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Utilization of 3D Printing Techniques in Prosthetics Manufacturing: Historical, Current, and Future

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Abstract

Prosthetics for people with upper-limb differences have an intriguing and extensive history, yet problems that have not been resolved still exist. Children's prosthesis requirements are more complicated because of their rapid growing. A child's psychological development can be significantly impacted by their access to technology. Children frequently cannot access technologies that support both cosmetic form and user function because of their high cost, insurance policies, medical availability, perceived durability, and complexity control. These difficulties have sparked an international movement to provide a workable solution for the millions of people who live with limb differences worldwide. The creative use of 3D printing to create user-specific and customized hardware has resulted in the open-source "DIY" creation of assistive equipment, which has had a remarkable influence on low-income families all over the world. The maker community and nonprofit organizations' recent research and creation of prosthesis is examined in this paper, along with examining the advancement of technology and available training techniques. These design initiatives are examined in more detail within the framework of Indian medical regulations, and they draw attention to recent related clinical research aimed at assessing the impact of these devices on quality of life.

Keywords: 3D printing, prosthetics, customized prosthetic devices, Open-Source DIY Prosthesis, Customized Upper-Limb Prosthetic Design

INTRODUCTION

Throughout history, prosthesis design has evolved globally and has roots in ancient civilizations, such as the Egyptian and Roman empires. Traditional techniques for making artificial limbs have long been used in India, but in recent decades, advancements, like the Jaipur Foot, have made contemporary prostheses more popular and inexpensive for thousands of people [1]. Although limb loss from illnesses and trauma has decreased because of medical improvements, there is still a considerable need for prosthetic devices [2].

Millions of people in India are thought to have limb differences, with a significant percentage of them having amputees of the upper limb. Trauma, which frequently results from traffic accidents, work-related injuries, and natural disasters, continues to be a major cause of upper-limb amputation, especially in men [3]. Additionally, amputations and congenital limb abnormalities in children are major contributors to the population in need of prosthetic care [4]. Programs, such as the National Birth Defects Registry track congenital limb abnormalities, underscoring the need for

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specialist pediatric prosthetics. The prevalence of people in need of prostheses is predicted to increase due to population growth and greater awareness, highlighting the significance of practical, accessible, and reasonably priced solutions catered to India's particular problems [5].

Every year, thousands of children in India undergo significant pediatric amputations, mostly because of damage from industrial and traffic accidents or congenital limb abnormalities [6]. According to estimates, upper-limb reductions occur in roughly two to four out of every 10,000 live newborns in India [7]. There are regional variations in the frequency and severity of limb reductions because of socioeconomic, environmental, and genetic factors [8].

Amputees continue to use prosthetic devices at low rates, despite advancements in prosthetic technology [9]. Even when they have access to a prosthetic device, a sizable portion of people who have lost limbs due to congenital or acquired causes decide not to utilize it. This is frequently the result of upper-limb prosthetics' unappealing design, weight, scarcity, and excessive price [10]. Because they are seen as more necessary, lower-limb prostheses are often used more frequently. Prosthetic usage rates among children, especially those who have had transverse upper-limb amputations, continue to vary, and adoption is further influenced by cultural beliefs and access to healthcare [11].

Combining aesthetics and practicality to meet practical and psychosocial needs has become a more important aspect of prosthetic device design. In addition to considering the device's aesthetics, contemporary prostheses seek to mimic the natural movement of the human hand. However, little research has been done in India on how prostheses' aesthetic qualities affect their use and acceptance [12].

Adoption of prosthetics is significantly influenced by psychosocial variables. Children and adults with limb differences frequently struggle with body image and self-esteem, which can negatively affect their quality of life. Though a lot of research has focused on functioning rather than aesthetics, studies have demonstrated that using prosthetic devices increases confidence and social involvement [13]. Prosthetic users' psychological development and general quality of life can be greatly enhanced by attending to both their functional and aesthetic demands. To better comprehend these elements and guide the development of prosthetic devices that are suited to the requirements of the populace, more study in India is required [14].

A NEW APPROACH TO PROSTHETIC LIMB DESIGN

Globally, the maker community is expanding because of the ability to digitally share 3D design models online. Following a carpentry accident in 2011, a global team worked to restore some of the carpenters' lost dexterity after they lost multiple fingers. Ivan Owen, a mechanical special effects artist, was hired by the carpenter Richard Van As. The first 3D-printed upper-extremity prosthesis device was created in 2012 because of this collaboration, and the designs were made available as an open-source format for the maker community worldwide to replicate and assess [15]. This body-powered apparatus, shown in Figure 1, activated uniform contraction of the phalanges by flexing the residual limb's wrist [16].

THE RISE OF 3D PRINTED PROSTHETIC ARMS

The possible use of a range of accessibility technologies was significantly impacted globally by the availability of the designs spearheaded by both Robohand and designer Ivan Owen [17]. This prompted academics and makers who wished to make a comparable impact to get in touch with the designers. Several maker communities and nonprofit organizations, such as e-NABLE [2], Enable Community Foundation [3], Robohand [4], and Limbitless Solutions [5], were established to support local access in their communities after observing the efficacy and impact of collaborative design and production. These groups have comprised research teams situated at different universities as well as local at-home designers, such as: Rochester Institute of Technology, Creighton University, University

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of Central Florida, and the University of Washington at Bothell. Everything from industry-standard equipment to home-built kit 3D printers has been used in additive manufacturing processes. Some groups have extended the research on electromyographically actuated devices to allow for higher degrees of limb loss via biosensing and electromechanical motors, even though most of the work has been done for body-powered devices [6].

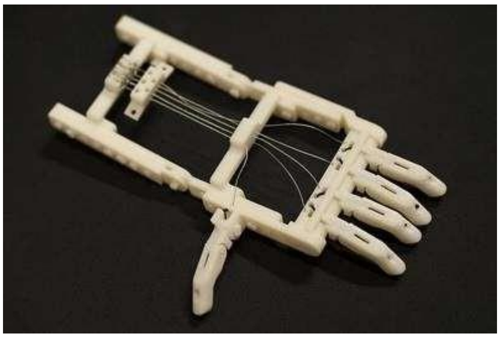

Figure 1. 3D-printed mechanical prosthetic hand featuring tendon-like cable mechanisms for basic finger articulation and movement.

Rapid production and iteration were made possible by custom size that was made for the end user using either volumetric scaling or more accurate parametric tailoring. The same underlying 3D model could be created using a user-specified color scheme, even though many printers now support a range of filament material colors. This has increased participation in and affinities for participatory design. The maker community and medical experts, such as surgeons, prosthetists, and therapists, convened at Johns Hopkins Hospital in 2014 for a symposium titled “Prosthetists Meet 3D Printers” to talk about the potential of 3D printing to enhance access and care quality [14]. Jen Owen and Jon Schull were part of the team that organized this conference and the e-NABLE online platform. The conference brought together a significant number of limb-different individuals, designers, and medical professionals [14].

Group support and improvements in functionality, reliability, and the ability to gather user-driven input were made possible by collaborative design efforts, many of which made use of cloud-based real-time design software like Autodesk Fusion 360 [18]. Significant advancements were made by the Enable network and made publicly available via the open-source repository on the Thingiverse.com website, with proper attribution. Figure 2(a & b) displays the design schematics and an image of a printed and assembled item that were made accessible [6]. Because of new 3D printers utilized in homes, libraries, and schools, as well as the availability of open-source, customizable designs, these technologies have become more accessible to kids worldwide [6].

This kind of international assistance has made it possible to use collaborative design mindsets in an accelerated prototyping phase. The maker movement has been incorporated into the university research environment as it has continued to grow. Using data-driven analytics, several research teams have attempted to standardize manufacturing processes and create best practices [19–24]. Jorge M. Zuniga’s work, which was founded while he was a student at Creighton University (now the University of Nebraska), serves as one illustration. Their study has advanced the field’s design efforts and application of additive manufacturing to speed up biomedical research and its application in the medical setting [6]. Figure 3(a & b) depicts their wrist-powered Cyborg Beast hand design, which has been widely used for kids with limb differences. It improved integration and assembly issues and built on earlier work [6].

APPEARANCE-COOPERATIVE EXPRESSION

More personalized device customization is now possible thanks to design work done with 3D printers [6]. The importance of user-driven design principles has become increasingly apparent as the

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network of developers that value collaboration has expanded [14]. End-user participation has been prioritized to enhance affinities to bionic designs. Our research team's approach to prosthesis design is referred to as "cooperative expression" and is based on participatory design methodology and related tactics, including cooperative inquiry [23].

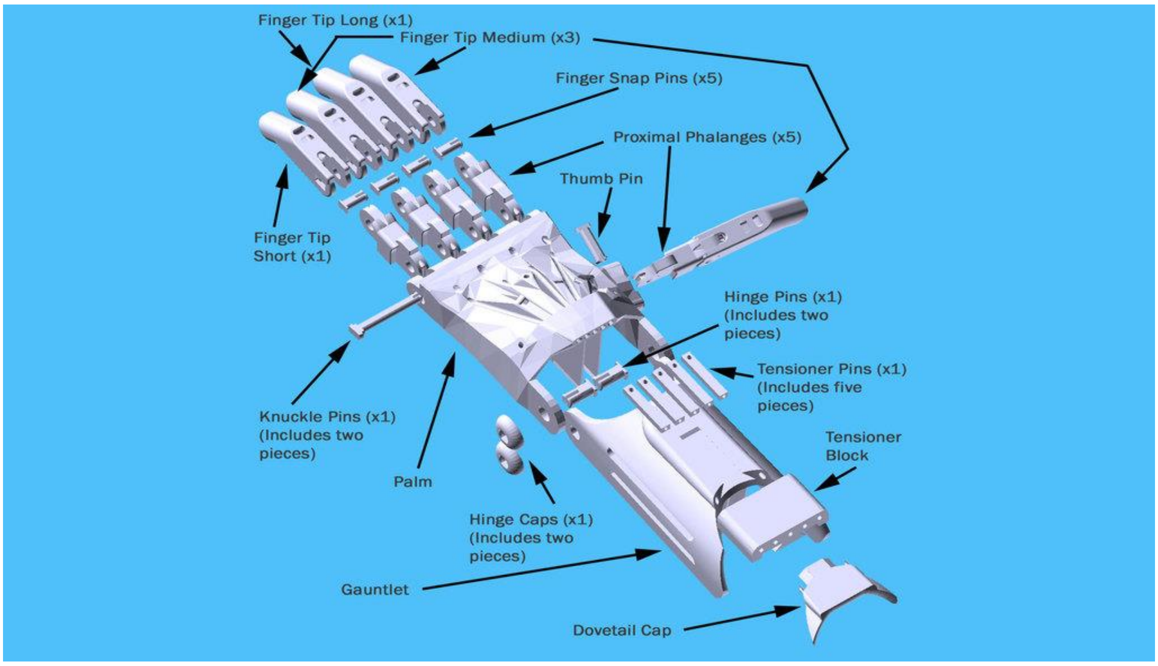

Figure 2(a). Exploded view of design and user assembly methods.

Figure 2(b). Completed assembly of device.

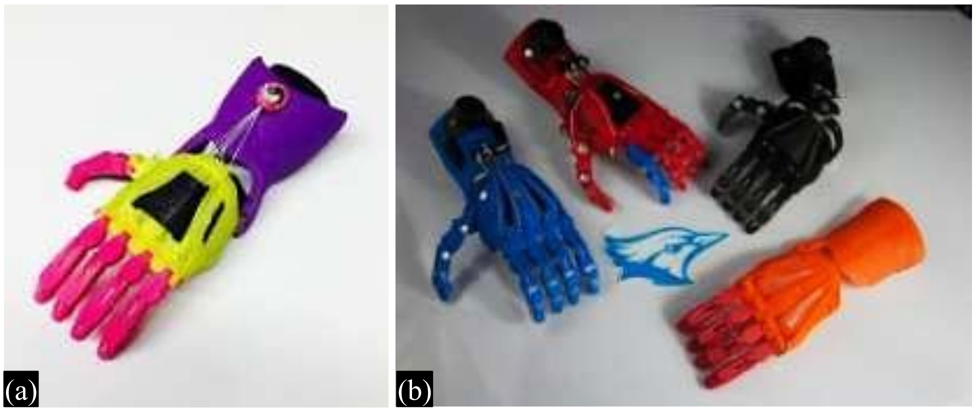

Figure 3. (a) Personalized assembled device. (b) A group of assembled hands featuring different cosmetic treatments.

The study of the role of direct user interaction with designers is the focus of the discipline of participatory design, which is defined by a range of methodologies [23]. Although this was first explored in relation to computer-based systems in the workplace, it can also be used to learn from children and their viewpoints when low-tech design prototypes are being developed [25–30]. Cooperative inquiry refers to certain questions in brainstorming techniques used in the design process. Three aspects of children as design collaborators were grouped by Druin et al. and are as follows: (i) the child's relationship to the adults who are participating; (ii) the child's relationship to the technology; and (iii) the inquiry's goals. When used as a technique for technological development, cooperative inquiry is adaptable. The method was used by Foss et al. to investigate how adults and children with special learning needs might collaborate to build software while enabling children to personalize their experience. Children reported feeling emotionally engaged when the cooperative inquiry method was used in their study. In the end, it is hypothesized that this increased involvement will give the kids a greater sense of ownership over the project.

To increase affinities with the bionic limbs, a novel modified participatory design technique called cooperative expression is now being used for visual aesthetic treatment. This collaborative and participative technique has been used by our design team to facilitate the modification of the appearance of 3D-printed bionic limbs [6]. Through an interactive website, recipients of the bionics can creatively personalize their interchangeable sleeves. It is possible to compare, choose, and further customize different 3D designs by altering the color and effect zones. The early development of visual scaffolding, including color palette design and zone discretization enabling customization, is aided by artists [14].

To reduce selection fatigue and enhance the participants' capacity to investigate creative designs that may be outside of their frame of reference, this scaffolding was created to offer a preliminary framework.

Figure 4. Overview of design process and methodology from design generation, user participation, and interdisciplinary manufacturing.

The goal of the distinctive customization design process and methodology shown in Figure 4 is to incorporate the end-user into the design process from beginning to end. The arm's mechatronic and structural elements have been standardized so that the digital designers can produce a 3D digital model of the creative shell. Through an interactive website, the user can alter the sleeve's colors, effects, and areas, enabling an expressive visual representation of the finished design. Sometimes, to assist the human–machine interaction, changes are made to the artistic design that is displayed on the

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user portal. An interdisciplinary approach that includes 3D printing, surface priming and preparation, automotive finishing procedures, and painting is used in the production of attractive sleeves. After validation, the entire system is ready to be fitted to the participant. Figure 5 is an example of how this approach enables participants to actively engage with their arm prior to production or fitting. Before the subject is fitted, it is expected that this initial engagement will create an emotional bond with the limb.

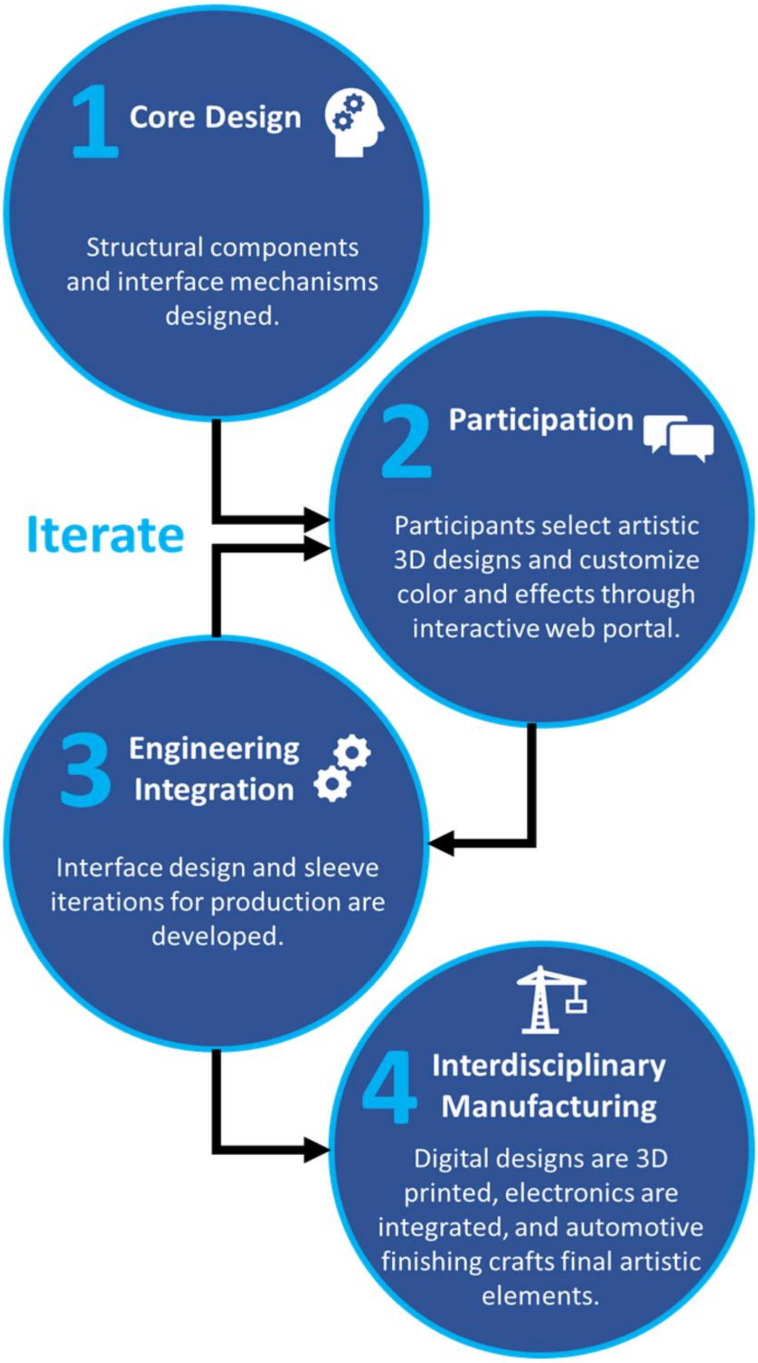

Figure 5. Four-stage iterative process for developing customized prosthetic devices, including core design, user participation, engineering integration, and interdisciplinary manufacturing.

Different categories or "empowerment classes" of replaceable aesthetic sleeves are made possible by a portion of the design process. Warrior, Shadow, Ethereal, and Serenity are the four distinct

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groupings into which these classes are divided. The purpose of these classes is to depict various personalities associated with emotional affinities. To relate to these personas, artists produce these inspired 3D models, and occasionally outside artists that portray characters have contributed ideas to the collection. Figure 6 shows examples of the "empowerment classes." The youngster can express themselves more freely thanks to this diversity and the replaceable possibilities, which should enhance the device's affinity development, reduce social stigma factors, and encourage longer-term involvement, all of which boost user performance [31].

Figure 6. Advanced myoelectric prosthetic arm featuring multi-articulating fingers, sensory feedback, carbon fiber casing, and customizable grip patterns for enhanced functionality.

FUNCTION–ELECTROMYOGRAPHY

According to a study by Antfolk et al., following a two-day training session, a 16-sensor electromyographic (EMG) system was able to anticipate desired control with an astounding 86% accuracy [1]. The system was tested on a male trans-radial amputee who was 25 years old. The results showed that the system learned to understand the user's EMG signals by using movement patterns from before the amputation. The utilization of several EMG inputs mapped to various computer-controlled outputs adds complexity to these systems. It can be difficult to purposefully activate muscle groups and, in certain situations, to activate them simultaneously for every extra monitored region [32]. This intricacy has frequently proven to be too much for kids, which has raised the rejection rates of prosthetic devices [33].

Given the high number of amputees in India – many of whom have suffered injuries in industrial settings or in traffic accidents – there is a critical need for more straightforward and reasonably priced prosthetic alternatives. A single EMG measurement is incorporated into this study team's creative 3D-printed prosthesis, making daily calibration and application easier. The muscular contraction's intensity or the quantity of contractions in each amount of time IS correlated by the onboard signal processing system [34].

This makes it possible to actuate a variety of hand motions, such as specific finger movements and motor postures. By addressing the shortcomings of existing EMG devices, there is a chance to improve design and training techniques and increase the accessibility and usability of prosthetic solutions for the Indian populace [35].

COMFORT AND DURABILITY

Like any production technique, 3D printing offers benefits and drawbacks. It has been demonstrated that the potential of customized medicine and the speed at which models can be created work well in clinical settings. Although it will not have a big effect on experts who use 3D printing to create representational models that aid in process planning, worries about the safety of 3D-printed components have been raised. The impact of the manufacturing process must be understood by professionals that use material attributes to maximize design. Samples of ABS plastic made by

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additive manufacturing have been shown to have varying mechanical properties depending on print orientation; they are thought to be between 10% and 73% stronger than injection-molded samples. Although the technique employed to print the layers affects the departure from material standards, performance predictability and dependability can be increased by optimization. The implementation of consistent standards and best practices is necessary to ensure that 3D-printed components used in medical settings are dependable and consistent [36]. A deeper comprehension of the fundamental ideas behind component vulnerability can help to reduce those risks in advance, even though FDA guidelines make several recommendations about workflow and paperwork for part tracking in the case of a part failure [20]. Additive manufacturing may produce robust and stable parts that can lower system weight and manufacturing costs when they are designed with realistic loading predictions and manufacturing considerations.

FUTURE OF PROSTHETIC ARMS: THE ABILITY HAND

Prosthetic arms of the future will be completely changed due to inventions, such as the Ability Hand. With progress in biomechanics, AI, and new materials, it is now possible to make these prosthetic devices more functional, intelligent, and affordable [37]. Patterns, like the Ability Hand, embody the future of assistive technology, a perfect example of what these devices are capable of. Sheltered within the outlines of this device are sample standards of future prosthetics with a perfect blend of technology and design around the end-user.

One such area seems to focus on improving the functionality and control of the prosthetic. Prosthetic arms in the future are envisioned to incorporate cutting-edge machine learning algorithms to improve their adaptability in real-time scenarios [24]. This means that some of the new systems will almost certainly be able to better “decode” the complex EMG signals, allowing the users to execute delicate finger movements with very little effort [28].

More developments in haptic feedback technologies will help amputees use prosthetics with a “sense” of pressure, temperature, and texture that comes closest to that of a biological hand [38].

Another crucial area of innovation is the utilization of 3D printing technology as a game changer in the production and personalization of prostheses. For example, in the Ability Hand, finger frames, structural covers, and other non-load-bearing elements produced with 3D printing technology help to cut down the cost of production while at the same time creating lightweight and robust designs. This approach is especially important in lowering the cost of advanced prosthetic devices and making them available in underdeveloped countries. From here on out, 3D printing is envisioned to facilitate the use of rapid prototyping and mass customization, whereby individual anatomical requirements can be addressed in the most accurate way possible when creating prosthetics.

Additionally, prosthetic arms, such as the Ability Hand of the future might put more emphasis on convergence into new technologies. For example, brain-machine interfaces (BMI) hold out the prospect that prostheses could be controlled by the brain, without muscle activity. With new developments in bionic skin that can replicate the look and feelings of human skin, these arms may one day look and serve the same functions as human arms.

Aside from technological factors, it is expected that sustainability will be a major influence on the design of prosthetic arms of the future. The use of recyclables and bioplastics, along with the introduction of low-energy-consuming operating systems, would be relevant in this context.

The Ability Hand and similar devices mark a watershed moment in the prosthetic industry as they help to close the affordability and high-end practicality divide. When 3D printing, artificial intelligence, haptic technology, and BMI become commonplace, there is an opportunity for millions of people worldwide to get prosthetic arms that are not just mechanical tools but engineering extensions of the human body.

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Working of the Ability Arm

Experience real-life abilities with the fully functional Ability Arm allowing its users to cut through the hazards of everyday life. Equipped with sophisticated neural interfaces, robotic components, and artificial intelligence, the arm arms itself with the ability to move like a normal arm [39].

With muscle signals detected by the automatic arm, users can maneuver the arm as they please. The working starts off with certain core components, the sensors embedded inside the prosthesis which generate and acquire EMG signals. Dilation of the passive arm generates muscle contractions which are read by the sensors, and which then serve as arm movements.

The captured EMG signals, however, suffer from low precision and interference, thus requiring further enhancement through signal processing [25]. This enhances their precision, strength, and most importantly, reduces noise interference. As users continue to learn how to use the arm and move it, the AI within the robotic component is then able to replicate the movements with the use of optimized algorithms, increasing the responsiveness of the arm over time.

Once the signals are processed, they are interpreted by a microcontroller, which acts as the central processing unit. The microcontroller then interprets these signals and converts them into instructions for motion, such as hand closing, wrist turning, or bending of fingers. The application can also include some already set programmed gesture patterns, which ease the control for standard operations and make the user experience more friendly.

The interpreted commands are put into operation via an actuation mechanism, most made up of servo motors or linear actuators. Such components enable the mechanical movement of the prosthetic arm and the separate motion of the fingers and joints of the arm. This configuration aids in the generation of the most natural multi-articulating movement of a limb, extending its functional capability to that of a human arm [39].

Haptic feedback devices can also be included in the advanced versions of the Ability Arm. Such devices can provide sensory feedback to the users. These systems are equipped with sensors that sense the grip and texture of the object and provide feedback with the help of vibrations or cues at the same time. This, in turn, helps solve the problem of gross and fine movement control, leading to better manipulation of objects.

A rechargeable lithium-ion battery powers the prosthetic arm, which guarantees steady performance for a long time. The battery system has been designed to save energy, allowing the arm to work all day without needing to charge often. Also, the prosthesis offers options to adjust and customize to meet each user’s specific needs. The device’s usefulness improves with adaptive grip control and the ability to program personal gestures, making it fit for many tasks and settings.

The Ability Arm gives a practical and easy-to-use solution for people with limb differences by mixing advanced tech with a design that focuses on the user. Its simplicity and ability to adapt make it a good choice for more study and improvement in places, like India, where low cost and ease of use are most important [40].

CONCLUSIONS

The revolutionary impact of 3D printing on 3D modelling has emerged as a revolutionary technology with a significant impact on the field of medicine. The ability to create complex and customized designs with precision and efficiency has opened new opportunities for people from different disciplines.

In the past, creating solid workstations was time consuming and expensive. 3D printing allows for rapid creation and customization of prototypes, simplifying this process and reducing production time

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and costs. This has made prosthetic devices more accessible to the public, especially in developing countries.

3D printing is currently used to create a variety of prosthetic parts, including bases, arms, hands, and legs. These devices are lighter, longer, and more comfortable than traditional prosthetic devices. 3D printing can also create highly customized designs that can be tailored to the needs and desires of each patient.

Looking ahead, the potential for 3D printing in the manufacturing industry is enormous. Advances in materials science and 3D printing technology are ultimately, 3D printing has revolutionized the field of manufacturing by providing a better, cheaper, and more personalized way to create. As technology continues to advance, there is no doubt that 3D printing will play a major role in improving the lives of people with different limbs.

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