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The Science behind Prosthetics and Advancements in the Field

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ABSTRACT

With advances in technology and design and the changing user expectations, lower limb prosthetics have experienced significant changes since the initial introduction of these devices. This paper examines how lower limb prosthetics have changed from simple mechanical devices to modern systems. These changes have been made through research, science, and user-centred design approaches. The paper looks at major areas surrounding the development of prosthetics for lower limbs, which include changes and improvements of materials over the years, design modifications to accommodate movement and comfort, and the ever-increasing impact of digital technology on prosthetic development. Issues related to the affordability, accessibility, and sustainability of lower limb prosthetics are also considered in the context of who benefits from modern-day lower limb prosthetics. Placing the design of lower limb prosthetics in the context of both the technical and social aspects helps to create a clear framework to identify the factors that comprise modern-day lower limb prosthetics and also assists in determining how future innovations in prosthetic technology will further enhance a person's ability to be mobile and independent.

Keywords: *Prosthetics, Advancements in Technology, Innovation, Challenges with Access and Cost, Design Modifications.*

INTRODUCTION

This paper looks into the science behind lower limb prosthesis, the improvements in the biomechanics of the same, and the adaptations made to their designs to enable specific activities. A prosthesis is an artificial replacement of a body part that mimics its natural movement and functions (Garcia et al.). Lower limb prosthesis in particular, enables users to not only walk and run, but also carry out daily activities independently and with confidence, and pursue hobbies with more ease (Garcia et al.). While the need for specially designed prosthesis for activities like sports and dance is rising, research and technology in these areas is increasing too (Garcia et al.). This paper examines how knowledge from different areas of science can be applied to improve the functionality and usability of lower limb prostheses.

Understanding and improving prosthetic development is important, as these devices help people regain mobility and independence after limb loss. As the design of a prosthetic limb can strongly affect comfort and long-term wellbeing, continued innovation plays a crucial role in making everyday use easier and more effective. Alongside technological progress, accessibility and affordability are also important to ensure that new prosthetic solutions can benefit a wider range of users.

Prosthetic devices have evolved due to changing user needs and advances in engineering methods. When developing new models, designers now focus not only on appearance but also on comfort, movement and practicality. Understanding sports, for example, has helped in creating more efficient and mobile designs for athletes to use (Garcia et al.). Modern prostheses are often lightweight and made from materials designed to tolerate repeated mechanical stress during use (Garcia et al.). With more people being open to the idea of using prosthetic limbs, research and developments in this area is increasing too (Garcia et al.).

In order to develop new lower limb prosthesis designs, it is essential to have a good understanding of the biological functioning of the leg. Today, innovations like torque-sensitive knee joints with elastic actuators and advanced toe-mimicking technologies are making prosthetic designs increasingly efficient and natural looking (Smith). When designing for a specific activity, it is also important to study in detail the levels and types of forces applied during any movement. Prosthesis designs should not only be mechanically efficient, but should also be as close to its biological part, in terms of weight, size and battery life, as it can (Garcia et al.).

THE HISTORICAL EVOLUTION OF PROSTHETICS

Prosthetics were initially very simple, and were made of wood and metals including steel and titanium, which made them bulky and heavy (Smith). A toe made of wood and leather, found in Egypt, dates back to the fifteenth century BC and is one of the earliest pieces of evidence of prosthesis usage (Smith). Further understanding of biomechanics of the limbs and advancements in the designs of prosthesis are seen in Dr. Pare's "'Le Petit Lorrain" which is a mechanical hand working on springs and pulleys (Smith). After WWI and WWII there was a major surge in demand for more dynamic prosthesis designs, and lighter metals including aluminium were being used to make them efficient (Smith). Designs from this time had more articulated fingers and toes, and had more complex mechanisms as compared to the previous ones (Smith). With time and continuous research, materials like carbon fibre, natural fibres and glass fibres among others were developed and incorporated in the design of prosthetic limbs, making them more comfortable, practical and mobile while allowing them to closely mimic the biomechanics of the biological parts (Smith). A major factor that affected prosthetic devices was the innovations and improvements in surgery procedures involving amputation. A few centuries ago, the best methods involved crushing or boiling oil which was not only unsanitary but also fatal (Smith).

Most survivors did not have a suitable stump for a prosthetic device to be fit (Smith). The introduction of anesthesia enabled surgeons to carry out advanced procedures that allowed the use of prosthesis after amputation (Smith). Biomechanical studies were undertaken to gain a better understanding of the movements and stress on limbs, which also allowed better designing (Smith).

With time and research, different materials began to be utilized. Devices that were once completely made of iron started being made with wood, copper and leather (Smith). Over time, heavy metals were replaced with lighter ones like aluminium, and hollow wooden cones took the place of the wooden blocks (Smith). The 1860's saw the use of hard rubber feet which were later adapted to absorb shock (Smith). Finally, by the 1940's, a lighter material- plastic laminate was developed and still being used today for prosthetic device construction (Smith).

Aside from changes in materials, another aspect that saw continuous experimentation was attachment methods. Designs went from having lace-up leather cuffs, harnesses and metal sockets with leather lining, to suction sockets based on the principle of air pressure and even direct bone fitting (Smith). The goal now is to develop the most effectively functional device possible, and fulfills all the needs of the user while being energy efficient, comfortable and natural-looking.

MATERIALS USED IN MODERN PROSTHETICS

Modern prosthetic devices should not only be lightweight, strong and durable, but also biocompatible. Materials science has allowed the advancement of materials used from wood, metals and leather, to polymers, metals and composite materials that better meet the functional and comfort requirements.

Metals

Metals such as aluminum, stainless steel, titanium, and magnesium have traditionally been used in components including pylons, joints, and structural frames, due to their ability to take load. Titanium is especially favoured for its high strength to weight ratio, biocompatibility and corrosion resistance. However, excessive use of metals in prosthesis makes it stiff and heavy, contributing to discomfort and impracticality.

Polymers

Polymers have a crucial role in modern prosthesis, and are used on sockets, liners and interface components. Some commonly used polymers are:

i. Polypropylene (PP)
ii. Polyethylene (PE)
iii. Polyvinyl chloride (PVC)
iv. Polyoxymethylene (POM)
v. Polyurethane (PU)
vi. Polymethyl methacrylate (PMMA)

Thermoplastics are mainly used for sockets because they are easy to shape and adjust. Elastomeric polymers like silicon on the other hand, are used in soft liners to improve comfort, load distribution, and skin protection. Using polymers alone may cause a lack of strength and fatigue resistance for high load usage.

Fiber-reinforced composites

To overcome the limitations of metals and polymers, fiber-reinforced composite materials are now extensively used in modern prosthetic design. Synthetic fiber composites, mainly carbon fiber–reinforced polymers and glass fiber–reinforced polymers offer excellent strength to weight ratios, corrosion resistance and a good fatigue performance. Carbon fiber composites commonly used in high performance prosthetic feet and sports prostheses due to their energy storage and return abilities. The main disadvantages of synthetic composites are their high cost, limited biodegradability, and increased stiffness.

In recent years, **natural fiber-reinforced composites** have gained attention as alternative materials for prosthetic components, especially sockets. Natural fibers including jute, flax, bamboo, pineapple and banana are used as reinforcements in polymer matrices like epoxy, polyester, polypropylene and bio-based resins. These materials offer low density, mechanical strength, biodegradability, renewability and a lower cost compared to synthetic composites. Natural fiber composites also provide improved comfort and reduced environmental impact. However, moisture absorption and long-term durability among others, are areas that require more research.

CHALLENGES WITH ACCESSIBILITY AND COST

The increasing demand for prosthesis is due to the rise in amputees' demand for a better quality of life. However, a high proportion of these patients are unable to afford the prosthetic device that they need. The cost of a prosthetic limb may vary based on type, functions, features and comfort. To ensure that more people are able to afford prescribed prosthesis, a more cost-effective method of production should be used. An example of such a method is 3D printing. 3D printing involves the use of affordable materials such as PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene) which reduces the manufacturing costs of prosthesis. Additionally, this process is less labour intensive (reducing the labour costs) and has lesser material waste as there is no need for molds, while also being faster and more efficient, with no need of manual work. A major advantage of 3D printing manufacturing is that it is easier and faster to make client-specific, personalized or customised products. 3D scanning technologies can take the exact measurements or dimensions of the patient's stump, allowing the final product to be very comfortable and aesthetically aligned with the patient's preferences.

Studies prove that people experience inequality with respect to the waiting time, availability and access, and professionalism in the service as a whole (Turner et al.). These differences are dependent on the rehabilitation center or the healthcare system that the patient is accessing (Turner et al.). Delays caused by waiting time, accessibility of components etc. can severely reduce the functional outcomes of prosthesis attachment (Turner et al.).

In publicly funded healthcare systems like the National Health Service (NHS), the supply of high quality and advanced prosthesis is often limited due to high costs of production and expensive materials (Turner et al.). Higher quality and lighter prosthetic limbs are therefore only available for those who can access private care (Turner et al.).

This usually includes military veterans and elite athletes (Turner et al.). People who do not have the access to this however, are usually provided with the more basic devices (Turner et al.). Most patients who require the advanced prosthesis have to buy the product themselves (Turner et al.).

The high cost of prosthetic materials directly contributes to the issues faced in accessibility. For example, components made of lightweight materials including carbon fibre are more costly as compared to heavier plastic-based prosthesis (Turner et al.). Due to this, most public healthcare systems prescribe these plastic based prosthesis (Turner et al.). Plastic based prosthesis are heavier, they cause discomfort, and have a negative impact on the users walking ability in the long term (Turner et al.).

Limitations in the accessibility of appropriate prosthetic devices leads to a reduction in the overall quality of life (Turner et al.). People face difficulty in maintaining employment, travelling independently and participating in social events (Turner et al.). This shows that the limited access and delays in rehabilitation not only have short term difficulties, but also economic and social consequences (Turner et al.).

SENSORY FEEDBACK AND HAPTIC TECHNOLOGY

Any kind of lower limb amputation brings drastic changes in a person's daily activities. It has been found that lower limb amputations are linked to loss of sensory and motor functions, which has a negative impact on proprioception, balance and gait (Karimi et al. 1). “Various haptic feedback mechanisms have been developed that provide real-time information through vibrotactile, electrotactile, and mechanotactile stimuli, each offering unique advantages and challenges” (Karimi et al. 1). Sensory substitution has been developed due to the need to regain the lost sensory functions after amputation. “Within the area of prosthetics, haptic feedback systems deliver real-time sensory feedback via vibrational, electrical or mechanical stimuli to transmit information regarding the prosthesis” (Karimi et al. 2). Different feedback methods serve different purposes, and can be selected based on the user's lifestyle and preferences.

In lower limb prostheses, haptic feedback is mainly used to improve the user- environment interaction. It does this by providing information about foot contact, load and gait (Karimi et al. 3). “This feedback helps users identify heel strike, stance phase, and toe-off, which supports better gait control and walking symmetry” (Karimi et al. 3). In order to collect the required data, pressure and force sensors are used along with inertia measurement units, to measure the motion and load on the prosthetic foot (Karimi et al. 4). A system of a signal processing unit, sensors and actuators, works to deliver feedback to the user’s residual limb (Karimi et al. 3).

Studies indicate that haptic feedback can improve balance and postural stability while reducing dependence on visual monitoring of the prosthesis (Karimi et al. 5). This feedback also lets the user feel their environment and gait more, and allows them to walk on uneven terrain with ease and hence, confidence.

Some limitations of this feedback technology are delay in signals and battery constraints. (Karimi et al. 6). Another problem with respect to the signal delivery is that every user has a different level of sensitivity to tactile stimulation (Karimi et al. 6). Even the location of the stimulation may differ from person to person due to the differences in stump measurements and location. This means that every prosthetic device that is fitted needs to be personally calibrated and placed as per the user's needs and preferences (Karimi et al. 6). Ongoing research is being carried out in order to improve power efficiency, miniaturization, and comfort of these systems (Karimi et al. 6).

AI AND MACHINE LEARNING IN NEXT GENERATION PROSTHETICS

A significant area of progress in prosthetics is Artificial Intelligence. “AI refers to a machine's ability to think and act intelligently” (Chopra and Emran, 4538). Recent advancements using AI and robotics have changed the future for post amputation recovery and physical rehabilitation The addition of AI to prosthetics allows an algorithm to decipher electrical impulses sent by the patient's muscles, allowing better control (Chopra and Emran, 4539). This greatly reduces the mental effort required to operate the device, making it easier for the user to adapt to the new prosthesis.

In order to move the field of AI towards a more integrated prosthetic device development, it is imperative to continue the research into certain algorithms and their uses in different prosthetics (Chopra and Emran, 4539). In order to help patients with limb amputation to develop navigational skills and object handling, prosthetic devices can make use of ‘convolutional neural networks’ which play a crucial role in processing and interpreting visual data (Chopra and Emran, 4539).

The use of a regenerative peripheral nerve interface and machine learning algorithms allow a prosthesis user to carry out simple actions like picking up a dropped item or bringing fingers together (Chopra and Emran, 4539). Researchers at the University of Texas at Dallas use AI and deep learning to control smart prosthetic hands through electrical signals taken directly from muscles (Chopra and Emran, 4539). As a result of this, prosthetic limbs are now able to move faster and more accurately than before (Chopra and Emran, 4539). An AI based prosthetic in India called Avocado allows users to perform activities like lifting light and heavy objects, gardening, sketching and ploughing (Chopra and Emran, 4539). BrainRobotics, another smart prosthetic hand, can be controlled solely by the user's thoughts (Chopra and Emran, 4539). “Japanese companies Cyberdyne and Esko Bionics have developed robotic suits that can increase a person's strength and movement by up to ten times” (Chopra and Emran, 4539).

Using AI in prosthesis comes with its own set of difficulties and drawbacks. As mentioned before, the function of a prosthetic device is to imitate human movement. It is difficult to create AI for this purpose because it often involves the use of complex algorithms in order to sense real-time signals. The same challenge is faced when incorporating brain-interpretable sensory feedback like temperature and pressure (Chopra and Emran, 4540). Another difficulty when using AI in prosthesis is reducing the need for adjustments carried out by a human. Prosthetics that force users to frequently go to get it recalibrated or adjusted take up time, and can make the patients feel uncomfortable. This makes it crucial that the prosthetic device is flexible and has the appropriate learning abilities (Chopra and Emran, 4540). Other key points that need attention while designing prosthesis is its power/energy efficiency and reliability. All of the points mentioned above ensure that the user is comfortable and trusts the AI system, improving the overall experience.

FUTURE SCOPE IN PROSTHETICS

Advances in technology including sensing technology, and haptic feedback, are becoming increasingly automated, and the manufacturing of sockets, among other parts, is now data driven (Safari 385). Osseointegration is a promising solution for people who are unable to use a prosthetic socket (Safari 385). Osseointegration is a process in which a direct, functional connection is made between the bone and the prosthetic limb, allowing the cells of the bone to grow directly on it.

The technique is known for its potential to facilitate neuromuscular integration (Safari 385). This almost negates the compulsion of having to have a suitable stump in order to get a prosthetic limb fitted. Advances in the mechanical features of osseointegration implants will greatly reduce risks of infection, and is likely to be the most ideal option for amputees (Safari 398).

Today, with the help of engineering, electronics and AI, we can better understand prosthetic sockets and use the most efficient manufacturing processes (Safari 385). Sockets are expected to develop into fully automated devices with advanced actuator technologies that may control aspects like fitting and temperature, by using AI and other techniques to process the data collected (Safari 398).

The global growth of prosthetic manufacturers indicates rapid expansion and increased innovation in the field (ASIF et al. 970). Improvements in the usability and reliability of prosthetic devices benefit amputees by enhancing mobility and independence, while also creating positive outcomes for society. Advances in 3D printing are especially important, as they can reduce costs and allow user specific customization, improving accessibility and comfort (ASIF et al. 970).

Due to the major set of advancements in lower limb prosthesis, researchers are incentivized to develop newer and more advanced technology, and are now used in most components of prosthesis (ASIF et al. 970). These developments highlight how future prosthetic limbs are moving toward easier and more natural control. Systems with nerve-based control show us a future that minimises the learning curve of a new prosthetic user, and reduces the mental effort required to operate the device.

Recent research on implantable devices shows a major shift in the traditional prosthetic design composed of a socket (ASIF et al. 970). Successfully developing implantable devices has led to the elimination of problems involving the socket including discomfort, skin issues and poor fit.

In addition, parallel advances in prosthetics in the field bioprinting, robotics and other upcoming technologies indicate that highly advanced, human-like prosthetic limbs may soon be reality (ASIF et al. 970). Together, these innovations point toward a future where prosthetic devices not only restore lost function but may also closely match, or even enhance the natural human capabilities.

CONCLUSION

This research paper contained an in-depth analysis of the evolution of lower limb prosthesis over the years, key technological features incorporated in modern prosthetic devices and their limitations, and problems faced with the cost and accessibility of prosthesis. The knowledge of modern prosthesis has had a long journey. From rudimentary and unsanitary peg-legs to modern haptic and AI based prosthetics, each stage has been marked by a drastic increase in the comfort and quality of life of the users. The idea of prosthetic use has seen a major shift over time. Prosthesis are no longer viewed as devices that merely replace a missing limb. Today's designs focus on allowing users to fully participate in everyday activities and pursue hobbies. Activity-specific prosthesis for sports, dance forms such as ballet, and other physically demanding movements reflect this change in perspective.

Recent research in prosthetic design also emphasizes environmental sustainability. Material development is now leaning towards biodegradable, eco-friendly alternatives, particularly through the use of natural fiber-reinforced composites and bio-based polymers. The use of these materials aims to reduce environmental impact, while maintaining the mechanical strength, comfort and durability needed for a prosthetic device. As sustainability becomes a priority in engineering and healthcare, the incorporation of renewable and biodegradable materials is an important direction for future prosthetic research and development.

This paper highlights the integration of biomechanics, materials science, and AI based technologies in the design and manufacturing of modern prosthesis. Improvements in lightweight materials, energy-efficient designs, and sensory feedback systems have enabled prosthetic limbs to better replicate natural movement and improve the user’s confidence and independence. However, it also highlights that access and affordability are still major problems. High material and production costs limit many users access to advanced devices.

The future scope of prosthetics lies in continued research into AI, haptic feedback, osseointegration, and automated and efficient manufacturing processes. Further advancements in power efficiency, reliability and personalised design are required to ensure that prosthetic technology is both functional, and widely accessible. Addressing these areas through interdisciplinary research is essential in developing prosthetic devices that not only restore mobility but also enhance long-term wellbeing and quality of life for amputees.

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