Frontiers and Applications of 3D Printing Technology in the Design of Prosthetic Orthotics

Zhihua Huang[1]

[1] School of Mechatronics and Vehicle Engineering, Chongqing Jiaotong University, Chongqing, 400074, China
1808010509@stu.hrbust.edu.cn

Abstract. This article comprehensively discusses the principles, processes, advantages and limitations of 3D printing technology. It provides an in-depth analysis of the types of materials used in 3D printing and their properties, including polymer materials, metal materials, and inorganic non-metallic materials. This paper explains the basic principles and operational processes of 3D printing technology. Later, the article analyzed the advantages of 3D printing technology, including high customization and improved production efficiency, but also explicitly mentioned its shortcomings such as limited material choices and relatively higher costs. This article extensively discusses the innovative application of 3D printing technology in the field of prosthetic orthotics, highlighting the advantages of personalized customization and improved comfort of 3D printed prosthetic orthoses compared to traditional techniques. The article delves into the specific applications of 3D printing technologies such as Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), and Multi-Jet Fusion (MJF) in the production of prosthetics and orthoses. Finally, this article analyzes and discusses the future development trends of 3D printed prosthetic orthoses, predicting that with advancements in technology and cost reductions. 3D printed prosthetic orthoses plays a larger role in personalized medicine by providing more patients with high-quality and comfortable treatment options.

Keywords: 3D printing technology, Prosthetics orthosis, Materials, Applications.

1 Introduction

3D printing, as an innovative additive manufacturing process, operates in stark contrast to traditional subtractive machining methods based on material removal. Originating from the United States, 3D printing technology has revolutionized the perspective of innovative practices, leading to widespread social attention upon its emergence. This technology became increasingly popular towards the end of the 20th century and is acclaimed as one of the key symbols of the Third Industrial Revolution [1].

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Traditional machine tools often have difficulty achieving complete processing in a single operation when dealing with complex structural parts. The uniqueness of 3D printing technology lies in its difference from traditional subtractive manufacturing. It uses additive manufacturing principles, which involve digitizing a model through 3D modeling techniques and then breaking it down into layers using algorithms to define the digital contours and height Z-axis data for each layer. Then, this information drives the printing device to stack materials layer by layer, accumulating into a physical entity [2].

The uniqueness of 3D printing lies in its ability to create three-dimensional objects, as opposed to the two-dimensional conventional printing methods; compared to traditional manufacturing processes, 3D printing has characteristics of high precision and automation. It is these advantages that have led to the rapid popularization and application of 3D printing technology. This technology indeed faces many challenges, including material research and development, equipment improvement, and the formulation of unified industry standards. The potential of the 3D printing market is huge, and it is currently focused on deepening understanding and application of this technology, while exploring innovation and optimizing strategies to become a current research hotspot [3].

Compared to traditional part manufacturing, 3D printing technology significantly improves production efficiency and accuracy. It does not rely on molds or cutting tools, saving costs and aligning with the current trend of economic development in society. Its wide applicability suggests that it has enormous potential for widespread use in various industries [4].

With continuous technological innovation, the influence of 3D printing technology is growing.3D printing technology has revolutionized the production process by constructing materials layer by layer to create three-dimensional objects. It is highly flexible and can customize production on demand at any location, enabling instant and personalized manufacturing. Significant progress has been made in production efficiency and cost control, successfully making up for previous shortcomings [5].

With continuous innovation in technology and materials, 3D printing technology has shown indispensable functional impact in key areas such as industrial manufacturing, biomedicine, and aerospace [6].

The prosthetics and orthotics industry are specifically designed for people with mobility impairments, aiming to improve their quality of life by manufacturing and fitting prosthetic limbs and braces. With the continuous advancement of medical and rehabilitation medicine, the average human life span is increasing. The demand for technical performance of prosthetics and orthotics, which are key components of rehabilitation medicine and engineering, is also rising. Modern prosthetics and orthoses are catering to the growing trend of personalization, placing a greater emphasis on customized design tailored to individual differences. Optimize the product to improve breathability and achieve lightweight design. Product design needs to cater to popular aesthetic trends. The product needs to meet a variety of functional flexibility requirements. When treating children, the key factor lies in their rapid growth, so products need to be regularly updated to meet their developmental needs.3D printing demonstrates unparalleled advantages in many aspects [7].

2 The Current Status of 3D Printing Technology

2.1 The Principles and Processes of 3D Printing Technology

3D printing technology operates based on the fundamental principle of layer-by-layer additive manufacturing. The process is as follows: first, product design is carried out, using computer-aided design (CAD) technology to construct a three-dimensional solid model. According to the process specifications, the model is divided into ordered two-dimensional slices, and then precise process strategy design is carried out for each slice's geometric characteristics. The processing parameters are optimized, and applicable CNC programming instructions are automatically generated. The molding system builds up materials layer by layer according to the received commands, constructing layers until all surfaces are integrated and ultimately producing a three-dimensional solid product [8]. The principle of 3D printing technology is shown in Fig. 1.

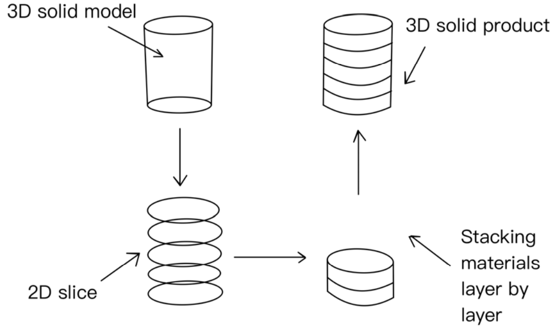

Fig 1. Principle of 3D printing technology. (Picture credit: Original)

2.2 Advantages and Limitations of 3D Printing

Advantages of 3D printing. Designed with high flexibility and adaptability.3D printing breaks through the limitations of traditional manufacturing techniques, eliminating the need for standard fixtures or tools. It can directly design parts with smooth channels, integrated structures, and highly complex shapes according to functional requirements.

The advantage of small-scale production lies in cost efficiency [9]. 3D printing bypasses the traditional mold making process, eliminating the need for additional clamping equipment. It is especially suitable for small-scale or single-piece production, with its main advantage being a significant reduction in expensive mold costs required for large scale production.

The production process demonstrates high predictability and stability. The 3D printing time of parts and the degree of deformation during part formation can be directly estimated based on the original design parameters. With the simulation technology of parameter fine-tuning and additive manufacturing process, it is possible to accurately control and manage deformations that may occur during the manufacturing process.

Optimize assembly steps. Integrated part manufacturing can be achieved through 3D printing technology, directly replacing the traditional method of assembling separate parts. This has significantly reduced complicated processes such as transporting components, assembly, fastening and welding. By optimizing the production process, the cost of parts manufacturing can be successfully reduced, which avoided additional investment in production lines.

Limitations of 3D printing. Despite the huge development potential and wide application space of 3D printing technology, its progress is still limited by some key constraints, mainly including reliance on special materials and strict requirements for demanding work environments. Some factors have posed certain obstacles to the rapid development of this technology. The following are key limiting factors [10]:

Constrained by material characteristics. Although industrial 3D printing can already cover a variety of materials such as metal, plastic, and ceramics, to expand its diverse applications and overcome the bottleneck of performance and efficiency, deepening material research and technological innovation is urgent. Currently, the shortage and high prices of printing materials are a critical issue that needs to be urgently addressed.

Limitations of hardware. With the continuous improvement of modeling software and technology, 3D computer modeling can now accurately reproduce various static objects with a high degree of precision, maturing over time. High precision printing of dynamic objects faces challenges, with the key issue being that during the printing process, the real-time changes in spatial positioning and speed of movement of the object lead to a sharp increase in complexity, significantly increasing difficulty in achieving clarity.

Constraints imposed by cost limitations. Like all emerging technologies, the high cost of research and development in the early stages is a common challenge for 3D printing technology. The funds required for equipment research and development in the initial validation stage are substantial.

2.3 Types and Properties of 3D Printing Materials

The characteristics of 3D printing technology significantly span across various fields, with materials science playing a foundational central role in its implementation process. The innovation bottleneck and future trends of 3D printing technology coexist in the research and development of new materials. The raw materials are mainly divided into three categories based on their physical and chemical properties: polymer materials, metal materials, and inorganic non-metallic materials [11].

Polymer materials. Polymer materials exhibit excellent thermoplasticity within a specific temperature range, combined with appropriate strength, outstanding flowability and cost-effectiveness, making them play an important role in additive manufacturing, especially in the 3D printing industry. The materials are mainly classified into two major types: engineering plastics and photosensitive resins. The performance indicators and characteristics of thermoplastic resins suitable for 3D printing technology are listed in Table 1.

Table 1. Common thermoplastic 3D printing materials and related properties [11]

Name	Characteristics
PLA	Environmentally friendly biodegradable materials. The raw materials come from a wide range of sources Low melting point Brittle texture
ABS	High melting point Shrinkage occurs during cooling More easily squeezed out Having a slight smell
PC	Anti-scratch, anti-impact High intensity, durability Exposure to ultraviolet rays will become fragile High size stability
PA	Stable performance Biodegradable Oil resistant, water resistant, wear-resistant Antibacterial
PEEK	High temperature resistance, corrosion resistance Self-lubricating Resilience, high resistance to fatigue Development of composite materials

Metal Materials. The rapid progress of metal 3D printing technology is widely expanding its applications in the traditional mechanical industry, and it is seen as an important enhancement tool for traditional manufacturing methods. Titanium and titanium alloys are widely used in the aerospace industry and medical device field for their excellent high strength, high temperature stability, outstanding corrosion resistance, and superior biological compatibility. The wing of the C919 large passenger aircraft innovatively incorporates titanium alloy 3D printing technology, successfully integrating into the design of the central wing skin. Cobalt-chromium alloy cleverly combines pre-alloyed powders to demonstrate outstanding mechanical properties: exceptional strength and hardness, while also possessing significant corrosion resistance and high temperature durability.

Inorganic Non-metallic Materials. 3D printing is widely used for inorganic non-metallic materials, such as ceramics and cement, often provided in the form of powder or liquid slurry for printing. Ceramics, a material with a long history, has been favored by humans since ancient times for its unique advantages such as high strength, super hardness, and excellent heat resistance, wear resistance and oxidizing properties. The unique insulation performance and strong chemical stability of ceramics make them occupy a core position in industrial production. However, the hard and fragile characteristics of molds make mold making time-consuming and expensive, limiting its technological development. The advantages of 3D printing technology significantly improve production efficiency, giving it a competitive edge.

3 The Current Application Status of 3D Printing Technology in the Field of Prosthetic Orthotics

3.1 Analysis of the Application Value of 3D Printing in Prosthetic Orthotics

Although the application of 3D printing in prosthetics and orthotics is relatively early compared to orthopedics and dentistry, its cost-effectiveness, high degree of personalized customization, and significant advantages in time efficiency suggest that this technology has huge potential for development in this field. The innovation of 3D printing technology in precision manufacturing is revolutionizing the production of prosthetics and orthotics, extending beyond traditional methods to cover head and facial structures. Experimental devices have also been developed to replace the ossicular chain, with the aim of restoring hearing. However, current development is restricted by available material technology [12].

3.2 Comparison Analysis of Key Technical Parameters Between 3D-printed Prosthetic Orthosis and Traditional Prosthetic Orthosis

Prostheses and orthoses utilize innovative technology, combining precise manual molding, personalized adjustments, and 3D printing to achieve a highly customized production process. In the initial design stage, the digital technology and professional software can be used for fine tuning and optimization. Then, utilizing advanced 3D printing technology, concepts can be transformed into actual physical assistive devices. Traditional orthopedic instrument manufacturing methods face limitations in individualized adaptation, improving patient comfort, and optimizing postoperative rehabilitation effects. The introduction of 3D printing technology has overturned this tradition. With detailed personal body data and the application of anatomical knowledge, it achieves highly personalized customized designs. The digital additive manufacturing technology has greatly reduced the production time of orthosis and allows for precise customization based on the specific joint and limb morphology of patients. In contrast, 3D printing technology demonstrates significant advantages in the production of plaster orthoses [13]. The comparison of traditional prosthetic orthoses fabrication and 3D printing technology as shown in Table 2.

Table 2. Comparison of traditional prosthetic orthosis fabrication and 3D printing [13]

Prosthetic orthosis manufacturing technology	3D printing production	Traditional plastering techniques
Body data model	3D scanning	Plaster bandage casting

Design, modify models	CAD design, mirroring, software processing	Plaster casting
Making products	3D printing model	Shaping of branches and boards
Advantages and disadvantages	High efficiency, personalized, convenient data collection, higher degree of fit, high cost, limited material selection	Low cost, wide variety of materials, low efficiency and complicated process

3.3 3D Printing Technologies and Materials Applied in The Field of Prosthetics and Orthotics

SLS Technology and Materials in the Field of Prosthetics and Orthotics. The core principle of SLS technology is based on the mechanism of layer-by-layer stacking and accumulation, cleverly integrating (CAD) with physical manufacturing processes. Using infrared laser as the core energy source, accurately scanning and drawing the cross-sectional profile layer by layer, heating powder to a melting state, bonding and sintering layer by layer, gradually accumulating to build a complete three-dimensional solid.

SLS technology is widely used in powder form materials, including both metals and non-metals. The research materials mainly focus on various metal alloys such as titanium alloy, aluminum alloy, copper alloy and high-temperature alloys; while non-metal components are primarily composed of thermoplastic plastics including polyethylene, polypropylene, polystyrene, polyvinyl chloride and nylon. In prosthetics and orthotics manufacturing, nylon and nylon carbon fiber are currently widely used core materials.

Nylon material is wear resistant. This material combines excellent toughness and high strength characteristics and shows outstanding heat resistance performance. The products produced by SLS molding technology stand out for their excellent breathability, making it an ideal material for 3D printed prostheses and orthoses, demonstrating significant advantages. The nylon carbon fiber composite material perfectly combines the excellent properties of nylon and greatly enhances structural strength by embedding carbon fibers, thus improving the mechanical performance of the product. BASF's subsidiary TriFusion Devices has partnered with Essentium to develop an advanced 3D printing prosthetic technology, using high-strength carbon fiber reinforced thermoplastic materials to produce efficient prosthetics and orthoses. Its uniqueness lies in the fact that even minor adjustments can maintain structural stability, ensuring patients can enjoy a highly personalized and comfortable fitting experience [7].

Applications of FDM Technology and Materials in the Field of Prosthetic Orthotics. FDM molding technology uses a hot nozzle to accurately follow the layered pattern designed in CAD, extruding and depositing semi-solid materials layer by layer at predetermined points. As the process of stacking layers and solidifying progresses, a physical model or functional component is gradually built. FDM technology mainly relies on linear building materials, especially in the manufacturing of prosthetics and orthotics. Typical choices include thermoplastic polyurethane (TPU) elastomers and ABS plastics.

TPU improves the efficiency and convenience of FDM extrusion molding with its excellent thermoplastic properties. At the same time, its excellent high moisture permeability and warmth features make it widely applicable in custom orthopedic shoe insoles. ABS material is renowned for its excellent heat stability, superb surface glossiness, and ease of dyeing processing. The medical field has widely adopted its technology, demonstrating effectiveness in devices such as lower leg prostheses, finger correctors and ankle orthoses. In the field of bioengineering, a graduate student from Poland has innovatively used FDM printing technology to customize a unique and lightweight finger splint for a quadriplegic patient. The goal is to significantly improve their ability to grasp objects [7].

Applications of MJF Technology and Materials in the Field of Prosthetics Orthoses. The core equipment of MJF technology relies on two key inkjet systems: one is specifically used for precise deposition printing materials to construct solid components; the other is responsible for material spraying and fusion to achieve mechanical performance and surface texture requirements of components. Its manufacturing process includes: first, the base layer is laid out with powder; next, by spraying melted auxiliary agents and refining agents, enhancing the clarity of edges; finally, introducing a heat source in the forming area to melt and shape the powder. Currently, MJF technology commonly uses materials in the nylon series, which are highly popular in the field of prosthetics and orthotics.

Heike Technology Company has successfully developed and carefully crafted an efficient wrist orthosis by integrating its innovative PA12 material application with MJF production technology. This design features personalized customization capabilities, able to accurately adapt to the finger joint characteristics of different users. With key contact areas on the back of the fingers and wrists, it ensures a smooth and unhindered operating experience [7].

3.4 Future Development Trends Analysis and Discussion of 3D-printed Prosthetic Orthoses

In recent years, researchers have been continuously researching to enhance the efficiency of prosthetic and orthotic design and manufacturing. Since the first 3D printer was introduced in 1986, the popularity of 3D printing technology has been steadily growing, with costs decreasing year by year. Customized prosthetic orthosis made by 3D printing effectively reduces the risk of injury and disease recurrence with its superior personalized design for cushioning and support. The production of custom 3D-printed prosthetics orthoses is a result of interdisciplinary collaboration, bringing together the expertise of medical professionals (doctors, rehabilitation therapists), materials engineering specialists, and skilled orthotists. The goal is to ensure that the product seamlessly integrates principles of biomechanics and personalized customization, accurately meeting the unique needs of each user. Each department needs to jointly formulate strict 3D printing industry entry standards and strengthen market supervision; optimize the user experience of the design process, improve software interface intuitiveness and ease of learning, so that users can quickly master design without needing in-depth study; promote the transformation of 3D printing technology towards intelligent efficiency, speed up printing speeds, enhance instant benefits in the medical field; research and develop economically efficient printing materials. Additionally work on popularizing applications for custom-made prosthetics and orthotics using 3D printing techniques. In the future, the increasing maturity of 3D printing technology will greatly promote its personalized customization, leap in accuracy and efficiency improvement in the field of prosthetics and orthotics, thus strongly driving progress in this industry [14].

4 Conclusion

With the rapid advancement of technology, 3D printing is gradually penetrating various industries as an innovative manufacturing method, especially in the field of prosthetics and orthotics. Its potential benefits and application value are becoming increasingly prominent. This article first reviews the principles and processes of 3D printing technology, explores its advantages and limitations, and then delves into the types and properties of 3D printing materials. It particularly focuses on the applications of polymer materials, metal materials, and inorganic non-metallic materials in 3D printing.

3D printing technology uses the principle of layer-by-layer accumulation of materials to directly transform digital designs into physical objects. This technology not only greatly improves production efficiency, but also allows designers and engineers to customize products according to specific needs. In the field of prosthetics and orthotics, 3D printing technology provides patients with more comfortable and customized orthotic options thanks to its high level of personalization and precision.

In the field of prosthetics and orthotics, the application value of 3D printing technology is particularly significant.3D printed prosthetic orthoses surpass traditional techniques in personalized customization, rapid adaptation, and superior comfort. By comparing and analyzing key technical parameters, 3D printed prosthetic orthoses have unique advantages in structural design, functional implementation, etc.

Various 3D printing technologies and materials are showing diverse trends in the field of prosthetics and orthotics. The application of technologies such as selective laser sintering, melt deposition manufacturing, and multi-jet fusion sintering has not only improved the precision and efficiency of prosthetic orthoses manufacturing but also brought more functionality and possibilities to them. Continuous technological advances and optimization will strongly drive innovation and upgrade in the field of prosthetics orthotics.

However, 3D printing technology still has several limitations. For example, the limitations of material selection may restrict the performance of products; at the same time, high equipment costs and printing expenses also limit its widespread application in some fields. Although present, the trend of continuous technological development and cost reductions suggests that these limitations are likely to be eliminated in the near future.

Looking into the future, 3D printing technology has broad prospects in the field of prosthetics and orthotics. With the continuous advancement of technology and gradual reduction in costs, 3D-printed prostheses orthotics will become more popular and widely used. The continuous development of new materials and cutting-edge technology is driving the performance upgrade of 3D printed prosthetics orthoses, bringing more high-quality and comfortable treatment options to patients. In addition, with the continuous development of digitalization and intelligent technology, the design and manufacturing of 3D printed prosthetic orthoses will become more efficient and convenient, bringing more innovation and breakthroughs to the medical field.

References

1. Wang, X. Y., Shen, F.: Overview of 3D Printing Technology. Jiangxi Chemical Industry (03), 242-243 (2019)
2. Zhao, Y. G., Liu, C. X., Xu, C. B., et al.: Current status of 3D printing technology and equipment development. Mechanical Research and Application (03), 224-227 (2021)
3. Meng, W.: Analysis of Trends in 3D Printing Technology and Applications. Science and Innovation Application (11), 146-148 (2021)
4. Zhang, X. D.: Research Status and Key Technology Research of 3D Printing Technology. Modern Industrial Economy and Informatization (11), 139-141 (2022)
5. Liu, M. M., Zhu, X. D.: Research Progress on 3D Printing Forming Technology and Material Application. Mechanical Research and Application (04), 197-202 (2021)
6. Wang, C., Chen, J. F., Feng, T., et al.: Development of 3D printing technology and its consumables application progress. China Foundry Equipment and Technology (06), 38-44 (2021)
7. Sun, Q., Zhang, Y. C.: Application of 3D printing technology and materials in the field of prosthetic orthosis. Technology and Market (10), 38-39 (2020)
8. Xin, Y. X., Cai, G. X., Hu, B., et al.: Progress in main forming processes and applications of 3D printing. Precision Forming Engineering (06), 156-164 (2021)
9. Ye, D. S., Shen, P. L., Zhang, D. C., et al.: A comparison of the advantages and disadvantages between 3d printing technology and traditional processing technology. Civil Aircraft Design and Research (04), 126-130 (2021)
10. Hou, L. H.: 3D printing technology and its applications. Electronic Manufacturing (12), 53-55+73 (2019)
11. Ma, X. K., Hou, J. F., Meng, X. D., et al.: Development and current application status of 3D printing technology. Chemical Engineering & Equipment (12), 246-248 (2020)
12. Hu, H. F., Zhou, Y., Chen, M. X., et al.: Application and development of 3D printing in the field of prosthetic orthosis. Chinese Journal of Rehabilitation Medicine (02), 233-237 (2020)
13. Zhang, P.: Application of 3D printing in the field of orthotic prosthetic technology: A trial analysis. Science and Technology Innovation and Application (10), 172-173 (2020)
14. Zhang, C., Li, C., An, C., et al.: Application of 3D printing technology in orthopedic rehabilitation treatment. Medical Health Equipment (02), 93-97+108 (2022)