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REVIEW OPEN ACCESS

Advancements of Upper Limb Prostheses can Improve Patient Quality of Life: A Technology Review

Anthony B. Makwanda, BSc Student [1]*, Anne O. Ikhile, BSc Student [2]

[1] Department of Biology, University of Toronto, Mississauga, Ontario, Canada L5L 1C6
[2] Department of Chemical and Physical Sciences, University of Toronto, Mississauga, Ontario, Canada L5L 1C6

*Corresponding Author: anthony.makwanda@mail.utoronto.ca

Abstract

Introduction: Based on the evolution of hand prosthetics, many original shortcomings have been addressed and further rectified. Some common past limitations include limited degrees of freedom, strained motion control/fine movements, weight of the design, and lack of ability to do thumb-index pinch [1]. Henceforth, this review highlights and assesses the effects of hand prosthetics advancements on the quality of life of patients with/requiring joint replacements.

Methods: Relevant literature between 2013 to 2023 was obtained using Web of Science and PubMed. Search terms were "Upper limb prostheses" OR "Body replacement technologies" AND "technology" as well as "Upper limb prostheses" AND "technology" AND "Quality of life" OR "Improvement". Literature was selected based on applicability to key aspects of the research topic after assessing the results and abstracts.

Results: Studies support the theory that over the decade, the ability to accomplish fine motion control with hand-prosthetics has aided in improving patients' quality of life. Overall, advancements to prosthetic design, prosthetic sensors, and waterproofing designs via myoelectricity, insulated and biopotential sensors, as well as waterproofing technologies, were reported to contribute greatly to patients' quality of life.

Discussion: As technological advances aid in improved dexterity and motility, recently advanced prosthetics help promote independence and confidence, and in some cases, decrease the cost of living for some patients. Myoelectric prostheses, flexible insulated sensors, capacitive biopotential sensors, and waterproofing technologies, have shown trends in increased dexterity, patient comfort and flexibility, as well as increased degrees of freedom of movement. The most notable limitations to these advancements were limited accessibility, comfort challenges, and lack of large-scale patient assessment. Hence, future advancements in further research and patient testing of these technologies were suggested.

Conclusion: This review will be deemed as supporting material for healthcare providers and policy makers while making decisions on the allocation of resources to ensure that patients from all demographics can acquire accessible technologies, improving their qualities of life. In addition, the advancements of hand prosthetic technologies from mechanics and robotics research can provide implications for the next-generation technologies with the determination to improve patients' life.

Keywords: upper-limb; prosthetics; myoelectric; capacitive sensor; dexterity; waterproof technology

Introduction

Upper extremity limb loss accounts for approximately one-third of all Canadians suffering from limb loss Few studies have explored the effects of emerging upper-limb prostheses on the quality of patients' lives in the long term, therefore, this study aims to bridge the current knowledge gap by assessing the effects of new-age technological advancements on patients' life quality. Traditional prosthetic technology relies on basic mechanical systems and lack of advanced sensory feedback, hampering their ability to moderately replicate intricate movements and sensations of a natural limb. Limited dexterity, lack of sensory feedback, difficulties in intuitive prosthetic control, cost, and impaired comfort are some of the biggest limitations sought to be improved by new-age hand prosthetics using technological advancements [3].

Prosthetic designs for upper limbs have evolved from solely substituting body parts to improving locomotion by focusing on the prosthetic-brain interface. Hand prosthetic devices today provide improved control over fine movements such as the thumb index pinch, strained motion control, and degrees of freedom [2]. The improvement to hand-prosthetic designs today is attributed mainly to the development of technologies that contribute to bridging the communication between the central nervous system (CNS) and the artificial limb itself [4]. Through the implementation of robotics, hand-prostheses have aimed to replicate sensory-motor capabilities of the amputated limb by mimicking common biological and technical based hand manipulation [5].

This review delves into the research that has contributed to the development of hand prosthetic technologies mimicking the kinematics and control methodologies present in the biological function of the missing limbs. One notable piece of implemented technology cited in this review is myoelectric control. Myoelectric prostheses are modulated by electrical signals which required an interface directly encapsulates with the peripheral nervous system (PNS) and central nervous system (CNS). This design aims to grant control to the owners of the prosthetics of the task they wish to accomplish in a more natural way. This ties into electrode based prosthetic hands, another technological advancement which addresses sensory feedback and design control strategies. These technologies utilize pressure sensors and tactile feedback systems that can simulate sense of touch, thus improving users' interaction with their environment.

Capacitive biopotential sensor, flexible insulated sensors, and waterproofing technologies are potential solutions to the traditional hand prosthetic drawbacks which are still in their research and development phases. This study quantitively reviews the revolutionary technologies and the qualities of patients' life upon the implementation. Coupled with the cosmetic efforts in making prosthetics appear life-like, technological advances to prosthetic devices have significantly improved the quality of life in patients who have or seek upper-limb prosthetics. The completion of tasks in their daily lives, hobbies, and/or jobs can be made possible with these advancements.

Methods

Search Strategy

This study highlights the myoelectric prosthesis after reviewing and comparing different prostheses with a clear selection criteria. This study also highlights new prosthetic sensors and waterproofing technologies. Independent variables are emerging bidirectional communication of upper-limb prostheses and dependent variables are the users satisfaction of corresponded technologies, such as wearing conformity.

Articles selected specifically evaluated prosthetics on the upper limb (hand or shoulder). The obtained research papers were collected through the search from data bases with two key aspects. The first aspect was based on any improved technologies used in upper limb prostheses, and the second research prompt focused on the holistic satisfaction and improvement to the lives of the patients receiving those prostheses.

The first set of search terms were obtained through a computerized search on the 'Web of science' database. The terms included were; "Upper limb prostheses" OR "Body replacement technologies" AND "technology". All pooled articles analyzed different qualities of the prostheses responsible for its improvement. The search on Web of Science yielded a total of 584 articles from years of 2000 to 2023, and 343 articles were selected by applying the above criteria. The second set of search terms used to assess the quality of life of patients were also obtained through a computerized search on Web of Science. The terms included: "Upper limb prostheses" AND "technology" AND "Quality of life" OR "Improvement". The narrow nature of this search contributed to a yield of only 26 results, and 21 results were remained after applying the above criteria. Note that the articles in the first data pool were also used to assess the patient's quality of life as per their own collected data.

Selection Criteria

The selection criteria for the pooled results were as follows:

- The paper was published fully in English.
- Primary and Secondary sources (review articles) of information were satisfactory.
- The paper was published within the past 10 years (i.e., 2013 - 2023).
- The document type was a full report and not excerpts such as books, abstracts, conference proceedings, or posters.
- All works were ensured to be peer reviewed.

Results

The traditional strategy employed by professionals used the prostheses to connect the residual limb with a socket, granting the amputee control of motion and position of the amputation stump [6,7]. Research shows that the early renditions of prosthetic hands were designed primarily for grasping tasks and not manipulative tasks. Modern technological adaptations have sought to address manipulative functions such as high dexterity, advanced sensors, complex control strategies, and natural interfaces [8].

Table 1. Table showing the summary of the advanced technologies explored in this study

Technology	Specialty of Technology	Year of Study	Author Names	Reflections of Users
Myoelectric Prostheses [12]	Electromyography (EMG) And Biosensing	2020	D'Shaun D Adams, Francisco A Schwartz-Fernandes	Increased dexterity. Increased range of hand motion. Improved physiological satisfaction, social adaptation, and cosmetic appearance.
Flexible Insulated Sensors [17]	Surface electromyography	2019	Roland T, Wimberger K, Amsuess S, Russold M, Baumgartner W	Non-invasive surgical procedures and non-conductive connection advantageous to patients with circulatory issues. Increased wear comfortability and stability. Prone to noise and false response.
Capacitive Biopotential Sensors [32]	electroencephalography (EEG) and electrocardiography (ECG)	2016	Y. Sun and X. B. Yu	Skins surface sensor, minimal noise from muscle contraction action. More intuitive prosthetic control. Contactless signal sensing helps with skin sensitivity and provides comfort.
Waterproofing Technology [20]	Material and Engineering science	2023	Amber Henson	Increased comfort and ability to perform various tasks.

<u>Advancements to Prosthetic Design</u>

Myoelectric Prostheses

Myoelectric prostheses are examples of modern-day novel approaches to prosthetic devices.

They are external, battery-powered devices that substitute missing arms or hands [9]. The device bridges the brain and artificial limb interface through an input of electric signals generated when muscles in the residual limb are contracted [10]. Electrodes sitting on the skin inside the socket then detect these signals and send them to a controller which ultimately triggers movements that correspond to the intentions of the user. Research has found that myoelectric prostheses are notable in their ability to restore control and functionality for upper limb amputees. The electric powered device gives the patient the same sensation of regulating the same nerves prior to amputation and has also been reported to improve dexterity and grip, and increase force [11]. As compared to body powered prostheses, myoelectric prostheses have reported higher rates of satisfaction with psychosocial, social adaptation, and cosmetic appearance [12]. They have also been shown to reduce phantom limb pain which 50% of upperlimb amputees face. Overall, advantages include the accessibility to multiple grip patterns and more natural hand movements [13].

In a paper retrieved from the National Center for Biotechnology Information repository, a range of motion (ROM) and movement variability study was conducted. Range of motion, absolute kinematic variability, and kinematic repeatability were quantified. Overall, myoelectric prosthesis users demonstrated absolute kinematic variability and range of motion. [14].

Additionally, researchers have shown results which detailed myoelectric prostheses to be beneficial for decreased task difficulty and more frequent bilateral use. It was noted that myoelectric prostheses are preferred by 64% of children, putting the prosthetic more frequently to use, and improving function and grasp of heavy objects [16].

<u>Advancements to Prosthetic Sensors</u>

Flexible Insulated Sensors

In the current development stage of sensors in prostheses, the devices have a conductive connection to the skin, thereby being sensitive to sweat and requiring skin preparation [17,18] Research conducted by Webb et al., (2013) reported that amputee patients with circulatory disorders must endure irritating pressure marks as a result of the sensors being applied with great pressure to ensure conductivity. The traditional prosthetics required significant effort for operation, leading to fatigue for users. The conventional sensors are also placed on the surface of the skin and could be prone to slipping or misalignment. Flexible insulating sensors operate with an insulating layer between the skin and sensor area. They require no conductive connection to the skin or skin preparation which serves as an advantage to patients with circulatory issues [19]. These sensors adapt to the anatomy of the human arm which has been reported to provide patients with wearing comfortability and stability, and they ensure consistent and reliable signal detection [17].

Capacitive Biopotential Sensors

Capacitive biopotential sensors have shown promising applications in prosthetics, revolutionizing the way amputees interact with their artificial limbs. Unlike traditional prosthetics that rely on mechanical switches and muscle contractions for control, capacitive biopotential sensors can directly detect the electrical signals generated by the user's muscles. By placing these sensors on the skin surface near the residual muscles, the sensors pick up the myoelectric signals generated during muscle contractions, enabling a more intuitive and natural control of the prosthetic limb.

Advancements to Waterproofing Technologies

One main limitation of myoelectric prostheses is that they cannot get wet. This shortcoming has been overcome with recent advancements in waterproofing technologies for some terminal devices. Terminal devices incorporated on the prosthetics hand are prone to damage once exposed with water, hence hindering daily human activities which are based upon usage of water [9,20].

One notable technology is a seal-in device known as Seal-In X5, which is liner system used in a specific knee prosthesis. It uses a specialized silicone liner that creates an airtight seal between the residual limb and the prosthesis socket, preventing water from entering the socket [21]. It has five integrated seals that adapt to the shape of the residual limb and the socket wall, providing an airtight seal. Additional cited benefits of this technology include minimized pistoning and enhanced rotational control which allow users to enjoy improved comfort and stability.

This waterproofing technology has been tested on patients, and the prosthesis has been designed to withstand exposure to water during activities like showering or swimming. The patient testing phase helps assess the durability, comfort, and effectiveness of the technology in real-life situations, ensuring its reliability and safety for users. However, the seal-in X5's performance paled in comparison to other liners such as the dermo liners which had the same benefits but to higher precision. Particularly, the feeling of the prosthesis with the liners, donning/doffing, walking as well as sitting with the prosthesis were notably satisfactory. The seal-in X5 results were favored in terms of patients not being bothered by sweating, pain, and swelling. This technology is most commonly used in lower limb prostheses, however, a similar device with the same features would be incredibly useful and applicable in upper limb prostheses.

Discussion

Advantages and Limitations of Myoelectric Prosthetics

One of the most notable drawbacks of prosthetic devices is their affinity to cause patients phantom limb pain. Phantom limb pain is typically found in transradial amputees [23]. Transradial amputation involves the bones of the lower arm being cut during the surgical procedure. It is a phenomenon that is described by amputees as pain or discomfort in a limb that is no longer there. Reports have shown less prevalence in phantom limb pain because the sensory feedback embedded in myoelectric devices allow the users' brain to adapt to the new sensory inputs and commands from the prostheses. By activating neural pathways associated with limb movement, such as the lateral corticospinal pathway that controls the voluntary movement of limb,, the brain may "relearn" the representation of the missing limb, potentially reducing the perception of pain in the phantom limb. Overall, the data collected by Biddiss & Chau, (2007) indicates that myoelectric prosthesis are better for locomotive activities, carrying heavy objects, and granting patients a greater range of motion [16].

However, myoelectric prosthetic devices are not economically friendly to most of the patient population, thus hindering their accessibility. Additionally, excessive training procedures are required to master their usages, accompanied by comfort and durability challenges.

In a study retrieved from the National Center for Biotechnology Repository assessing the experiences of patients with body powered prostheses in comparison to patients with myoelectric control, myoelectric prostheses displayed troubles with "Prosthesis embodiment" [25], which is the physical and mental perception of an artificial limb as a biological one. In the survey they conducted with regards to prosthesis agency, participants with transradial limb difference were asked to do a limb length estimation task where they would estimate the length of their artificial limb through an opaque tube. There was a trend towards a stronger sense of agency for body-powered prosthesis users as compared to myoelectric prosthesis users.

Unfortunately, average rejection rates for body-powered and myoelectric prostheses are 26% and 23%, respectively [16]. Consequently, it was described that a sense of agency over the prosthesis is dependent on the matching of the efferent copy and sensory feedback. Therefore, it was hypothesized that in the case of myoelectric prosthesis users, they do not receive adequate sensory feedback to make a comparison with the expected outcome of the motion [25]. Therefore, this control difficulty is an area in need of improvement in myoelectric prostheses.

Overall, one of the major challenges and frustrations in upper limb prosthetics is providing people with prosthetics that appear natural, anthropomorphic movement and easy prosthetic operation. Henceforth, there is a more recent and technical approach that allows for direct nerve stimulation

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by wrapping electrode wires around the nerve or longitudinally placing electrode wires on the nerves directly [26]. The information from the tactile sensors placed on the prosthetic hand will then communicate directly to the nerve, allowing for somatosensory stimulation of different peripheral receptors. This approach contributes to the evolution of electrically powered prosthetics (such as myoelectric ones) [27].

Limitations to Flexible Insulated Sensors and Future Work

The most apparent limitation to these sensors is that they are still in their research and development stages. This means that large scale testing on amputees to assess feedback data has not been carried out yet.

Studies show that there is still a problem in bio-signal measurement due to noise from various sources. For instance, only a 50 Hz hum can disturb the EMG signal, causing the sensors to become unstable [11,12]. Thus, the future aim for these sensors is to improve mechanical stability. Additionally, the sensors need to be sealed to become waterproof. Long term, this makes sweat and washing an issue as it could cause short circuiting.

Advantages of Capacitive Biopotential Sensors and Limitations

Myoelectric prostheses typically use surface electromyography (sEMG) sensors to detect and interpret the electrical signals generated by muscle contractions [29]. Surface electromyography (sEMG) sensors are placed on the surface of the skin over specific muscles, and the signals are then processed and used to control the movements of the prosthetic hand or limb [29]. Unlike sEMG sensors that require direct contact with the skin, capacitive biopotential sensors can detect electrical signals without the need for direct skin contact. This contactless sensing can be beneficial for users who may have sensitive skin or discomfort with electrodes adhered to their skin for extended periods.

Capacitive biopotential sensors face limitations in their research and development stage. The development and integration of capacitive biopotential sensors into myoelectric prostheses may be more complex and costly compared to the well-established use of sEMG sensors. Therefore, akin to the flexible insulated sensors, there are limited concrete data assessing the quality of life.

Limitations to Current Waterproofing Technologies

While the Seal-In liner provides a secure seal and improved suspension for many users, achieving a perfect fit can be challenging for some individuals. Ensuring comfort over extended wear periods and addressing potential issues like liner bunching or discomfort due to pressure points might be areas of improvement. The durability of the Seal-In liner is also an important factor, especially for users who lead highly active lifestyles or require their prostheses for demanding tasks. Improving the longevity of the liner under such conditions could be an area for further research [29,30].

Additionally, some users might experience skin sensitivities or allergies to the materials used in the Seal-In liner [30]. Future work could involve exploring alternative materials that are hypoallergenic and suitable for a wider range of users. Finally, accessibility to this material, cost friendly products, and user education and training could hinder mass use of recent waterproofing technologies. To ensure optimal performance and comfort, users need to be educated on how to use and maintain the Seal-In liner properly. Improving training and resources for both users and prosthetists could enhance the overall experience.

Conclusions

Overall, the relevant data has aided in a comprehensive understanding of the impact of technological advancements on patients' lives. Taking advantage of nerve signals and sensors for signal detection has granted a greater level of comfort, increased dexterity, greater degrees of freedom to hand movements, and the reduction of susceptibility to phantom limb pain. Waterproofing devices have granted patients flexibility in performing daily tasks easily, and opportunities to indulge their hobbies. Further research in these advances and testing to assess patient recovery would be beneficial and aid in more ground-breaking developments. The hopeful impact of this study on patients, healthcare practitioners, and policy makers is to instill priority on prosthetic advancements that improve life quality.

List of Abbreviations Used

CNS: central nervous system
PNS: peripheral nervous System
ROM: range of motion

Conflicts of Interest

The authors declare that they have no conflict of interests.

Ethics Approval and/or Participant Consent

This study did not require ethics approval or participant consent because it is a literature review which did not involve humans, animals, or tissues throughout its completion.

Authors' Contributions

ABM: made contributions to the design of the study, collected and analysed data, drafted the manuscript, and gave final approval of the version to be published.
AOI: made contributions to the design of the study, collected and analysed data, drafted the manuscript, revised the manuscript critically, and gave final approval of the version to be published.

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