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REVIEW

A narrative review: current upper limb prosthetic options and design

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ABSTRACT

Purpose: This review was conducted to provide an overview of current literature as it relates to upper limb difference, available componentry, and prosthetic options and design. Emerging technologies combined with an increased awareness of the limb difference community have contributed to recent advancements in upper extremity prosthetics.
Methods: A search of five major clinical databases utilizing keywords relating to upper limb prostheses, componenty and limb difference levels resulted in over 1200 articles. These articles were subjected to inclusion and exclusion criteria in order to identify current peer reviewed research relevant to this topic.
Results: Fifty-five applicable articles and sources of standards were reviewed based on the inclusion and exclusion criteria, presenting five general options for prosthetic intervention. This information was assimilated and categorized in this article, which provides an overview of the aforementioned options.
Conclusion: While a noteworthy amount of research focuses on technological advancements, the five options for prosthetic intervention are inherently represented in the current literature. For individuals with upper limb difference, as well as their care team, successful rehabilitation hinges on awareness of new components, the functional efficacy of these components, and the evolved techniques used in prosthetic design and fabrication. It is noted that the rapid evolution of upper limb prosthetics consistently outpaces research and publication of information.

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KEYWORDS
Upper limb; amputation; prosthesis; prosthetic options; design; rehabilitation

➤ **IMPLICATIONS FOR REHABILITATION**

- To provide an overview of prosthetic design considerations and options to help create a more informed rehabilitation team, leading to improved outcomes in prescription and management of upper limb prosthetics.
- To bring awareness of current research in the field of upper limb prosthetics in order to provoke further exploration of the efficacy of prosthetic options and design considerations.

Introduction

Losing a limb, often due to a catastrophic event, can be a devastating injury. Many people find that this loss is equivalent to losing a loved one and the grieving process may be similar throughout recovery. In addition, physical rehabilitation is required to restore useful and meaningful function. In the case of the congenital limb difference, while there is no grieving process, the lifelong effects of limb absence can be similar to that of an amputation. The upper limb prosthetic rehabilitation team understands these complexities and has the task of helping the individual achieve their goals through the appropriate recommendation of prosthetic options along with other rehabilitative strategies. Technology has advanced significantly, which has made prosthetic intervention viable for more levels of limb difference than were possible before. With this improvement of technology and fitting methodologies, it is important to stay up to date with current practice in order to provide meaningful assistance to those in need of prosthetics rehabilitation.

This paper will provide an overview of upper limb differences and subsequently define the five prosthetic options available, their associated componentry, and the design principles reviewed from the current literature. Our intent is to provide a comprehensive analysis of the current state of upper limb prosthetic science and its impact on the provision of prosthetic rehabilitation for those pursuing functional upper limb (UL) prosthetic solutions. This review is relevant to manufacturers, engineers, research and development communities, device regulation and review entities, prescribing physicians, prosthetists, occupational and physical therapists, and other allied health professionals involved in the rehabilitative care for this unique population.

Methods

A systematic search of literature was conducted in May 2018 using the following databases: PubMed, Medline Complete, CINAHL, Academic Search Complete and Google Scholar. Keywords relating to UL prostheses, componentry and limb difference levels were organized into search statements (Table 1). Search terms were adapted primarily from those used within the VA/DoD Evidence-Based Clinical Practice Guideline for the Management of Upper Extremity Amputation Rehabilitation Search Terms, Appendix A [1]. Collectively, these results yielded over 1200 articles.

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Table 1. Search Statements: PubMed, CINAHL, Medline, Academic Search Complete, Google Scholar.

Search terms 1	Search terms 2	Total results > unique reviewed articles
Amputation and (prosthesis or prosthetic or prostheses)	Arm or finger or hand or thumb or wrist or transradial or transcarpal or elbow or transhumeral or shoulder or forequarter or upper limb or upper extremity	484 > 13
Prosthesis or prosthetic or prostheses	Body-powered	78 > 16
Prosthesis or prosthetic or prostheses	Myoelectric or electrically powered or externally powered	484 > 15
Prosthesis or prosthetic or prostheses	Passive or cosmetic or restoration	158 > 3
Prosthesis or prosthetic or prostheses	Activity specific	3 > 0
Prosthesis or prosthetic or prostheses	Protocol or prescription or upper extremity or upper limb or arm	37 > 0
Prosthesis or prosthetic or prostheses	Component or terminal device or harness or socket or frame	211 > 2

Specific inclusion and exclusion criteria were established to select appropriate articles relevant to the purpose of this paper. Given that this review intends to identify current literature, articles published prior to 2008 were excluded. Furthermore, non-English articles, experimental or investigational research, and surgical and animal studies were excluded. The articles were required to be published within the last 10 years, to be peer-reviewed, and to pertain to the purpose of this paper by specifically referencing advantages or disadvantages, individual requirements, available devices, relevance to current practice, and/or fabrication processes of upper limb (UL) prosthetic devices. A resulting 55 sources, including the VA/DoD Evidence-Based Clinical Practice Guideline mentioned previously, were deemed appropriate for this review and all were utilized in this paper. All materials identified in the initial search were then reviewed by certified prosthetists and subject matter experts, for relevance to the purpose of the paper. Digital copies of applicable reference material were obtained.

Overview of upper limb difference levels

While there may be variations in the literature, the generally accepted nomenclature to delineate upper extremity limb difference is as follows: Interscapulothoracic, Glenohumeral (Shoulder) Disarticulation, Transhumeral, Elbow Disarticulation, Transradial, Styloid/Wrist Disarticulation, Transcarpal and Partial Hand (Figure 1) [2]. Approximately 40% of all amputations are of the UL, and the majority of these occur distal to the wrist [3]. In the paediatric population (e.g., ages 0–18), most UL differences have a congenital aetiology, as opposed to acquired [4]. In the congenital population, deficiencies are categorized as transverse, intersegmental or longitudinal, with further subcategorizations. The level of limb difference is the most fundamental principle when considering prosthetic options.

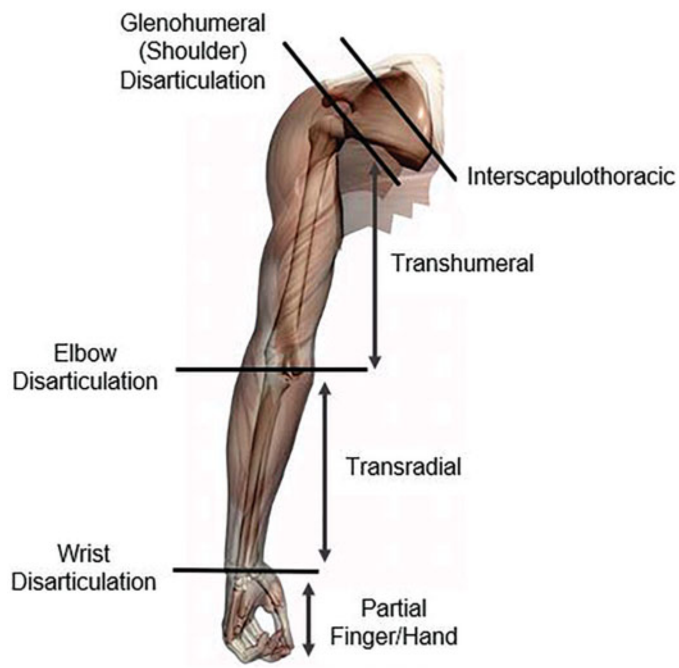

Figure 1. Levels of amputation.

Current prosthetic options

Many guidelines are in place for selecting an appropriate prosthesis [1,5]. The factors associated with this decision include, but are not limited to: level of limb difference, vocational/avocational and recreational needs, desires and functional goals of the individual, residual limb integrity, work and home demands, level and type of activities, as well as aesthetic priorities [1]. It is beyond the scope of this article to discuss how to strategically request multiple devices in today's health care setting, but it is important for readers to be aware that one type of prosthesis is rarely suited for all activities and settings, and more than one prosthetic option is often necessary to meet the user's complex functional needs vocationally and avocationally [5].

The available options are categorized by the following descriptors: passive, body-powered, electrically powered, hybrid and activity/task specific [1]. It is important to note that there are multiple manufacturers that develop products in these categories (Table 2). Discussing considerations regarding combining different options into one prosthesis is beyond the scope of this paper. Knowledge of each manufacturer and their systems must be taken into account when recommending a particular device as not all components are compatible with each other when combined together. Also, many of the options when combined together may have components that require manual manipulation, requiring activation from the opposite arm or pushing the prosthesis into or against something in the environment. These actions would be considered "passive" in nature because they are not powered either by the affected body part, nor by a motor. One example of this would be a locking wrist. The wrist can be positioned, but typically requires use of the other arm to manipulate the lock and move the wrist into position and then lock it again.

Passive prostheses

Passive prostheses restore the anthropomorphic limb-length necessary to carry or stabilize an object during ipsilateral or bilateral use, but do not actively move. A passive device can also provide opposition to the remaining digits, as is the case for those

Table 2. Major manufacturers of ULP componentry, non-exhaustive.

Manufacturer	Partial Hand/fingers				Terminal devices					Wrists			Elbows		Shoulders			
						Electrically Powered												
	Passive Positional	Passive Static	Body Powered	Electrically Powered	Body Powered	Utility	Prehensor	SDOF	MDOF	Flexion	Electric Rotator	Body Powered Rotator	Body Powered	Electrically Powered	Body Powered, Locking, Passive	Electrically Powered	Adaptive devices	Controllers, Batteries, Misc.
Alternative Prosthetic Services www.alternativeprosthetics.com		×																
COAPT www.coaptengineering.com																		×
College Park Industries www.college-park.com														×	×			
Fillauer fillauer.com					×	×		×	×	×	×		×	×	×			×
Infinite Biomedical Technologies www.i-biomed.com																		×
Midwest ProCAD www.midwestprocad.com																	×	
Mobius Bionics www.mobiusbionics.com									×	×	×			×		×		
Naked Prosthetics www.npdevices.com		×	×															
Ossur www.ossur.com		×		×					×	×	×							×
Ottobock www.ottobock.com		×			×	×		×	×	×	×		×	×	×		×	×
Partial Hand Solutions www.partialhandsolutions.com	×		×															
Point Designs www.pointdesignsllc.com	×																	
RSL Steeper rslsteeper.com					×			×					×				×	×
Texas Assistive Devices n-abler.org												×					×	
TRS Prosthetics www.trsprosthetics.com					×												×	
Vincent Systems vincentsystems.de/en	×			×					×	×								

SDOF: Single Degree of Freedom.
MDOF: Multiple Degrees of Freedom.

with partial hand presentations. Passive prostheses can be described as static or positional.

Static devices have no moving parts, while positional designs incorporate malleable armatures or ratcheting joints. Static passive devices do not inherently provide active grasp, so the user has a relatively limited grasping ability compared to positional passive devices. This option is typically created with a highly customized task in mind and for the most demanding of environments where other options would have a higher tendency towards failure.

When a user with partial hand limb difference requires a more rugged design, passive positional digits offer an industrially designed articulation. Once positioned, passive fingers options such as those by manufacturers listed in Table 2, can resist forces through detent-retained or locking joints. These joint mechanisms allow for restoration of a broad range of activities including the potential of heavier duty activities. While there is scarce peer-reviewed research available for these new systems, published case studies are available by manufacturers that demonstrate the necessity of these devices.

Static and positional passive prostheses may also be designed to appear natural; however, their appearance is ancillary to their function. Sculpted re-creations of the absent limb (Figure 2) primarily serve to protect sensitive areas on the residual limb and to restore limb length, which together, improves the functional use of the affected side. The restoration gives the remaining or intact digits a surface area to oppose for the light grasp of objects and the material properties of flexible latex, rigid PVC or silicone can enhance friction [6–15]. The natural appearance also helps to restore the individual's body image, reduce unwanted attention, and aid in his/her psychological well-being [6]. This option can be fit to any amputation level and, depending on presentation, may not require harnessing.

Passive prosthetic options are light weight, require minimal componentry maintenance and have been shown to contribute to psychological improvements for the user [16]. As found in the literature, there are benefits to the use of passive devices in general. It is the experience of these authors that new passive positional designs take this already established benefit and expand on it for additional patients. This extrapolation is not experimental, but rather an expansion of previous work such that more people can benefit from the established paradigm.

Body-powered prostheses

Body-powered prostheses use a harness to capture proximal body motion, which produces excursion of a cable. The cable terminates on a hook or hand and affects movement of the components [10,12,17–22]. Body-powered prostheses (Figure 3) have been prescribed for those with UL differences for centuries, and a considerable number of users continue to value the benefits this prosthesis type [23].

Body-powered prostheses offer several advantages over the alternative options. They typically are lighter weight, more durable, more tolerant of environmental conditions (e.g., wet, dusty, etc.), provide secondary proprioceptive feedback to the user, have a lower initial price point, and incurred maintenance costs are less as compared to electrically powered options [10,12,17–21,23–27]. Even though these devices are considered more durable and rugged, it is expected with heavy use that repairs to the cable systems, terminal devices, and other components are frequent and necessary to maintain the individual's functionality.

Despite the advantages of body-powered prostheses, there are several disadvantages. Harnesses are restrictive in that they: limit

Figure 2. Passive Prosthesis, ©Arm Dynamics. Photo permission obtained.

Figure 3. Body Powered Prosthesis, ©Arm Dynamics. Photo permission obtained.

available motion for function with the device, can exert significant forces on the residual limb, and can compress the contralateral axilla [28]. Users with more proximal levels of limb difference have greater difficulty generating the necessary excursion to operate these devices, and some individuals dislike the appearance of the hooks, cable and harness [10,22–24,26,27]. The parameter surrounding a user, where the prosthesis functions consistently, is referred to as the "functional work envelope". As a body-powered prosthesis is moved further away from the body, it becomes more difficult for the user to produce excursion for device operation. Grip force may be limited when compared to electrically powered options, depending on the terminal device (TD) configuration. While body-powered options have been historically viable for higher level presentations, there has been a recent introduction of body-powered options for the partial hand which will be discussed later. The following sections describe body-powered

Figure 4. Body Powered Figure of 8 Harness, ©Arm Dynamics. Photo permission obtained.

components; these are intended as a brief overview and do not divulge all options or details.

Harness/control

Successful control through a harness relies on four critical concepts: a secure suspension of the prosthesis, a cabling system to connect the harness and TD, adequate range of motion in the body segment affecting the harness, and sufficient force to create the excursion needed to actuate the components. The most commonly utilized harnessing system for transradial prostheses is the figure-of-8, Northwestern style harness (Figure 4) [17]. It is comprised of an axilla loop around the contralateral shoulder; a suspension strap over the ipsilateral shoulder that connects to an inverted "Y" strap and triceps pad; and a control strap linking the harness to the cable, which is then connected to the TD. Variations of this design, including custom options, are applied when conventional harnessing is insufficient to meet the comfort or functional requirements of the user.

Terminal devices

Body-powered TDs come in either a hook or hand configuration. Table 2 lists commonly utilized manufacturers of these terminal devices. Body-powered hooks are generally preferred TD because, although body-powered hands appear more anatomical, they typically weigh more, have a preset and limited pinch force [23], are less versatile for handling objects, and their shape can visually obscure objects being grasped [29]. Hook configurations are further identified as either voluntary opening (VO) or voluntary closing (VC). VO TDs remain closed at rest from the tension of rubber bands or springs, and they only open with cable excursion. Pinch force is limited to the tension from the rubber bands or springs that hold the TD closed. VC TDs remain open at rest and close with cable excursion, therefore pinch force directly correlates to the amount of force exerted on the cable system, so some users can achieve enough force that the resulting grip exceeds that of electrically powered TDs [23]. Cable operation has been documented to provide proprioceptive feedback relative to the amount of pinch force being applied and, for an experienced user, can indicate how wide the opening is on the TD [23]. Newly available designs can interchange between VO and VC via a switch or change in cable excursion [19].

Wrist, elbow and shoulder components

A positive aspect of body-powered prostheses is the available joint mechanisms for wrists, elbows and shoulders. Commonly utilized manufacturers of these components are listed in Table 2.

Wrist components create additional degrees of freedom such as flexion/extension and rotation for TD operation in various planes of space [12,30,31]. Some options on the market for wrist attachments include friction, quick disconnect, rotational, flexion and multifunction units.

Available elbow components can be endoskeletal or exoskeletal. Depending on the design, humeral rotation of the forearm is possible. Most versions lock, and some use friction to maintain their position. Each of these options has its own indication and function [12].

Shoulder components for body-powered prostheses currently rely on passive positioning assisted by the sound limb or gravitational prepositioning. Shoulders also have friction and locking options. Shoulder locking is typically achieved by activating a lever or nudge control with the contralateral limb or chin. These are classified by the degrees of motion at the joint, either single-axis or double-axis, which refer to shoulder flexion/extension and/or abduction/adduction, respectively [12].

Partial finger/hand

Body-powered finger and hand prostheses have seen improvements over the last decade. Three of the most prominent partial finger prostheses utilize flexion of the residual finger to cause flexion of the prosthesis. There may be a significant mechanical disadvantage because excursion is reduced over the surface of the prosthesis as the finger flexes. Partial hand body-powered prostheses utilize motions of the wrist to create excursion. The most commonly utilized manufacturers of partial hand options are listed in Table 2.

Electrically powered prostheses

Electrically powered prostheses utilize motors to effect movement, which are powered by a rechargeable battery system. The most common control method is through electromyography (EMG) signals, although there are other inputs available if these signals are too weak. Other inputs include servos, linear potentiometers or transducers, force-sensing resistors, rocker switches, push-button switches and harness pull switches, as well as Inertial Measurement Units (IMUs). There is also the option of utilizing multiple control schemes in the same prosthesis. Electrically powered prosthetic component options range from a single digit through hand, wrist elbow and shoulder componentry (Figure 5).

Figure 5. Myoelectric Prosthesis, Complex Hand, ©Arm Dynamics. Photo permission obtained.

To successfully operate an electrically powered prosthesis, an individual must be physically capable of operating an electrically powered device, as well as have sufficient cognitive awareness to understand and control the device. More proximal levels of limb difference require more advanced and multifunctional prostheses, which can impose a greater cognitive burden on the user [32].

Advantages of electrically powered prostheses include, speed and grip force that is both VO and VC as well as proportionally controlled depending on the strength of the muscle contraction; more anthropomorphic appearance; ability to control two components simultaneously; higher grip force potential; and increased functional work envelope.

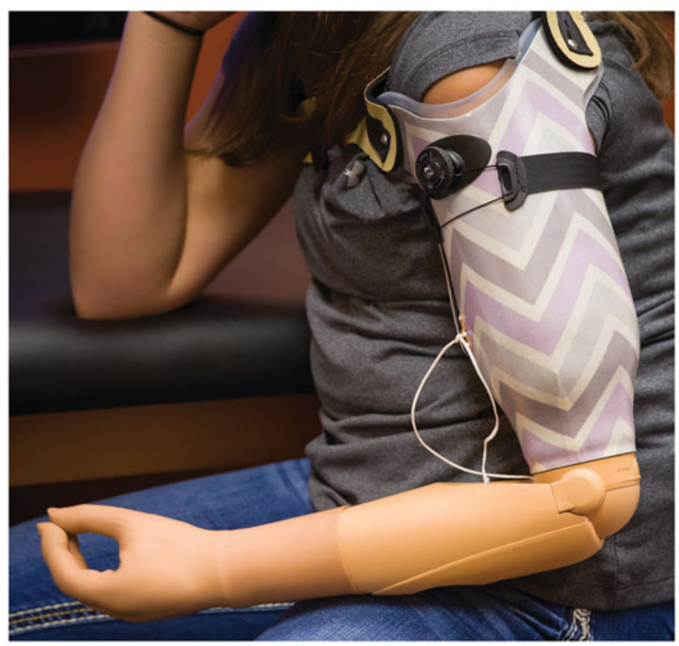

Figure 6. Simple Myoelectric Hand, ©Arm Dynamics. Photo permission obtained.

Disadvantages of this prosthesis include, higher initial costs, required battery maintenance, heavier weight, more complex repairs, and intolerance to wet, dirty or corrosive environments [17,20]. Thankfully, recent advances in waterproofing and rugged hand and hook designs negate some limitations with operating these devices in contraindicated environments.

Terminal devices

TDs for electrically powered prostheses are broken down into single or multiple Degrees of Freedom (DOF) and anthropomorphic or nonanthropomorphic prehensors [33].

Single DOF, anthropomorphic prehensors (Figure 6) operate using a single motor that provides a powerful and consistent tripod grasp. The motor articulates the metacarpophalangeal (MCP) joints of digits one, two and three; the MCP joints of digits two and three move in unison as the first digit abducts/adducts to oppose them. The fourth and fifth digits passively follow, and there are no motion distal to the MCP and carpometacarpal (CMC) joints. Manufacturers of single DOF hands include those listed in Table 2. Most of these hands can be fit with locking or friction-controlled flexion/extension wrist units.

The single DOF, nonanthropomorphic prehensors are traditionally in the shape of a hook or gripper. Referred to as "utility prehensors", these options were developed to be more durable and robust, to increase visual connection, and to provide a stronger pinch; up to 36 pounds of force depending on the type of prehensor. Commonly used manufacturers of utility prehensors are listed in Table 2. These utility prehensors can also be fit with locking or friction-controlled flexion/extension wrist units [12].

Multiple DOF, anthropomorphic prehensors (Figure 5) have digits that articulate over multiple joints within the fingers, and some models have multiple motors to move fingers individually, thereby increasing the number of available functional grasp patterns to as many as thirty-six pre-programmed grasps. Having multiple grasp patterns, rather than a single tripod grip, can present advantages and challenges that depend on the user and his/her adeptness with this technology. A user must be properly trained to access these grasp patterns and gestures by triggering the device, typically using a muscle trigger (specified myoelectric impulses). The most commonly utilized manufacturers of multiple DOF hands are listed in Table 2 [12,34–36].

Wrist, elbow, and shoulder components

Utilization of prosthetic wrists, including rotation and flexion/extension components, reduce compensatory movements that may occur in the elbow, shoulder or torso [37]. Most prehensors connect using a quick-disconnect wrist that enables the exchange of TDs.

Elbow components can be either electrically powered or body-powered. The body-powered elbows use the same control mechanisms as any other body-powered system, i.e., harness or gravitational control. If a body-powered elbow is configured for use with a electrically powered TD, the prosthesis is then deemed a hybrid prosthesis. Electrically powered elbows do not include any body-powered controls. Electrically powered and body-powered elbows have characteristics reflective of their general prosthetic classification; body-powered elbows are lighter, more durable and have a lower initial cost as opposed to electrically powered elbows. Notable advantages of electrically powered elbows are that they can function in a larger work envelope, and they can offer live lift functionality where body-powered elbows have virtually no live lift capability. This significantly changes the function of the elbow from being a preposition device (in the case of the body-powered elbow) to a functional device (in the case of an electrically powered elbow). The most commonly utilized manufacturers of electrically powered elbow components are listed in Table 2.

There are a limited number of shoulder components available across the industry. The most commonly utilized manufacturers of shoulder components are listed in Table 2. Most shoulder components are passive and function for electrically powered prostheses in the same capacity as they do for body-powered prostheses. Prepositioning of the shoulder joint in the sagittal and coronal planes can only occur passively, and the shoulders can only lock with a manual locking mechanism in the sagittal plane.

Prosthesis control

Electrically powered prostheses typically utilize noninvasive electrodes that read surface EMG signals from intact muscles in the residual limb. A small electrical signal is produced when a muscle contracts, and the external electrodes detect the electrical impulses from these muscle contractions. Determining the specific muscle to use depends on the level of limb difference and the residual anatomy. Most electrodes filter and amplify the electrical impulse and produce an output message to the prosthesis [17,18,33,35,38–41].

With multi-articulating prehensors, control strategies have expanded to include specific myoelectric input triggers, Radio-Frequency Identification (RFID) tags or chips, smart phone applications, motion capture from gyroscopes or the previously mentioned IMUs. New control methods include Pattern Recognition and Targeted Muscle Reinnervation (TMR).

Pattern Recognition is a commercially available control system that uses an array of electrodes covering the entire residual limb to capture muscle contractions. The muscle signals are analyzed and assigned to a "pattern", which is designated to a specific movement and allows for more intuitive myoelectric control. This promises a more intuitive control method akin to writing a document using voice recognition instead of manually typing on a keyboard. Pattern recognition software like COAPT© (Coapt, LLC. Chicago, IL) aims to ease the cognitive burden of switching between components, and potentially can provide a newer, faster control scheme for controlling the advancing multi-articulating hands [42].

Targeted Muscle Reinnervation (TMR) is a nerve-transfer surgery that reassigns the remaining nerves after amputation and replants them into an intact muscle. For those with transhumeral amputations, TMR transfers the remaining large brachial plexus nerves and their motor fibres to viable muscle tissue in the residual limb [43,44]. Like pattern recognition, TMR can allow for a more intuitive control strategy with electric devices. A surface EMG signal will correspond to the previous nerve function once the transferred nerves and host muscle fibres are reinnervated. Multiple nerves can be transferred so that more than two EMG sites can control the device. With more sites available, there is the potential for simultaneous control of multiple DOFs (e.g., flexing the elbow and closing the hand simultaneously) [43,44]. Without TMR, the nerve pathway would be incomplete, and the severed nerves would not generate useful muscle signals.

To a similar end, the Starfish procedure has been developed to salvage muscles from partial hand amputations and move them more proximally. Isolating each muscle not only facilitates more intuitive myoelectric prosthetic control, but it also provides the potential for controlling individual prosthetic digits [45].

Hybrid

Hybrid prostheses (Figure 7) combine two prosthetic options into one device. The most commonly used hybrid configuration is a body-powered elbow and electric powered hand/wrist for those who present with an above the elbow amputation.

The advantages and disadvantages of a hybrid prosthesis are dependent on which components are powered and in what way. Generally, hybrid devices provide simultaneous control of multiple components, are lighter in weight than a fully electrically powered prosthesis and offer increased grip force as compared to a fully body-powered prosthesis. The disadvantages, as stated above, are that the body-powered elbow must be moved by gravity or a harness and cannot provide live lift. The necessity of a

Figure 7. Hybrid Prosthesis, ©Arm Dynamics. Photo permission obtained.

harness for body-powered component control can be difficult for those with more proximal levels of limb difference.

Activity/task specific prostheses

Activity-specific prostheses are designed to facilitate tasks that entail a higher level of performance, such as performing a push-up, holding a golf club, or throwing a ball [27]. Often these types of activities are contraindicated to perform with the primary prosthesis because of safety or reliability concerns. The TD of an activity-specific prosthesis can replicate the form of the human hand during an activity or the tool used for an activity. There are multiple TD options, so this type of prosthesis is often designed with a wrist unit that allows TDs to be quickly disconnected and interchanged so that multiple activities can be accomplished.

Upper limb socket design

The socket interface is imperative for the function and success of the prosthesis [46,47]. It serves to contain the residual limb, connect the person to the prosthesis and must be fitted securely and comfortably [48]. A variety of materials can be used, such as thermoplastic or high consistency rubber (HCR) silicone [46]. The frame surrounds the socket and is typically matched to the length and circumference of the contralateral limb. The frame is typically rigid and sturdy and is used as a protective housing mechanism for the prosthetic components.

As electrically powered prostheses become more prevalent, socket designs have been adjusted to stabilize electrodes against the residual limb [49]. Electrically powered prostheses do not require a harness for operation of the device, so these designs have become self-suspending on the residual anatomy to eliminate the need of a harness for ancillary suspension. Clinically relevant design styles include the Muenster, TRAC (Transradial Anatomically Contoured), and Northwestern sockets for transradial level presentations, as well as the Dynamic Socket for transhumeral level presentations.

Alley et al. [49] investigated the fabrication of a socket utilizing alternating areas of compression and release. Alley reported that despite being self-suspending, sockets may inhibit range of motion of the residual limb, lose transmission of motion between residual limb and prosthesis, and load the bone in localized areas. This work found that the compression release socket (CRS) achieved greater control of the underlying bone, which "offers enhanced performance regarding stability, comfort, energy efficiency, ROM and the perceived weight of the prosthesis" [49].

Razak et al. [47], explored an anthropomorphic socket design that utilized pressure sensors to determine the required socket size and fitting, and an oscillometric pump which varies the air volume within the socket. The study revealed that although the system requires improvement, it may pave the way for new socket techniques in the near future.

Creative socket designs continue to evolve, and the most successful ideas incorporate a strong clinical focus on comfort, suspension, range of motion, and appropriate structural integrity to house components and control elements that may be integral to the socket itself, such as electrodes, access fenestrations and anchor points for frameworks and components.

Future and developing technology

Options for prosthetic rehabilitation will continue to evolve which may require the list of options represented herein to expand. Several of the future and developing technologies are described for the purpose of awareness. Osseointegration is a surgical procedure developed in Europe circa 1950s as an alternative prosthetic suspension strategy. The procedure includes either a one or two-step surgical approach with an initial "fixture" implanted directly into the bone, proceeded by the attachment of a percutaneous abutment to the fixture. The primary benefit of osseointegration is the elimination of a conventional socket that can cause skin breakdown, pain, discomfort and sweating. Other benefits include the potential for unrestricted movement through minimal to no harnessing, ease of donning/doffing the prosthesis, proprioceptive feedback and increased muscle mass. The potential disadvantages include the risk of skin infection and the obligatory daily skin care around the abutment [50].

The use of implantable electrodes for prosthetic control is becoming a popular area of research due to the advantages these pose over surface EMG systems. With implantable systems, the control of the prosthesis is not susceptible to body sweat, nor will it be affected by electrode displacement or poor socket fit. This leads to a reduction of unintended movements and therefore improved control when performing tasks above or below body midline. One such current research system is the Implantable MyoElectric Sensor (IMES) project [51].

Haptic feedback has been an important topic for many years. The ability to replicate sensation has been trialled with a variety of approaches that include mechanotactile, electrotactile, vibrotactile and modality matched feedback [20,24,33,52]. A more recent and invasive approach allows for direct nerve stimulation by wrapping electrode wires around the nerve or longitudinally placing electrode wires on the nerves directly. 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 [33,52]. The Defense Advanced Research Projects Agency (DARPA) Hand Proprioception and Touch Interfaces (HAPTIX) programme is advancing this technology, which allows for constant, permanent communication between an upper limb prosthesis and the peripheral nervous system of the user [53]. Further proprietary information regarding the DARPA and HAPTIX projects are available through their individual programme sites.

Discussion

Function of the UL is far more complex than that of the lower limb and often involves an open kinetic chain of movement to perform an array of activities such as self-care, interaction with the environment, interaction with others, self-expression, and other fine and gross motor activities. Contributing factors to function are the ability to perform tasks correctly, quickly, rationally and resourcefully [54]. There is little consistency across the literature when defining the function as it specifically pertains to prostheses, and currently utilized measures of UL prosthetic function are insufficient at doing so effectively and objectively [55].

Additionally, technological advances in electrically powered components are rapid. By the time research is completed and results are published on the benefits of a specific powered component, findings may be considered “outdated” as new generations of a component are commercially available. The small population size and heterogeneous variables across patients with upper limb difference create an added challenge to produce evidence that is considered adequate to demonstrate the efficacy of a device. Belter et al. [29] provided a systematic review on anthropomorphic prosthetic hands in 2013. Four of the hands reviewed (Vincent [Vincent Systems, Karlsruhe, Germany], i-limb and i-limb Pulse [Touch Bionics by Össur, Foothill Ranch, CA], Bebionic and Bebionic v2 [Ottobock, Austin, TX]) have already been updated with newer versions (i-limb Quantum [Touch Bionics by Össur, Foothill Ranch, CA] and Bebionic v3[Ottobock, Austin, TX]) and new hands such as the TASKA (Fillauer, Chattanooga, TN) are now available with similar functions such that the review would apply to these updates. Even though the technology has been updated, the category of prosthetic option that the change applies to has not and the value of those options remain.

Passive prostheses have developed over the years in terms of detail and durability. Passive devices designed for the purpose of restoring limb length and surface area have been studied for the psychosocial implications on the individual and have been found to be beneficial [6]; however, the literature did not reveal any studies regarding current updates to fabrication, fit and function. Newly developed passive positional options are now available and case studies have shown the efficacy of these devices. The continual evolution to this category of prosthetic options with the addition of new technologies does not make the category experimental; on the contrary, the new options make the category more valuable.

The available published works for body-powered prostheses vary in age and application. Due to the longevity of use of body-powered systems, most commonly cited research on these devices was conducted more than ten years ago, with some publications dating back to the 1950s and 1960s [28]. One recent publication attempted to define a global optimal setup with the current standard configuration for fitting a transradial body-powered prosthesis, determined through robotic testing of prostheses [17]. Despite this group’s efforts, it was not feasible to define a suggested clinical guideline, and some of their results were conflicting with other recently published studies [17]. Ayub also mentions that “unfortunately, few studies have attempted to explore the effectiveness or optimize the operation of a Bowden cable-operated gripper” [17]. The body-powered prosthesis is one of the oldest and least variable mainstays of prosthetic care, and with minimal research attention in the last ten years, users could still benefit from enhancing the control capabilities of these systems [27].

As innovation evolves, the issues of durability and complexity of electrically powered prostheses are being addressed. The componentry and technology are comparatively newer than the body-powered prostheses, and therefore more current research is available; however, upon review of the available publications, most focus on future and developing technologies, and few address the current options for electrically powered prostheses. Those that do address the purpose of this paper are limited in their scope.

Functional requirements of the patient and the process that the rehabilitation team goes through to align the individual’s requirements with the appropriate prosthetic option is beyond the scope of this review, however; that exploratory process is equally important to understand as are the prosthetic options available. Utilizing outcome measures to assess function specific to this patient population will greatly improve understanding of effectiveness and aid in a proper prescription of prosthetic devices [55]. Further, keeping pace with the changes in available technologies, fitting techniques and therapy protocols is a worthy effort for the rehabilitation team. Wang et al. [55] specifically address outcome measures directly applicable to ULP rehabilitation.

Limitations

Given the purpose of this review, specific inclusion and exclusion criteria were developed. This eliminated some studies (e.g., single case studies, magazine articles) that, despite their value, could not be included as it would decrease the confidence in the information delivered herein. These outside publications and presentations demonstrate that a consensus of the effectiveness of these technologies and techniques is present in the field.

The literature search for this publication was limited in scope to more current publications. It was necessary to set this limitation since our purpose is to analyze current practice. There are older references in literature, thus excluded because of their age, which show pertinent fittings and techniques that are still in practice today but have been modernized because of materials and available componentry. These papers are therefore necessary for the body of knowledge but again were excluded because of their age.

Conclusion

A noteworthy amount of research focuses on the technological advancements of modern UL prosthetic componentry and control systems. The five general options for prosthetic intervention are inherently represented in the current literature. While some of these options are better developed than others, there is enough information to provide an overview of each prosthetic option. Updated publications are outpaced by the rapid evolution of UL prosthetic rehabilitation; however, the value of this review is to equip the rehabilitation team with the fundamentals of limb difference and their respective prosthetic options. Advancements in the field of prosthetics broaden the implementation of these options so that more individuals can benefit from their application.

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References

[1] Department of Veteran Affairs, Department of Defense. VA/DoD Evidence-Based Clinical Practice Guideline for the Management of Upper Extremity Amputation Rehabilitation. Washington D.C.; 2014.

[2] ISO/TC 8549-4. *Prosthetics and orthotics – vocabulary – part 4: terms relating to limb amputation*. International Organization for Standardization. 2014.

[3] Ziegler-Graham K, MacKenzie EJ, Ephraim PL, et al. Estimating the prevalence of limb loss in the United States: 2005 to 2050. Arch Phys Med Rehabil. 2008;89:422–429.

[4] Egermann M, Kasten P, Thomsen M. Myoelectric hand prostheses in very young children. Int Orthop. 2009;33: 1101–1105.

[5] Melton D. Physiatrist perspective on upper-limb prosthetic options: using practice guidelines to promote patient education in the selection and the prescription process. J Prosthet Orthot. 2018;12:40–44.

[6] Arazpour M, Mardani MA, Ahmadi Bani M, et al. Design and fabrication of a finger prosthesis based on a new method of suspension. Prosthet Orthot Int. 2013;37: 332–335.

[7] Arazpour M, Mardani M, Bahramizadeh M, et al. The effect of new method of suspension on quality of life, satisfaction, and suspension in patients with finger prostheses. Prosthet Orthot Int. 2015;39:197–203.

[8] Cabibihan J. Patient-specific prosthetic fingers by remote collaboration-a case study. Plos ONE. 2011;6:1–6.

[9] Goyal A, Goel H. Prosthetic rehabilitation of a patient with finger amputation using silicone material. Prosthet Orthot Int. 2015;39:333–337.

[10] Imbinto I, Peccia C, Controzzi M, et al. Treatment of the partial hand amputation: an engineering perspective. IEEE Rev Biomed Eng. 2016;9:32–48.

[11] Jacob PC, Shetty KH, Garg A, et al. Silicone finger prosthesis. A clinical report. J Prosthodont. 2012;21:631–633.

[12] Kistenberg RS. Prosthetic choices for people with leg and arm amputations. Phys Med Rehabil Clin N Am. 2014;25: 93–115.

[13] Kuret Z, Burger H, Vidmar G, et al. Impact of silicone prosthesis on hand function, grip power and grip-force tracking ability after finger amputation. Prosthet Orthot Int. 2016;40: 744–750. Accessed May 22, 2018.

[14] Maat B, Smit G, Plettenburg D, et al. Passive prosthetic hands and tools: a literature review. Prosthet Orthot Int. 2018;42:66–74.

[15] Reddy K, Bandela V, Bharati M, et al. Acrylic finger prosthesis: a case report. J Clin Diagn Res. 2014;8:7–8.

[16] Ahmad M, Balakrishnan D, Narayan A, et al. Comprehensive rehabilitation of partially amputated index finger with silicone prosthesis: a case report with 3 years of follow up. J Indian Prosthodont Soc. 2014;14:222–226.

[17] Ayub R, Villarreal D, Gregg RD, et al. Evaluation of transradial body-powered prostheses using a robotic simulator. Prosthet Orthot Int. 2017;41:194–200.

[18] Behrend C, Reizner W, Marchessault JA, et al. Update on advances in upper extremity prosthetics. J Hand Surg Am. 2011;36:1711–1717.

[19] Berning K, Cohick S, Johnson R, et al. Comparison of body-powered voluntary opening and voluntary closing prehensor for activities of daily life. J Rehabil Res Dev. 2014;51: 253–261.

[20] Brown JD, Kunz TS, Gardner D, et al. An empirical evaluation of force feedback in body-powered prostheses. IEEE Trans Neural Syst Rehabil Eng. 2017;25:215–226.

[21] Gemmell KD, Leddy MT, Belter JT, et al. Investigation of a passive capstan based grasp enhancement feature in a voluntary-closing prosthetic terminal device. Conf Proc IEEE Eng Med Biol Soc. 2016;2016:5019–5025.

[22] Huinink L, Bouwsema H, Plettenburg D, et al. Learning to use a body-powered prosthesis: changes in functionality and kinematics. J Neuroeng Rehabil. 2016;13:1–12.

[23] Smit G, Bongers R, Van der Sluis C, et al. Efficiency of voluntary opening hand and hook prosthetic devices: 24 years of development? Jrrd. 2012;49:523–534.

[24] Hichert M, Plettenburg D. Ipsilateral scapular cutaneous anchor system: an alternative for the harness in body-powered upper-limb prostheses. Prosthet Orthot Int. 2018; 42(1):101-106.

[25] Sensinger J, Weir R. Modeling and preliminary testing socket-residual limb interface stiffness of above-elbow prostheses. IEEE Trans Neural Syst Rehabil Eng. 2008;16: 184–190.

[26] Hashim NA, Abd Razak NAB, Gholizadeh H, et al. Analysis of voluntary opening Ottobock Hook and Hosmer Hook for upper limb prosthetics: a preliminary study. Biomed Tech (Berl). 2017;62:447–454.

[27] Carey SL, Lura DJ, Highsmith MJ, CP: FAAOP. Differences in myoelectric and body-powered upper-limb prostheses: systematic literature review. J Rehabil Res Dev. 2015;52: 247–262.

[28] Smit G, Plettenburg D. Efficiency of voluntary closing hand and hook prostheses. Prosthet Orthot Int. 2010;34:411–427.

[29] Belter J, Segil J, Dollar A, et al. Mechanical design and performance specifications of anthropomorphic prosthetic hands: a review. Jrrd. 2013;50:599–618.

[30] Abd Razak N, Abu Osman N, Wan Abas W. Kinematic comparison of the wrist movements that are possible with a biomechatronics wrist prosthesis and a body-powered

prosthesis: a preliminary study. Disabil Rehabil Assist Technol. 2013;8:255–260.
[31] Deijs M, Bongers R, Ringeling-van Leusen N, et al. Flexible and static wrist units in upper limb prosthesis users: functionality scores, user satisfaction and compensatory movements. J Neuroeng Rehabil. 2016;13:26.
[32] Hancock L, Correia S, Ahern D, et al. Cognitive predictors of skilled performance with an advanced upper limb multifunction prosthesis: a preliminary analysis. Disabil Rehabil Assist Technol. 2017;12:504–511.
[33] Saikia A, Mazumdar S, Sahai N, et al. Recent advancements in prosthetic hand technology. J Med Eng Technol. 2016; 40:255–264.
[34] Atzori M, Müller H. Control capabilities of myoelectric robotic prostheses by hand amputees: a scientific research and market overview. Front Syst Neurosci. 2015;9:162.
[35] Kulkarni T, Uddanwadiker R. Overview: mechanism and control of a prosthetic arm. Mol Cell Biomech. 2015;12: 147–195.
[36] Luchetti M, Cutti A, Verni G, et al. Impact of Michelangelo prosthetic hand: findings from a crossover longitudinal study. J Rehabil Res Dev. 2015;52:605–618.
[37] Kyberd P, Lemaire E, Brookeshaw M, et al. Two-degree-of-freedom powered prosthetic wrist. Jrrd. 2011;48:609–617.
[38] Chadwell A, Kenney L, Thies S, et al. Corrigendum: the reality of myoelectric prostheses: understanding what makes these devices difficult for some users to control. Front Neurorobot. 2018;12:15.
[39] Head JS, Howard D, Hutchins SW, et al. The use of an adjustable electrode housing unit to compare electrode alignment and contact variation with myoelectric prosthesis functionality: a pilot study. Prosthet Orthot Int. 2016; 40:123–128.
[40] Segil J, Controzzi M, Weir R, et al. Comparative study of state-of-the-art myoelectric controllers for multigrasp prosthetic hands. J Rehabil Res Dev. 2014;51:1439–1454.
[41] Toledo C, Simon A, Muñoz R, et al. A comparison of direct and pattern recognition control for a two degree-of-freedom above elbow virtual prosthesis. Conf Proc IEEE Eng Med Biol Soc. 2012;2012:4332–4335.
[42] Simon AM, Lock BA, Stubblefield KA. Patient training for functional use of pattern recognition–controlled prostheses. J Prosthet Orthot. 2012;24:56–64.
[43] Kuiken TA, Dumanian GA, Wilson C, et al. Targeted reinnervation – surgical outcomes of 30 Patients. Academy Annual Meeting-Journal of Proceedings (American Academy of Orthotists & Prosthetists). 2010.
[44] Kuiken T. Targeted muscle reinnervation: a promising new approach to the prevention and treatment of painful amputation neuromas. Acad Today. 2016;12:10–12.
[45] Gaston R, Bracey J, Tait M, et al. A novel muscle transfer for independent digital control of a myoelectric prosthesis: the starfish procedure. J Hand Surg. 2018;44(2):163.e1-163.e5.
[46] Lake C. The evolution of upper limb prosthetic socket design. JPO. 2008;20:85–92.
[47] Razak N, Gholizadeh H, Hasnan N, et al. An anthropomorphic transhumeral prosthesis socket developed based on an oscillometric pump and controlled by force-sensitive resistor pressure signals. Biomedizinische Technik [Biomed Eng]. 2017;62:49–55.
[48] Schofield J, Schoepp K, Williams H, et al. Characterization of interfacial socket pressure in transhumeral prostheses: a case series. Plos One. 2017;12:e0178517.
[49] Alley R, Williams T, Albuquerque M, et al. Prosthetic sockets stabilized by alternating areas of tissue compression and release. Jrrd. 2011;48:679–696.
[50] Li Y, Brånemark R. Osseointegrated prostheses for rehabilitation following amputation: the pioneering Swedish model. Unfallchirurg. 2017;120:285–292.
[51] Scheme E, Englehart K. Electromyogram pattern recognition for control of powered upper-limb prostheses: state of the art and challenges for clinical use. Jrrd. 2011;48: 643–659.
[52] Hsiao SS, Fettiplace M, Darbandi B. Sensory feedback for upper limb prostheses. Prog Brain Res. 2011;192:69–81.
[53] Emondi A. Hand Proprioception and Touch Interfaces (HAPTIX). Defense Advanced Research Projects Agency Website; [cited January 2018]. Available from: https://www.darpa.mil/program/hand-proprioception-and-touch-interfaces
[54] Bongers RM, Kyberd PJ, Bouwsema H, et al. Bernstein's levels of construction of movements applied to upper limb prosthetics. J Prosthet Orthot. 2012;24:67.
[55] Wang S, Hsu J, Trent L, et al. Evaluation of performance-based outcome measures for the upper limb: a comprehensive narrative review. Pm&R. 2018;10:951–962.e3.