моделей анатомії людини для підтримки прийняття клінічних рішень у протезуванні. Цифровий атлас забезпечує ефективну систему керування анатомічними 3D-моделями з можливістю приведення типів даних для 3D-друку або реконструкції. Цифровий атлас також надає можливість зберігати точні анатомічні характеристики у структурованому вигляді, зокрема як опис моделей еталонних кінцівок із прив'язкою до спеціалізованої бази даних, що забезпечує зручність доступу та обробки даних. Завдяки цьому значно підвищується точність 3D-реконструкції, спрощується процес проєктування протезів, покращується якість діагностики та планування хірургічних втручань, а також забезпечується ефективний доступ лікарів до необхідних анатомічних 3D-моделей і супровідної інформації.
Ключові слова: 3D-моделювання, 3D-реконструкція, спеціалізована база даних, інформаційні технології, цифровий атлас, персоналізована медицина, протезування, підтримка прийняття клінічних рішень

A. Volkov, S. Antoshchuk. **Method for creating a digital atlas of 3d models of human anatomy for prosthetics.** Modern methods of 3D modeling and computer graphics play a key role in medicine, particularly in the development of personalized prostheses and implants. The use of 3D scanning technology enables specialists to accurately assess the extent of damage to the human body and to create detailed digital models of the affected areas. This opens new perspectives in diagnostics, surgical planning, and the production of customized prosthetic and implantable devices. The application of 3D reconstruction allows physicians to design medical devices that precisely replicate the anatomical structures of a specific patient. The implementation of such methods facilitates the selection of optimal treatment strategies, accelerates patient recovery, and improves the overall efficiency of the therapeutic process. Currently, there are numerous digital atlases of the human body; however, most of them are not specialized for prosthetic applications, which complicates the reconstruction of limbs considering individual anatomical features of patients. The aim of this work is to develop a method for creating a digital atlas of 3D human anatomy models to support clinical decision-making in prosthetics. The digital atlas provides an effective system for managing anatomical 3D models, with the capability of adapting data formats for 3D printing or reconstruction. It also enables the storage of precise anatomical characteristics in a structured form, specifically as descriptions of reference limb models linked to a specialized database, ensuring convenient data access and processing. As a result, the accuracy of 3D reconstruction is significantly improved, the process of prosthesis design is simplified, diagnostics and surgical planning are enhanced, and medical professionals gain effective access to anatomical 3D models and supporting information.
Keywords: 3D modeling, 3D reconstruction, specialized database, information technology, digital atlas, personalized medicine, prosthetics, clinical decision support

Introduction

In the modern world, the significance of 3D reconstruction is steadily increasing. This growing relevance is primarily attributed to the rapid advancement of information technologies, which continue to make this method more accessible, highly efficient, and extremely versatile in its applications.

The use of 3D reconstruction today encompasses a broad spectrum of industries, including architecture, medicine, prosthetics, restoration of infrastructure, education, forensic science, and many others. Thanks to modern tools – such as high-precision 3D scanners, digital modeling technologies, and powerful data processing software – it is now possible to create highly accurate virtual replicas of real-world objects. This, in turn, opens up entirely new possibilities and solutions for a wide range of fields in human activity.

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A particularly important area of application for 3D reconstruction is the field of medicine and prosthetics. With the help of advanced 3D scanning technologies, medical specialists are able to evaluate the degree of bodily damage with high precision and to generate detailed and accurate digital models of the affected anatomical regions. This capability opens the door to new diagnostic methods, careful surgical planning, and the production of personalized prostheses and implants. These technologies enable medical professionals to determine the most appropriate and rational treatment solutions for each individual patient, which significantly enhances the chances of a faster recovery and a higher overall quality of life. Moreover, 3D reconstruction plays an essential role in simulating and modeling complex surgical procedures. This allows doctors to prepare in detail for upcoming surgeries, thereby improving both the safety and effectiveness of medical interventions.

Due to the conflict in Ukraine, the issue of creating customised implants and prostheses has become critical. Military and civilians who have been injured in the fighting need high-quality and fast medical care. Thanks to 3D reconstruction, doctors can create personalized prostheses that best match the anatomical features of each patient. This significantly reduces the time required for the preparation and production of implants, as well as improves their convenience and functionality. In addition, the latest research in the field of bioprinting allows the creation of tissues and even organs using 3D printers, which opens up new prospects in transplantation.

This paper proposes a methodology for creating a digital atlas of 3D models of human anatomy, which is intended to support clinical decisions in the field of prosthetics. A method has been developed that provides for the efficient management of 3D anatomical models with the ability to convert various types of data into a format suitable for 3D printing or reconstruction. The digital atlas provides for the systematic storage of detailed anatomical characteristics in a structured format, in particular in the form of descriptions of reference limb models integrated with a specialised database, which ensures convenient access, editing and efficient processing of anatomical information.

Literature review

In modern scientific research, great attention is paid to the creation of comprehensive and integrated 3D atlases of the human body, covering various levels of biological organisation — from individual organs and tissues to cellular structures, molecular targets and biomarkers, which are critically important for advancing personalised medicine. In particular, the international research programme HuBMAP (Human BioMolecular Atlas Programme) [1] has developed the Common Coordinate Framework (CCF), a unified coordinate system that serves as a robust platform for integrating 3D organ models, histological images, spatial transcriptomes and other omics data. This framework provides a standardised, unified and open digital space for in-depth analytical processing of complex biomedical data, which facilitates interdisciplinary collaboration between biologists, anatomists, bioinformaticians and clinicians. The use of modern biomedical ontologies, such as Uberon (for describing anatomical structures), FMA (Foundational Model of Anatomy) and CL (Cell Ontology), allows for efficient structuring, systematisation and annotation of large amounts of complex information, which is the essential basis for long-term development, ongoing project support and reproducibility.

The use of 3D printing plays an increasingly important role in modern medical education and the training of healthcare professionals. Numerous recent studies, including [2, 3], convincingly show that the creation of physical 3D models of anatomical structures significantly enhances spatial perception and understanding of the complex configurations of the human body. This leads to improved precision and greater confidence among future surgeons during preparation for surgical procedures, and also serves as a highly effective tool for interactive, hands-on learning for medical students. Despite existing technical challenges, such as relatively high costs of equipment and consumables, and the ongoing need for specialised personnel training, 3D printing technology is becoming more widespread and increasingly recognised as a powerful supplement to traditional methods of teaching anatomy and surgical planning.

A number of papers focus on the use of 3D modelling and printing to create personalised medical prostheses. In particular, the studies [4, 5, 6] show that combining 3D printing with bionic technologies and CT scanning allows development of highly functional and anatomically accurate prostheses maximally adapted to individual patient characteristics. The use of advanced computer-aided design and simulation environments helps customize prosthetic limb geometry and improve ergonomic, functional and aesthetic characteristics. An important addition is the use of specialised software for virtual implantation, as described in [7], and the recent development of anatomically accurate 3D printed prosthetic ossicles for ossicular chain reconstruction, extending 3D printing applications to delicate middle ear prostheses with high biocompatibility [8].

The reconstruction of bone structures using modern 3D technologies is covered in the studies [9, 10]. These demonstrate the importance of an individual approach to creating titanium prostheses and porous scaffolds that best match anatomical bone defect features, ensuring high mechanical stability, biomechanical compatibility and promoting osseointegration, which significantly increases implants' long-term durability.

Special attention should be paid to the fact that several studies, in particular [11, 12], demonstrate digital 3D reconstruction methods allowing fast, cost-effective, and highly accurate creation of models based on photographs and other digital data, replacing traditional labour-intensive impression methods. This greatly simplifies, automates and speeds up the prosthesis design process, reducing time and costs while improving the prosthetic fit accuracy.

The review of current research confirms the high relevance of creating a digital atlas of 3D models of human anatomy as a tool to support clinical decision-making in the field of prosthetics. The results of the analysis indicate the need for an integrated digital system that combines multi-level anatomical data (from macrostructures to the cellular level), standardised 3D models, CT/MRI images in DICOM format, medical reports, and textual descriptions of prostheses and anatomical standards.

Important functional requirements for such an atlas are:

1. Support for heterogeneous data types (3D models of various formats - STL, OBJ, DCM, as well as annotated images, text medical reports, omics data, etc.);
2. Integration of DICOM images and medical reports, which allows you to automatically match patient scans with the corresponding 3D models and prosthetic standards;
3. Search by textual descriptions of models and anatomical references, which allows you to quickly find relevant options for virtual planning of surgery or designing an individual implant;
4. The ability to adapt models to the patient based on CT data, taking into account individual anatomical features, which is especially important for the manufacture of prosthetic limbs, joint replacements and bone defect reconstruction;
5. Export of 3D models to formats suitable for 3D printing, while maintaining anatomical accuracy and compliance with the patient's physical parameters.

All of these aspects demonstrate that an effective digital atlas should not only store and structure complex 3D anatomical data, but also provide interactive, adaptive and clinically oriented functionality that will facilitate more accurate reconstruction, individualised treatment approaches, and decision support based on comparative analysis of anatomical models, clinical findings and prosthetic standards. The availability of tools for searching by text descriptions, automatic comparison with reference structures and the use of DICOM data allows doctors to quickly select the best intervention options, which significantly improves the quality of diagnosis, surgery planning and personalised prosthetics.

Therefore, the aim of this work is to develop a digital atlas of 3D models of human anatomy to support clinical decision-making in prosthetics. The digital atlas provides an efficient system for managing 3D anatomical models with the ability to specify data types for 3D printing or reconstruction. The digital atlas also provides the ability to store accurate anatomical characteristics in a structured manner, including descriptions of reference limb models linked to a specialised database, which ensures easy access and data processing.

Creating a digital atlas of 3D anatomical models

To achieve this goal, it is planned to design a specialised database of 3D anatomical models of the digital atlas, which will provide centralised storage, access and interaction with spatial medical data. In addition, it is planned to create an information system capable of efficiently working with heterogeneous sources of medical imaging, including DICOM images obtained as a result of computed tomography (CT) or magnetic resonance imaging (MRI), as well as 3D scans of physical models or anatomical objects and digital 3D models in STL, OBJ, BLEND and other popular formats. Of central importance in this process is bringing all the collected data into a single unified format that will be suitable for further computer processing, 3D printing and integration into clinical information systems. It is also important to ensure that rational solutions can be offered based on the data received, processed and compared, taking into account the individual characteristics of the patient. To better understand the logic of the digital atlas of 3D human anatomy models, which is focused on supporting clini-

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cal decision-making in the field of prosthetics, a conceptual diagram of information flows was developed, which reflects the key stages of data processing and integration (Fig. 1).

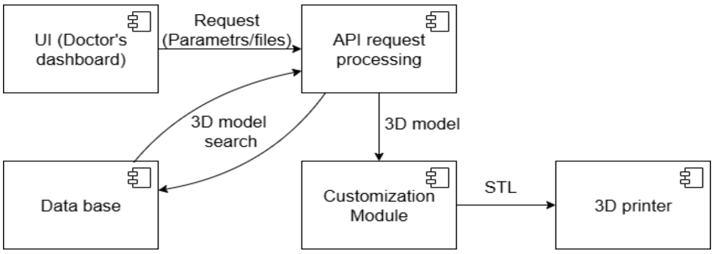

Fig. 1. Information Flow Diagram

The process begins with the formation of a request specifying the required parameters, which is sent to the API interface. Here, the input data is processed, checked for correctness, and prepared for further stages. The digital atlas supports work with DCM, STL, OBJ, BLEND, as well as PDF, DOCX, TXT files. DCM files are processed without any third-party medical software: ready-made 3D models are generated from them. Text documents are analysed to search for models by description. The results are saved in STL format, suitable for 3D printing and visualisation.

The main focus is on the personalisation module, which unifies models in different formats (DCM, OBJ, BLEND, etc.) by converting them into a single internal structure. Once the processing is complete, all data is exported to STL format, a standard for 3D printing.

The next step is to search for a 3D model in the database. Both reference and adapted models are available, taking into account individual parameters, including ready-made prostheses. The user can view the result and download it in the desired format.

The final step is to transfer the model to a 3D printer or other device for physical reproduction. The system covers the entire cycle from digital request to finished product, remaining flexible, scalable and adaptable to both educational and clinical tasks. Given the complexity and diversity of the data being processed, a key element of the system is a reliable and structured database capable of efficient storage, retrieval and reuse of 3D anatomical models.

The database design considers the specifics of medical formats, supports models with different levels of detail, and establishes clear links between 3D models, their sources, and related information. It is essential for the digital atlas, ensuring personalization, integration with clinical systems, and adaptability. Microsoft SQL Server is used for efficient data storage and management. The database includes Prosthesis, Model, and Etalon tables: Prosthesis stores data on prosthetic devices linked to Model, which holds 3D model descriptions; Etalon also links to Model but stores anatomical references. The structure of the database is shown in (Fig. 2).

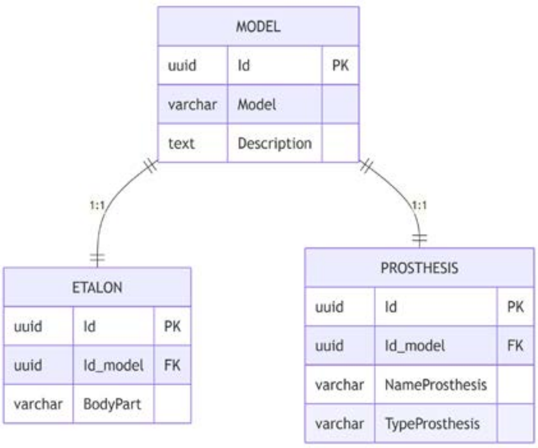

Fig. 2. Database Structure

Description of the structure of the database of prostheses and standards is given below.

The MODEL table contains a Model (varchar) field that stores the name of the model, and a Description (text) field that contains a detailed description of the model (anatomical for reference models or technical for prostheses). Each entry in this table corresponds to a separate 3D model. An example of a record in the Model table (Fig. 3).

MODEL			
UUID	Id	PK	4C0BFE48-54C5-4F32-AC80-F57350DD3430
binary	Model3D		0x424C...50DD
string	Description		hand, cosmetic

Fig. 3. Table Model

The ETALON table contains a foreign key Id_model that refers to MODEL. The BodyPart (varchar) field defines the anatomical region for which the reference is intended. The 1:1 relationship between MODEL and ETALON ensures that each reference model has only one corresponding entry. An example of an entry in the Etalon table (Fig. 4).

ETALON		
UUID	Id	6358A9E4-D0CF-4502-AE28-241F3FCD01C3
UUID	Id_model	4C0BFE48-54C5-4F32-AC80-F57350DD3430
string	BodyPart	Hand

Fig. 4. Table Etalon

The PROSTHESIS table also contains the Id_model foreign key that links it to MODEL. The NameProsthesis and TypeProsthesis (varchar) fields store the name and type of prosthesis (for example, "bionic"). The 1:1 relationship between MODEL and PROSTHESIS ensures an unambiguous correspondence to the prosthesis model. Thus, each model can be either a reference (linked to ETALON) or a prosthesis (linked to PROSTHESIS). An example of a record in the Prosthesis table (Fig. 5).

PROSTHESIS		
UUID	Id	AD4D8D5B-43B3-467E-9EF9-77448AD6B01D
UUID	Id_model	4C0BFE48-54C5-4F32-AC80-F57350DD3430
string	NameProsthesis	Hand
string	TypeProsthesis	Cosmetic

Fig. 5. Table Prosthesis

The proposed database structure ensures efficient data management and quick access to the necessary information. The use of a relational model allows for a clear organisation of the relationships between anatomical standards and prostheses, which ensures data unambiguity and ease of processing. The normalised structure minimises duplication of information and enhances the integrity of the database, while a well-thought-out system of foreign keys simplifies data search and analysis.

Unification of digital atlas data

The digital atlas supports the processing of heterogeneous types of data coming in the form of a text description of a prosthesis or reference limb, as well as in file format. The system accepts only certain types of files: three-dimensional models (STL, OBJ), medical images (DCM), text documents (TXT, DOCX), and PDF files. Formats that do not meet the requirements are automatically rejected at the upload stage.

Once the data is received, it is unified: text, image and volume files are converted to internally consistent structures to ensure correct interpretation and compatibility within the anatomical database. This allows the digital atlas to effectively integrate different types of information, contributing to the formation of a single space to support clinical decisions and design tasks related to prosthesis modelling and selection. A diagram of data unification for further processing is presented (Fig. 6).

Atlas provides comprehensive processing of input data for the generation of 3D prosthetic models. The user forms a request via the API, specifying the necessary parameters, after which the system analyses and verifies the input data, including medical scans in DCM format, 3D models (STL, OBJ) or text descriptions (PDF, DOCX, TXT). Medical scans are automatically converted into ready-made 3D models without the use of third-party software – this process is implemented through a Python script that uses PyVista libraries. PyVista is used to process volumetric data, build polygonal meshes, and perform further visualisation. Files in DCM format are processed by the pydicom library, after which a three-dimensional geometry is created, which can be exported to the required STL format. Conversion between formats is also performed automatically using PyVista and related tools [13].

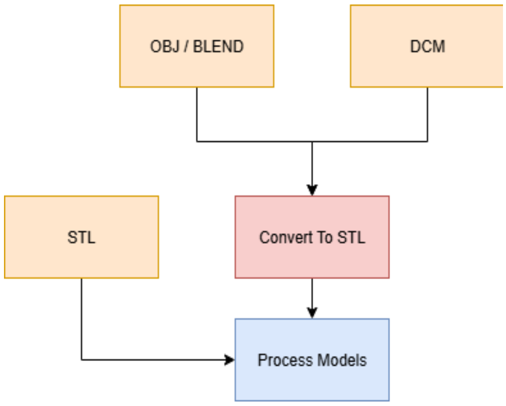

Fig. 6. Data Unification Diagram

Text files are used to search for relevant structures in the database, ensuring semantic correspondence between the query and the finished model. In cases where there is no text description, the system tries to recognise the name of the file that was uploaded. This happens according to the following algorithm:

1. The input string containing the full path to the file is normalised - all backslashes are replaced with forward slashes to unify the format, unnecessary consecutive delimiters and edge spaces are removed;
2. Each character of the string is analysed sequentially;
3. If the character does not belong to the set delimiters (slash, backslash, underscore, period, hyphen), it is added to the current word buffer;
4. When a delimiter is encountered, the contents of the buffer are added to the resulting word list, and then the buffer is cleared to accumulate the next word;
5. After the entire string is processed, the result is filtered to remove empty lines that may have been created by several consecutive delimiters, and, if necessary, all words are lowercased;
6. The final list of words obtained by dividing the original path by the specified delimiters is returned as the result of the algorithm.

After that, the database is searched using the list of words obtained. Using the Description field, the system finds the highest-priority limb reference models or prosthesis models.

Conclusions

Based on the analysis of the current state of 3D modelling and the current needs in the field of medical prosthetics, potential opportunities were identified for developing a methodology for creating a digital atlas of 3D models of human anatomy for prosthetics that implements the functionality required by specialists in the field of medicine, bioengineering and technical modelling. Based on an understanding of these requirements, a list of key components was identified, including automated 3D reconstruction, medical scan processing, and adaptation of reference models to individual anatomical defects.

As part of the development, we created an architecture for a methodology that integrates the processing of CT/MRI data in the DCM format with subsequent automatic conversion into 3D models (STL, OBJ, BLEND) through Python scripts using PyVista libraries. A model search mechanism based on text markers has also been implemented, which significantly speeds up the selection of prostheses without processing the full geometry.

Further development may include expanding the library of 3D models of anatomical structures and improving methods for classifying and comparing models to ensure full automation of the process of selecting anatomical structures. This will allow for a more accurate consideration of individual patient characteristics and provide more efficient decision support in clinical practice. Additionally, the development of mechanisms for filtering and contextual comparison of models with medical data will help to create a more adaptive and flexible system capable of responding to a wide range of clinical scenarios.

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