A Review of Current Upper-Limb Prostheses for Resource Constrained Settings

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***Abstract*—In lower-middle income countries (LMICs), untapped land mines, war, and diseases such as diabetes and polio have left many residents in need of a prosthetic device. For many whose primary source of income is derived from manual labor, lack of an appropriate prosthetic device often results in decreased productivity and lower quality of life. Across the world, the primary purpose of prostheses is to restore functional capacity in a manner that is both natural and aesthetically pleasing to the user. Some practices from the Western world, such as manufacturing methods, are transferrable to these contexts. However, the availability of materials, resources, and skilled personnel pose particular challenges for LMICs. In general, prostheses designed for LMICs exhibit simplified designs, as well as limited materials and electronic components. This article reviews current upper-limb prosthetic devices developed specifically for resource-constrained environments. An overview of the materials and design for each device as well as a discussion of their limitations are provided.**

Keywords–upper-limb prostheses, LMICs, prosthetic devices, upper-limb amputee

I. INTRODUCTION

The World Health Organization (WHO) estimates that 650 million individuals worldwide suffer from a disability. Untapped land mines, war, and diseases such as diabetes and polio have left many with amputated limbs. Of the disabled population, 80% reside in resource-constrained countries [1]. More specifically, 2.4 million of the 3 million upper-limb amputees worldwide live in developing countries [2]. Upper-limb amputations include wrist disarticulations, long transradial amputations, mid-level transradial amputations, elbow disarticulations, and transhumeral amputations. Wrist disarticulations are partial amputations of the fingers or hand. Long transradial amputations are at or right above the wrist. Mid-level transradial amputations are between the elbow and the wrist but closer to the elbow. Elbow disarticulations are at or slightly above the elbow. Transhumeral amputations are between the elbow and shoulder.

According to WHO, less than 5% of the population in the developing world has access to rehabilitation services. Rehabilitation has been shown to improve chances of long-term prosthetic use. Universal guidelines for rehabilitation of lower-limb amputees exist; however, for upper-limb amputees, the guidelines vary. In general, it is recommended to begin fitting and training with a prostheses within a month of amputation for a higher chance of success using the device. Follow-up fittings and care are also important for continued use of the device [3]. These services are predominantly located in urban areas, increasing the challenge of accessibility for those in rural communities [4]. Many nonprofit organizations, such as faith-based organizations (FBOs), will often donate prostheses to amputees, but these organizations typically find prosthetic devices too expensive to purchase in large quantities [5]. With most individuals relying on labor-intensive occupations for their primary source of income, upper-limb amputations can leave people entrenched in a cycle of poverty.

There have been several papers on the use and expectations of prostheses in LMICs. One review is a compilation of papers describing designs of the various devices. The article concluded that a device must be affordable, durable, and have successful field testing in order to be suitable for an LMIC [6]. Another investigated eight different approaches for designing prosthetic hands and created a new device using the best determined techniques. This paper determined that a hand must be aesthetically pleasing, have high power and varying speed, incorporate sensor integration, and be manufacturable for under $2,000 [7]. Although these papers cover various prostheses, there are no reviews that cover all of the upper-limb prostheses specifically designed for LMICs. An extensive review on lower-limb devices has been completed recently, leaving a gap in the literature surrounding upper-limb prostheses [8]. Only upper-limb devices have been reviewed in this paper, as the authors sought to gain an understanding of the current landscape of upper-limb prostheses and how a 3D printed, open-source design, such as those available through e-NABLE, might address unmet needs.

The WHO has developed a set of criteria known as ASSURED: Affordable, Sensitive, Specific, User-friendly, Rapid and robust, Equipment-free, and Deliverable to end-users to ensure that biomedical devices are applicable to LMICs [9]. While not all of these criteria are applicable to the evaluation of current upper-limb prostheses, Affordable, User-friendly, Robust, and Equipment-free were used to analyze the prosthetic devices discussed in this article. Based on these factors and research into the conditions of LMICs, biomedical devices for low-resource settings need to be simple, easy to manufacture and repair at a low cost, and provide amputees with increased function. This article is a comprehensive review of current upper-limb prostheses designed for LMICs. An analysis of 18 devices, as well as a detailed description of

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several representative prostheses for each category, is included. Appropriate devices that overcome the challenges of production, maintenance, cost, and durability that are prevalent in such harsh conditions can help with moving forward to solve the problems that these amputees face.

II. EXPECTATIONS OF PROSTHESES

A. *User-Friendly*

The primary goal of rehabilitation for an individual who has recently undergone an upper-limb amputation is the optimum restoration of function [10]. Though there are many other factors that can affect the rehabilitation process, including surgical care, physical and occupational therapy, and psychological support, one of the primary determinants in outcome is the quality of the prosthesis. A prosthetic device must be able to withstand the loads and physical brutalities imparted by the daily activities of the user, while providing comfort and confidence. The tasks required to be performed by the user vary, however, depending on the context. Therefore, a thorough understanding of the target market and its expectations must be achieved before design and distribution can occur [10].

In most LMICs, agriculture dominates the economy. In an environment such as this, where daily life is extremely labor intensive, a prosthetic device is a necessary means for maintaining productivity and therefore preventing the loss of income [11]. This tremendous responsibility can be taken on by even the simplest of devices by taking into account the physical and functional needs of the user. The prostheses must ensure comfort and maximum mobility to provide optimal function [10].

B. *Equipment-free and robust*

In order for a device to be adopted, it must be usable in the natural environment of the end-user [12]. Currently, a majority of LMICs receive donated prostheses that are unsuitable for the terrain [1]. In LMIC settings, this means the device must be both equipment-free and robust. Equipment-free refers to the avoidance of electronic aspects in a biomedical device due to the increase in complexity, fragility, and cost that results. Robust means that it can function under the typical conditions amputees are exposed to regularly and for an extended period of time.

Prostheses distributed in LMICs are typically high cost and do not follow the previously stated design needs for these environments [5]. Furthermore, the presence of precipitation and winds upwards of 99 m/s in dry regions can lead to thick layers of dust that have the potential to permeate the smallest of spaces within the prosthesis. Ruggedization of the device is therefore paramount in ensuring its longevity. It must be able to operate across all terrains and be able to withstand the varying temperatures and precipitation of the environment in which it is immersed. In terms of durability, the material used and its properties, including melting point and level of corrosion when exposed to moisture, are a crucial factor in determining the ability of the device to survive in such harsh climates. A device that incorporates electronics will be less likely to successfully function in these conditions.

The more routinely the device is maintained, the longer it will last. The prosthesis must be simple and quick to repair, requiring minimal and basic parts, so that repairs can be easily performed. Furthermore, the device must be able to be cleaned with soap and water or a moistened rag so that dirt can be removed before it impedes function.

The equipment-free and robust criteria entail an extremely simple device that is durable enough to survive the rugged conditions of LMICs. With this in mind, devices with electronic components can often prove too complex and difficult to both produce and maintain in the given context. It is for this reason that they are best to be avoided.

C. *Affordable*

According to a 2007 study that investigated the roles of predisposing characteristics, established need, and enabling resources in upper-limb prosthesis use and abandonment, more than 50% of those surveyed indicated that cost played at least a minor role in the decision process of whether to wear a prosthesis [12]. An amputee’s inability to afford the prosthesis can have damaging effects in LMICs where income disparity is a significant issue, resulting in more than half of the population living below the poverty line [10]. In Kenya, for example, 23% of residents live on less than $1 per day. With minimal expendable capital available, fewer than 3% of people with disabilities in low-income countries are able to gain access to the required rehabilitation services and devices [1]. Therefore, prosthetic devices costing upwards of thousands of dollars, not only for their purchase but for their maintenance, are impractical. In order to make the greatest impact, a prosthesis must be a reasonable and practical purchase, not from the perspective of the Western world, but from that of LMICs.

III. CURRENT PROSTHESES

In order to design an affordable, durable, and culturally acceptable device, however, one must first look at the upper-limb prostheses currently designed for resource-constrained settings, their successes, and more importantly, their failures. An extensive literature review was conducted, with over one hundred articles, blogs, and research papers on upper-limb prostheses yielding a total of 18 prosthetic hands designed for LMICs. Additionally, information was obtained from manufacturer websites, which contained details about the designs. These devices, as shown in Table I, have three kinds of actuation mechanisms: electric, myoelectric, and body-powered. The prostheses were analyzed based on parameters including (1) amputation type, (2) material, (3) manufacturing method, (4) manufacturing time, and (5) cost in order to provide a standard method of comparison.

TABLE I. UPPER- LIMB PROSTHESES CATEGORIZED BY ACTUATION MECHANISM

Electric	Nonspec Hand
	OpenBionics Hand
	Nevedac Arm
Myoelectric	University of Illinois Hand
	Dextrus Hand
	Limbitless Arm
	LaChappelle Hand
Body-Powered	Helping Hand
	Socketless Holder
	Flexy-Hand
	Robohand
	Raptor Hand
	Cyborg Beast
	RIT Arm
	Odysseus Hand
	Talon Hand
	Underactuated Hand
	Trautman Hook

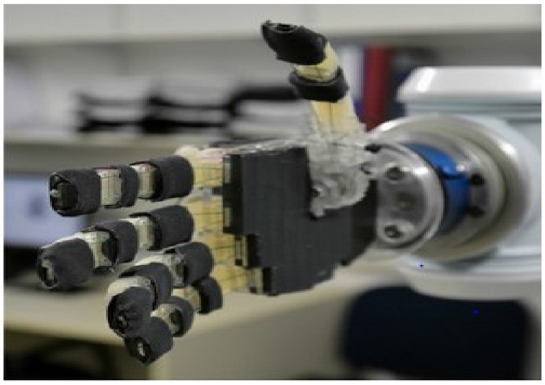
A. Electric

Electric prostheses use an external power source and an external controller to operate the device. These prosthetic devices integrate specific commands that interact with a motor. The motor, controlled by a microcontroller, then actuates the hand. Three upper-limb prosthetic devices controlled electronically were identified: the Nonspec and OpenBionics hands, and the Nevedac arm [13], [14], [15]. Due to a lack of available information on the devices, only one electric prosthetic hand, the OpenBionics hand, will be discussed in depth.

The OpenBionics hand, shown in Fig. 1, is manufactured using a combination of 3D printing and materials found at any hardware store [14]. The design uses Python, a programming language, and a Robot Operating System (ROS). The servo motor is controlled by the Arduino Microcontroller platform [14]. The fingers are developed to closely mimic the joints of human hands, which allow the prosthetic hand to have a broad range of motion and the ability to grasp a variety of objects [14]. The OpenBionics hand is designed for amputees that no longer have a wrist since it requires the user to have a previously fitted wrist connection. This can result in additional cost and hospital visits to have a connection fitted. Manufacturing the OpenBionics hand costs approximately $200.

In comparison, the Nevedac arm is made from indigenous materials (locally-available) and costs $300. It is designed for bilateral arm amputees and operated using a switch control system. Nonspec components are 3D printed and designed for children. In particular, the length of the fingers can be adjusted as the child grows.

Fig.1. The OpenBionics hand is an electric prosthesis designed to be attached to an existing wrist connection.

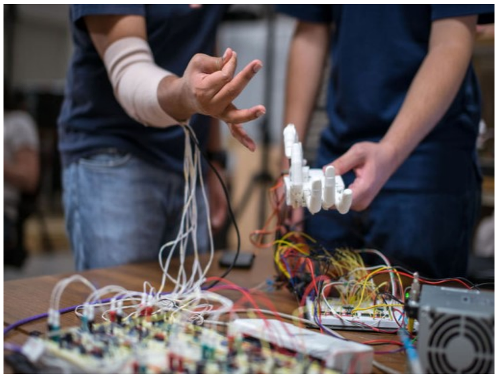


B. Myoelectric

Myoelectric prostheses use the axon potentials given off by muscles remaining in the residual limb during contraction. The prostheses use electromyography (EMG) sensors to detect these electrical signals and translate them into commands for the motors to move the device. Four myoelectric upper-limb prostheses were indentified: a hand developed at the University of Illinois, the Dextrus hand, the Limbitless arm by e-NABLE, and the LaChappelle hand [16], [17], [18], [19]. The University of Illinois, LaChappelle, and the Limbitless prostheses share manufacturing and operating methods. Myoelectric designs are always operated using the same technology (i.e., EMG sensors), and the identified devices are primarily 3D printed. The difference lies in the amputation type that they fit. The Limbitless Arm and University of Illinois hand both fit wrist disarticulations, and the LaChappelle and Dextrus hands are both for long transradial amputations. As a result of extreme similarities between the devices, only the hand developed by the University of Illinois and the Dextrus hand will be discussed more extensively.

1) University of Illinois Hand: The majority of this hand, shown in Fig. 2, can be produced with 3D printing. The electrical signals retrieved by the electrodes placed above the remaining muscles in the residual limb are sent to an EMG board. They are then sent to a microprocessor that contains a machine-learning algorithm, which interprets the signals and causes the hand to move. The prosthetic hand can perform five actions: open, closed, relaxed, a pinch, and a three-finger grip [19]. The user must have functionality of the wrist for use of this prosthetic hand. This hand takes around 32 hours to manufacture with a cost of $270 [16].

Fig. 2. University of Illinois hand is a 3D printed, myoelectric prosthesis for amputees with wrist functionality.



2) Dextrus Hand: The Dextrus design, developed by Joel Gibbard and shown in Fig. 3, requires an existing fitted wrist connection where the prosthetic hand will connect to prevent additional fitting. Users of this hand must have an amputation above the wrist. It is produced using 3D printing with ABS plastic. Each finger is controlled using one stainless steel tendon. Incorporating steel maximizes the load each finger can hold (18 kg). Joints are created with natural placement to increase the effectiveness when grasping objects. The total cost of the Dextrus hand is approximately $1,000 [17].

Fig. 3. The Dextrus hand is a 3D printed, myoelectric prosthesis for amputees with above the wrist amputation.

C. Body-Powered

Body-powered prostheses use a cable control system to operate by flexion of remaining limbs. Eleven body-powered upper-limb prostheses were identified. These include the Helping Hand [20], the Socketless Holder [15], Flexy-Hand [21], Robohand [22], Raptor Hand, Cyborg Beast, RIT Arm, Odysseus Hand, Talon Hand [18], Underactuated Hand [15], and Trautman Hook [23]. The RIT Arm, the Talon Hand, the Odysseus Hand, the Cyborg Beast, the Robohand, the Flexy-Hand, the Trautman Hook, and the Helping Hand are almost entirely created using 3D printing. The prostheses are designed for wrist disarticulations except for the RIT arm, Trautman Hook, and the Socketless Holder, which are for long transradial amputations. The RIT Arm, the Trautman Hook, and the Socketless Holder are operated using a cable system controlled by the shoulder, and the rest are operated using wrist flexion. Due to similarities among the devices as well as a lack of information provided for several, only the Trautman Hook and the Raptor Hand will be discussed in more detail.

1) Trautman Hook: The Trautman Hook, shown in Fig. 4, is manufactured using metal 3D printing, specifically with stainless steel powder. It incorporates backlock when closed to prevent the hook from opening without the user's intent. A combination of rubber bands and a cable system are used to control the hook. The Trautman Hook is attached to a preexisting fitted wrist connection, therefore requiring the user to have had an above the wrist amputation. The total cost of this device is approximately $550 [23].

Fig. 4. The Trautman Hook is a body-powered prosthesis fit to a preexisting wrist connection [21].

2) Raptor Hand: The Raptor Hand, produced by e-NABLE, is manufactured using 3D printing. A tendon system connecting the fingers to the wrist is used so that when the wrist of the user is flexed, all of the fingers close. The tendon system incorporates elastic bands and 80 pound fishing line for these connections. The amputee must still have wrist function and most of their palm for the device to properly function. As such, it is suitable for those with finger amputations. The cost to manufacture the Raptor Hand is approximately $35 [18].

Fig. 5. The Raptor Hand is a 3D printed, body-powered prosthesis for amputees with finger amputations.

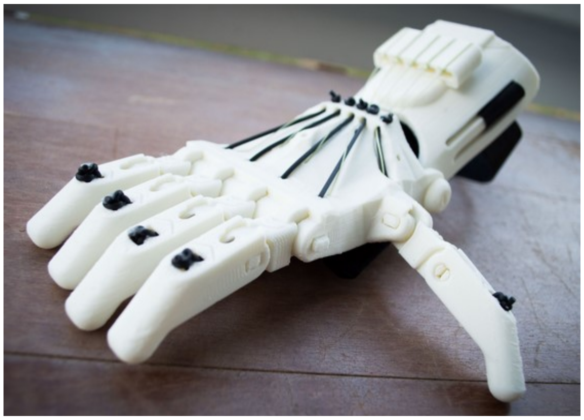


TABLE II. CURRENT UPPER-LIMB PROSTHESES DESIGNED FOR LOW-RESOURCE SETTINGS. EACH OF THE FIVE PARAMETERS CONTAINS THE 18 PROSTHETIC DEVICES IN THE APPLICABLE SUBCATEGORY.

	Electric	Myoelectric	Body-Powered
1) Amputation Type			
Wrist Disarticulation	1	2	7
Long Transradial	2	2	4
Mid-Level Transradial	0	0	0
Elbow Disarticulation	0	0	0
Transhumeral	0	0	0
Shoulder Disarticulation	0	0	0
2) Material			
Indigenous Materials	1	1	0
Plastic	0	3	8
Metal	2	0	3
3) Manufacturing Method			
Injection Molded	2	0	0
3D Printed	1	4	8
Indigenous Materials	0	0	3
4)Manufacturing Time (hours)	7	30	50
5) Cost (USD)	200-300	270-1,000	15-550

V. PREVALENT ISSUES AND OPPORTUNITIES FOR IMPROVEMENT

All 18 devices reviewed in this article are designed for LMICs, and the five outlined parameters, (1) amputation type, (2) material, (3) manufacturing method, (4) manufacturing time, and (5) cost, can compromise their use. The findings from this literature review are summarized in Table II. Of the arm amputees in LMICs, 4% have wrist amputations, and it is likely then that the number of wrist disarticulations will be even lower [2]. Most devices are designed for wrist disarticulations, and therefore, are relevant to a very small portion of the amputee population. Three manufacturing methods were studied: injection molded, 3D printed, and assembled. Assembly methods use discrete materials such as parts from a hardware store as well as metals and plastics. These materials may be more readily available but are also more complex to manufacture. Injection molding and 3D printing require a specific material, primarily plastic but also metal, and create a specific shape. These two manufacturing methods minimize the materials used, but the parts needed (i.e., thermoplastic filaments, the machine, and the mold for injection molding) are not readily available in low-resource settings. Injection molding prohibits customization due to a high startup cost and the need for aluminum molds. 3D printing is a simple process that allows for customization, but exhibits a high manufacturing time of up to several days. This is acceptable if the need is low, but may inhibit scalability. The thermoplastics that can be used in 3D printing and injection molding have relatively low glass transition states that can compromise the structural integrity of the device. Acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET), and polylactic acid (PLA) are common thermoplastics used in these processes. The glass transition temperatures, the temperature at which the plastic would begin to morph, are 80-125 °C, 69 °C, and 57 °C, respectively [24]. In LMICs these temperatures can be reached during the summer season, particularly inside a car where more heat accumulates.

1) Electric: A majority of electric prostheses were designed for long transradial amputations. They, like the OpenBionics hand, are typically unaffordable due to the addition of the electronic components. In addition, the electronic aspect makes the design significantly less durable and maintainable. The hand incorporates a computer through which the user types commands to control the hand. The microcontroller needed to operate the device will limit functionality, and the computer will necessitate occasional charging, requiring access to reliable electricity. Access to electricity, however, is something that is not always guaranteed in LMICs. Furthermore, the computer and wiring are too difficult to manufacture and repair if they were to break. Equipment- and electronic-free designs are the most realistic for LMICs.

2) Myoelectric: The myoelectric designs were evenly distributed between the wrist disarticulations and long transradial amputations. Much like the electronic design of OpenBionics, myoelectric designs on average are too expensive and complex to implement in low-resource settings. The use of EMG sensors makes the devices much more fragile compared to electric and body-powered prostheses. These sensors tend to only work when applied on a very clean surface, and they need to be replaced after each use. Many times, healthcare employees will sterilize and reuse disposable items due to the lack of resources [25]. If the sensors are reused, they are more likely to malfunction. The complex programming and wiring also significantly increase the difficulty to manufacture and repair the prostheses. The high costs, ranging from $270-1,000, will also prohibit amputees in these areas from being able to initially purchase the product. Even if the device is donated by a nonprofit, the aforementioned ASSURED criteria can still cause suitability issues.

3) Body-Powered: The body-powered prostheses had the highest fraction of designs for wrist disarticulations, but it also had the highest number of designs for long transradial amputations. Body-powered hands can be created at a considerably lower cost than either of the electronic-based designs, which will give amputees in resource-constrained settings an opportunity to make use of the product. The simplicity of the designs will allow the manufacturing method to be easily taught to prosthetists who will produce and repair the prosthetic hands. The costs range from $15-550, with a majority of the designs able to be manufactured for under $30. Based on the WHO's ASSURED standards, this affordable and simplistic design meets the most criteria for devices in LMICs.

VI. Conclusion and Further Direction

The current prosthetic hands designed for resource-constrained settings are not necessarily appropriate for LMICs. In order for a design to be implementable in a low-resource setting, the device must be affordable, simple, and durable. Through the use of a low-cost and accessible material, as well as an optimal manufacturing method such as 3D printing, prostheses that meet these criteria and are simple to use and maintain can be created to reach a larger population of amputees. 3D printing, a manufacturing method implemented in 13 of the 18 prosthetic hands listed in this article, is optimal for these settings. The manufacturing process is simple, requiring just the click of a button once the 3D printer is ready, and a broken piece can easily be reprinted, enabling maintainability. The ultimate goal is to reduce the number of amputees who experience difficulties that are only enhanced by the limited access to prostheses in their living environment. In addition, due to the harshness of the terrain, the devices will have to be repaired or replaced over time. Therefore, the manufacturing method must be simple, and repairs must be minimal. Having an appropriate design is the first step in pursuing a business for distributing prosthetic devices in these areas.

Given the available resources in LMICs, or lack thereof, options such as the electric and myoelectric prostheses become impractical. Their use of battery power and extensive wiring requires the type of maintenance, skill, and capital that cannot be expected in rural areas. With this in mind, the body-powered device becomes the logical choice. Based on the literature, three types of manufacturing options come into play when body-powered devices are considered: 3D printed, injection molded, and assembled, which encases methods such as assembly line. With its relatively low start-up costs, as compared with injection molding, and minimal required skill, 3D printed is the most realistic choice of the proposed methods. Recent advancements in this technology, such as solar-powered 3D printers and open-source designs for a variety of medical and agricultural equipment, make it a viable option for both the Western world and LMICs [26] [27] [28]. The option for an alternative energy source to power the printer will allow for use of this technology in both urban and rural areas where electricity may be scarce.

Furthermore, the possibility for customization with 3D printing is unparalleled, which allows more individuals the ability to gain access to a hand that not only works, but fits them comfortably. A study performed on upper-limb amputees in India using body-powered prostheses indicated that the primary reasons for rejection included the weight and improper fitting of the device [29]. An ill-fitting prosthesis can lead to non-use of the device, particularly for those with an intact limb—leading to complications after years of repetitively using the remaining limb [30]. Although future studies need to be performed with amputees on the devices discussed in this review, 3D printing allows for an inexpensive way to manufacture and repair a lightweight prosthesis.

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