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A THREE-DIMENSIONAL REVOLUTION IN MEDICINE—THE USE OF 3D PRINTING TECHNOLOGY IN ORTHOPEDICS, SURGERY, AND NEUROSURGERY

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ABSTRACT

3D printing has become one of the most dynamically developing technologies in medicine in recent years, and the use of products made using a 3D printer is increasingly influencing medicine in areas such as medical education, surgery planning, personalizing implants and tissue engineering. Despite how quickly this field is developing, research and discussions are still ongoing whether this technology is safe for the patient, cost-effective and how it affects the health care system in the long term. The aim of this work is to present the applications of 3D printing in medicine and to assess its benefits, development prospects and limitations.

Brief description of the State of Knowledge: The narrative review presents the current state of knowledge about 3D printing in medicine, with particular emphasis on the operation of this technology in the fields of orthopedics, surgery and neurosurgery. The most popular methods of producing 3D models, the main advantages and disadvantages of the technology and predictions for the future development of the field of 3D printing in the development of medicine were discussed.

Methodology: A narrative literature review was conducted. The analysis covered scientific publications on 3D printing in healthcare. Sources from 2019-2025 were included, searching for terms such as: “3D printing in medicine,” “additive manufacturing in healthcare,” “personalized implants,” “3D printing,” “surgical models,” and “the future of 3D printing in medicine.”

KEYWORDS

3D Printing, Additive Manufacturing, Prosthetics and Implants, Customized Implants, Preoperative Simulation, Medical Innovation, Surgical Planning, Patient-Specific Models

CITATION

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Introduction

3D printing (additive manufacturing) is a technology that involves the production of three-dimensional products based on a digital model. It enables the precise reproduction of specific structures, training models, components, and anatomical representations. The design prepared in CAD (Computer-Aided Design) software is printed layer by layer to prevent waste of raw materials. [1]

Over the past two decades, we have seen rapid development in 3D printing technology in medicine. But how did it all begin? The history of 3D printing began in the 1980s, when Charles Hull invented 3D printing, which he called “stereolithography.” [2,3] The next step was to construct the first 3D printer, which was launched on the market in 1988. [4] Over the next few years, intensive research was conducted on them [5,6]. Over the years, more and more companies began to produce their own printer models and introduce increasingly improved models. Production was revolutionized and they were put to use in many fields, including medicine. [4] Particularly rapid development was observed in the early 2000s, when this technology began to be used in the manufacture of prostheses and dental implants. [7] The next step was the spread of biocompatible metals, such as titanium alloys and medical polymers, in 2010-2015. [8] With the development of 3D printing technology, this enabled the production of implants and prostheses with customized porosity and scaffolds to facilitate tissue regeneration. [9] After 2015, there was a dynamic development of cell bioprinting, which ushered in a new era and made it possible to produce skin, cartilage, bone, and other tissues on a large scale. [10]

3D printing in medicine primarily paves the way for the production of personalized, individually tailored, anatomically compatible prostheses and implants. This generates greater benefits for patients and doctors alike. [11] It ensures shorter waiting times for prostheses or implants and cheaper production than conventional methods. 3D technology is primarily used in orthopedics and surgery. In surgical fields, thanks to the individual adaptation of prosthesis models to the patient's anatomy, it allows for shorter operation times. [12,30] This increases the availability of medical staff and operating rooms, which benefits other patients. It ensures shorter hospital stays and recovery times, which is also important in economic terms. By increasing the certainty of prosthesis fit and reducing the amount of materials and tools needed for production, 3D technology can save up to several thousand dollars. [13,24,25,26]

The aim of this paper is to analyze and evaluate the use of 3D printing in orthopedics, surgery, and neurosurgery based on available scientific literature, with particular emphasis on its role in planning surgical procedures, manufacturing personalized implants, and creating digital training models. The choice of topic was dictated by the dynamic development of 3D printing technology in modern medicine. It opens up new possibilities, leads to shorter operating times and reduces the number of perioperative and postoperative complications. It also improves communication between the patient and the doctor. [28]

Materials and Technologies Used in 3d Printing

Additive Manufacturing (AM) is a term used to describe the process of combining materials layer by layer to create a three-dimensional physical object using computer-designed models. Models can be created using a variety of materials, such as ceramics, metals, liquids, powders, plastics, or even living cells. This process is commonly referred to as "3D printing," and the "printing" process itself involves melting or depositing materials onto the substrate of a 3D printer. AM is a process characterized by rapid production, unlike traditional methods (e.g., subtractive manufacturing methods), and a significant advantage is the ability to create unique or low-volume products that will be manufactured with digital precision. [14]

The most commonly used 3D printing technologies in medicine

FDM (Fused Deposition Modeling) is the most popular 3D printing technology, which involves heating a thermoplastic polymer filament to high temperatures. The semi-liquid polymer is then extruded from a heated nozzle and laid down according to the design on the working platform (base) of the 3D printer. After one layer has been deposited, the process is repeated layer by layer until the finished solid designed in the CAD system is obtained [9].

SLA (stereolithography) is the oldest method of manufacturing objects in 3D. It was developed by Charles Hull in 1984. To create objects using this technique, a high-energy light source and photo-reactive resin or monomer solutions are used. [15] The process involves pouring a photo-reactive material into an SLA printer, then a laser or highly focused UV light creates the desired structure in the liquid by solidifying the appropriate fragments in the liquid. [16] SLA products are also created layer by layer, but in this case, the base platform changes its position relative to the laser, making room for subsequent layers of the final product. This method is used to create microdevices for medical applications, such as microneedles, cell culture scaffolds, blood vessel models, dental prostheses, or anatomical models used for surgical planning. This method is very precise compared to other 3D printing methods, but this makes it very time-consuming and more expensive than others. [15]

SLS (Scaffold) is a selective laser sintering method that uses powder as a building material, which is then bonded together under high temperatures using a laser beam to form the desired pattern. This method is used to create biocompatible and biodegradable polymer scaffolds, allowing for a final product with high mechanical strength, making it a great solution in tissue engineering, especially in bone engineering. SLS is a precise and durable process, but its biggest limitation is the temperature at which the materials are welded together, which can reach up to 1400 degrees Celsius. [9]

SLM (Selective Laser Melting) is a technique that is very similar to SLS, but is designed for different types of materials. In SLS, the material used as a building block is polymer powder, while SLM uses metal powder, most often aluminum or titanium.[17]

The most commonly used materials in 3D printing in medicine

The choice of a specific material for 3D printing depends on the patient's needs and the mechanical and biological requirements of the application. Various materials are used, including synthetic polymers (e.g., PLA, PA12, or PEEK), metals (e.g., titanium, aluminum, cobalt-chromium alloys), bioactive composites, and, in recent years, 3D printing using ceramics has also begun to gain popularity.

The table below groups the most popular materials used in 3D printing according to the type of printing technique they are used for and the type of end product:

Material	Properties	3D printing technique	Medical application
Synthetic polymers (PLA, PA12, PEEK)	Biocompatible, flexible, easy to adapt and customize	FDM	Implants, tissue engineering, drug delivery systems
Ceramics	Mechanically strong, biocompatible, osteoconductive	SLA	Bone tissue engineering, dental fillings
Composite materials (graphene, carbon fibers)	Lightweight, high strength, electrical conductivity	SLS	Tissue engineering, drug delivery systems
Metals (titanium, aluminum, stainless steel, cobalt-chromium)	High strength, stainless, biocompatible	SLM	Implants, prostheses, dental fillings
Biomaterial	Biocompatible, biodegradable	SLS, FDM	Tissue engineering, wound treatment

table: own compilation based on Mamo, H. B., Adamiak, M., & Kunwar, A. (2023). 3D printed biomedical devices and their applications: A review on state-of-the-art technologies, existing challenges, and future perspectives. *Journal of the mechanical behavior of biomedical materials*, *143*, 105930.https://doi.org/10.1016/j.jmbbm.2023.105930

The Use of 3d Technology in Orthopedics and Surgery

3D printing technology is becoming increasingly important in the fields of orthopedics and surgery. Thanks to the use of imaging tests such as X-rays, MRIs, and CT scans, it can reproduce the patient's anatomy with great accuracy. [18] This ensures the individualization of the process of creating prostheses and orthoses for patients, which translates into a better fit of the equipment to the body and increased comfort, as well as reduced production time and costs. [19]

The first step in the production of prostheses using 3D technology is to create a digital model of the patient's lower or upper limb using an image obtained from imaging tests. Based on this data, a virtual model is created, which can later be printed using special materials [16,17]. Unlike standard casting methods (in plaster), this allows for accurate reproduction of the patient's anatomy, including all depressions, protrusions, irregularities, and the type of stump surface. [19,20] The creation of virtual prosthesis models also allows for the adjustment of the thickness of the material from which they are made, their weight, flexibility, and even color, which is particularly important among the youngest patient population and ensures greater acceptance and psychological comfort for patients. [19,47] Thanks to this, we are able to use printers to create equipment that is well-suited to the patient. This ensures greater comfort of use for the patient and reduces the risk of chafing and skin irritation.

An important feature of the technology used in 3D design is the ability to simulate pressure. This allows for the selection of the appropriate material for the prosthesis, as well as the adjustment of its flexibility and thickness to ensure resistance to material wear. As a result, the prosthesis is adapted to the load of the patient's individual stump, which ensures optimal distribution of pressure forces, greater strength, and durability. [19,21,22,48]

During post-operative rehabilitation, the shape and volume of the stump change as a result of swelling subsiding, healing, and scar tissue forming. The prosthetic socket then becomes too loose and ill-fitting, which causes problems with movement, pain, and discomfort for the patient. In such a situation, it is necessary to change and readjust the prosthesis. The use of standard casting methods would then involve a longer waiting time for a new prosthesis, which would also generate additional costs. Thanks to 3D technology, this process is much faster, and the production time for a new prosthesis can be reduced from several months or weeks to even a few days. [21,22]

All that is needed is to rescan the limb and update the previously generated design, which ensures a quick and much cheaper than standard methods creation of a new prosthesis model, tailored to the patient's current image. [23] In addition, the digital design is stored in a database, which allows doctors to return to previous prosthesis models to compare the dynamics of changes in the patient's morphology and modify the treatment and rehabilitation process on this basis.

3D technology is also beneficial in economic terms. Traditional prostheses can cost thousands of dollars, while the price of prostheses made using 3D technology can be reduced to between several dozen and several hundred dollars, depending on the type of materials used and the complexity of the prosthesis. [13,24,25,26]

The Use of 3d Technology in Traumatology

Traumatology is a field of orthopedics that deals with the treatment of injuries and fractures resulting from accidents, falls, or other unexpected events. The use of 3D printing technology in this field is particularly promising due to the diversity and complexity of the resulting pathologies (damages).

The effectiveness of 3D technology surpasses that of conventional technologies. A study conducted on a group of 13 patients proved that the duration of surgery using 3D technology was shorter than when using conventional methods. Thanks to 3D technology, a slightly higher percentage of patient satisfaction with the functioning of the upper limb after surgery was observed. [27,48] In addition, studies have shown a reduced frequency of fluoroscopy, which is associated with reduced exposure of patients and medical staff to harmful ionizing radiation [29,31,33]. This is further confirmed by studies conducted on patients who underwent wrist bone surgery. It has been proven that the duration of surgery, the period of radiation exposure, and the amount of blood lost during surgery were reduced. This allows us to conclude that operating with the use of 3D printing technology allows surgeons to operate faster and safer, reducing bleeding and X-ray exposure for patients and staff. However, long-term observation of patients after surgery and their assessment using the Gartland-Werley scale did not prove better wrist functionality—its mobility and range of motion were similar in both patients operated on using conventional methods and those using 3D techniques. [28] In addition, 3D technology improves communication between patients and staff and allows patients to better understand the type of surgery they are undergoing and the nature of their injury. [28] As in the case of the upper limb, the use of 3D technology in lower limb traumatology is becoming increasingly successful. The best example is tibial plateau fractures, which, due to the complexity and multi-fragment nature of the injury and, in most cases, its intra-articular character, pose a challenge for orthopedics. Therefore, the need for precise planning and execution of surgery has drawn attention to the rapidly developing technology of 3D printing. In a meta-analysis conducted in a group of patients with Shatzker type IV-VI fractures, as in the case of the upper limb, the duration of surgery performed with the help of 3D techniques is reduced compared to conventional methods. This is mainly due to better preoperative planning and the possibility of analyzing the patient's case on a created 3D model. 3D techniques enable accurate mapping of the patient's anatomy and the morphology of a complex fracture, accurate visualization and positioning of fragments, the condition of the joint surface, and the degree of damage to ligaments and structures around the fracture. This allows surgeons to determine the method and sequence of the operation before it begins, precisely adjust screws and bone plates, and avoid wasting time during the operation on anatomical orientation. Better spatial visualization on a 3D model reduces the number of corrections and technical errors, which shortens the duration of the procedure and reduces the need for reoperation in long-term treatment. All this contributes to increased safety of the procedure, less blood loss, shorter anesthesia time for the patient, and less exposure to radiation. In addition, patients operated on using 3D technology, thanks to greater precision and accuracy during the procedure, show better functioning after the procedure, faster healing, and less postoperative pain. [29]

3D technology is particularly helpful in surgeries involving patients with complex hip socket injuries. Analyzing the patient's anatomy before surgery and printing implants tailored to the morphology of the fracture allows for the plates to be adjusted to the shape of the bone in advance, rather than during surgery. In addition to shortening the duration of the procedure and reducing blood loss, this results in a more accurate reconstruction of the patient's anatomy. [12,30]

Similar results were shown in a meta-analysis conducted in a group of patients with calcaneal, talocalcaneal, and pilonidal fractures. In this case, the use of 3D techniques also resulted in shorter surgery times, less blood loss, and a reduced number of fluoroscopies. [31]

In addition to the use of 3D techniques for precise preoperative planning, its potential is also evident in the creation of implantable components that are personalized for the patient and their condition. In a study conducted by Liang et al. [32] compared the treatment of complex transtarsal fractures using an implantable fracture stabilization plate (for osteosynthesis) produced by 3D printing with conventional treatment methods using a titanium plate. The customized plate was designed according to the patient's CT scan, tailored to the patient, and then printed using a 3D printer. It was observed that the duration of the operation with the 3D-printed plate was shorter than that of the procedure performed with the implantation of a titanium plate. As in the above-mentioned studies, blood loss and radiation exposure were also reduced. However, the preparation time for the procedure was longer in patients with planned implantation of a personalized plate. This was due to the additional time needed for its preparation and printing. The results of joint functionality after the procedure were higher in patients with a 3D-printed plate implanted.

The Use of 3d Technology in Neurosurgery

3D printing is a breakthrough in modern reconstructive neurosurgery. It enables the creation of accurate visualizations of the patient's anatomical structures, such as the skull, vertebrae, blood vessels, and intracerebral elements. This allows neurosurgeons to thoroughly analyze the complexity of the patient's pathology and practice operations on a pre-printed 3D model. As a result, the duration of the operation and the patient's stay under anesthesia are reduced. In addition, the number of predictable intraoperative complications is reduced. [33]

Personalized, 3D-printed implants (such as PEEK) show better anatomical compatibility with the patient. They are well tolerated and lightweight, and their strength is comparable to that of real bone. [34] Unfortunately, the costs of such implants are very high, which is why their use is limited. [35]

Spinal disorders are one of the most common reasons for neurosurgical procedures. The history of 3D printing in spinal surgery dates back to 1999. At that time, the first preoperative model of the spine was created based on the patient's imaging studies. [36]

The use of 3D-printed spinal models provides an accurate visualization of the anatomy and degree of deformation of the patient's spine. This allows for better preparation for surgery, thereby shortening its duration and reducing the risk of complications and intraoperative bleeding. [37,38] Printed models are also used in the training of medical personnel. Unlike standard replicas, they contain detailed elements and pathologies. The high fidelity of the model provides a good basis for educating the younger generation of doctors and improving surgical procedures. [39]

In vascular neurosurgery, 3D printing also allows the creation of personalized models of cerebral vessels based on patient imaging studies, which plays a key role in the treatment of complex aneurysms and vascular malformations. [40]

In the case of aneurysms, generating a 3D print in advance allows for the analysis of surgical access and the assessment of aneurysm parameters such as shape, size, and its relationship to the parent vessel. [41]

Innovative 3D training models realistically reflect not only the anatomy of cerebral vessels and their pathologies. They enable not only learning how to prepare and clip, but also simulate emergencies that may occur during surgery, such as aneurysm rupture and intraoperative hemorrhage. This allows the surgeon to practice operating in such conditions and thus reduce mistakes in real situations, during surgery on a real patient [33,42].

The Future of 3d Printing in Orthopedics, Surgery and Neurosurgery

Additive manufacturing (AM), commonly known as 3D printing, is recognized as a technology that could revolutionize the healthcare sector. One of the strongest advantages of this technology is its ability to personalize, i.e., tailor a product precisely to the requirements and needs of an individual patient. As a result, 3D printing can fundamentally improve the effectiveness of treatment and clinical outcomes in complex areas of medicine such as surgery and orthopedics. [21]

In surgery, the development of in situ printing technology, i.e., printing structures directly in the patient's body during surgery, is predicted. This mechanism involves the possibility of depositing layers of biomaterials, cells, and growth factors at the site of damage or loss. The first trials of this technique were conducted in the field of skin regeneration and cultivation, and future goals include internal organ reconstruction and reconstructive surgery. [21]

In orthopedics and traumatology, 3D printing technology will significantly influence the development of next-generation implants, prostheses, and surgical instruments. One of the main areas of progress in this field is the development of structures that enable better osseointegration, i.e., the effective fusion of implants with the patient's bone tissue. Future implants will be designed to take biomechanical loads into account, which will increase their strength, improve patient comfort, and extend their service life. [43] In these areas, the integration of 3D printing with "smart" technology is also anticipated, which will allow sensors monitoring pressure, temperature, or joint function to be installed in prostheses or implants. A major challenge in the development of this technology remains ensuring the full biocompatibility of the materials used to print implants and prostheses. [43]

In the longer term, the combination of 3D printing with tissue engineering and regenerative medicine is also anticipated. This will enable the production of “biohybrid” prostheses and orthopedic implants colonized by the patient's cells. Such a combination has the potential to create implants that will eventually remodel into natural tissue, eliminating the need for surgical revisions. [43]

Neurosurgery is also feeling the strong impact of advances in 3D printing technology. This is primarily due to bioprinting of neural structures, nerve regeneration, and personalized skull implants. In the long term, 3D printing may enable the creation of scaffolds to support nerve tissue reconstruction and regeneration after central nervous system injuries, which could result in effective treatment of, among other things, brain and spinal cord injuries.

In the future, cranial implants may be highly personalized and manufactured from bioactive materials that support osteogenesis, thereby minimizing the risk of infectious complications. The possibility of using 3D printing to construct nerve tissue fragments and test drugs for neurodegenerative diseases is also being considered. [44]

The advancement of 3D printing in medicine also presents numerous technological, ethical, and regulatory challenges. At this point, the biggest limitations are the low strength of some materials, very limited multi-material 3D printing, and print resolution. However, the biggest challenge is the issue of long-term material safety in terms of degradation and the risk of inflammatory reactions. [43]

Another direction that may prove to be a breakthrough is so-called 4D printing, i.e., the printing of intelligent structures that change their properties under the influence of stimuli or time. This type of material could be used in orthopedics, e.g., in implants that adjust their stiffness to the stage of healing of damaged bone tissue. [45]

The future of 3D printing lies in the transition from static structures to bioactive, fully personalized solutions that will play a major role in surgery, orthopedics, neurosurgery, traumatology, and many other fields of medicine. It is predicted that 3D printing will become a pillar of personalized medicine, enabling more effective treatment and reconstruction of tissues and organs, and above all, greater comfort for patients.

Advantages and Disadvantages of 3d Printing in Medicine

The introduction of 3D printing into medicine has opened up incredible prospects for the development of a completely new branch of medical technology. 3D printing offers great hope in many areas of medicine. However, it is not a technology that will solve all problems. On the contrary, this technology has created its own challenges, such as technological effectiveness, costs, safety, and the prevalence of its use.

Advantages

Many scientific studies present 3D printing as a tool that saves time, primarily during surgery, but also affects the cost of producing prostheses, implants, and orthoses, and improves patient comfort and safety. [46] The printing process is not the longest part of the prosthesis manufacturing process; the most difficult element of this complex puzzle is the precise design of the product in CAD programs. [32] Saving time during surgery can result in better overall treatment outcomes, including reduced need for pain medication, less time spent under anesthesia, and reduced risk of infection.

The personalization of medical solutions is another major advantage in the field of medicine. Thanks to 3D printing, it is now easy to create not only implants but also personalized tools that provide greater comfort for the patient. Adapting the product to the patient's anatomy is particularly important in cases of non-standard body deformities, tumors, or developmental defects. In such situations, standard implants may be useless in treatment. In traumatology and orthopedics, personalized implants or surgical and postoperative tools allow for precise reconstruction of bone structures, improved clinical outcomes, and increased patient comfort and satisfaction. [47] In traumatology and orthopedics, 3D printing also plays a very important role in bone implants. Thanks to the possibility of printing materials with a porous structure, printed implants can reproduce the mechanical properties of cancellous and cortical bone, which promotes the process of osseointegration and eliminates the phenomenon of "stress -shielding" phenomenon that occurs with prostheses created using traditional methods, and allows the creation of complex structures that enable a better fit to bone surfaces, thus reducing the risk of implant loosening in the future. [48]

Contemporary biomaterials used as building blocks in 3D printers are also noteworthy. Synthetic polymers combined with natural materials such as collagen or hyaluronic acid result in products with high mechanical strength that also benefit from biological properties supporting cell differentiation processes. [49]

Disadvantages

Although 3D printing is a breakthrough in medicine and offers a wide range of benefits, this technology also has its significant drawbacks. One of the main problems with 3D printing is the time-consuming nature of the design and model preparation process. Creating a precise model of a finished prosthesis for a patient can take up to several weeks, which limits the use of this technique in emergencies that require immediate intervention. Costs are also a significant limitation, and these can amount to enormous sums of money. The costs include not only the equipment, i.e., the 3D printer and its accessories, but also the cost of materials and specialized software, as well as the necessary training for medical personnel. [49]

In some cases, the complexity of the process and the need for cooperation between multiple specialists will also be a major limitation of this technique. Operations performed using fillings or implants created using 3D technology require the involvement of 3D modeling technicians, surgeons, biomedical engineers, and radiologists. This is a significant obstacle for many facilities, and a lack of smooth communication can lead surgeons to fear losing control over the planning stage of the procedure. [46]

Conclusions

3D printing technology is having a huge impact on medicine today, and in particular, the use of three-dimensional printing is proving effective in fields requiring high precision and an individual approach to the patient, such as orthopedics, surgery, traumatology, and neurosurgery. The use of 3D models allows for more accurate surgical planning and preoperative simulation, reducing surgery time, limiting the risk of complications, and improving the effectiveness and results of treatment.

One of the most popular and common applications of 3D printing technology is prostheses and implants, which, thanks to their ability to be individually tailored to the patient's anatomy, provide greater stability, comfort, and functionality after surgery. In orthopedics and traumatology, this technology enables precise reconstruction of complex bone structures, but also supports the healing process by mapping tissue biomechanics. In neurosurgery, anatomical models printed using 3D printing allow for accurate and detailed analysis of nerve structures and the development of more precise surgical techniques. Additive Manufacturing has many advantages, but this technology still faces significant challenges. Technical, legal, and economic limitations often hinder the development of this field. Several examples of such limitations include: limited availability of biocompatible materials, high costs of implementation and maintenance of this technology, and lack of standardization in the implant manufacturing process. Despite this, the future looks promising, and advances in bioprinting and materials engineering may contribute to the production of functional tissue structures or even organs. This will open a new chapter in medicine.

In summary, 3D printing is a technology with incredible clinical and research potential, and its development should be closely monitored and studied, as 3D printing is certain to become an integral part of modern, personalized medicine in the coming years.

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