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Beyond Bionics: The Future of Augmented Modular Prosthetics

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Abstract. The majority of modern prosthetic limbs are made to resemble actual human hands in both appearance and movement. However, in practice, they have limited capabilities and frequently need repair. Using a literature review and insights from various fields, this paper examines both the current state and the key issues of traditional prosthetics. It also discusses why augmented prosthetics might be a better direction. The findings reveal that augmented limbs can be more flexible and functional, offering users more options based on their needs. Beyond that, modular design may help lower production costs, making prosthetics more accessible, especially for people in developing countries or with fewer resources and lower income. Another advantage of modular design would be the simplification of verification and compliance process, which enables new designs to benefit patients at the earliest possible stage. Although the current technological limitations of augmented limbs are complex, the rapid advancement of neuroscience is likely to overcome them in the near future.

Keywords: Augmented limb, Modular design, Affordability, Brain-computer interface

1. Introduction

Most current prosthetic limbs are designed to mimic the appearance and basic functions of the human body. This approach limits their performance, especially in complex environments. In addition, most advanced prosthetic technologies are developed and distributed in high-income countries, leaving a large gap in accessibility for low- and middle-income regions.

Some recent research suggests a possible alternative. Soft prosthetic hands, for example, use postural synergy in soft robotic structures to support diverse grasp patterns with minimal control effort [1]. This makes them a potential form of augmented prosthetics, able to go beyond traditional limitations. Technically, soft hands have a higher angular tolerance when holding objects, making them less likely to tip or drop things.

Modular design may also help solve key problems in cost and scalability. Aguwa et al. argue that modularity reduces development cost and time without reducing quality [2]. Applied to prosthetics, this could make them more affordable and adaptable, especially in low-resource settings.

This paper reviews existing literature and explores how modular and augmented designs could offer a future direction for prosthetics—one that expands both function and access using technologies that are already close to being feasible. The significance of this research lies in its

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potential to enhance the quality of life for users by improving prosthetic functionality and accessibility.

2. Advantages of augmented modular limbs

2.1. Function exploration

The majority of artificial limbs in the market are focusing on restore regular appearance and function of human limbs, which, to be fair, is suitable for many everyday human tasks. However, in a rapidly changing society, the evolution of the human body has long lagged behind the shifting demands of modern life. Benton et al. stated that, many genetic variations were advantages under that specific condition or time period in history, but no longer advantage now [3]. For example, sickle cell disease once helped people avoid malaria, but in today's world—where malaria is treatable—it has instead become a burden.

The similar approach applies for limbs. Although modern human society increasingly depends on cognitive labor and sedentary tasks, the evolutionary design of the upper limb remains primarily optimized for physical activities such as grasping, manipulating objects, and locomotion. Marzke suggests that the functional integration of derived traits accommodates changes in locomotor and manipulative behaviors, indicating that upper-limb morphology reflects adaptations for activities like climbing, tool use, and item transport [4]. These evolutionary traits highlight a design shaped by ancestral environments and behaviors, which are quite different from the fine motor demands of contemporary brain-intensive tasks such as typing, writing, or prolonged desk work.

Augmented limbs, however, can be designed to continuously follow the needs of the time and the condition. For example, an augmented limb suitable for current generation might be specialized for typing, enabling office workers to type several times faster than they could with their natural hands. Looking ahead, in a possible future where physical production may no longer be necessary, an augmented limb might evolve into a social organ, used primarily to express thoughts and emotions, rather than perform labor.

Thanks to modular design, augmented limbs can also be adapted to suit a variety of situations with only brief adjustments. For instance, a bartender with an augmented arm could swap one hand module for a bottle opener or stirrer during work, and then reattach a realistic hand after hours for daily life comfort and aesthetics.

According to Dillingham et al., they have developed a prosthetic system named by iFIT. This specific modular system can be adjusted by the patients themselves without help from the professionals [5]. The study was conducted in Jamaica, a less developed region, where patients had to face many different harsh local environment conditions with limited healthcare. The result indicates that the iFIT system give patients lower average socket pressure, and they also felt better. Figure 1 shows the how the iFIT system give lower average pressure to the patients at most part of their limb comparing to conventional system. The estimated pressure in pounds per square inch (psi) is indicated next to the mean values and reflects an estimated pressure determined through nomographic scoring (Fujifilm). These peak pressures occurred during ambulation [5].

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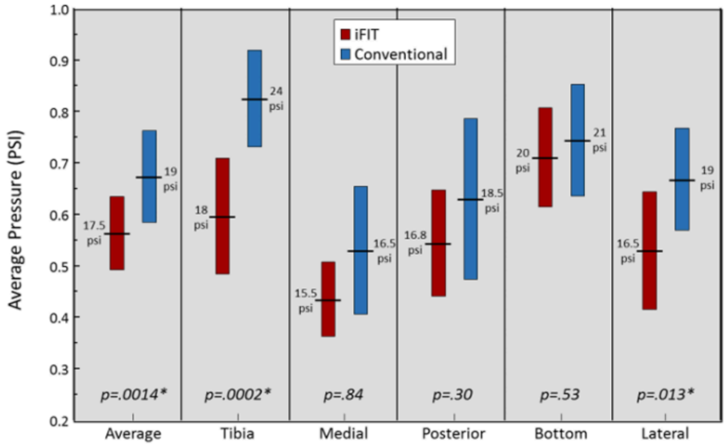

Figure 1. Average peak pressure: iFIT versus conventional prosthesis [5]

2.2. Commercial application

Even though prosthetic limbs are much cheaper than they used to be, they're still unaffordable in many less developed regions. According to The Real Cost of Artificial Limbs, even the most basic ones can cost hundreds, sometimes over a thousand dollars—not including the extra costs for maintenance and fitting. For many people, that's just too much. And the issue isn't only the price — it's also that many places don't have support systems or trained staff to help people actually use them.

One major advantages of modular design is that standard parts and a consistent production method can enhance manufacturing efficiency and simplify production line management, ultimately reducing costs. This approach also facilitates the establishment of factories in areas lacking robust industrial infrastructure, as the setup and management processes are more straightforward. Besigomwe detailed analyzed the situation of Uganda by Interviews with 40 local firms, and states that with the poor infrastructure and skill gap there, it would be really hard to produce Monolithic Designed equipment [6]. However, with the modular design approach, it would be possible to utilize the low-cost local land and labor. At the same time of reduction of production cost, local communities will also benefit from the creation of numerous high-quality jobs, contributing to the advancement of humanitarian efforts.

Besides the reduction of cost during initial production, modular design also enables the reuse of devices. Oturu states that with modular design, medical devices can be refurbished and reused at a much lower cost, even if they are damaged [7]. For example, Philips' Diamond Select project collects functionally obsolete, modular-designed X-ray machines like the Allura Xper FD20/10. They replace and upgrade certain parts of the machines to make them qualified for use again. With this approach, they achieve savings of approximately 15% to 40% for healthcare providers, without compromising on quality or service [8].

Another advantage of modular design is that a new version of an augmented limb — often involving only an updated component rather than the entire device—can go through verification in a much shorter time. According to FDA guidelines, the modular Premarket Approval (PMA) process allows manufacturers to submit different parts of their application as they become ready [9]. This is in contrast to traditional monolithic designs, where every update requires a full-system reapproval, often delaying access to improvements.

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3. Challenges and possible solutions

With all the advantages mentioned above, there are still technical barriers preventing us from fully realizing augmented modular design. Most of the mechanical aspects have already been made feasible, at least when control complexity is not considered. According to Maiseli et al., key components like actuators, joints, and structural materials have become advanced and reliable enough for daily use [10]. Current devices can already support complex physical functions without major mechanical failures. Because of this progress, research and development in the field can now focus more on other aspects of improvement, instead of being stuck on basic physical construction. Currently, most challenges concentrated in the area of brain-computer interfaces. Most commercial artificial limbs on markets rely on peripheral nerve interfaces, which are connected to the user’s existing limbs. However, augmented limbs are essentially extensions beyond the human body itself, making brain-computer interfaces increasingly important. A recent review by Elashmawi et al. introduces a possible way to develop brain–computer interfaces (BCI) by using electroencephalogram (EEG) as a non-invasive alternative to traditional implanted methods [11]. The study uses machine learning approaches to interpret EEG signals and suggests that this technique may offer a more flexible and accessible path for future BCI design. Another possible way, stated by Chopra, is to utilize artificial intelligence to decipher the muscle electric signals of the patients. After constant learning by AI, it might be able to understand the intended movement by user simply receiving the electric signal from muscle. As a result, finer-grained movements can be achieved [12].

4. Conclusion

In conclusion, this paper demonstrates the advantages of modular augmented limbs from two perspectives: the expansion of function and economic advantage. Compared to traditional artificial limbs, modular augmented limbs can handle multiple distinct tasks with switching of modules. Also, the augmented limb would allow users to achieve functions that human hands can barely replicate, like extremely delicate surgical procedures or opening a metal cap without tools. Besides that, users don’t need to remove the entire artificial limb for maintenance or upgrades. With a modular design, individual parts can be repaired or replaced on their own, making the process quicker and less disruptive. Focusing on commercial applications, the modular design provides a possibility for being produced in less developed countries with little infrastructure, utilizing the local cheap land as well as labor to reduce the cost of production. At the same time, providing great amounts of good-quality employment opportunities for local residents. After production, the modular design will also empower highly cost-effective refurbishment and significant value recovery at the end of the product's life. Apart from that, according to FDA regulations, a modular design allows new parts to be reviewed individually rather than requiring the entire device to undergo reapproval. This approach makes it easier for companies to update their products more frequently and helps users access the latest technologies without unnecessary delays. The major technical barrier for researchers to achieve modular augmented limbs is neuron input. Hopefully, as the brain-computer interface becomes more mature, it will become possible to eliminate limbs deficiency and equip more individuals in need with functional, life-enhancing prosthetic solutions. This paper summarizes a new approach for artificial limb, the augmented limbs and demonstrates the advantage of using idea of modularization from other industry.

However, several limitations should be noted. For instance, the exploration primarily focuses on theoretical benefits and lacks extensive empirical evidence from real-world implementations.

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Further studies are necessary to evaluate the long-term impacts of modular designs in various socioeconomic contexts, particularly in developing regions. This will help refine the approach and ensure that augmented limbs can effectively meet the needs of diverse users.

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