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Physics-Driven Innovations and Future Trends in Prosthetic Limb Design

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Abstract

Prosthetic technology has significantly improved the lives of individuals with limb loss by enhancing their independence and overall quality of life. Although substantial progress has been achieved in prosthetic materials and structural design, the incorporation of Artificial Intelligence (AI) is expected to bring further advancements to this field. Prosthetic limbs represent one of the most effective solutions that enable amputees to lead a more independent and functional life without continuous reliance on external assistance. Over time, various manufacturing and fitting techniques have been developed to accommodate different medical conditions and user needs.

Artificial arms and legs are designed to compensate for lost limbs by restoring a level of natural movement and functionality. Historical evidence suggests that mechanical prosthetic devices have existed since ancient civilizations, evolving gradually into more advanced systems. This paper examines limb prosthetic devices by presenting a clear definition, followed by an overview of their historical development and technological evolution. Additionally, it explores future research opportunities and emerging trends in prosthetics, highlighting their importance in bioengineering and their broader impact on society. Particular attention is given to the role of AI in shaping next-generation prosthetics, including aspects related to personalization, adaptability, and ethical considerations.

1. Introduction

Prosthetic devices have become increasingly prevalent across the fields of materials science, physics, and medical engineering, with current technologies enabling the replacement of nearly any human body part. Prosthetics fall within the domain of bio-mechatronics, a discipline that integrates mechanical systems with the human muscular, skeletal, and nervous systems to restore or enhance motor functions lost due to injury, disease, or congenital conditions.[1,2]

Because prosthetic users differ in physical characteristics, lifestyle, and level of amputation, prosthetic devices must be individually tailored to each user. Consequently, no single material, structure, or design can adequately meet the diverse requirements of all amputees, highlighting the need for customized solutions and continuous innovation in prosthetic development [3–6].

1.1 The history of prosthetics

The earliest known prosthetic device dates back to the 18th dynasty of ancient Egypt in the fifteenth century BC and is commonly referred to as the Greville Chester Toe. This artifact, currently preserved in a museum in Cairo, Egypt, is a prosthetic big toe made from cartonnage and was attached to the foot in a manner similar to traditional Egyptian sandals [5,6]. It is considered one of the oldest prosthetic limbs discovered, originating from the Pharaonic era. In addition, prosthetic devices designed to replace the right thumb have been found in ancient Egyptian tombs, further demonstrating early attempts at limb replacement [5].

Research conducted by scientists at the University of Manchester revealed that these ancient prosthetics were constructed from durable materials that allowed repeated use and could be easily removed and cleaned. This evidence suggests that the devices were intended for functional compensation rather than purely cosmetic purposes, contrary to earlier assumptions [1,2].

Subsequent developments in prosthetic technology were observed in ancient Greek and Roman civilizations, where limbs made from wood and leather began to serve as early rehabilitation aids. Historical records also indicate the use of an iron prosthetic limb by a Roman general in 218 BC [4-6]. However, these early iron prostheses were heavy and rigid, limiting the user's ability to control movement. Even after Ambroise Paré introduced articulated joints in the sixteenth century, voluntary limb flexion remained largely restricted. Although artificial hands from this period were often intricate and visually impressive, their functional performance was limited [5] .

During the nineteenth century, advancements in upper-limb prosthetics began to emerge. Peter Baliff of Berlin developed a functional prosthetic arm for below-elbow amputees in

1812, followed by Van Peetersen's design for above-elbow amputees in 1844. Despite these improvements, prosthetic devices of this era continued to fall short of optimal functionality .[4,5]

A significant milestone occurred when J. E. Hanger, an engineering student who lost his leg during the American Civil War, designed an artificial leg for personal use. In 1861, he established a company dedicated to the manufacture of prosthetic limbs, which remains operational today. Similarly, A. A. Winkley, another amputee, founded the Winkley Company in 1888 and promoted prosthetic legs during the National Civil War Veterans Reunion.

In 1909, D. W. Dorrance introduced a terminal device to replace the human hand after losing his right arm in an accident. His design included a leather socket and a steel framework, offering options such as a cosmetic hand, a basic mechanical hand, or a passive hook lacking grasping capability. Variations of these hook-based designs continue to be used in modern prosthetics, often concealed beneath lifelike cosmetic coverings.[7]

More recently, digital technologies have significantly enhanced prosthetic fitting and design processes. Today, approximately 85% of private prosthetic facilities employ computer-aided design and manufacturing (CAD/CAM) systems to create precise models of patients' limbs. These models are used to fabricate molds for customized prosthetic components, while laser-guided measurement and fitting techniques further improve accuracy and comfort [8].

2. Prosthetic components

Despite the wide range of technologies and materials used in their design and fabrication, prosthetic limbs share many common structural features. The fundamental components of prosthetic devices are largely similar for both upper and lower limbs, as they are designed to perform comparable functional roles. In general, a prosthetic limb consists of the following main elements:

- A socket that interfaces with and securely fits the residual limb.
- A prosthetic support or holder.
- A central pylon or axis that provides the required length and structural stability.
- A terminal component, such as a hand, foot, or functional end-effector.

- A cosmetic covering that enhances appearance and is often shaped and colored to resemble natural human skin.

The socket is one of the most critical parts of a prosthetic limb and is typically manufactured from materials that protect the residual limb and distribute pressure evenly. Common socket materials include foam-based liners or silicone, which improve comfort and reduce irritation. In many cases, the socket is additionally covered with a sock-like sheath to enhance comfort during movement and provide extra protection to the amputated area.

3. Requirements for an Effective Prosthetic Limb (Rewritten)

A prosthetic limb must be anatomically compatible with both the patient's body structure and the specific site of amputation. It should enable the user to perform daily activities and a wide range of movements comparable to those of an able-bodied individual. Achieving this level of functionality presents a significant challenge for professionals working in the field of prosthetic design and fabrication.

In recent years, the prosthetics industry has experienced rapid growth driven by the increasing number of amputees and their strong desire to regain independence and return to a normal lifestyle. As a result, certain essential characteristics must be incorporated into any prosthetic limb fitted after amputation, including the following:

- The prosthetic socket must fit the residual limb accurately, conform to its shape, and provide effective protection.
- The prosthesis should be manufactured from carefully selected materials; lightweight plastics are among the most commonly used due to their low weight and good compatibility with the human body.
- Lightweight metals should be utilized where necessary to minimize the overall weight of the prosthetic limb while maintaining structural strength.

4. Types of Common Prosthetic Limbs

The most widely used prosthetic devices are designed to replace specific parts of the upper and lower limbs. Among these, lower-limb prostheses are the most common and are required to provide both flexibility and durability to withstand body weight, walking, and repetitive movement, as illustrated in Fig. 1.

Prosthetic legs incorporating a knee joint represent a more advanced category. Modern designs allow for improved control of walking speed and body motion, with several models available to accommodate different levels of amputation, as shown in Fig. 1.

Upper-limb prostheses, including artificial arms and hands, are primarily developed to assist users in performing everyday tasks. Some advanced models incorporate motors and battery-powered systems to enhance movement control and functional flexibility [9].

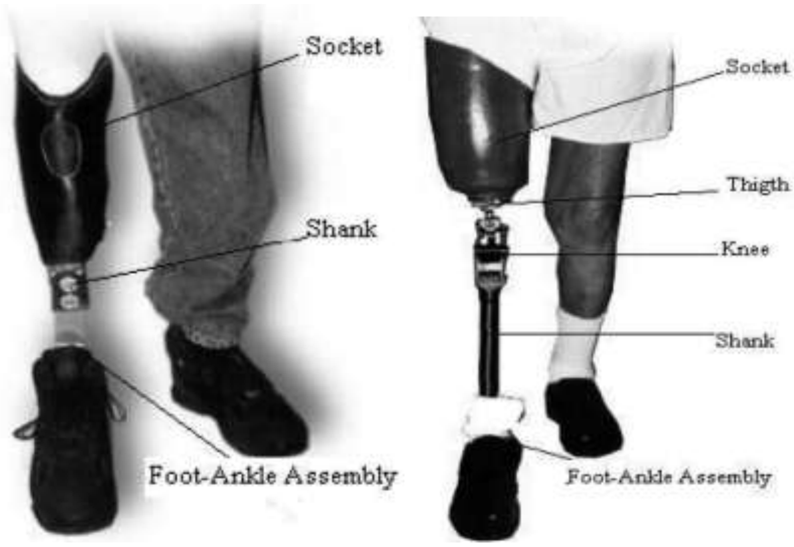

Figure 1. Two types of prosthetic limbs: lower leg and foot (left) and leg with knee (right

5. Materials used in Prosthetic Limbs

5.1 Metals

Metals selected for use in prosthetic limbs must exhibit a combination of desirable mechanical and biological properties. Key requirements include a high strength-to-weight ratio, favorable strength-to-density ratio, excellent resistance to corrosion, low density, and biocompatibility. Additionally, a low modulus of elasticity is advantageous, as it more closely resembles that of natural bone. This similarity allows mechanical loads to be distributed more evenly between the skeletal structure and the implant, contributing to a more natural and comfortable gait for the user [3].

A wide range of metals is utilized in the fabrication of prosthetic limbs, including aluminum, titanium, steel, magnesium, copper, and various alloys. These materials are selected in different proportions depending on their specific functional requirements and may be used in either pure or alloyed forms. Common alloying elements such as copper, iron, aluminum, and nickel are combined with other metals to enhance specific properties, with aluminum and vanadium being among the most frequently used additives. Titanium, in particular, offers strength comparable to certain steels while maintaining a significantly lower density, making it both lightweight and corrosion resistant. When the characteristics of these materials are properly understood and optimized through design, metal-based prosthetic components can provide durable and cost-effective solutions over the product's lifetime [3].

5.2 Polymers

Polymers are widely used in prosthetic limb design, particularly for smaller components and specialized functional features. They are generally not employed as primary load-bearing structures; instead, their use is concentrated in elements such as phalanges, joints, and other minor structural parts. Commonly used polymers include polyoxymethylene (POM), a rigid and durable material; polyurethane (PU), which offers greater flexibility; and polyvinyl chloride (PVC), often applied as a protective coating. Polyethylene, known for its flexibility, is especially suitable for prosthetic components that require water resistance. Silicone materials are valued for their resistance to staining, although they tend to be less durable. PVC, on the other hand, is sensitive to heat and light exposure and therefore requires the incorporation of stabilizing additives.

Ionometric polymer–metal composites (IPMCs) have gained attention as promising electro-active polymer materials due to their ability to undergo significant electrically induced bending, combined with mechanical flexibility, low operating voltage, low density, and ease of fabrication.

During the twentieth century, carbon fiber emerged as a major advancement in prosthetic manufacturing. Carbon fibers exhibit exceptional mechanical properties, including high stiffness, high tensile strength, low weight, excellent chemical resistance, high temperature tolerance, and low thermal expansion. Their high specific strength and modulus have proven sufficient even for use by heavier amputees [3]. As a result, one of the most recent developments in prosthetic design has been the adoption of carbon fiber to produce lightweight pylons.

Traditionally, certain prosthetic components were manufactured from materials such as wood—including maple, hickory, basswood, willow, poplar, and linden—as well as rubber. Even in modern prosthetic feet, urethane foam combined with a wooden internal keel is still commonly used. Most endoskeletal prostheses are covered with a soft polyurethane foam layer that is shaped to match the patient's intact limb. This foam is subsequently covered with a cosmetic sock or artificial skin, which is colored to closely resemble the patient's natural skin tone [3, 11-13].

6. The manufacturing process of prosthetics

The process of manufacturing prosthetic limbs typically begins when the patient visits a prosthetist, usually following medical consultation. Prosthetic limbs are generally not mass-produced due to the need for individual customization. While certain components—such as feet and pylons—may be factory-manufactured, other parts, particularly the socket, are custom-made to meet the specific anatomical and functional requirements of each patient [3,11]. The main steps involved in the prosthetic manufacturing process are outlined below.

- Initially, the prosthetist evaluates the amputee and obtains either a physical impression or a digital scan of the residual limb.
- The positions of bones and tendons in the remaining limb are identified, and measurements of relevant body segments are taken to ensure proper alignment and fit.
- A plaster cast of the residual limb is then produced, commonly using plaster of Paris due to its rapid drying time and ability to capture fine anatomical details.
- Plastic components are fabricated using standard forming techniques such as vacuum forming, injection molding—where molten plastic is injected into a mold and allowed to cool—and extrusion, in which plastic is drawn through a shaped die.

- To manufacture the socket, a transparent thermoplastic sheet is heated in an oven and vacuum-formed over a positive mold. During this process, the heated sheet is placed over the mold within a vacuum chamber.
- Air is evacuated from between the sheet and the mold, causing the plastic to collapse tightly around the mold and accurately replicate its shape.
- The resulting test socket is fitted to the patient to assess comfort and alignment. In the case of lower-limb prostheses, the patient is asked to walk while wearing the socket and provide feedback regarding fit and comfort.
- Based on patient input, the test socket is adjusted as needed. The thermoplastic material can be reheated to allow minor shape modifications, and thicker socks may be used to enhance comfort.
- Pylons made from materials such as titanium or aluminum are often produced using die-casting techniques, in which molten metal is forced into steel molds of the desired shape.
- Wooden components are shaped using processes such as planing, sawing, and drilling. All prosthetic parts are assembled using methods including bolting, adhesive bonding, and lamination.
- Finally, the permanent socket and fully assembled custom prosthetic limb are fitted to the patient, and final adjustments are made to ensure optimal function and comfort [3].

7. Rehabilitation and Functional Training

Following prosthetic fitting, patients must undergo specialized rehabilitation exercises aimed at strengthening the muscles responsible for controlling the prosthetic device in order to achieve comfort and effective use. Individuals fitted with upper-limb prostheses, particularly artificial arms, are required to learn how to operate and coordinate the device during daily activities. In cases where limb loss results from an accident and the patient is later fitted with a myoelectric prosthesis, adaptation is generally easier compared to cases of congenital limb absence.

For lower-limb amputees, physical rehabilitation typically requires approximately 18 to 20 weeks for patients to relearn walking. During this period, individuals fitted with artificial legs are trained to perform essential movements such as getting in and out of bed, entering and exiting vehicles, walking on uneven surfaces, ascending and descending slopes, and learning safe techniques for falling and recovering balance.

In addition to patient training, prosthetic devices undergo mechanical testing to evaluate durability and performance. Load is applied to the prosthetic limb until failure occurs in order to determine strength limits. Experimental prostheses are generally considered acceptable if they can withstand approximately 250,000 loading cycles. These tests often involve applying loads at a rate of one cycle per second for a total of two million cycles, simulating roughly five years of regular use [3, 4].

8. The prosthetics industry in Libya

In December 2010, two Libyan engineers, Khaled Al-Bargathi and Fathia Alzwai, initiated a research project focused on upper-limb prosthetics after witnessing the growing number of amputees in Libya. This initiative emerged in response to the urgent need for local solutions to address limb loss resulting from health conditions, workplace injuries, and accidents.

Libya has historically allocated substantial financial resources to overseas medical treatment, often facing public criticism and challenges related to payment settlements. Investing in domestic scientific research and strengthening the healthcare sector could contribute significantly to economic development in an area that has remained underdeveloped for decades. Prolonged neglect has led many Libyans to lose confidence in local medical institutions, prompting them to seek treatment abroad [12].

Motivated by post-conflict reconstruction efforts, a group of electrical and electronic engineers sought ways to support national development by addressing the needs of amputees. Among these efforts was the continuation of the research initiated by Al-Bargathi and Alzwai through the formation of the Electronic Prosthesis Engineering Team (EPET) [12]. EPET was officially established in October 2011 and registered as a non-governmental organization under the Ministry of Culture and Civil Society.

The founding researchers, together with Sondos Al-Athram and Amal El-Gehani, focused their work on upper-limb prosthetics and aimed to expand local services by establishing a dedicated workshop. The Benghazi Rehabilitation Centre (BRC) supported these efforts by providing office space and assisting with individualized prosthetic measurements and socket fabrication.

EPET concentrated on improving its initial prototype, a mechanical hand capable of basic “open and close” motions. Although this device was tested on amputees, it was not permanently fitted. The team designed and manufactured the software and electronic circuitry, while the physical hand component was produced by the international prosthetics company Otto Bock [12].

In 2020, Misurata University signed a cooperation agreement with the National Center for Prosthetics to strengthen collaboration in prosthetics and physiotherapy. This partnership aimed to facilitate knowledge exchange, user training, and the provision of materials, equipment, and technical support, emphasizing the importance of serving individuals with disabilities [13].

Establishing a national center or specialized unit for electronic prosthetics—equipped with manufacturing, development, and maintenance capabilities—could offer substantial support to Libyan amputees and enhance their integration within local communities. The long-term objective is to provide prosthetic limbs free of charge to Libyan patients, contingent upon securing adequate funding. As stated by Al-Athram, achieving this goal depends on obtaining financial grants [12]. Nevertheless, restoring public trust and strengthening the healthcare system remains a significant challenge for Libya’s future governments [12].

One notable initiative in this field is the Libyan–Jordanian Center for the Manufacture of Prosthetic Limbs, illustrated in Fig. 2. This center produces prosthetic limbs with several distinctive features, including the absence of metal components, the use of compressed medical-grade plastic (Ultra Bladder), lightweight construction, resistance to extreme temperatures, and affordable pricing. The cost also includes training and rehabilitation services, enabling patients to regain mobility within a processing period of four to seven days.

Fig. 2. The prosthetics industry in Libya represented by the Libyan–Jordanian Center for the Manufacture of Prosthetic Limbs [14].

The prosthetic limbs are manufactured by Dr. Mohamed Shalash Ismail, a Jordanian specialist in prosthetics who holds a registered patent for this type of limb in Switzerland, as shown in Fig. 3 [14].

Fig. 3. Lightweight prosthetic limb production at the Libyan–Jordanian Center for the Manufacture of Prosthetic Limbs [14].

9. Skin-Related Problems and Management

Skin complications are among the most common issues associated with the use of prosthetic limbs. The skin is frequently exposed to friction and pressure at the interface between the residual limb and the prosthesis, which may result in irritation or wounds. However, these problems can be effectively managed through appropriate care measures, including the following:

- Removing the prosthetic limb periodically, particularly after prolonged physical activity, to relieve pressure on the amputation site.
- Promptly treating any skin wounds or irritations that may occur.

- Regular use of moisturizers to reduce friction and prevent skin dryness.
- Taking special precautions during harsh weather conditions, especially in extreme cold, by wearing suitable footwear, using assistive devices such as crutches when necessary, maintaining adequate warmth, and continuing the use of moisturizers to protect the skin from drying.
- Ensuring regular cleaning of the prosthetic limb to maintain hygiene.
- Removing the prosthesis before sleeping to avoid prolonged pressure and discomfort.
- Frequently inspecting the amputation site to detect early signs of skin damage.
- Maintaining cleanliness around the residual limb to prevent contamination and reduce the risk of infection [15].

10. Timing of Prosthetic Fitting

Following an amputation, the selection and fitting of an appropriate prosthetic limb must be carefully planned according to the patient's medical condition. The patient is required to undertake several preparatory measures before and after the amputation, continuing through the completion of prosthetic fitting and the adaptation process, in order to regain functional independence and resume a normal lifestyle. Using high-quality and well-suited prosthetic devices is essential to achieving optimal outcomes.

In addition, coordination with the attending physician is necessary to determine the appropriate timing for prosthetic fitting after amputation, as well as to establish the required preoperative and postoperative procedures. This collaborative approach ensures proper healing, effective rehabilitation, and successful integration of the prosthetic limb into the patient's daily life [15].

11. Determine the appropriate prosthetic

One of the major challenges associated with prosthetic limb implantation is determining the most suitable prosthetic option for the patient, particularly in countries where prosthetic devices are not locally manufactured. In such cases, relying on informal information, reports, or unverified recommendations is often insufficient for making an informed decision. It is therefore important for patients to have clear and accurate knowledge regarding the type of prosthetic limb required, as well as the associated medical and procedural costs, in order to make well-informed choices.

An additional challenge arises from the financial burden imposed by travel and accommodation expenses, which are often added to the cost of the prosthetic limb itself. These combined costs can significantly increase the overall economic impact on patients seeking prosthetic treatment abroad [15].

12. Intelligent prosthetics and Artificial Intelligence

Human movement begins when the brain transmits signals to the muscles responsible for executing motion. Recent advances in artificial intelligence have enabled the integration of intelligent control systems into modern prosthetic devices, allowing users to operate artificial limbs through neural signals. These smart systems are capable not only of responding to preprogrammed commands but also of recognizing and classifying objects based on the required type of interaction or movement. As a result, intelligent prosthetic limbs can successfully manipulate unfamiliar objects, representing a significant advancement in prosthetic functionality.

Innovative technologies have further enhanced fine motor control, enabling coordinated finger movements such as combining the index finger with other fingers to grasp small or soft objects, including items like sponge balls. This level of dexterity marks a notable milestone that was previously unattainable in conventional prosthetic systems.

A key future objective in this field is the development of prosthetic limbs capable of transmitting sensory feedback—such as perceptions of heat and weight—back to the brain. Achieving this goal would constitute a major breakthrough in creating more natural and intuitive prosthetic experiences.

Today, patients are able to control prosthetic limbs with greater precision and practicality than ever before. Smart prosthetics interface directly with the human nervous system, enabling real-time interaction and control through brain-generated signals. This technology applies to both upper- and lower-limb prostheses, including intelligent arms and legs, and significantly enhances flexibility, functionality, and user comfort. Consequently, smart prosthetics reduce dependence on external assistance and improve overall quality of life, as illustrated in Fig. 4.

Figure 4. illustrates the smart prosthetic leg.

12.1 Artificial Intelligence in Human Body Organs: A Futuristic Perspective

The integration of Artificial Intelligence (AI) into human body organs represents a pioneering advancement in the field of biomedical engineering [16]. This fusion of biological systems with intelligent technologies offers remarkable potential to transform healthcare by enabling the restoration, enhancement, or augmentation of the functions of damaged or missing organs. Through this integration, AI-driven systems can improve physiological performance, adaptability, and patient outcomes, opening new pathways for advanced medical interventions and therapeutic applications.

12.1.1 AI-Powered Prosthetics

AI-enabled prosthetic systems have undergone substantial advancement, surpassing the limitations of traditional mechanical limb replacements. These modern systems incorporate intelligent technologies that enhance control, adaptability, and user interaction. Key developments in this area include:

- **Neural Interfaces:** These systems employ AI-based algorithms to interpret neural signals originating from the user's brain or nervous system, allowing for intuitive and responsive control of prosthetic limbs [16].
- **Adaptive Learning:** Through machine learning techniques, prosthetic devices can continuously learn from the user's movement patterns and surrounding environment, leading to improved performance, personalization, and overall user experience [17,18].

Sensory Augmentation Applications

- **Artificial Vision:** AI-driven retinal implants are capable of processing visual data and stimulating the remaining functional retinal cells, thereby providing partial visual perception for individuals experiencing vision impairment or loss [18].
- **Cochlear Implants:** Sophisticated AI algorithms are integrated into cochlear implant systems to optimize sound signal processing, resulting in enhanced speech recognition and improved auditory clarity for individuals with hearing loss [19].

12.1.2 Organ Regeneration and Tissue Engineering

- **Bioprinting:** Artificial Intelligence plays a vital role in optimizing bioprinting processes, facilitating the fabrication of complex, patient-specific tissues and organs intended for transplantation [20].
- **Tissue Engineering:** AI-based algorithms enable the prediction and regulation of cellular behavior, thereby accelerating tissue formation, growth, and regenerative processes within the human body [21].

12.2 Challenges and Considerations

12.2.1 Ethical Considerations

- **Privacy and Security:** Protecting sensitive patient information by ensuring secure data storage and transmission is a critical requirement in the deployment of AI-enabled medical technologies.
- **Equity and Access:** Guaranteeing fair and equal access to advanced healthcare technologies is essential to prevent disparities related to socioeconomic status and to promote inclusive medical innovation.

12.2.2 Technical Hurdles

- **Biocompatibility:** The development of materials and devices that are fully compatible with the human body is crucial to minimize immune rejection and reduce the risk of medical complications.
- **Long-Term Stability:** Ensuring the sustained reliability, durability, and functional performance of implanted devices within the complex and dynamic environment of the human body remains a significant technical challenge.

12.2.3 Machine Learning and Adaptive Control Algorithms

Machine learning and adaptive control algorithms are expected to play a central role in the future of prosthetic control systems by enabling devices to learn from user behavior and adapt to changing skills and preferences. These algorithms improve personalization, control accuracy, and system performance while supporting advanced sensory feedback such as tactile and proprioceptive perception. Recent research demonstrates that integrating machine learning with adaptive and haptic feedback systems enhances prosthetic functionality, user interaction, and overall realism, contributing to more intelligent and human-like prosthetic devices [22].

12.2.4 Future Directions

- **Brain–Computer Interfaces:** Continued advancements in brain–computer interface (BCI) technologies are expected to enable more precise and sophisticated control of prosthetic devices, with the potential to assist in restoring certain lost cognitive or neurological functions.
- **Personalized Medicine:** Artificial Intelligence is anticipated to play a pivotal role in the development of personalized medical treatments by tailoring therapeutic strategies to individual patient characteristics, including specific clinical conditions and genetic profiles.

12.3 Examples of the smart prosthetic hand

12.3.1 Hans Prosthetic

According to its developers, the device closely resembles the human hand in both form and function, demonstrates practical usability, has been tested on patients, and is ready for commercial deployment following the acquisition of regulatory approval, as illustrated in Fig. 5.

Figure 5. Hans Prosthetic [23]

12.3.2 Fluid hand

Figure 6 illustrates the Fluid Hand, a soft prosthetic device designed to provide a more natural appearance and function compared to conventional artificial hands. The device enables users to fully envelop and grasp objects while simultaneously perceiving the applied gripping force.

Figure 6. Fluid hand [24]

12.3.3 Immaculate hand

It is a lightweight prosthetic arm characterized by a sleek and modern design, manufactured using advanced materials, with the capability to integrate additional devices—such as portable electronic accessories - into its structure [21,23], Fig. 7.

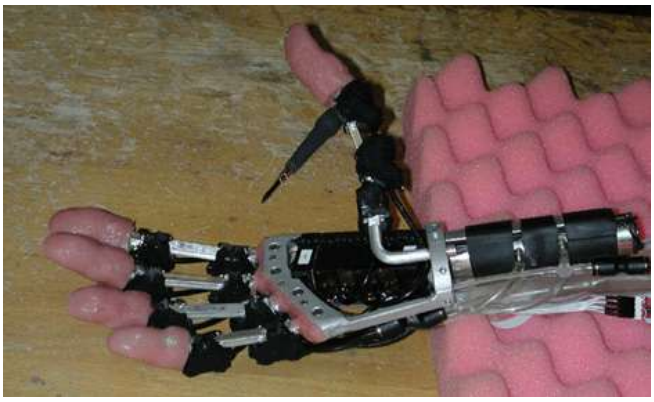

Figure 7. Immaculate hand [23]

12.3.4 I-limb Hand

This prosthetic device features individually powered fingers, providing a more intuitive and natural control mechanism for limb movement. It operates by detecting electrical signals generated by the user's muscles, which are captured by electrodes placed on the surface of the skin. Studies indicate that the system is user-friendly and can be learned and adapted to within a short period of time [23].

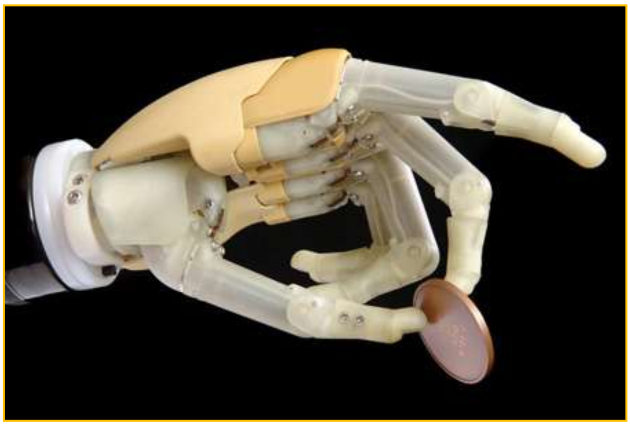

Figure 7. Immaculate hand [23]

In these prosthetic systems, each finger is equipped with an independent motor and gearbox, allowing precise and flexible movement. The design can be adapted for individuals with partial hand amputations, and the I-digit configuration is available for cases involving the loss of individual fingers, as illustrated in Fig. 10. Control inputs are managed through myoelectric sensors that detect electrical signals from muscles typically responsible for activating a natural hand, enabling intuitive and functional operation of the prosthesis [10].

Figure 8. I-limb and I-digits [10].

12.3.5 BeBionic hand

Figure 9 presents the prosthetic hand in two configurations, showing the relaxed position and the finger-pointing pattern from left to right. All fingers are capable of powered movement, while the thumb can be manually adjusted to either an opposed or unopposed position, thereby expanding the range of available grip patterns [10].

Figure 9. BeBionic hand Examples of different grip patterns possible [10].

12.4 Internet penetration risk of smart prosthetics

Modern technology not only enables the development of highly realistic prosthetic limbs but also introduces intuitive control mechanisms for both upper- and lower-limb prostheses. Intelligent prosthetic systems increasingly rely on interfacing with the human nervous system and brain to enhance movement precision, responsiveness, and user comfort.

Contemporary prosthetic devices are equipped with customized sensors attached to the skin that detect and analyze muscle contractions in order to generate the intended movements [25, 26]. According to reports from a Russian company, electronic prosthetic hands can be manufactured using 3D printing technologies with materials such as plastic, metal, and other composites. These devices incorporate a range of smart features, including built-in displays, near-field communication (NFC) chips for payment applications, and global system for mobile communication (GSM) units that enable calling and messaging via mobile networks. Additional functionalities may include activity-tracking sensors and smartwatch-like features.

However, as these advanced prosthetic systems rely on internet connectivity to deliver enhanced capabilities, they are also exposed to cybersecurity risks. Recent warnings have highlighted the increasing threat of electronic intrusion, emphasizing the potential dangers such breaches may pose to users of connected prosthetic technologies [25].

12.5 Protection of prosthetics

Protecting medical devices has become a critical requirement, particularly as advanced technologies are increasingly integrated into healthcare systems. According to a report published by ZDNET, security researchers have emphasized that recent analyses highlight the importance of incorporating cybersecurity measures into new technologies from the earliest stages of development [26]. This approach helps reduce vulnerabilities and enhances overall device safety.

One practical method proposed for improving the security of prosthetic devices is the inclusion of a SIM card within the system. This configuration allows data transmission to occur in a one-way direction—from the device to the cloud—without enabling reverse communication, thereby significantly reducing the risk of unauthorized access or cyber intrusion. In addition, selecting reputable and reliable manufacturers when acquiring prosthetic devices is considered an essential factor in ensuring higher security standards and minimizing potential risks [25, 28].

Conclusion

The primary objective of medical professionals is to enhance the quality of life of their patients, while engineers aim to improve systems in ways that positively impact society as a whole. In the development of prosthetic limbs, these two goals converge, resulting in transformative outcomes for users. Modern prosthetics are no longer limited to restoring basic functionality; they are increasingly designed to be comfortable, lifelike, and aesthetically appealing. By closely replicating the comfort and usability of natural limbs, prosthetic devices help reduce social stigma and feelings of pity often experienced by amputees.

Advancements in prosthetic design, fitting techniques, and appearance enable users to walk with greater confidence and a more natural gait. Through the application of innovative technologies and improved material selection, amputees can regain mobility, independence, and a sense of normalcy in their lives.

A key future objective of this research is to identify suitable materials for use in developing countries. Ideally, these materials should be strong, lightweight, and locally accessible. The ability to source and manufacture prosthetic materials locally presents significant socioeconomic benefits, including reduced costs, increased affordability for patients, and the stimulation of local economic activity. While some regions—such as South Africa and major cities in Central and South America—possess the capacity to manufacture prosthetic components, access to appropriate raw materials remains a critical challenge. Local production would not only lower dependency on imports but also create employment opportunities and foster sustainable healthcare solutions.

Throughout this study, a variety of materials used in prosthetic limb fabrication were examined. Prosthetic devices are mechanical systems designed to replace or enhance lost body functions, primarily in the arms and legs. Effective prosthetic development relies on close collaboration between medical professionals and engineers to identify optimal designs and material choices tailored to each patient's environment and functional needs. Traditional wooden structures have largely been replaced by pure metals and metal alloys for load-bearing components, while carbon fibers and polymers have substituted leather straps and older supporting materials. Each material is carefully selected based on its mechanical properties, durability, and suitability for the user's lifestyle and surroundings.

In summary, both conventional and smart prosthetic limbs have provided significant benefits to individuals who have lost limbs due to accidents, disease, or armed conflict. As this field continues to evolve—particularly in post-conflict regions—prosthetic technologies are becoming increasingly diverse, accessible, and adaptable. By offering prosthetic solutions at varying levels of complexity and cost, these advancements help ensure inclusivity and allow users to feel integrated and no different from those around them.

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