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The Technological Advances of 3D Printing in Orthopedics and Sports Medicine

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ABSTRACT

3D printing has revolutionized orthopaedics and sports medicine by offering personalized and effective solutions for the treatment and prevention of injuries. In orthopaedics, the technology enables the manufacture of prostheses and implants adjusted to the patient's anatomy, as well as scaffolds for bone regeneration. In sports medicine, personalized devices such as face masks and insoles improve athletes' performance and recovery. Recent advances include tissue bioprinting for cartilage and ligament regeneration, as well as surgical planning tools that reduce complications. Despite challenges such as regulation and cost, the outlook includes the development of biocompatible materials and integration with artificial intelligence, broadening the scope of personalized medicine. 3D printing is becoming an indispensable ally for more efficient treatments adapted to individual needs.

Keywords: 3D Printing, Orthopaedics, Sports Medicine, Personalization, Bioprinting, Tissue Regeneration, Medical Technologies.

INTRODUCTION

3D printing, or additive manufacturing, has revolutionized several areas of medicine, including orthopaedics and sports medicine. This technology enables the creation of precise anatomical models, customized prostheses and medical devices adapted to the individual needs of patients and athletes. Combining innovation and efficiency, 3D printing has proven to be a powerful tool for improving diagnoses, treatments and injury recovery (Wu et al., 2022).

In orthopaedics, 3D printing is widely used to develop customized implants and prostheses. 3D printed bone implants can be designed to adapt perfectly to the patient's anatomy, promoting greater comfort and efficiency in treatment. Recent studies show that these devices offer better integration with biological tissues, reducing the risk of rejection and post-operative complications (Zhang et al., 2021).

In addition, technology has made it possible to create personalized surgical guides. These guides help surgeons perform procedures with greater precision, reducing operating time and improving results. According to Peng et al. (2020), the use of 3D printed guides in orthopaedic surgery has reduced hospitalization time by up to 25% compared to traditional methods.

In sports medicine, 3D printing has been used to develop customized protective equipment such as helmets, orthoses and insoles. These devices are designed to meet the specific biomechanical needs of each athlete, contributing to injury prevention and increased sports performance (Chin et al., 2023).

In addition, technology is key to the development of advanced sports prostheses. Athletes with disabilities have benefited from lightweight and resistant prostheses designed to withstand high levels of impact and provide optimized mobility. One notable example is the use of customized running blades for paralympic athletes, which are created based on precise scans of the users' residual limbs (Wu et al., 2022).

Another important advance is related to rehabilitation. 3D printed rehabilitation devices, such as dynamic orthoses, are designed to assist in the recovery process of sports injuries, allowing personalized adjustments during treatment (Wu et al., 2022).

Despite significant advances, 3D printing in orthopaedics and sports medicine still faces challenges. The regulation of 3D printed medical devices is one of the main obstacles, as it requires rigorous testing to ensure safety and efficacy. In addition, the initial costs of the technology can be high, limiting its adoption in clinics and hospitals (Li, Y et al., 2023).

However, the continued evolution of printing techniques and biocompatible materials promises to overcome these barriers. Future innovations include the printing of biological tissues and functional organs, which could completely transform medical practice. The integration of artificial intelligence with 3D printing could also accelerate the development of even more personalized and effective solutions (Li, Y et al., 2023).

3D printing has established itself as a technology in orthopaedics and sports medicine, offering innovative solutions that improve patients' quality of life and athletes' performance. With continued advances in this area, it is expected that the technology will become increasingly accessible and integrated into day-to-day clinical practice, redefining the standards of treatment and recovery.

OBJECTIVES

General Objective

To analyze the technological advances of 3D printing in orthopedics and sports medicine, highlighting its main applications, benefits and challenges, as well as the impact of this technology on improving medical treatments and sports performance.

Specific objectives

- ✓ To explore the applications of 3D printing in orthopaedics, with a focus on the development of implants, prostheses and personalized surgical guides that promote greater precision and efficiency in treatments.
- ✓ To identify the advances of 3D printing in sports medicine, addressing the development of personalized devices, such as orthoses, insoles and protective equipment, which contribute to injury prevention and optimize the performance of athletes.
- ✓ Analyze the clinical and sporting benefits provided by 3D printing, such as reduced recovery time, better integration of devices into the human body and greater comfort for patients and athletes.
- ✓ Discuss the challenges associated with the use of 3D printing in the medical field, including issues related to regulation, costs and technical limitations.
- ✓ Present future prospects for the use of 3D printing in medicine, highlighting potential innovations such as the integration of biomaterials and the development of printed functional tissues and organs.
- ✓ To provide a theoretical basis for researchers and professionals in the field, encouraging the use of 3D printing as a strategic tool for advances in orthopaedics and sports medicine.

METHODOLOGY

Type of research

This study is characterized as bibliographical and descriptive research, focused on identifying and analyzing the technological advances of 3D printing applied to orthopaedics and sports medicine. The approach is qualitative, focusing on the analysis of scientific publications relevant to the topic.

Data Sources

- ✓ Data was collected from scientific articles indexed in international databases, including:
- ✓ PubMed: Source of medical and clinical studies.
- ✓ Scopus: Covering systematic reviews and technological research.
- ✓ IEEE Xplore: For publications related to biomedical engineering.

- ✓ Publications between 2018 and 2023 were analyzed, ensuring that the information was up-to-date. Articles in English, Portuguese and Spanish were used as selection criteria.

Inclusion and exclusion criteria

Inclusion criteria

- ✓ Studies discussing the application of 3D printing in orthopaedics and/or sports medicine.
- ✓ Peer-reviewed articles published in scientific journals.
- ✓ Papers focusing on technological innovations and their clinical and sporting impacts.
- ✓ Exclusion criteria
- ✓ Studies with no practical application or direct clinical relevance.
- ✓ Papers published before 2018.
- ✓ Opinion articles, editorials or reviews without clear methodology.

Search strategies

- ✓ The keywords used were combined in order to broaden the scope of the searches:
- ✓ "3D printing in orthopedics"
- ✓ "3D printing in sports medicine"
- ✓ "customized implants 3D printing"
- ✓ "additive manufacturing in rehabilitation"
- ✓ "3D-printed prosthetics for athletes"

The Boolean operators "AND" and "OR" were used to refine the results, and specific filters were applied to exclude studies that did not meet the inclusion criteria.

Data collection

The selected articles were organized using reference management software, such as Mendeley, to facilitate sorting and categorization. Each article was assessed for:

- ✓ Methodological quality.
- ✓ Relevance of the results presented.
- ✓ Clinical and sporting impact of the technologies discussed.

□ **Data analysis**

- ✓ The data was analyzed qualitatively, with the aim of identifying:
- ✓ Main areas of application of 3D printing.
- ✓ Clinical and sporting benefits of the technology.
- ✓ Challenges and limitations reported in the literature.
- ✓ The results were grouped into categories, such as:
- ✓ Customized implants.
- ✓ Rehabilitation devices.
- ✓ Protective equipment for athletes.

RESULTS AND DISCUSSION

Biomechanical analysis is a fundamental tool in orthopedics, providing a detailed understanding of mechanical forces and body movements. This field combines principles of engineering and physiology to study the behavior of the musculoskeletal system under normal and pathological conditions. Its application in orthopaedics is broad, ranging from the diagnosis of dysfunctions to the planning of surgical interventions and conservative treatments.

Biomechanics enables the identification of abnormal movement patterns that can contribute to orthopaedic conditions such as arthrosis, scoliosis and sports injuries. Studies show that gait analysis, for example, can help in the early diagnosis of conditions such as osteoarthritis (Astephen Wilson et al., 2020).

In addition, it is used to develop personalized orthopedic devices, such as orthoses and prostheses, which improve functionality and reduce pain (Prithvi et al., 2018).

In surgical orthopaedics, biomechanical analysis plays a crucial role in planning procedures such as arthroplasties and deformity corrections.

Techniques such as finite element modeling help predict the behavior of implants and tissues in different scenarios (Taylor et al., 2024). This allows for a more precise and personalized approach, reducing the risk of surgical failures and post-operative complications.

In addition to diagnosis and treatment, biomechanics is essential in the rehabilitation of orthopaedic patients. Rehabilitation programs based on biomechanical analysis can be more effective by addressing the underlying causes of dysfunction, promoting faster functional recovery (Escamilla et al., 2022).

It is also widely used in injury prevention, especially in athlete populations, by identifying biomechanical risk factors (Hewett et al., 2022).

Biomechanical analysis is indispensable in modern orthopaedics, contributing to more accurate diagnoses, personalized interventions and more effective rehabilitation strategies. Its seamless integration with advanced technologies such as motion sensors and artificial intelligence promises even greater advances in orthopaedic care.

A review of the literature on 3D printing in orthopaedics and sports medicine highlights three main areas of impact.

According to Zhang et al. (2021), 3D manufacturing of bone implants improves integration with biological tissues, reducing complications and speeding up recovery.

Peng et al. (2020) emphasize that patient-specific guides increase the accuracy of procedures, saving time and hospital costs.

Wu et al. (2022) point out that 3D printing has enabled the creation of adapted orthoses and insoles, essential for rehabilitation and prevention of sports injuries.

3D printing has contributed significantly to the creation of personalized solutions in orthopaedics. Bone implants designed specifically for the patient's anatomy improve success rates in surgery. In addition, 3D-printed prostheses are lighter and more comfortable, helping with patient rehabilitation and mobility (Zhang et al., 2021).

In sports medicine, the manufacture of protective devices, such as customized orthoses and helmets, allows athletes to receive treatments adapted to their biomechanical needs. These devices reduce the risk of injury and optimize performance. Chin et al. (2023) highlight the impact of technology on rehabilitation, especially in the creation of adjustable devices during treatment.

Despite the advances, 3D printing faces major challenges: Regulation: The lack of clear standards for 3D printed medical devices may delay their large-scale adoption (Peng et al., 2020).

Although costs are decreasing, 3D printing still requires significant initial investment.

3D printing, also known as additive manufacturing, has been transforming several areas of medicine, including orthopaedics. This technology allows customized structures to be created with high precision, using three-dimensional models generated by software such as CAD (Computer-Aided Design) (FIGURES 1 and 2) or medical images such as CT scans and MRI scans (Li, Y et al., 2023).

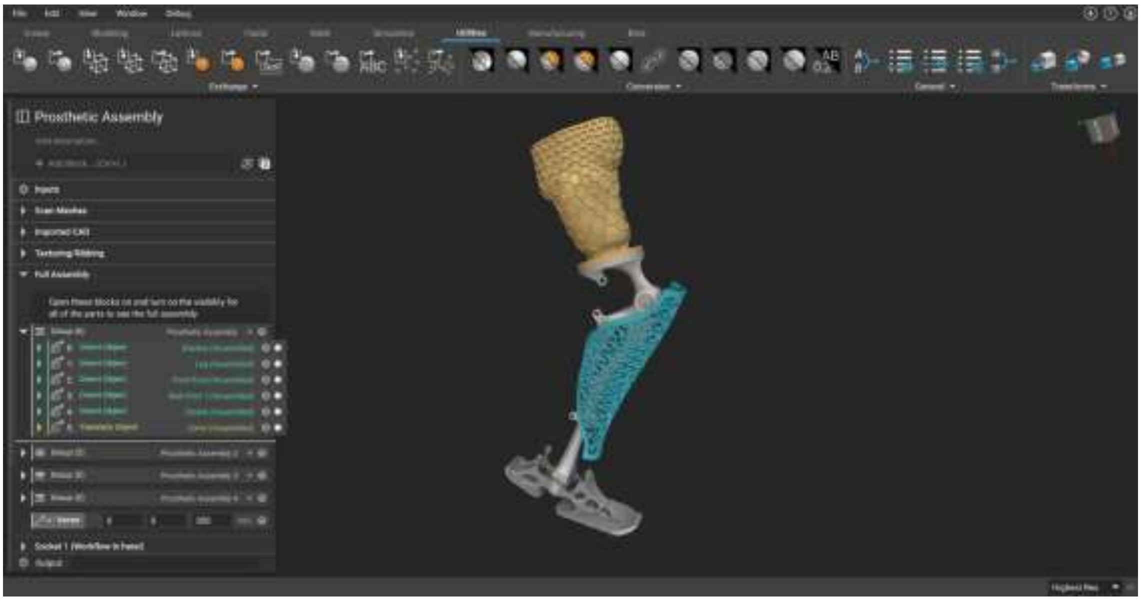

Figure 1. Additive Manufacturing (AM). Source: ntop.com/resources

Figure 2. Concept of engineered 3D printed arm prosthetics. Source: Jade Myers at nTo

According to Moskowitz et al. (2020), one of the most relevant applications of 3D printing in orthopaedics is the creation of personalized anatomical models. These models are manufactured based on radiological images of the patient, allowing surgeons to simulate complex procedures prior to intervention. This practice has demonstrated significant benefits, including: Improved anatomical visualization: Facilitates understanding of deformed or damaged bone structures; Reduced surgical time: Prior identification of anatomical challenges reduces intraoperative complications; Medical training: Models allow practice in simulations close to reality.

Studies indicate that the use of 3D models reduces surgical time in complex orthopaedic procedures by up to 20% (Moskowitz et al., 2020).

The manufacture of customized implants is one of the most promising innovations. 3D printing makes it possible to create prostheses adjusted to the patient's morphology, improving adaptation and functionality. Examples include: Joint prostheses: hip and knee implants with specific geometries for each patient; Bone reconstruction: replacement of bone segments with biocompatible materials such as titanium and polymers; Bioactive implants: structures that promote bone integration and reduce the risk of rejection.

In addition, the ability to print porous materials that simulate human bone is essential to accelerate osseointegration (FIGURE 3) (Patel et al., 2019).

Osseointegration is a physiological process consisting of the union of an implant to bone, so that the implant can withstand functional loading (Li, Y et al., 2023).

This process occurs when a piece of titanium is inserted into the bone and bone cells migrate to the surface of the metal. The body regenerates the bone around the implant, allowing the surgical element to integrate into the bone (Patel et al., 2019).

Osseointegration is a fundamental process in orthopaedics, allowing implants to be fixed to the bone. Osseointegration time can vary from weeks to months, depending on several factors, such as the location of the implant, bone quality, the patient's situation and the surgical technique (Li, Y et al., 2023).

Osseointegration is also a technique used for amputees, but it has some disadvantages, such as the need for surgical intervention and the rehabilitation process which can be longer (Patel et al., 2019).

Figure 3. Osseointegration. Source: bot-mg.org.br/osteointegracao-esqueletica-transcutanea-para-amputados/ (2024).

In the manufacture of orthoses, 3D printing makes it possible to create lighter, more comfortable and aesthetically pleasing devices. This approach improves patient compliance with treatment. Devices such as orthopedic insoles, spinal support vests and exoskeletons are frequent examples (Li, Y et al., 2023).

Customization also makes it possible to meet the specific needs of children and the elderly, groups with unique morphologies and susceptible to mobility limitations (Smith et al., 2021).

The combination of 3D printing and bioprinting is revolutionizing bone and cartilage regeneration. Recent research indicates significant advances in the use of biological materials, such as stem cells and hydrogels, to manufacture scaffolds (FIGURE 4) that stimulate the formation of natural tissue. These advances are promising for: Bone regeneration in complex fractures; Treatment of joint injuries with customized cartilage (Moskowitz et al., 2020; Li, Y et al., 2023).

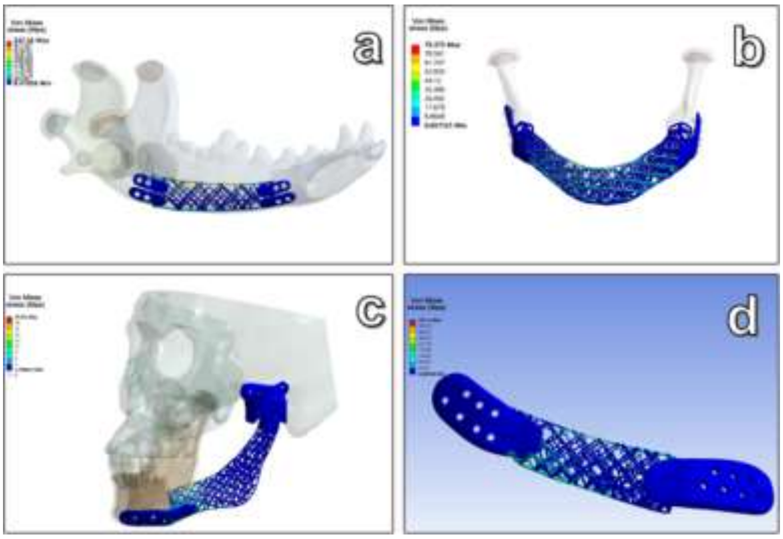

Figure 4. a Von Mises stress scaffold in animal experiments. b Von Mises stress scaffold in case 1. c Von Mises stress scaffold in case 2. d Von Mises stress scaffold in case 3. Source: (Li, Y et al., 2023).

Tissue engineering still faces challenges, such as the biocompatibility and durability of biomaterials, but offers great potential in the long term (Wang et al., 2022).

3D printing reduces production costs by minimizing material waste and optimizing processes. In addition, the possibility of local manufacture reduces the need for transportation and storage of parts. These factors make the technology accessible to healthcare systems in developing countries (Li, Y et al., 2023).

3D printing is reshaping the field of orthopaedics, offering personalized, affordable and innovative solutions. Although the technology still faces regulatory and technical challenges, its potential impact on orthopaedic treatment is undeniable. Continued advances in materials, software and bioprinting techniques should further consolidate its role in modern medicine (Li, Y et al., 2023).

3D printing (FIGURE 5) has revolutionized sports medicine by making it possible to create personalized, efficient and economically viable solutions for athletes. Its impact extends from the development of protective devices to the manufacture of implants and rehabilitation equipment (Patel et al., 2019).

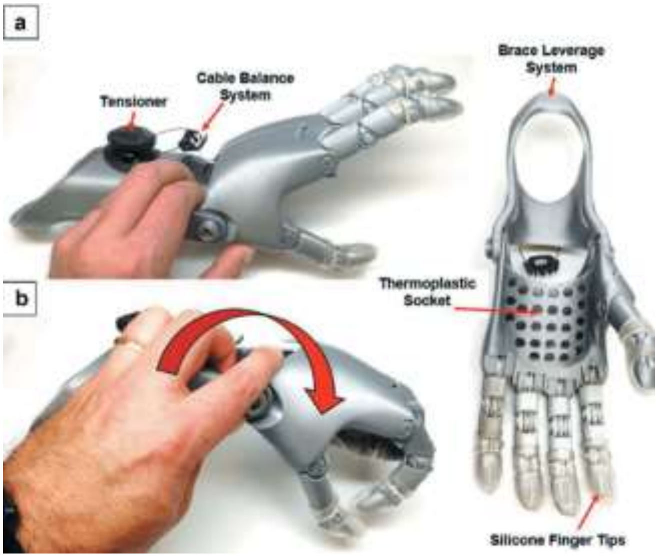

Figure 5. The 3D printed partial hand prosthesis (Cyborg Beast 2). (a) The prosthetic hand in the open position. Elastic cords placed inside the dorsal surface of the fingers prolong the passive extension of the fingers. (b) Finger flexion was developed by nonmetallic cords along the palmar surface of each finger and was activated through a 20° flexion of the residual functional joint wrist. The red arrow shows the direction of wrist flexion to close the fingers and produce a functional grip. Source: (ZUNIGA, et al, 2019).

One notable example is personalized face masks, widely used by players after facial fractures, which combine protection and ergonomics (Smith et al., 2021).

In sports rehabilitation, 3D printing has been used to develop orthoses and assistive devices. These products are custom-made to speed up recovery from injuries such as fractures and ligament ruptures. In addition, the printing of customized insoles has been shown to be effective in treating chronic injuries such as plantar fasciitis and tendinitis (Patel et al., 2020).

Simulation and training equipment also benefits from this technology. Tools such as printed anatomical models help educate professionals and plan specific treatments for athletes (Wu et al., 2022).

First, the prosthetist takes an impression or “mold” of the residual limb to make an exact copy of it. The manufacturer uses this mold to make custom-molded sockets, with specific measurements adapted to each user, according to their unique anatomy and range of movement. To create the custom-molded bases, the thermoplastic material is heated to adapt to the shape of the patient's amputated area (Wu et al., 2022).

Once the bases are ready, you can connect them to ready-to-use components that make up the artificial limbs. These components are designed for easy assembly and can be adjusted to ensure maximum comfort and functionality for each user (Zhang et al., 2021).

Finally, you can put on the artificial limbs and make the necessary adjustments. This includes fine-tuning any joint tension or release and ensuring that all components are aligned (Zhang et al., 2021).

The digital fabrication process begins with the acquisition of patient data. This involves capturing high-resolution anatomical data using 3D medical imaging technologies such as portable 3D scanners, MRI scans or CT scans. It then segments and converts this data into digital surface meshes used in design operations (Zhang et al., 2021).

The second step is to generate the design. Depending on the personalization strategy, it can generate the device design with different levels of automation, and can opt for single manual designs or fully automated devices adapted to the patient. It should be noted that the design process is just as important as the design outcome to ensure regulatory compliance (Chin et al., 2023).

The next step is manufacturing. You can use 3D printing to produce your prosthesis directly or indirectly by creating customized tools for the primary process. In general, the direct approach is the best option when developing prostheses with design features that are only feasible. However, the economics of the indirect approach are better when dealing with large production volumes (Chin et al., 2023).

In both cases, the prosthesis must undergo specific post-processing to meet all the necessary functional requirements or improve the aesthetics of the device (Chin et al., 2023).

Finally, the device can be delivered to the patient. Since the device corresponds to the patient's anatomy and physiology, the effort required by the doctor to adapt the prosthesis should be minimal (Wang et al., 2022).

The adoption of a fully digital manufacturing process offers many advantages in the development of prosthetic components (Smith et al., 2021).

For medical device manufacturers, creating comfortable, well-fitting prostheses can be costly and require highly skilled specialists. With the growing demand for more complex products, healthcare providers are always trying to make production more efficient (Smith et al., 2021).

Digital manufacturing can help healthcare providers achieve this by reducing the number of processes and manual steps needed to bridge the gap between product and patient. Starting with a scan, healthcare providers can customize and create accurate digital models ready for production, saving time and money. Once the prosthesis is designed, 3D printing allows them to manufacture complex geometries that are impossible to create with other production technologies (Wang et al., 2022).

This digitization process results in shorter waiting times for the patient, a more comfortable and personalized fitting and time and cost savings for the provider. In addition, by automating this process, the healthcare provider can spend more time with the patient, optimizing fit and comfort (Moskowitz et al., 2020).

Digitalization also creates opportunities for the development of new geometries, which can be easily adapted to meet the patient's personal wishes in terms of aesthetics and function (Moskowitz et al., 2020).

Once approved, the design can be manufactured and iterated quickly. On the other hand, with traditional manufacturing processes, the healthcare provider often has to start from scratch if changes are needed (Patel et al., 2019).

Digital manufacturing processes also help the industry evolve because they create opportunities and time for experts to innovate and develop new ideas (Patel et al., 2019).

For many people living in developing countries, prosthetics are out of reach. They often rely on non-profit organizations to access the care they need in their daily lives.

The search for sustainable and low-cost materials, such as biodegradable polymers and advanced bioinks, should increase the accessibility and scalability of 3D printing in medicine, benefiting healthcare systems around the world (Li, Y et. al, 2023).

The combined use of 3D printing, virtual reality and artificial intelligence can improve surgical planning, simulations and treatments. For example, AI algorithms can optimize anatomical designs for printing, reducing errors and improving clinical results (Li, Y et. al, 2023).

3D printing allows medical devices to be manufactured directly in hospitals or clinics, reducing transportation costs and waiting times. This approach can be especially useful in remote regions or in emergency situations.

Although several biocompatible materials are available, many still face challenges related to durability, toxicity and interaction with the human organism. In addition, the development of materials suitable for specific applications, such as tissue regeneration, remains a technical barrier (Patel et al., 2021).

Despite the cost savings compared to traditional methods, medical 3D printing still requires significant investment in equipment, software and professional training (Moskowitz et al., 2019).

The adoption of 3D printing depends on qualified professionals to operate equipment and design digital models. The lack of specialized training in many medical institutions slows down the integration of the technology into day-to-day clinical practice.

The customization inherent in 3D printing makes large-scale reproducibility difficult. Each part or device is unique, which can lead to inconsistencies in production and delays in clinical implementation.

CONCLUSION

Technological advances in 3D printing have had a transformative impact on orthopaedics and sports medicine, providing personalized, high-precision solutions for diagnosis, treatment and rehabilitation. In orthopaedics, this technology enables the production of prostheses, implants and scaffolds tailored to the specific needs of patients, while in sports medicine it offers tailor-made protective devices and rehabilitation equipment that improve performance and speed up recovery from injuries.

Despite challenges such as high costs, regulation and the need for specialized training, ongoing advances in biocompatible materials and bioprinting broaden the prospects for future applications, including tissue regeneration and the manufacture of functional organs. Integration with other emerging technologies, such as artificial intelligence and virtual reality, further enhances the relevance of 3D printing in modern medicine. Thus, this technology is consolidating itself as an essential tool for more effective, personalized and accessible treatments, contributing significantly to the evolution of human health.

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