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Innovations in Prosthetic Design: Enhancing Mobility and Functionality

Nampiima Prisca J.

Faculty of Engineering Kampala International University Uganda

ABSTRACT

The field of prosthetic design has seen transformative advancements driven by innovations in materials, technology, and user-centered approaches. With over 40 million amputees worldwide, and an additional million new cases annually, the demand for accessible and affordable prosthetics has never been higher. This paper explores the historical evolution of prosthetics, the impact of modern materials and technologies, and the crucial role of biomechanics and ergonomics in designing effective prosthetic limbs. Additionally, the adoption of user-centered design methodologies has empowered users, especially in low-income regions, to co-create prosthetics that meet their specific needs. Emerging technologies, such as 3D printing, smart materials, and AI-driven systems, are poised to further revolutionize prosthetic design, making prosthetics more affordable, customizable, and functionally integrated with the human body. This study highlights the current state of prosthetic innovation and discusses future trends that will continue to enhance the mobility and functionality of amputees globally.

Keywords: Prosthetic Design, Mobility Enhancement, User-Centered Design, Lightweight Materials, Biomechanics.

INTRODUCTION

There are 40 million amputees globally, with 1 million new cases each year. The challenge lies in providing affordable prosthetic limbs, especially in low-income countries. PhD projects are empowering users to create their own prosthetics using simplified tools based on open-source designs. Design kits allow for rapid and low-cost prototyping of above-elbow prosthetic hands. An open design platform is being developed to improve design engagement and the affordability of local designs [1]. Traditionally, prosthetics design is linear and impersonal. A design researcher aimed to create user-initiated design projects for prosthetics. The focus is on upper-limb prostheses for above-elbow amputees. Bionics and myoelectric designs require more skills, resources, and time, while simple mechanical designs offer an alternative approach. The aim is to develop simplified tools based on pre-existing open-source designs that empower users with limited access to means. The democratization of design and production technologies enables fabricating prosthetic technology with co-development. Principles of free, open-source, and democratizing design are being explored. However, many of these technologies have yet to reach amputees who could benefit. With a focus on above-elbow prosthetics, design and development of technological affordances for democratizing prosthetic design is a creative act mediated by design tools.

HISTORICAL OVERVIEW OF PROSTHETICS

Prosthetics have been used for thousands of years to address injury or congenital anomaly. They can take any form and are often considered an art form in and of themselves. As technology improves, so do the limbs with which prosthetists can work. One of the earliest known artificial limbs dates to ancient greece, where an iron leg was found in a tomb from 500 bce. In ancient rome, roman soldiers used wooden toes to replace body parts lost in battle. The Middle Ages saw arab physicians inventing more sophisticated limbs as art became more accepted in the medical world. In the renaissance, prosthetic design saw its biggest leap forward with leonardo da vinci's drawings of a mechanical knight that offered different movements at the knee, elbow, and shoulder. Subsequently, intricate designs emerged, such as prosthetic hands that could open, grip, and raise to the mouth to eat. These designs, however, depended purely on mechanical functions and dramatic movements rather than simplicity [2]. It wasn't until the industrial revolution that prosthetics shifted from a craft-based process to a more scientific approach. In the 1790s, frenchman pierre desault took a scientific look at amputation surgery by attending the patient throughout the entire process. In the early 1800s, the american revolutionary war sculptor thomas bewick surveyed the anatomy of a right arm's corresponding structure drawn on paper. After this, prosthetics began melding human anatomy, mechanics, and art. More than a hundred patents were drafted in the United Kingdom alone, including a wooden leg with an "ankle joint" and a mechanism that mimicked human movement. Leg designs were fitted with springs that utilized stored energy to propel the limb forward. One english inventor made a hand of brass pipe, 2900 moving parts imitation fingers [3].

MATERIALS AND TECHNOLOGIES IN PROSTHETIC DESIGN

The design of prosthetics has shifted to a new generation of body-integrated devices based on advances in technology. The prosthetic must mesh with the human body and be discreet. Cost, accessibility, and modularity are important considerations. Engineering departments can use simulation tools for development, reducing the gap between consumer demands and product sustainability [4]. The materials employed in prosthetic limbs significantly influence their weight, cost, durability, and structural resilience. Although prosthetic limbs made from rare metals are lightweight and durable, their extravagant cost proves to be a barrier for poorer socioeconomic strata, who depend on alternate materials for making prosthetics. The choice of materials is extremely cardinal in prosthetic design, not just in technical and economic senses but also in cultural implications. Blending modern analytical prosthetic design with traditional materials sensitivities therefore creates a holistic design methodology. A few studies illustrate this approach, which results in shared design philosophies with emerging social innovation potentials. Biological systems are astonishing in their long-term mechanical use under a changing environment. They provide inspiration for engineers working on bioengineering/biomimetic structures like prostheses. In a recent prosthetic limb design project, tests for parameters like solidity, thermal expansion, tensile and bending stress, were performed on imitation wood, composite, titanium, and magnesium, and prosthetic limb designs were made on composite and titanium materials considering economic constraints. Analyzing the interplay of mechanical and bioelectrical design in bone-prosthesis systems suggests alternative lines for innovation, deepening a technological understanding that encourages research collaboration across disciplines and provides design rules for medical engineers and designers [5].

ADVANCEMENTS IN LIGHTWEIGHT MATERIALS

Prosthetics have been around for centuries, yet there's still a long way to go before they work as good as or better than biological limbs. Developmental difficulties that inhibit ordinary function must be addressed for prosthetics to succeed and stimulate growth. Units of sensing, control, actuation, and energy are used to simulate human ppc and robustness. The design of new lightweight composites plays an essential role in the development of prosthetic limbs. Historically, materials that were inexpensive have been used to fabricate prosthetic limbs. Initially, wood was used to manufacture the shell of prosthetic limbs. As technology matured, high-strength metals were introduced. These metals were not only high strength but also durable, which increased the longevity of prosthetic limbs. However, a metal shell is heavy and results in a snowshoe effect during ambulation. To combat the problem of sensitivity, high-toughness plastics like polyurethane were introduced. It was lightweight but could not sustain a heavy-use environment [6]. Considering the problems with traditional prosthetic design, the invention of new composite materials was paramount. Polymeric foams became widely used for their lightweight but could not tolerate temperatures above 80°c. This involved some trade-offs from fire safety equipment. Non-flammable polymer composites with heat resistance were developed to overcome the issues with polymer/foam composites. Recently, a new servo-hydraulic testing machine has been developed that can measure the durometer hardness, foam density, and flexural bending of experimental foams efficiently and effectively. The mechanical output of the serocomposite limb was found to be up to five times larger than that of a traditional prosthesis. It is possible to have thermal conductivity much lower than that of foam - 0.0809±0.0002 wm-1k-1, lightweight with a density of only 0.12±0.015 gcm3, and good mechanical performance with yield and tensile strength of 903.90±18.291 mpa and 3.99±0.112 mpa respectively.

BIOMECHANICS AND ERGONOMICS IN PROSTHETIC DESIGN

The intricate interplay of biomechanics and ergonomics forms the bedrock of modern prosthetic design, meticulously sculpting devices that mimic the complex symphony of human movement while remaining comfortably adaptable. The science of biomechanics involves applying principles of physics and engineering to biological systems, while ergonomics seamlessly integrates human factors into the design process itself. Together, these domains converge to ensure that prosthetic limbs harmonize with the physique and movement patterns of their users [7]. Fundamental to this fusion are kinematics and kinetics, which methodically study how joints and segments move within a prescribed frame of reference and unfurl the internal forces and torques at play. Even the finest of prosthetic joints, meticulously engineered, would fall woefully short of ensuring comfortable and adaptive operations if these principles go unheeded. A broadly adopted instrument for quantitatively studying these principles is pressure-mapping technology that can precisely gauge the amplitude and distribution of pressure points between the prosthetic and the residual limb. Planned with wear comfort as a priority, the prominence of any pressure points is ideally limited to below 30 mmhg, below which skin perfusion is still sustained within the bare minimum threshold. Matched to this quantifying principle "device-induced pressure" is the more subjective "stump-induced pain," the effect of which, however immeasurable with any instrument, can greatly affect functionality and hence user acceptance. More than anything, ergonomics seeks to ensure that the moved, movable, and operating systems are born of a specific synergy with respect to human limits, skills, and requirements. It should rest on a clear understanding of the individual user's physical and psychiatric state, his or her involvement in other activities like work and leisure, the degree of functional loss, and the expected contribution of the prosthetic limb to the entirety of expected outcomes [8].

USER-CENTERED DESIGN APPROACH

The user-centered design approach in prosthetic development is predicated on a comprehensive understanding of user needs, preferences, and expectations through participatory design methods. Such methods engender a deeper comprehension of the everyday realities faced by users, which may not be self-evident to designers, thereby guiding the design process. This section discusses participatory design inspiration, rationales, principles, and practical methods. It includes a theoretical background, case studies of participatory design trials with users post-amputation, and user-testing of prosthetic devices developed by engineers in the context of university collaboration with manufacturers. The analyzed test methods can assist in early participation, augmenting traditional prosthetic need assessment interviews. Prosthetics engineers generally lack practical experience with limb loss and therefore symbiotic design partnerships between users and engineers are vital to enhance design relevance and adoption. However, prostheses are complex systems, challenging to understand for individuals without subject-matter expertise. Yet these individuals are considered users and describers of problems, needs, and preferences for existing devices. Failing to involve users early in the design and development leads to mismatches between prostheses developed and the needs of users, ultimately hampering adoption. Awareness raising regarding needs, preferences, and experiences with prostheses is crucial for the successful uptake of new devices [9]. The lack of balance is due to the absence of a holistic multi-disciplinary team that promotes symbiotic partnerships. Recent literature highlights the importance of involving users in the design process, embracing social perspectives on technology. Designers can explore the embedding of device functions in the social fabric. User engagement can be enhanced through participatory design methods, which originated in scandinavia in the mid-1970s. This approach considers the skills and needs of users within complex socio-technical contexts, empowering non-designers as co-designers.

FUTURE TRENDS AND EMERGING TECHNOLOGIES

The domain of prosthetic design is not static; it is poised for groundbreaking shifts thanks to advancements in various enabling technologies and recent research breakthroughs. As an extension of the human body that becomes an integral part of its wearer, prostheses must follow the natural control and functional properties of human limbs. Following this paradigm, sophisticated control mechanisms of prostheses are warranted. Crucial innovations in this regard are instrumentation and communication technologies that nest biosignal sensing technologies, occasional 3d motion capture systems, wsns, and wsn sensing platforms implementing self-powered piezoelectric energy harvesters and mems inertial sensors [7]. In biomedical signal processing, research on intelligent prostheses systems using mathematical modeling and artificial intelligence has advanced since the 1980s. Machine learning and neural networks with deep learning techniques have improved classification accuracy and reduced classification time for controlling myoelectric prostheses. These advancements have led to more accurate decoding of multi-channel biosignal interactions. Recent technological advances have made portable 3d motion capture technology successful in characterizing the gait of amputee subjects. These advances, along with flexible 3d printing, smart materials, and mems technologies, show great promise for foot prosthetic applications. Affordable prostheses that compensate for the lack of human anatomical characteristics are being investigated. The design of developmental prosthetics is focused on low-cost 3d printing technologies. These advancements are expected to lead to affordable and customizable prosthetic solutions. Designers, educators, manufacturers, and business models are working to address market availability and wealth inequality. Ensuring commercial success involves addressing risk and legal issues. In the next decade, there will be a wave of affordable and societal-oriented smart prosthesis solutions. This work has profound implications for health and physical integrity [10].

CONCLUSION

Innovations in prosthetic design are redefining the possibilities for amputees, offering enhanced mobility and functionality through the integration of advanced materials, technologies, and user-centered design approaches. The transition from traditional, linear design processes to more inclusive, democratized methods is enabling the creation of more affordable and accessible prosthetics, particularly for individuals in low-income regions. As the field continues to evolve, driven by advancements in 3D printing, smart materials, and AI, the future of prosthetics holds the promise of devices that not only restore lost function but also integrate seamlessly with the human body. These developments are paving the way for a new era in prosthetic design, where innovation is not just about technological progress but also about improving the quality of life for millions of people around the world.

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