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Article

Revision of Robotic Prostheses Manufactured with 3D Printing: Advances, Challenges and Future Perspectives

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Abstract: 3D printing has significantly transformed the design and manufacture of robotic prostheses, making these devices more accessible, customized, and functional. This paper examines the historical evolution of prosthetic technology, tracing its development from rudimentary mechanical devices to the integration of advanced technologies, such as 3D printing. This innovation has enabled the production of prostheses at lower costs while enhancing their adaptability and performance. The review highlights how 3D printing has driven a disruptive shift in prosthetic customization, and how emerging technologies—including smart materials and artificial intelligence—have expanded the capabilities of prosthetic devices, offering more adaptive and natural movement. However, challenges persist, particularly regarding the need for standardization and infrastructure expansion to ensure equitable access to these technologies. Future research into novel materials and manufacturing techniques holds the potential to improve further the functionality, affordability, and accessibility of prosthetic devices. In conclusion, while 3D printing has marked a significant milestone in the evolution of robotic prosthetics, overcoming existing challenges is essential to realize its global impact and benefits fully.

Keywords: Robotic prostheses; 3D printing; personalized design.

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1. Introduction

Prostheses have historically been essential tools for enhancing the quality of life for individuals with amputations or physical disabilities. Over the centuries, technological advancements have facilitated the development of increasingly functional and aesthetically refined prosthetic devices. Despite these advancements, the high cost and limited access to cutting-edge technologies have constrained the availability of high-quality prostheses for many patients, particularly in developing countries. The emergence of 3D printing over the past two decades has introduced a transformative shift in prosthetic manufacturing, providing more affordable, customized, and efficient solutions [14].

3D printing has revolutionized numerous fields, including engineering and medicine. Its capability to produce three-dimensional objects from digital designs by sequentially depositing material layers has significantly impacted healthcare, enabling the creation of highly personalized medical devices. In the realm of robotic prosthetics, 3D printing has facilitated the design of devices that precisely match the anatomical requirements of each patient, thereby enhancing both the functionality and comfort of the prosthesis [10]. Traditional robotic prosthetics have been characterized by costly materials and complex manufacturing processes, limiting their accessibility to a broad segment of the population. The integration of 3D printing has notably reduced production costs, enabling the development of affordable, functional, and aesthetically customized prostheses [22]. Moreover, this

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technology offers increased design flexibility, allowing for the creation of modular prostheses that can be easily adapted and updated as patient needs evolve.

This paper aims to review recent advancements in the field of robotic prosthetics produced through 3D printing, as well as to address current challenges and prospects. Through this review, a comprehensive overview of the current state of this technology will be presented, emphasizing its impact on improving the quality of life for amputees and identifying areas requiring further research to optimize functionality and accessibility.

2. A Brief History Of Prostheses.

Prostheses have a history that goes back thousands of years. Over the centuries, the technology and materials available have evolved significantly, allowing prosthetics to evolve from simple mechanical substitutes to highly sophisticated devices, such as modern robotic prosthetics. This progress has greatly improved the quality of life for people with physical disabilities. The following is a historical overview of the evolution of prostheses, from their first rudimentary versions to contemporary innovations.

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Table 1. Evolution of Prosthetic Technology. Tables should be placed in the main text near to the first time they are cited.

Period	Description	Materials Used	Technology / Innovation
Antiquity Example: finger prostheses in Egypt (950-710 B.C.).	First rudimentary prostheses, mainly for aesthetic replacement. Wood, leather, metal	Manual craftsmanship	
Middle Ages	Limited developments; Prostheses are used for knights who lost limbs in battle.	Iron, leather, wood	Manual and basic adjustment
Renaissance	Innovations in mechanical prostheses for upper and lower limbs; advances in mobility.	Wood, iron, leather, paper	Basic hinge mechanisms
Nineteenth-century	Emergence of functional prostheses with more mobility, the introduction of the use of arm hooks.	Metal, rubber, leather	Movements controlled by belts and pulleys
Twentieth century	Development of advanced prosthetics after World War I and World War II for veterans.	Aluminum, steel, plastic	Myoelectric prostheses, devices controlled by muscle signals
Late 20th century	Appearance of bionic prostheses that interact with the nervous system.	Titanium, carbon fiber, silicone	Electromyography (EMG), neural sensors
XXI Century	Integration of advanced technologies such as 3D printing, AI, and smart materials.	Plastics, smart polymers, light metals	3D printing, artificial intelligence, brain-machine interfaces (BCI)

Data sources: [7,13–15,19,24,28].

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The earliest prosthetics, dating back to ancient times, were simple tools made of wood, metal, or leather, designed to replace lost limbs, but with very limited functions. An iconic example is the Capua leg (third century BC), made of bronze and iron, which provided stability, but without articulated mobility [38]. For centuries, prosthetics maintained this rudimentary approach, focusing on the basic function of replacing a limb without considering mobility or aesthetics.

With the advancement of engineering and bio-mechanics, in the mid-twentieth century, the first robotic prostheses emerged. These devices introduced the use of electrically controlled mechanisms to perform more complex movements. However, high cost and lack of customization limited its adoption on a large scale. These early robotic prosthetics, while revolutionary for their time, were far from ideal, as their manufacture relied on expensive production processes and rigid materials that did not adapt well to the patient's anatomy [25].

The first robotic prosthetics emerged in the mid-20th century as a response to the growing need for functional solutions for amputees, largely driven by the aftermath of the world wars. These early attempts to combine robotic technology with human prosthetics marked a milestone in the evolution of the field, although the technological limitations of the time presented numerous challenges. Initial robotic prosthetics faced restrictions related to weight, durability, autonomy, and controllability. However, advances in engineering, materials, and electronics allowed for the progressive development of more functional prosthetics, with a focus on improving mobility, dexterity, and integration with the human body.

3. Limitations Of Early Robotic Prostheses

The first robotic prosthetic devices, especially those designed in the 1960s, were developed primarily to restore some ability to move in people with upper limb amputations. One of the earliest examples is the myoelectric prosthesis, which used electrical signals generated by the user's residual muscles to control the movements of the prosthesis [1]. Although this approach was innovative, it had several limitations.

3.1. Weight and Size

The first robotic prostheses were considerably heavy and bulky due to the technology available at the time. The electric motors and batteries needed to power the device added significant weight, which was uncomfortable for users and limited prolonged use [25]. The size of these components also negatively affected the aesthetics and functionality of the prosthetics, as they could not effectively mimic the natural shape and movement of a human limb.

3.2. Lack Of Autonomy

Early myoelectric prostheses had limited autonomy due to the capacity of the available batteries. Users had to frequently recharge the prostheses, which reduced the practicality of their daily use. In addition, battery life was insufficient for prolonged operations, compromising all-day functionality [31].

3.3. Limited Control and Lack of Feedback

One of the biggest challenges for early robotic prosthetics was the lack of precise control. Although myoelectric prostheses allowed some degree of control through muscle signals, this was limited to basic movements such as opening and closing the hand. In addition, the absence of sensory feedback meant that users could not feel contact with objects, making tasks that require fine precision difficult [1]. This lack of tactile feedback also affected the user's learning and adaptation to the prosthesis, as the control of force and position was less intuitive than in a natural limb.

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3.4. Cost and Accessibility

Another major challenge of early robotic prosthetics was their high cost. Since the technology involved was complex and limited in production, only a small number of people could afford to access these types of devices. This limited the mass implementation of robotic prostheses and restricted the impact they could have on the physically disabled population [27].

4. Evolution of Robotic Prostheses with 3D Printing

The evolution of prosthetics has been marked by constant technological and scientific advances, from simple mechanical extensions to highly functional robotic devices. In this context, the introduction of 3D printing has represented a paradigm shift, allowing greater customization, cost reduction, and wider access to advanced technologies. To understand the magnitude of this advance, it is important to trace the development of robotic prosthetics from their earliest mechanical designs to modern devices that combine sensors, actuators, and 3D-printed bio-compatible materials.

The development of 3D printing at the end of the twentieth century radically changed the landscape of the manufacture of robotic prostheses. This technology, which allows the creation of three-dimensional objects by superimposing layers of material, transformed the design and production processes. The ability to create custom parts accurately and quickly made it easier to adapt robotic prosthetics to the individual needs of users [10].

The e-NABLE project, launched in 2011, was one of the pioneers in the use of 3D printing to manufacture low-cost prosthetics for children. This project demonstrated that it was possible to produce functional devices at a fraction of the cost of traditional prosthetics, and ushered in a trend towards democratizing access to customized robotic prosthetics [2].

The evolution of robotic prostheses with 3D printing has allowed the creation of devices that not only fulfill the basic functions of a prosthesis (such as replacing a lost limb), but can also incorporate advanced features such as pressure sensors, myoelectric control, and actuators that replicate complex movements. This has been made possible by the use of computer-aided design (CAD) software, which allows engineers to create highly accurate three-dimensional models that can then be printed with various materials, from plastics to light metals [4].

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Table 2. Advances in 3D Printing for Prosthetics. Tables should be placed in the main text near to the first time they are cited.

Period	Description	Materials Used	Technology / Innovation	Real Examples
Early life (2000–2010)	First applications of 3D printing on prosthetics. Manufacture of simple and non-functional parts, mainly aesthetic.	Basic plastics such as ABS and PLA	Fused Deposition Modeling (FDM), Limited Designs, and Prototyping	Leg prostheses developed by Scott Summit for aesthetic amputees (2008).
2010-2015	Advances in the customization of prostheses at low cost, aimed at people with upper limb amputations.	ABS, PLA, and some composite polymers	Improvement of FDM techniques; Emergence of open source projects such as e-NABLE	e-NABLE Community: "Cyborg Beast" Hand Prosthesis for Children (2014).
2015-2020	Creation of custom-made functional prosthetics, using 3D scans and simulations to improve fit and comfort.	Flexible plastics, carbon fiber filaments	Advanced 3D printing (SLA, SLS); Incorporation of sensors and myoelectric systems	Open Bionics: personalized "Hero Arm" prosthesis with 3D scanning for children (2018).
2020-Present	Integration of smart materials and advanced customization for bionic prostheses, with a focus on adaptive functionalities.	Biocompatible polymers, smart materials	4D printing, brain-machine interfaces (BCI), AI integration	Bionic hand prosthesis 3D printed with artificial intelligence by Unlimited Tomorrow (2021).
Near Future	Completely customized prostheses with adaptive response to the environment and direct connection with nervous systems.	Nanomaterials, advanced biocompatible	Development of 3D printing with full biocompatibility, advances in bioprinting	Research in muscle tissue bioprinting for adaptive prostheses (expected by 2030).

Data sources: [3,16,23,32,36].

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5. Advantages Of Including 3D Printing In The Manufacture Of Prostheses

The inclusion of 3D printing in prosthetic manufacturing has revolutionized the field of medicine and engineering, providing more accessible, personalized, and cost-effective solutions for amputees. This technology allows the creation of customized devices, adapted to the individual needs of each patient, significantly reducing production times and costs compared to traditional methods. In addition, the ability to experiment with new materials and innovative designs expands the possibilities of improving the functionality, comfort, and aesthetics of prostheses, offering a better quality of life to users.

The integration of 3D printing into robotic prosthetic manufacturing has been a disruptive breakthrough that has radically transformed the prosthetic field in terms of accessibility, customization, production time, and cost reduction. Traditionally, prosthetic manufacturing involves long, expensive, and inflexible processes, making it difficult for many people to access high-quality devices. However, the advent of 3D printing has enabled a revolutionary approach to the design and production of robotic prosthetics, democratizing access and enabling significant advances in terms of customization and functionality.

5.1. Revolution in Customization

One of the most significant changes that 3D printing brought to the realm of robotic prosthetics is the ability to customize at an unprecedented level. Through three-dimensional scans of the patient's body, designers can create devices that perfectly adapt to each person's anatomy, improving not only the functionality of the prosthesis but also comfort and aesthetics. This is especially relevant for children, who require prostheses that can be adjusted or replaced as they grow [2]. Unlike traditional prostheses, which were often mass-produced and then adapted in a limited way to the individual needs of patients, 3D printing makes it possible to create tailor-made devices. Digital prosthetic models can be tailored exactly to the patient's dimensions and physical characteristics, resulting in a prosthesis that is not only more comfortable but also more functional [20]. This is particularly relevant for children, whose needs change rapidly as they grow, and 3D printing makes it possible to create prostheses that can be easily adjusted or replaced.

3D printing also offers the possibility of biomimetic designs, i.e. prostheses that mimic not only the shape but also the function of natural limbs. This has allowed for greater dexterity in robotic prosthetics, facilitating more precise and natural movements, something that previous technologies could not easily achieve [10].

5.2. Reduced Costs and Production Time

Another disruptive change brought by 3D printing was the drastic reduction in production costs. Traditionally, the manufacture of robotic prosthetics involved complex and expensive techniques, such as precision molding or machining, which meant that many people could not access advanced robotic devices. 3D printing, on the other hand, makes it possible to manufacture high-quality prostheses at a fraction of the cost, using more affordable materials such as PLA, ABS, and nylon, which have good mechanical properties for prosthetic applications [17]. Traditional robotic prosthetics can cost between $5,000 and $50,000, making them inaccessible to many people, especially in developing countries [27]. In contrast, 3D printing has allowed the production of functional prostheses at a cost of between $50 and 500$, depending on the complexity of the design and the materials used [36].

5.3. Reduced Production Time

This advancement has not only enabled more people around the world to access robotic prosthetics but has also drastically reduced production times. While a conventional prosthesis could take weeks or even months to produce, 3D printing can produce a prosthesis in a matter of days [34]. Not only is this beneficial for patients who require a quick fix, but it also facilitates quick and economical iteration of the design, allowing for continuous adjustments and improvements until the prosthesis meets the patient's exact requirements.

Below is a table showing the average time that a prosthesis manufacturing process can take using various technologies (It is important to note that these times are only an average since each prosthesis performed has great differences) [21,32].

Table 3. Comparison of Production Methods for Prosthetics. Tables should be placed in the main text near the first time they are cited.

Production Method	Estimated Production Time	Description
Traditional Prosthesis Manufacturing	4 to 8 weeks	It includes mold making, manual manufacturing, adjustment, and testing. The process is lengthy and laborious.
3D Printing on Prosthetics	24 to 72 hours	3D printing allows for faster manufacturing, from custom design to final production.
3D Printing with Pre-Scan	12 to 48 hours	Using 3D scans of the patient, the personalized design is streamlined, further reducing the overall time.
3D Printing of Functional Prostheses	3 to 7 days	Prostheses that require assembly of functional components, such as sensors or motors, may take longer.
4D printing (future)	Estimated less than 24 hours	Emerging technology that could adapt materials to produce prosthetics even faster.

5.4. Innovation in Materials and Functionality

With the integration of 3D printing, designers have had access to a wider variety of materials that can better adapt to the different parts of a robotic prosthesis. 3D printing allows the combination of different types of materials in a single construction, such as rigid plastics for external structures and flexible materials for moving parts or contact surfaces. This ability to use multiple materials in the same printing process has made it possible to develop more functional and resistant prostheses [29].

In addition, technology has allowed prostheses to be lighter without sacrificing durability. This has been crucial in improving comfort and usability, especially in upper limb prosthetics, where weight is a determining factor in the user's ability to use the device for long periods [9].

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5.6. Ease of Distribution and Global Collaboration

3D printing has facilitated international collaboration in the development of robotic prosthetics, as digital designs can be easily shared around the world through online platforms. This has allowed communities of developers, researchers and clinicians to work together to improve prosthesis designs, adapting them to the specific needs of different patients. In addition, nonprofits have used 3D printing to distribute prosthetics to communities in resource-limited regions, something that was previously unthinkable due to high costs and logistical complexity [34].

For example, projects such as "e-NABLE," a global network of volunteers who use 3D printing to create prosthetic hands for children and adults, have demonstrated the impact this technology can have. Through open collaboration, volunteers design and ship personalized prosthetics to people who might not otherwise have access to them, exemplifying the disruptive power of 3D printing in the field of robotic prosthetics [29].

5.7. Rapid and Accessible Prototype Development

3D printing has allowed researchers and designers to experiment with new concepts more quickly and cheaply, which has accelerated the development cycle of robotic prosthetics. Researchers no longer need to wait weeks to receive test prototypes; They can produce them in their own labs or workshops

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in a matter of hours, allowing for rapid iteration of designs. This has not only improved the quality of the prostheses but has also allowed for further innovation in terms of functionality and design [17].

The ease with which prototypes can be modified and tweaked has significantly reduced the time between conceiving an idea and creating a viable final product. This immediate access to 3D-printed prototypes has been a crucial factor in the evolution of robotic prosthetics, where the needs of users vary greatly from person to person.

6. Recent and Future Innovations

As 3D printing technology continues to evolve, so do robotic prosthetics. Advances in materials, such as flexible plastics and bio-compatible materials, are enabling the development of lighter, more durable, and more functional prostheses. In addition, the integration of technologies such as artificial intelligence (AI) and machine learning in the control of robotic prostheses promises a future in which these devices can learn and adapt to the needs of the user in real-time [30].

The evolution of robotic prosthetics with 3D printing is a testament to the transformative power of additive manufacturing and biomedical engineering. As technologies continue to advance, we are likely to see a future where robotic prosthetics are even more accessible, customized, and efficient, providing a better quality of life for millions of people around the world.

Despite the limitations, the following decades saw significant advances in the development of robotic prosthetics. Improved materials, miniaturization of electronic components, and advances in control engineering made overcoming some of the initial barriers possible.

6.1. Improved Materials

During the 1970s and 1980s, lighter and more durable materials, such as aluminum and carbon fiber composites, began to be used, which considerably reduced the weight of robotic prostheses without compromising their strength [37]. This allowed users to wear them for longer, increasing their daily functionality. In addition, advances in tough plastics and bio-mechanical components helped improve the aesthetics of prosthetics, bringing them closer to the appearance of a human limb.

6.2. Advances in Electronics and Control

The evolution of microelectronics allowed the creation of more efficient prostheses with better controllability. Electromyographic sensors became more sensitive, making it easier to detect weaker muscle signals and thus more precise control of the prosthesis [30]. In addition, the integrated microprocessors allowed the prostheses to analyze the user's signals in real-time and adapt movements more naturally and fluidly. In the 1990s, prosthetics with multiple degrees of freedom were introduced, allowing for more complex and functional movements, such as wrist rotation and finger flexion independently.

6.3. Incorporation of Artificial Intelligence and Advanced Sensors

The development of control systems based on artificial intelligence (AI) has allowed robotic prostheses to learn and adapt to the patient's wearing style. These advanced prostheses use algorithms that analyze the pattern of use and anticipate the desired movement, improving response and control [5]. In addition, the use of haptic sensors has begun to allow sensory feedback, which provides users with a sense of pressure or contact with objects. This advancement has been crucial in improving the dexterity and accuracy of robotic prosthetics, making everyday tasks more intuitive and natural.

6.4. Increased Accessibility

As technology has advanced, the cost of robotic prosthetics has gradually decreased. The adoption of 3D printing has played a key role in reducing costs, as it allows for the rapid and customized production of prostheses at a fraction of the price of traditional prostheses [10]. This cost reduction has

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expanded access to quality robotic prosthetics, making it possible for more people to benefit from the technology.

7. 3D Printing Technologies Applied to Prostheses

3D printing has revolutionized the development of robotic prosthetics due to its versatility, accuracy, and ability to manufacture customized devices at a low cost. Several 3D printing technologies have been applied to the creation of prostheses, each with particular advantages depending on the specific needs of the patient, the type of prosthesis, and the materials used. Among the main technologies used for prosthetic manufacturing are stereolithography (SLA), selective laser sintering (SLS), and fused deposition modeling (FDM). These technologies have enabled advances in terms of functionality, durability and accessibility, transforming the field of robotic prosthetics.

7.1. Fused Deposition Modeling (FDM)

Fused deposition modeling (FDM) is one of the most widely used 3D printing technologies for prosthetic manufacturing due to its simplicity, low cost, and ease of access. In this process, a filament of thermoplastic material, such as ABS or PLA, is heated and extruded through a nozzle, depositing layer by layer to form the prosthesis. FDM has become the preferred technology for many prosthetic manufacturers due to its low cost of materials and the availability of printers in the market, which allows both professionals and amateurs to create custom prostheses [29].

In addition, FDM makes it possible to manufacture lightweight but durable prosthetics, which is crucial for users who need functional devices that do not cause discomfort during prolonged use. The technology has proven particularly useful for creating upper limb prostheses, such as hands and fingers, that require a balance between structural rigidity and flexibility in moving parts [10]. However, one of the main limitations of FDM is the relatively low surface quality and limited accuracy compared to other printing technologies, which may require post-processing processes to improve the aesthetics and functionality of the device [17].

7.2. Stereolithography (SLA)

Stereolithography (SLA) is another widely used technology in the manufacture of robotic prosthetics. Unlike FDM, which uses thermoplastic filaments, SLA employs a photosensitive liquid resin that solidifies layer by layer when exposed to an ultraviolet laser. This allows for extremely precise details and smooth surface finishes, which is essential for prostheses that require a high degree of precision in shape and fit [10].

The SLA process is particularly suitable for creating prostheses that fit more ergonomically to the patient's body. Due to the high resolution of the technology, it is possible to design devices with very fine details, such as joints or complex structures that better mimic the body's natural functions. In addition, prostheses created with SLA often have superior aesthetics than those made with FDM, which improves the patient's perception of the device and their willingness to use it [19].

However, one of the main challenges of SLA is the relatively high cost of both the equipment and the resins used, which limits its adoption in countries or regions with more limited resources [34]. However, its ability to create prostheses with high precision and its potential for design customization make this technology a preferred choice in applications where quality and fit are paramount.

7.3. Selective Laser Sintering (SLS)

Selective laser sintering (SLS) is a 3D printing technology that uses a laser to fuse dust particles from materials such as nylon or polyamide into a solid structure. This process has the advantage of being able to create prostheses without the need for support structures, which allows more complex and robust shapes to be manufactured than with FDM or SLA [29]. In addition, prostheses made using SLS are often stronger and more durable, making them an ideal choice for users who require devices that can withstand intensive use under demanding conditions [20].

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One of the biggest advantages of SLS technology is its ability to create prostheses that combine rigidity and flexibility in different areas of the same device. For example, in a prosthetic hand, the parts that make up the fingers may be made of more flexible materials to facilitate movement, while the rest of the structure may be more rigid to provide stability [34]. This versatility has allowed the development of more advanced and functional robotic prostheses, which provide greater freedom of movement and better adaptation to the user's daily activities.

Although SLS is an expensive technology compared to FDM, its ability to produce highly functional and customized prosthetics has been instrumental in the evolution of robotic prosthetics. In addition, the use of more durable materials such as nylon has expanded the range of applications of these prostheses, allowing users to perform physical activities that they could not previously carry out [18].

7.4. Metal Powders in 3D Printing

Metal powder 3D printing is an emerging technology that has begun to be applied in the manufacture of robotic prostheses, particularly for those that require greater structural strength, such as lower limb prostheses. In this process, a laser is used to melt layers of metal powder, such as titanium or stainless steel, creating extremely strong and lightweight structures. This technology has been used mainly in specialized clinical settings due to its high cost, but it promises to considerably improve the durability and functionality of prostheses [9].

The use of metal materials has allowed prostheses to be much more resistant to fatigue and wear, which is essential for users who rely on devices that support heavy loads. Although metal 3D printing technology is still in its early stages of adoption in the prosthetic space, its long-term benefits in terms of durability and customization are undeniable [20].

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Table 4. Comparison of 3D Printing Technologies for Prosthetics. Tables should be placed in the main text near the first time they are cited.

Technology	Materials Used	Precision and Detail	Print Speed	Production Cost	Applications in Prosthetics
Fused Deposition Modeling (FDM)	Plastics such as PLA, ABS, PETG	Moderate accuracy, limited detail	Medium to fast	Low	Manufacture of functional and economical prostheses. Common use in low-cost prototypes.
Stereolithography (SLA)	Light-curable liquid resins	High precision and surface quality	Slow to medium	Moderate to High	Highly detailed prostheses, especially small parts and aesthetic components.
Selective Laser Sintering (SLS)	Nylon powders, polymers	High precision, complex details	Medium to fast	High	Creation of robust, resistant and customized prostheses, ideal for functional applications.
Metal Powders (Metal 3D Printing)	Metal alloys such as titanium, steel, cobalt	Very high precision, complex parts	Slow	Very high	Bionic or mechanical prostheses, strong and resistant structures, such as hip implants or joints.

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8. Current Challenges In The Development Of 3D Printed Prostheses

Despite the significant advances that 3D printing has brought to the field of prosthetics, there are still technical and economic challenges that limit its widespread adoption. The upfront costs of high-quality 3D printers and specialized materials remain major barriers, especially in developing countries. In addition, although technologies such as FDM and SLA allow for rapid production of prosthetics, the time and post-processing costs to improve finishes and functionality still represent a challenge [29].

The future of 3D printing in prosthetics looks promising, with advances in hybrid technologies that combine plastic and metal materials, as well as the use of bio-compatible materials that allow for more natural integration with the human body. More advanced 3D printers that can print on multiple materials simultaneously are also being developed, which could further expand the design and functionality possibilities of robotic prosthetics [10].

Despite significant advances in 3D printing and its application in the development of robotic prosthetics, several technical, economic, and integration challenges persist that limit its large-scale adoption. Key challenges include material optimization, prosthetic durability and functionality, advanced customization, integration with biological systems, and affordability. In addition, aspects such as regulation and standardization in the use of these technologies also play a key role in their expansion.

8.1. Material Optimization

One of the main challenges in the manufacture of robotic prostheses with 3D printing is the selection and development of materials that meet the requirements of durability, flexibility, bio-compatibility and resistance. Although the most commonly used materials, such as PLA and ABS, are accessible and easy to print, they have limitations in terms of mechanical strength and long-term bio-compatibility. According to [29], 3D printed materials do not always withstand prolonged use, which can lead to deformation or structural failure in prostheses.

The search for new, more robust and flexible materials is an area of active research. Advanced polymers and hybrid composites, such as those that combine plastics with carbon fibers or metal materials, offer higher levels of durability and strength. However, these materials are often more expensive and complex to process, making them difficult to use in affordable prosthetics [10].

8.2. Durability and Functionality of Prostheses

Durability is a key concern in the design of robotic prostheses, especially those used in intensive physical activities or extreme conditions. Prostheses must be able to withstand daily wear and tear and continue to function optimally for long periods of time without the need for constant maintenance. This problem is amplified in robotic prosthetics, where the integration of electronic components and motors increases the risk of failure due to continuous use.

In addition, functionality is also a challenge. Although modern robotic prosthetics have advanced in terms of control and movement, there are still limitations in terms of the accuracy, speed, and force they can exert. Current control systems, based on myoelectric signals or sensors, do not yet allow completely natural and precise control, making it difficult to perform complex tasks such as manipulating small objects or performing fine movements [35]. The development of more advanced control algorithms, such as those based on artificial intelligence, is helping to mitigate this problem, but implementing these systems in accessible prostheses remains a challenge.

8.3. Customization and Adjustment of Prostheses

While 3D printing has made it easier to customize prosthetics, there are still barriers in terms of perfect fit and dynamic fit. Individual differences in the anatomical and physiological characteristics of each person make the design of personalized prostheses a complex process. In many cases, even if

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an adequate initial adjustment is achieved, the prosthesis may not fit well over time due to changes in the user's body, such as growth or weight changes [29].

Research into adaptive prosthetics, which can be adjusted automatically or by manual calibration, is ongoing, but the available solutions are expensive and difficult to implement in 3D printed models. In addition, the lack of standardization in the methods of measuring and manufacturing custom prostheses adds complexity to the process [10].

8.4. Integration with Biological Systems

A crucial challenge in the development of advanced robotic prosthetics is efficient integration with the user's biological systems. Myoelectric prostheses, which detect electrical signals from muscles to control the movement of the prosthesis, have made significant advances, but they still have limitations in terms of accuracy and sensitivity. The interpretation of these signals is often imperfect, leading to imprecise movements or delays in the response of the prosthesis [17].

Research in brain-computer interfaces (BCIs) has also shown potential to improve the connection between robotic prosthetics and the human body. However, these technologies are in the early stages of development and their implementation in affordable prostheses is not yet viable. In addition, the possibility of BCI systems being invaded by infections or biological rejections remains a major obstacle [18].

8.5. Economic Accessibility

Despite the fact that 3D printing has significantly reduced the costs of manufacturing prosthetics, access to these technologies remains limited, especially in low-income regions. While the costs of 3D printed dentures are much lower than those of traditional dentures, they still represent a considerable investment for many individuals and families. In addition, the costs associated with maintenance, customization, and integration of electronic components increase the total price of the device [34].

Global initiatives seeking to improve access to 3D printed prosthetics have helped bridge this gap, but a lack of adequate infrastructure, such as access to high-quality 3D printers and materials, remains a challenge. Advances in low-cost 3D printing, as well as the availability of printing technologies in rural and developing areas, are critical to making these prostheses more accessible [29].

8.6. Regulation and Standardization

The lack of clear regulations and standardization in the use of 3D printing for prosthetics is another major challenge. 3D printed prostheses must meet strict quality and safety standards before being used by patients, but current regulations vary widely between countries. In addition, the personalized nature of these prostheses complicates the regulation process, as each device must be adapted to the specific needs of the user.

Setting international standards for the manufacture and use of 3D-printed robotic prosthetics is crucial to ensure their quality and safety. Regulatory organizations should collaborate with engineers, manufacturers, and healthcare professionals to develop guidelines that balance technological innovation with patient protection [10].

9. Design and Manufacture of Robotic Prostheses with 3D Printing

The design and manufacture of robotic prostheses with 3D printing represent a paradigm shift in the field of biomedical engineering. These technologies make it possible to develop customized, lightweight, functional and low-cost prostheses that are better adapted to the individual needs of users. The process of creating a robotic prosthesis includes several phases: digital design, selection of suitable materials, manufacturing using 3D printing, and integration of electronic components and actuators that enable movement. This approach has made robotic prostheses more accessible and efficient, improving the quality of life for people with disabilities.

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9.1. Digital Design Phase

Robotic prosthetic design begins with the creation of a three-dimensional digital model using computer-aided design (CAD) software. This model is customized according to the anatomical characteristics of the user, allowing a precise and comfortable fit. One of the main advantages of 3D printing is that designs can be easily modified to suit each person's specific needs, from the length of a limb to the level of flexibility of joints [10].

CAD software allows engineers to design functional prosthetics that integrate complex structures, such as gear and joint systems, that would not be possible to manufacture using traditional methods. For example, it is possible to simulate the movement of fingers on a robotic prosthetic hand before printing, making it easier to optimize the design to improve functionality. In addition, the use of force and motion simulations in the digital design phase helps ensure that prostheses can withstand the stresses and loads of daily use without compromising their structural integrity [17].

9.2. Selection of Printing Materials

The choice of materials is crucial in the robotic prosthetic manufacturing process, as it impacts both the durability and comfort of the device. The most common materials used in prosthetic 3D printing include plastics such as PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene), both of which are known for their strength, lightness, and ease of printing. In addition, for components that require flexibility, such as joints, softer materials such as TPU (thermoplastic polyurethane) or silicone can be used [29].

The flexibility of 3D printing allows the combination of different materials in the same prosthesis. For example, in a robotic prosthetic hand, rigid parts can be made from ABS to provide structure and support, while areas that require movement or skin contact can be printed with TPU for comfort and flexibility. The ability to integrate rigid and flexible materials in the same device has been one of the most significant advances in the design of 3D printed prostheses [10].

In addition, some researchers are exploring the use of bio-compatible materials and even recyclable materials for prosthetic printing, which not only reduces costs, but also makes prostheses more sustainable and globally accessible [35].

9.3. Printing and Post-Processing Phase

Once the digital model has been designed and the materials selected, the next step is the printing of the prosthesis. At this point, 3D printing technologies such as fused deposition modeling (FDM), stereolithography (SLA), and selective laser sintering (SLS) are applied to manufacture the prosthesis layer by layer. Each technology has its own advantages and challenges: while FDM is more accessible and economical, SLA and SLS offer greater accuracy and better surface finishes, which is critical in prostheses that require an ergonomic and aesthetic fit [18].

Post-processing is an important stage that is often overlooked. This includes cleaning the part, sanding to improve surface smoothness, and in some cases, assembling multiple parts if the prosthesis has multiple components. In robotic devices, this stage also includes the integration of sensors, motors, and electronic systems that allow movement control. For example, in a robotic hand, servo motors can be integrated to provide precise finger movements, while pressure sensors allow the user to regulate the force with which an object is gripped [29].

9.4. Electronics and Control Integration

One of the most distinctive features of robotic prostheses is the ability to interact with the environment using actuators and sensors. In the final manufacturing stage, electronic components are integrated that allow the control of the prosthesis. This includes the installation of microcontrollers such as Arduino or Raspberry Pi, servo motors that facilitate the movement of the limbs, and sensors that collect data from the environment, such as pressure or temperature. A major advance in this

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area is the use of myoelectric signals, which pick up electrical signals from the muscles to control the prosthesis. These signals are detected by sensors placed on the skin and transmitted to a microcontroller that interprets the user's intentions, allowing the prosthesis to move intuitively. This type of control is particularly useful in upper limb prostheses, where precise movements and grip control are critical for everyday tasks [34]. Another development in the integration of control systems is the use of artificial intelligence and machine learning to improve the ability of prostheses to adapt to the needs of the user. By analyzing movement patterns, robotic prosthetics can adjust their behavior, improving control accuracy and energy efficiency, thereby increasing battery life and device life [35].

10. Social Impact and Clinical Applications of Robotic Prostheses with 3D Printing

The integration of 3D printing in the development of robotic prostheses has had a profound impact on society and the clinical field. This technology has changed not only the way prostheses are designed and manufactured, but also their accessibility and the rehabilitation opportunities they offer patients. The social impact of 3D printed prosthetics is manifested in several aspects, such as the democratization of access to personalized medical devices, the empowerment of people with disabilities, and the improvement of quality of life. In the clinical context, these prostheses have revolutionized the treatment of amputees, offering personalized, functional solutions and, in many cases, at a much lower cost than conventional prostheses.

10.1. Democratization of Access to Personalized Prostheses

Historically, traditional prosthetics have been expensive and difficult to obtain, especially in developing countries and communities with limited resources. However, the emergence of 3D printing has allowed for the manufacture of low-cost robotic prosthetics, which has democratized access to these devices for a wider population. Nonprofits, such as e-NABLE, have embraced 3D printing to produce prosthetic hands and arms at a much lower cost, providing hope to thousands of people who might not otherwise be able to afford a functional prosthesis [29].

This expanded access has been particularly beneficial for children with amputations, as traditional prostheses are often prohibitively expensive and must be replaced as the child grows. 3D printed prosthetics, being more affordable, allow children to receive new prostheses as they need them, without a significant financial burden on families. According to [34] devices such as the Cyborg Beast, a 3D-printed prosthetic hand design, have shown that it is possible to create customized solutions at a low cost, providing a positive impact on children's lives.

10.2. Empowerment and Quality of Life Improvement

The use of 3D-printed robotic prosthetics has transformed the perception of people with disabilities, allowing them not only to perform everyday tasks, but also to participate in recreational and work activities more fully. This change not only improves their quality of life, but also offers them greater independence and autonomy. The ability to customize the design of prostheses not only in terms of fit, but also in aesthetic appearance, has allowed users to choose prostheses that suit their personal style, which improves their self-esteem and confidence.

In addition, advances in robotic system integration allow for greater control of prosthetics using microelectric signals or even through brain-computer interfaces. These technological innovations have increased the functionality of prosthetics, allowing users to perform more complex tasks, such as manipulating small objects or engaging in activities that require dexterity [17].

10.3. Cost Reduction in Clinical Treatment

In the clinical setting, 3D printing has significantly reduced the costs associated with prosthetic design and manufacturing. While traditional prosthetics can cost tens of thousands of dollars, a 3D-printed robotic prosthesis can be manufactured for a fraction of that cost, allowing hospitals and

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clinics to serve a larger number of patients on the same budget [10]. This is especially relevant in public health systems where resources are limited and demand for medical devices is high.

In addition, the ability to produce custom dentures in a short period of time has also improved the clinical experience for patients. Instead of waiting weeks or months to receive a custom-made prosthesis, 3D printing allows patients to receive a personalized device in days or even hours. This faster process not only reduces waiting time, but also improves the effectiveness of rehabilitation treatment, as patients can start using and adapting to their new prostheses more quickly [29].

10.4. Clinical Applications and Prosthesis Customization

The flexibility of 3D printing has allowed robotic prosthetics to be adapted to the specific needs of patients in an unprecedented way. By using 3D scanners to map the user's anatomical features, engineers can design highly customized prosthetics that fit precisely to the patient's body. This level of customization not only improves user comfort, but also reduces the risk of complications, such as skin irritations or wounds, which are often associated with the poor fit of traditional prostheses [36].

In the context of rehabilitation, 3D printing has also enabled the creation of temporary prostheses and training devices that help patients adapt to their new prosthesis gradually. These transitional devices can be used in the early stages of rehabilitation, allowing patients to gain strength and skill before receiving their final prosthesis. According to [18] the combination of 3D printing and robotics has made it possible to develop more dynamic solutions for rehabilitation, optimizing long-term outcomes for patients.

10.5. Social Impact on Labor and Social Inclusion

3D-printed robotic prosthetics have also been shown to have a significant social impact in terms of labor and social inclusion of people with disabilities. By improving the functionality and aesthetics of prosthetics, people with physical disabilities have been able to re-enter the labour market more competitively, which has reduced the stigma attached to amputations. This has been especially evident in industries that require manual skills, where the ability to manipulate tools or perform precise movements is critical [10].

The social impact extends to communities as well, as access to affordable and functional prosthetics has promoted the participation of people with disabilities in recreational, sports and cultural activities. This change has been essential to foster greater social inclusion, reducing the physical and psychological barriers that previously limited these people in various spheres of daily life [29].

11. Future Perspectives in the Design and Manufacture of Robotic Prostheses with 3D Printing

The future of robotic prostheses made with 3D printing promises even more profound transformations in the medical and social spheres. With the continuous advancement in technology, materials, and impression techniques, robotic prosthetics are on the threshold of a new era of customization and functionality. Future prospects range from the integration of emerging technologies to the expansion in global access, which could redefine the impact and effectiveness of these solutions on the lives of people with disabilities.

11.1. Advances in Printing Materials and Techniques

One of the most promising developments in 3D printing for robotic prosthetics is innovation in materials. Researchers are exploring new types of polymers and compounds that offer improved properties, such as increased strength, flexibility, and biocompatibility. Smart materials, which respond to external stimuli such as temperature or humidity, could allow the creation of prostheses that automatically adjust to changing environmental or user conditions [10].

In addition, 3D printing techniques are evolving towards faster and more accurate methods. Multi-material 3D printing and 4D printing, where materials change shape in response to stimuli, are beginning to influence the design of robotic prosthetics. These advances could allow the manufacture of prostheses that dynamically adapt to the needs of the user and environmental conditions, thus improving functionality and durability [29].

11.2. Integration of Emerging Technologies

The convergence of 3D printing with other emerging technologies, such as artificial intelligence (AI) and advanced robotics, is opening up new possibilities for prosthetic design. AI algorithms can improve the control of robotic prosthetics by interpreting signals from myoelectric or other sensors more accurately. The integration of machine learning systems will allow prostheses to adapt and optimize their operation based on the user's activity, offering a more natural and efficient experience [18].

Augmented reality (AR) and virtual reality (VR) are also beginning to play a role in prosthetic design and rehabilitation. These technologies can be used to simulate the use of a prosthesis in a virtual environment, allowing users to train and adapt to their device before physically receiving it. This approach could improve rehabilitation outcomes and facilitate faster and more effective adaptation [34].

11.3. Advanced Customization and Customization

Customization will continue to be one of the main areas of development for 3D-printed robotic prosthetics. Advances in 3D scanning and digital modeling will allow for more precise adaptation to patients' individual anatomical characteristics. Future prosthetics could incorporate automatic adjustment systems that adapt to changes in the user's body shape over time, providing a more comfortable and functional fit [10].

Customization will also extend to the integration of brain-computer interfaces (BCIs), which could allow for more intuitive and natural control of prosthetics. Research into advanced neural interfaces is progressing, and in the future, we could see prosthetics that connect directly with the wearer's nervous system, offering seamless integration and a more precise response to neuromuscular signals [17].

11.4. Global Access and Cost Reduction

One of the main promises of the future of 3D printed robotic prosthetics is the expansion of their global access. With the continued reduction in 3D printing costs and the increased availability of printing technologies in disadvantaged regions, these prostheses are likely to become a viable option for a greater number of people around the world. Non-profit initiatives and grant programs could play a crucial role in expanding this access, ensuring that innovations in robotic prosthetics benefit communities in need [29].

Collaboration between governments, international organizations and technology companies will be essential to develop strategies to reduce the cost of prostheses and improve the infrastructure needed for their manufacture and distribution. Public policies and international cooperation efforts will be critical to ensure that the benefits of 3D printed robotic prosthetics are equitably distributed globally [34].

11.5. Global Regulation and Standards

Finally, the creation of global standards and clear regulations will be crucial for the future development of robotic prosthetics with 3D printing. Standardizing manufacturing processes, quality testing, and safety requirements will ensure that prosthetics are safe and effective for users worldwide. Collaboration between standards bodies, manufacturers and healthcare professionals will be essential to develop and implement these standards [10].

Creating a unified regulatory framework will help ensure that innovations in 3D printed robotic prosthetics are not only technologically advanced, but also safe and accessible to all. Implementing these standards will contribute to trust in the technology and promote its widespread adoption.

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12. Discussion

The integration of 3D printing into the design and manufacture of robotic prostheses represents a significant advance in medical technology, offering a number of benefits that transform both the clinical and social spheres. This discussion explores the implications of these advances, analyzing the impact on the accessibility, customization, and functionality of prostheses, and addressing the challenges that still persist in this field.

One of the greatest achievements of 3D printing in the field of robotic prosthetics has been the reduction of costs and the democratization of access to personalized devices. Traditional, often prohibitively expensive, prosthetics have been replaced by 3D-printed alternatives that offer an economical solution without compromising quality. This has been particularly beneficial for populations in developing countries and for families with limited resources. The ability to manufacture prostheses at a low cost has allowed organizations such as e-NABLE to provide functional devices to a greater number of people, contributing to a significant improvement in quality of life [29].

However, cost reduction is not the only factor at play. The ability to customize prostheses to fit the user's individual needs is another crucial aspect. This customization not only improves the comfort and functionality of the prostheses, but also allows for a more precise fit and better performance in the wearer's daily life [10]. 3D printing facilitates this level of customization through the use of 3D scans and digital modeling, resulting in devices that more precisely match the patient's anatomical features [18].

Continuous development in materials and impression techniques has expanded the capabilities of robotic prosthetics. Advanced materials and multidimensional printing techniques make it possible to create prostheses with improved properties, such as greater strength, flexibility and adaptability. 4D printing, where materials respond to external stimuli, opens up new possibilities for the design of prostheses that adapt to changing environmental conditions [10].

The integration of emerging technologies, such as artificial intelligence and brain-computer interfaces, promises to take the functionality of robotic prosthetics to an even higher level. AI algorithms can improve the control of prostheses by interpreting myoelectric signals more accurately, while advanced neural interfaces could allow for more intuitive and natural control [18]. These innovations have the potential to deliver a more natural and efficient user experience, moving ever closer to full integration with the user's neuromuscular system.

Despite significant advances, there are still challenges that need to be addressed to maximize the impact of 3D printed robotic prosthetics. One of the main challenges is global standardization and regulation. The lack of a unified regulatory framework can lead to inconsistencies in the quality and safety of prostheses. The creation of global standards and the implementation of clear regulations are essential to ensure that prostheses are safe and effective [29].

In addition, although 3D printing has reduced costs, the infrastructure for the manufacture and distribution of prosthetics remains limited in many regions. The global expansion of technology and access to resources are crucial to ensure that the benefits of robotic prosthetics reach the communities most in need [35]. Collaboration between governments, international organizations and businesses will be critical to overcoming these barriers and improving accessibility.

Finally, the adaptation of prostheses to the changing needs of the user and to environmental conditions remains an active area of research. The development of prostheses that can be dynamically adjusted and adapted to different situations will represent an important advance in the functionality and usefulness of these devices [18].

13. Conclusions

3D printing has revolutionized the design and manufacture of robotic prosthetics, offering a number of significant advantages that transform the field of prosthetics. Through this technology, a notable reduction in production costs has been achieved, allowing prostheses to be more accessible to people with disabilities around the world. The ability to customize these devices to fit individual anatomical features and specific user needs has significantly improved their functionality and comfort.

Advances in printing materials and techniques, such as 4D printing and the use of smart materials, have expanded the capabilities of robotic prosthetics, allowing for greater adaptability and strength. The integration of emerging technologies, such as artificial intelligence and brain-computer interfaces, promises to further improve the accuracy and naturalness of prosthetic control, approaching full integration with the user's neuromuscular system.

However, despite these advances, challenges remain that need to be addressed to maximize the positive impact of 3D printed robotic prosthetics. A lack of standardization and global regulation can lead to inconsistencies in device quality and safety. Expanding infrastructure for manufacturing and distribution, as well as developing strategies to improve access in disadvantaged regions, are crucial to ensure that the benefits of these technologies are equitably distributed.

In conclusion, as the field of 3D printed robotic prosthetics continues to advance, it is essential to continue addressing these challenges to fully realize the potential of this technology. The combination of technological advances with a strategy focused on accessibility and standardization will allow 3D printed robotic prostheses to have an even greater impact on the lives of people with disabilities, promoting greater equality of opportunities and an improvement in the quality of life globally.

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