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Emerging Trends in Additive Manufacturing for Prosthesis Applications - A Review

[1,*]A.G.C.S. Amarasinghe, and [2]N.K.U.K. Chandrasri

[1]Department of Engineering Technology, Faculty of Technological Studies, Uva Wellassa University, Badulla, 90000, Sri Lanka
[2]Department of Biosystems Technology, Faculty of Technological Studies, Uva Wellassa University, Badulla, 90000, Sri Lanka
[*]saranga.private@gmail.com

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Abstract- Additive Manufacturing (AM) also denoted as 3D printing has greatly enhanced the area of prosthetics since it allows for the creating of highly functional and personalized prosthetic devices. As a review paper, this paper aims to offer insights on the latest trends in AM for prosthetic application in terms of the new technologies, materials, and the incorporation of smart technologies. Some of the AM technologies like Stereolithography (SLA), Selective Laser Sintering (SLS), and Fused Deposition Modelling (FDM) have revolutionized prosthetic manufacturing by providing designers with vast freedom of design and manufacture with higher accuracy levels. Advancements in the material have provided AM prosthetics with a better material with biocompatible polymers like PEEK and high-strength alloys like Ti-6Al-4V. Advanced technologies such as sensors, myoelectric systems, and others have also improved the features and interaction of prosthetic devices with users. Still, some issues are present, such as material anisotropy, high costs of production, and difficulties in integrating smart components. To overcome these challenges, further work on the enhancement of the material properties, the reduction of costs, and the integration of high-tech solutions are needed. This review discusses the current status of AM in prosthetics, the issues, and future research opportunities for the AM prosthetics field to enhance its development and the quality of life of patients. Due to the constant improvements and the exploration of the current shortcomings, AM has the capability to transform prosthetic production and the lives of amputees for the better.

Index Terms- Additive Manufacturing (AM), 3D Printing, Prosthetics, Biocompatible Materials, Smart Technologies, Myoelectric Systems

1. INTRODUCTION

AAdditive Manufacturing (AM), also referred to as 3D printing, is a technology that has transformed several industries through the creation of structures that cannot be made using conventional methods.

One of the greatest achievements of AM is its application in the medical industry especially in the production of prosthetics. Orthotics, which are devices that mimic or supplement the function of a lost extremity or other body parts, have been manufactured using techniques that are highly labor-intensive and time-consuming, making the cost of prosthetics high. However, the integration of AM has significantly minimized these drawbacks by offering possibilities such as rapid prototyping, mass customization, and design flexibility. The latest technologies in AM including stereolithography (SLA), selective laser sintering (SLS), and fused deposition modeling (FDM) enhance the biomechanical functionality, material strength, and patient-specific customization of prosthetic limbs hence improving the quality of life of those who require prostheses [1][2]. The greatest advantage of AM in prosthesis development is that it is possible to create highly individualized prosthetic components that would fit the patient's anatomy perfectly. In the case of MRI and CT scans, anatomical data is converted to 3D models and prosthetics are made from these models providing a better fit than prosthetics made from traditional manufacturing processes. These models enable healthcare professionals to make modifications to the design before printing and thus minimize misfits and discomfort to the patients [3]. The economic benefits of AM especially in the developing world where quality prostheses are hard to come by offer a revolutionizing prospect. Less material usage, cheap labor, and a short time to produce the prosthetics make AM cheaper than the traditional methods that involve a lot of handwork [4][5].

AM has been shown to yield positive outcomes in the fabrication of both utilitarian and cosmetic prosthetics; however, further studies are still being conducted to discover better materials and processes that would enhance the stability, flexibility, and efficiency of the prostheses. Advancements such as multi-material printing and the use of smart materials are able to detect changes in the environment and respond to them are already opening the door for prosthetic devices that are more biologically accurate [6]. There is a great potential for the improvement of the performance, availability, and cost of prosthetics as the AM technology advances, making a positive impact on the lives of those who have lost limbs or have deformities.

1.1. Background of the Research

The application of Additive Manufacturing in the medical field especially in the fabrication of prostheses can be traced back to the general application of AM technology in different sectors. The use of AM in the medical field started in the late 1980s with the use of the technique for rapid prototyping and making surgical models [7][8]. AM technology continued to progress and with it, the uses of the technology expanded from using the technology to create anatomical models that would be used for pre-surgical planning to using the technology to create personalized implants, dentures, and even artificial limbs. The initial attempts to use 3D-printed prosthetics were constrained by the materials used for printing, which did not possess the biomechanical properties required for load-bearing or long-term implants [8]. However, the advancement in new biocompatible materials such as titanium alloys, polymer composites, and high-strength thermoplastics has made AM produce prostheses that have both aesthetic and functional properties [9].

The transition from conventional manufacturing to AM in the production of prostheses can be attributed to the following reasons; personalization, complexity of the structures of the human body, and constraints of conventional manufacturing. Conventional prosthesis manufacturing often requires time-consuming techniques such as molding, carving, and manual assembling; this makes the process time-consuming and costly, particularly for personalized devices [10]. AM on the other hand provides the option of manufacturing a product directly from a 3D model without the need for several intermediate steps as seen with conventional manufacturing techniques [11]. This digital fabrication capability also increases design freedom as it is possible to design and build structures and geometries that would be very difficult or highly inefficient to manufacture using conventional methods.

Besides the technical and economic benefits, AM has also been credited for its ability to bring prosthetics to people in developing countries or other disadvantaged groups. There is a high prevalence of limb loss worldwide, with millions of people in need of prostheses because of congenital abnormalities, trauma or diabetes, and vascular diseases among others [12].

Unfortunately, the availability of quality prosthetics is a challenge due to cost, availability, and qualified personnel. AM presents a possible solution to this problem since it is a cheaper and more flexible manufacturing technique that can be adapted to the needs of patients in various parts of the world. In addition, the application of open-source designs and decentralized manufacturing centers including local 3D printing centers also increases the availability of prosthetic devices to communities that may not have access to sophisticated healthcare facilities [8]. With the growing body of knowledge on AM, there is growing concern about creating new materials and methods that can improve the performance of prosthetic limbs. Some of the recent investigations have focused on the application of advanced composites including; carbon fiber-reinforced polymers and bio-inspired composites that have better strength-to-weight ratios and better mechanical properties as compared to conventional prosthetic materials [13]. Moreover, the integration of smart technologies including sensors and actuators is likely to pave the way for the creation of prostheses with improved sensory feedback and self-controlled systems [14]. This is the future of prostheses and is a clear indication of how AM can help improve the lives of people who have lost a limb or have a limb deformity.

2. METHODOLOGY

This systematic review is thus organized in a step-by-step process of identifying and synthesizing new trends in AM for prosthesis. The research methodology entails the following steps; collection of literature, literature screening and selection, literature review, and comparison of the findings. The method of the review was developed based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to maintain the scientific rigor and the reporting of the study [14]. The following sub-sections provide an account of the materials and methods employed in this study.

2.1. Literature Search and Collection

The literature search was done for seven months starting from the 1st of February, 2024 to the 1st of September, 2024. Several reputable academic databases were utilized for the search, such as PubMed, Scopus, Web of Science, IEEE Xplore, and ScienceDirect. These databases were chosen because of their large number of full-text articles in engineering, medical technologies, and materials sciences. Keywords used were “additive manufacturing, 3D printing, prosthesis, biocompatible materials, smart prosthetics, and multi-material printing” and their related terms. The use of Boolean operators including AND, OR, and NOT were used to filter search queries and exclude any irrelevant outcomes [15][16]. The literature collection process sought to obtain articles, conference papers, technical reports, and review papers that were mostly published between 2014 and 2024 to capture the current state of the art in the field.

2.1.1. Inclusion and Exclusion Criteria

A set of inclusion and exclusion criteria was applied to ensure that the review remained focused on high-quality, relevant studies.

2.1.1.1. Inclusion Criteria

- Most of the Articles published between the year 2014 and 2024.
- Literature reviews that investigated AM applications in prosthetics in terms of materials and technologies.
- Journal articles that analyze the mechanical characteristics, bio-compatibility, and service life of prosthetics fabricated through AM.
- Articles that propose the incorporation of smart features into 3D-printed prosthetic limbs, for example, sensors or motors.

2.1.1.2 Exclusion Criteria

- Research that was conducted on AM in other industries that are not related to prosthetics such as aerospace and automotive industries.
- Newspapers, magazines, blogs, and other non-academic sources, articles that are not necessarily written by experts in the field.
- Publications that were published but for which there was no full text available.

Using these criteria, 625 articles were found in total across all the databases. These articles were exported to the Mendeley Reference Manager for further sorting and elimination of irrelevant articles.

2.2. Screening and Shortlisting

The shortlisted articles were reviewed in a two-step procedure. Firstly, the titles and abstracts were scanned to identify papers that may be relevant to the study objectives. This process brought down the number to 210 articles. In the second phase, the full texts of these articles were evaluated for their depth of analysis, experimental rigor, and relevance to the following key areas; technological developments in AM, mechanical properties of prosthetics, methods of customization, and intelligent systems for prosthetics.

To refine the search even more, the studies that should be published in the journal with an impact factor greater than 2.0 were retained. For this purpose, the Journal Citation Reports (JCR) of Clarivate Analytics were used [17]. Finally, 38 articles were considered for a detailed review.

2.3. Data Extraction and Analysis

A structured extraction form was used for extracting the data based on the categories that were defined in line with the objectives of the study. Categories included;

- Type of AM technology such as SLA, SLS, and FDM are employed.
- Material classes such as polymers, metals, and composites.
- Physical characteristics such as tensile strength, elastic modulus, as well as durability.
- Biocompatibility studies
- Functional improvements such as the installation of smart sensors and feedback systems.

The data were exported into Microsoft Excel and frequency counts of key findings were computed for analysis. The flowchart of the systematic literature review is presented in Fig.1 based on the PRISMA guidelines.

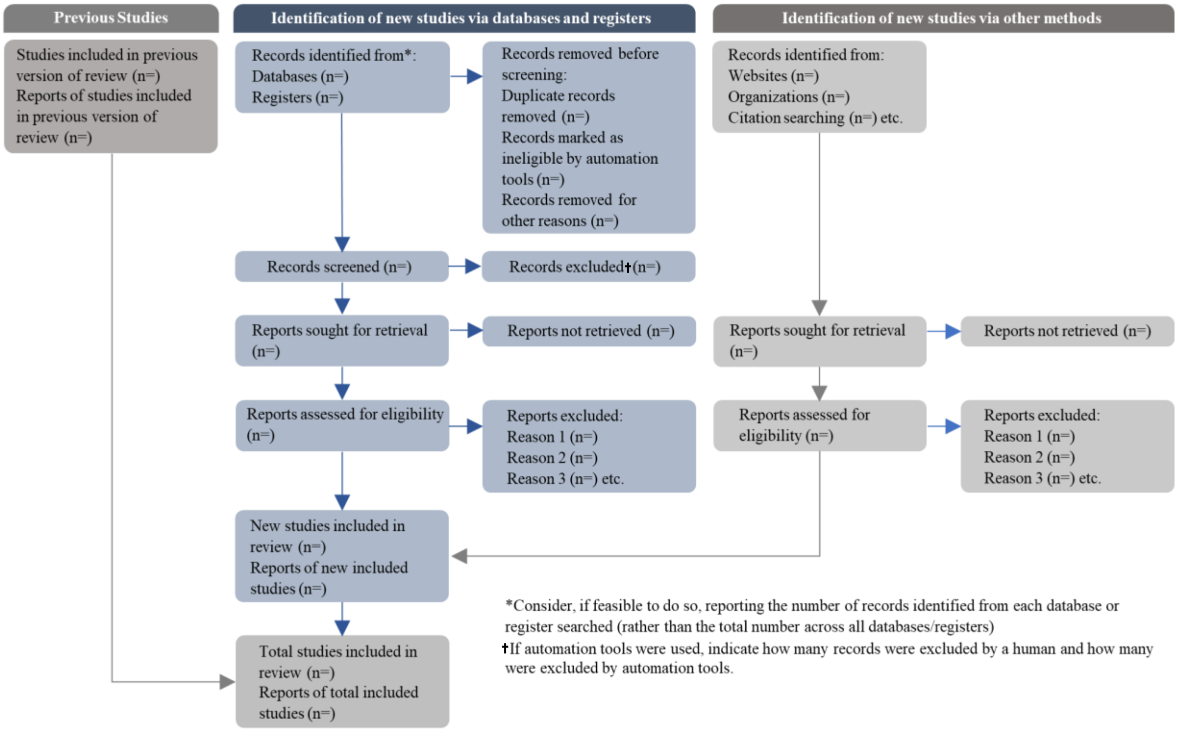

Fig 1. PRISMA 2020 flow diagram template for systematic reviews. (Guidelines were updated [14]. The boxes in grey should only be completed if applicable; otherwise, they should be removed from the flow diagram. Note that a “report” could be a journal article, preprint, conference abstract, study register entry, clinical study report, dissertation, unpublished manuscript, government report, or any other document providing relevant information.)

2.4. Synthesis of Results

The integration of the selected literature was done thematically, and as such, the trends that were seen to be recurring were highlighted. Papers were categorized according to the focus on AM technologies, material science, and functional application in prosthetics. Some of the comparisons that were made included material properties, prosthetic performance, and the incorporation of smart technologies. Where quantitative data were available, meta-analysis techniques were employed especially in the studies that assessed the mechanical properties or performance characteristics [18]. An overview of the selected studies, the AM technologies, and the materials employed are presented in Table 1 below.

Table 1. Summary of key studies on AM technologies for prosthesis applications [18]

Study	AM Technology	Material	Key Findings	Journal
Wang et al. (2017)	SLS	Nylon composites	High durability and customization potential	Composites Part B: Engineering
Tebyetekerwa et al. (2021)	SLA	Biocompatible resin	Improved patient-specific fitting accuracy	Materials Today Communications
Nguyen et al. (2021)	FDM	PLA/Carbon fiber	Strong structural integrity for lightweight prosthetics	Composites Part B: Engineering

2.5. Figures and Tables Integration

Besides Table 1, other figures were incorporated to improve the understanding of trends and technologies in AM for prosthesis applications. For example, Fig. 2 illustrates a comparison of the tensile strength of various AM materials used in prosthetic devices [19][20][9].

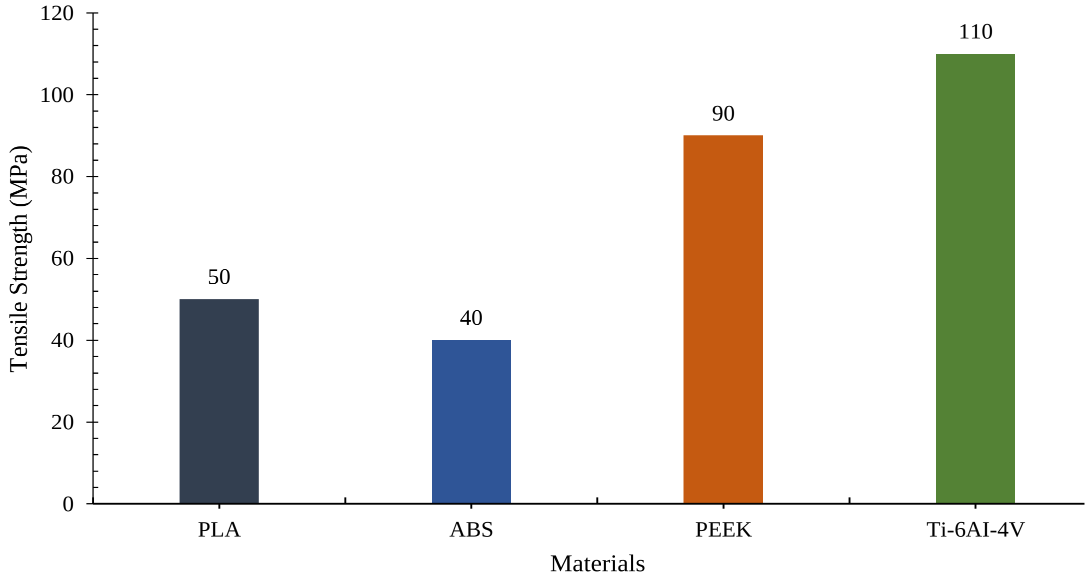

Fig. 2. Comparative Analysis of Tensile Strength Across AM Materials for Prosthetic Applications. (The chart presents typical tensile strength values for four common materials used in additive manufacturing for prosthetics such as PLA: 50 MPa, ABS: 40 MPa, PEEK: 90 MPa, and Ti-6Al-4V (Titanium alloy): 110 MPa [13].)

2.6. Ethical Considerations and Standards

All chemical names, materials, and formulas used in this review are in accordance with international standards such as ISO and ASTM. Some of the material codes and classifications used include PLA, PEEK, and Ti-6Al-4V where ISO and ASTM standards were followed [21].

2.7. Limitations of the Methodology

This review focuses on the most recent and relevant trends in AM for prosthesis applications. However, the shortlisting criteria included only the full-text articles and an impact factor greater than 2.0. Also, this review does not consider any other proprietary or industrial research that has not been published in the academic journal and may be useful in the future development of this field.

3. RESULTS AND DISCUSSION

This review compiles the recent trends and developments in the use of AM for prostheses, including materials, AM techniques, and the incorporation of smart systems. The subsequent sections present the results of the research concerning the mechanical, functional, and socio-economic effects of AM in prosthetics creation.

3.1. New Development in Additive Manufacturing Technologies

The use of additive manufacturing has also been proven to be quite effective in developing highly personalized prosthetic limbs. Stereolithography (SLA), Selective Laser Sintering (SLS), and Fused Deposition Modeling (FDM) are the most common techniques applied in this regard [22][13]. Table 2 below presents an overview of the strengths and weaknesses of each technique.

Table 2. Comparison of AM technologies for prosthesis applications [23]

AM Technology	Material Compatibility	Accuracy	Production Speed	Strengths	Limitations
SLA	Resins, Biocompatible Polymers	High	Medium	Excellent surface finish, good detail	Limited material options
SLS	Nylon, Polyamide, TPU	Moderate	High	No support structures required, good durability	Surface roughness, post-processing required
FDM	PLA, ABS, PETG, Carbon Fiber	Low	High	Low cost, wide material range	Lower accuracy, anisotropic properties

SLA has provided the most accurate and finest surface finish and therefore it is most suitable for making prosthetic parts of patients with special details such as finger joints or facial prostheses. SLS is more suitable for making sturdy and load-bearing parts such as leg sockets because the method involves using powder and results in higher material density. Although FDM is relatively cheaper, it has poor mechanical strength because of the layer anisotropy [23].

3.2. Advancements in Material for Additive Manufacturing for Prosthetics

The selection of the material in AM determines the strength, usability, and comfort of the prosthetic devices. The most popular materials that are used are FDM, PLA, and ABS because of their simplicity for printing, however, they are not very strong and can be used in low-stress applications only [13]. Superior mechanical properties and biocompatibility have led to the development of more sophisticated materials such as Polyether Ether Ketone (PEEK) and Titanium Alloy (Ti-6Al-4V).

PEEK is especially valuable due to its strength-to-weight ratio and wear resistance, making it suitable for load-bearing applications such as knee joints in prosthetics [23]. However, it has a high cost and is difficult to process in FDM and this has been a major factor that has prevented its use in many applications. On the other hand, Ti-6Al-4V, a titanium alloy, has proved to be efficient in SLS for the manufacturing of light, corrosion-resistant parts, especially in spinal and orthopedic implants [23][24][25].

The integration of flexible and rigid materials in a single print has been made possible by multi-material printing. This approach is important in areas such as prosthetic limbs where there is a need for flexibility at the joints and at the same time there is a need for rigidity in the limbs' structure. Progress in the multi-material printing technology especially via SLA and SLS has enabled the creation of prosthetics with gradients in their mechanical properties that replicate the gradient between soft tissue and bone [13]. Table 3 summarizes the key material properties used in AM for prosthetics.

Table 3. Material properties of AM materials for prosthetics [13]

Material	AM Technology	Tensile Strength (MPa)	Elastic Modulus (GPa)	Applications
PLA	FDM	60–70	3.5–4.0	Lightweight prosthetics, non-load bearing
ABS	FDM	40–50	2.0–2.5	Lightweight prosthetics, non-load bearing
PEEK	FDM, SLS	90–100	3.6–4.0	Load-bearing prosthetics (knee joints)
Ti-6Al-4V	SLS	900–950	110–120	Orthopedic implants, high-stress components

3.3. Smart Prosthetics and Functional Improvements

The application of smart technologies in AM prosthetics is a relatively new area, which has witnessed tremendous developments in sensory feedback, actuation, and electronics. Such innovations are capable of improving user functionality significantly since they are real-time and adaptive [26],[27]. For instance, the 3D-printed prosthetics have pressure, movement, and temperature sensors that give the users sensory feedback which are not available in normal prosthetics. Fig. 3 shows the design of a bionic ear with pressure sensors placed inside it [28][29][13].

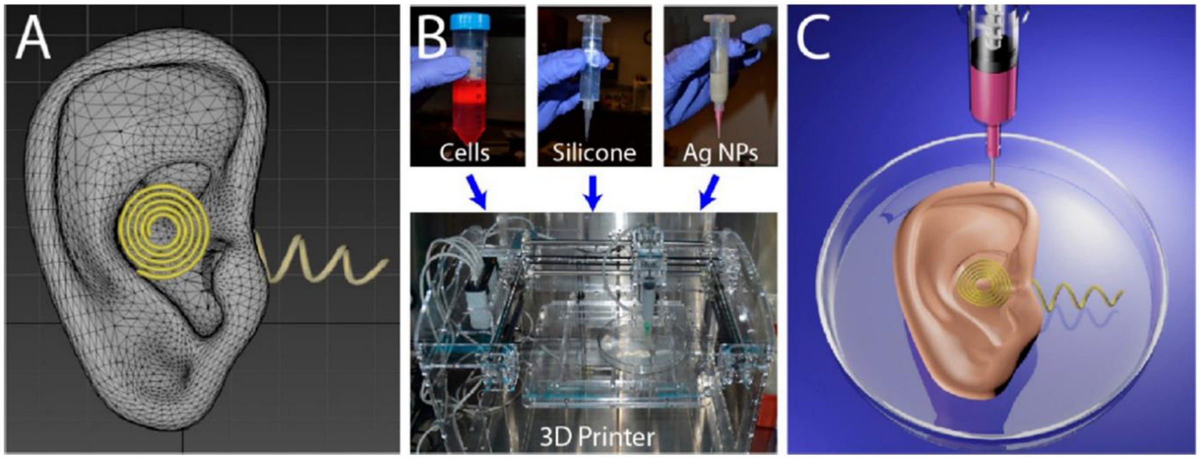

Fig. 3. Three-dimensional interweaving of biology and electronics via additive manufacturing to generate a bionic ear. ((A) CAD drawing of the bionic ear. (B) (top) Optical images of the functional materials, including biological (chondrocytes), structural (silicone), and electronic (AgNP-infused silicone) used to form the bionic ear. (B bottom) A 3D printer is used for the printing process. (C) Illustration of the 3D printed bionic ear. [13][30].)

Some of the research that has been conducted in this field includes the application of electroactive polymers (EAPs) in smart prosthetics. These materials can alter their shape based on electrical signals and thus allow prosthetics to replicate normal movements of limbs. For instance, Polypyrrole (PPy), one of the most popular EAPs, has been applied in developing artificial muscles for prosthetic hands that are lightweight and responsive in their actuation [23][31][32]. While they are yet in the experimental phase, these materials hold great potential in improving the performance and flexibility of prostheses.

Also, the advancement of myoelectric prosthetics in which the prosthetic limb is controlled by the electrical signals from the muscles of the user has been realized. AM process involves myoelectric sensors which enable the prosthesis to be fitted to the user's body and to blend with the natural system. These prosthetics offer better control than mechanical ones and enhance the overall experience of the users [23][33].

3.4. Effects of Additive Manufacturing on the Economy and Socio-Economy of Prosthetics

Another advantage of AM in prosthetics is the possibility of cost reduction and increased availability of prosthetic devices, especially in developing countries. Conventional prosthetics can range from $5000 to $50000 depending on the type and material used in the manufacture of the prosthetics. On the other hand, AM is cheaper than the traditional method of making prosthetics with the prosthetics being made for as low as $50 to $1,000 using low-cost FDM machines [34]. The overall decrease in the cost of labor and materials alongside the opportunity to create unique designs at the same time makes AM a suitable way of solving the problem of providing people around the world with affordable prosthetics.

AM facilitates local production thus minimizing long supply chains and making it possible for remote areas to access quality prosthetics. This has a major impact on developing countries since they are unable to afford most of the medical technology such as e-NABLE has led the way in open-source 3D-printed prosthetics with a view of enabling people to design and distribute affordable prosthetic hands [13].

3.5. Challenges and Future Directions

However, some issues can be considered as obstacles to the further development of AM for prosthetics. Material performance especially in the areas of long-term stability and biocompatibility is still an area of concern. The directionality of AM-printed materials where strength is not uniform in all directions is a challenge to load-bearing prosthetic components [23][35].

Although smart technologies have a lot of potential, their implementation into AM prosthetics is still in the experimental phase. The integration of sensors, actuators, and electronics into 3D-printed prosthetics is expensive and challenging; therefore, it requires further development to become more common. Future research should be directed at the enhancement of the stability and cost-effectiveness of these technologies, as well as the creation of new materials that could be as close as possible to human tissue. Table 4 outlines the future research directions and current challenges in AM for prosthetics.

Table 4. Challenges and future directions in AM prosthetics [23]

Area	Current Challenge	Future Direction
Material Durability	Anisotropic properties, limited material choices	Development of new composites, multi-material printing
Smart Prosthetics	High cost of sensors and actuators	Affordable integration of smart technologies
Customization	Limited adaptability for complex anatomical structures	Advanced multi-material and gradient printing

4. CONCLUSION

This systematic review focuses on the extensive use of AM in prostheses, showing the progress in customization, material selection, and the incorporation of intelligent systems. Advancements in AM techniques including SLS, SLA, and FDM have made it possible to design and develop prosthetics that are comfortable to wear, strong mechanically, and easy to use by the patients. New materials such as PEEK, Ti-6Al-4V, and multi-material printing have broadened the scope of application, and smart technologies such as the incorporation of sensors and myoelectric systems have the potential to add functionality. There are some issues with the use of AM in prosthetics manufacturing such as the durability of the material, anisotropic properties of the material, and the issue of smart prosthetics being affordable for everyone but the opportunity that AM offers for the manufacturing of prosthetics cannot be doubted. While research advances to meet these challenges, AM offers the possibility of enhancing the quality of life of those who require prosthetic limbs.

5. RECOMMENDATION

Future research in additive manufacturing (AM) for prosthetic applications should be directed toward the improvement of multi-material and gradient printing to improve the level of customization and integration of the prosthetic components [36][37][38]. Further research on biocompatible materials such as PEEK and Ti-6Al-4V alongside the availability of smart technologies such as sensors and myoelectric systems is important in enhancing the functionality and availability of prosthetic devices. However, two issues remain unsolved and should be further investigated to make AM prosthetics more applicable for further demanding, load-bearing applications; anisotropic material properties, and long-term stability. Efforts to focus on low-cost manufacturing techniques and open-source designs, especially for the regions that remain underserved, should also be highlighted to improve the quality of prosthetic care. The future of prosthetics can be greatly enhanced by using the opportunities of AM and its growing availability for millions of people around the world.

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