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Systematic review of neural control and sensory feedback in prosthetic hands

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SYSTEMATIC REVIEW OF NEURAL CONTROL AND SENSORY FEEDBACK IN PROSTHETIC HANDS

by

MARIAM EZZAT HAFEZ

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Approved by

First Reader

Keith Tornheim, Ph.D.
Associate Professor of Biochemistry

Second Reader

Insoo Kim, Ph.D.
Assistant Professor of Medicine
University of Connecticut School of Medicine

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ABSTRACT

Limb loss has severe physical and psychological effects on individuals with upper limb amputations. Higher rates of prosthetic device abandonment has contributed to a need for prosthetic hands that are functional and comfortable for the user. Prosthetic hands have been abandoned for many reasons including weight, size, limited functionality, training time, and discomfort. An optimal prosthetic hand considers both neural control and sensory feedback. Neural control of the prosthetic is crucial to obtain accuracy and desirable functions. Popular methods of sensory feedback such as visual feedback are mentally exhausting and require constant focus from the user. Control and feedback of prosthetic devices differs based on the type of prosthetic. Passive, myoelectric, body-powered, electrocorticographic, adaptive, and sonomyographic prosthetic hand devices focus on a variety of hand movements and each utilizes different methods of control. It is also important to consider the biomaterials of prosthetic hands to enhance comfort and ease-of-use. Mechanical and AM-ULA testing ensure prosthetic hands can perform necessary movements for the user. To develop an ideal prosthetic hand, control and feedback must be considered along with comfort and functionality of the device.

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LIST OF ABBREVIATIONS

AM-ULA	Activities Measure for Upper-Limb Amputees
CORE	Compliant rolling-contacts elements
ECoG	Electrocorticography
EMG	Electromyography
ICMS	Intracortical microstimulation
IMES	Implantable myoelectric sensor
PCI	Prosthetic control interface
PCM	Phase change material
PVC	Polyvinyl chloride
SHP	SoftHand Pro
SMA	Shape-memory-alloy
SNR	Signal-to-noise ratio
TPU	Thermoplastic polyurethane
TSE	Thermoplastic styrene elastomer

INTRODUCTION

Background

About 50,000 people in the United States have upper limb loss as a result of trauma or disease (Dhawan et al., 2019). Upper limb loss resulting from amputation can have severe mental and physical impacts on individuals. Many United States service members have suffered injuries and had amputations over the last 50 years including loss of their upper limbs (Pasquina et al., 2015). For this reason, improvement of the design and functionality of prosthetics has been on the rise. More advances in lower limb prosthetics have been made over the last 20 years, resulting in higher abandonment rates for prosthetic hands (Pasquina et al., 2015). Upper limb prosthetic users have complained of discomfort, size, and weight related to available prosthetics. In addition to this, many individuals have abandoned their prosthetics due to low functionality or high training time and effort required to learn how to use prosthetic hands. Abandonment of prosthetic hands is an issue facing individuals with upper limb loss since complications can arise following this. A higher chance of developing arthritis or overuse injuries results from continued use of only one hand for all tasks (Pasquina et al., 2015).

Upper limb prosthetics vary based on the level of amputation the user faces. A trans-humeral amputation occurs above the elbow, while trans-radial amputation occurs below the elbow. Hand prosthetics are necessary when the user has an amputation at the wrist, known as a wrist disarticulation. Finger prosthetics are required when the user has a digital amputation. The mode of control of an upper limb prosthetic depends on the level of amputation. Trans-humeral amputations typically use body-powered prosthetics and do not incorporate electromyography. Since prosthetic hands are used as a result of a trans-radial amputation or wrist disarticulation, residual muscle is available for use of electromyography. This allows for increased control of the hand and its degrees of freedom. For this reason, the type of neural control depends on the level of amputation. This review will focus specifically on control of hand prosthetics.

Carpal bones, metacarpal bones, proximal phalanges, middle phalanges, and distal phalanges make up the human hand (Dunai et al., 2021). Each finger consists of a metacarpal bone, proximal phalange, middle phalange, and distal phalange as shown in Figure 1. The thumb consists of a metacarpal bone, proximal phalange, and distal phalange. The human hand has 14 joints associated with the phalanges (Dunai et al., 2021). It is important to consider this anatomy when understanding the degrees of freedom of the hand for prosthetic design.

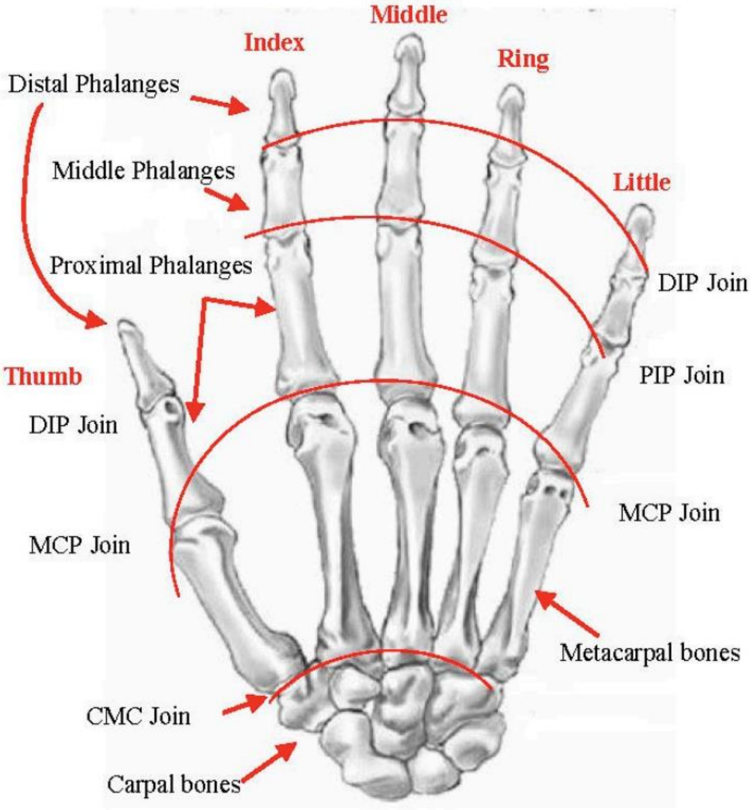


Figure 1. Anatomy of Human Hand. The human hand is composed of carpal bones and a metacarpal bone, proximal phalange, middle phalange, and distal phalange on each finger. The thumb has a metacarpal bone, proximal phalange, and distal phalange. Fourteen joints make up the human hand. Figure taken from (Dunai et al., 2021).

Development of a functional and precise prosthetic hand that provides a user with accurate dexterity and automated control involves multidisciplinary research (Kumar et al., 2019). There are many shortcomings involved in current prosthetic hand models. To achieve practical use, biocompatibility of these devices with the human body is essential for proper functioning. Considering the many degrees of freedom involved specifically in the hand as opposed to other limbs, a faultless prosthetic hand must have accurate control to create a motion. Biomechanical analysis of prosthetics evaluates the hand's movements to provide for fine motor control. For this reason, it is crucial to investigate neural control and sensory feedback involved in current prosthetic hand models.

Although myoneural control is necessary for basic control and movement of a prosthetic hand, the challenge is creating a device that can perform multiple movements and smooth transitions between these motions (Gigli et al., 2020). It is important to consider that unconscious routine actions, such as holding a cup while drinking water, requires grip strength and pressure sensation (Kumar et al., 2019). For this reason, a device that can optimize grip strength based on the object being held is necessary to mimic the natural control and movement of the hand. In a prosthetic that follows an underactuated mechanism, this optimization is not available and accurate grip strength is reliant on visual feedback. Providing sensory feedback to the user would eliminate the need for visual validation since it would allow dynamic adjustment of force required for a command (Kumar et al., 2019). Optimizing a prosthetic hand device with natural control and seamless movements would eliminate injury and accidents caused by many current passive models.

The current challenge with prosthetic hands is the high abandonment rate due to discomfort, training time, and functionality. This review evaluates several types of prosthetics, including passive, myoelectric (surface and implantable), body-powered, electrocorticographic, adaptive, and sonomyographic prosthetic hands. It is important to review types of prosthetics to understand the methods of control available to the user and develop feedback mechanisms for optimal use. This review will also compare biomaterials used for prosthetic hands as related to comfort and functionality. The final section of this review explains testing of prosthetic hands for everyday tasks by the user. The topic of a prosthetic hand is reviewed to evaluate the factors related to its abandonment and two features, neural control and sensory feedback, of current models for design of an optimal prosthetic hand in the future.

Prosthetic Control of Command-Based Movement

To control a prosthetic limb, an interface is needed to detect nerve signals at the amputated or residual limb which originate from the brain. The signals are collected through a sensory mechanism in the prosthetic such as an electrode and converted to an electrical signal by the prosthetic to perform a movement (Kumar et al., 2019).

Neural Control

Once the central nervous system transmits information to the peripheral nervous system, neural control generally involves signal detection and recording. Since the prosthetic must be alerted of the signal that reaches the limb, it is important to consider the quality of detection and recording and reduce any signal noise using signal processing and filtering. External mechanical artifact during movement is another drawback related to signal detection.

Another consideration is related to electrode use and placement because this affects the signal detected by the prosthetic. Signal detection can be via surface or implantable electrodes. Surface electrodes must be replaced by the user as they may move and decrease quality of signal. Implantable electrodes can involve invasive procedures as they are implanted near a muscle to obtain a signal. Again, parameters such as the number of electrodes, distance between electrodes, and skin conduction must be considered to monitor this.

Sensory Feedback

Sensory feedback of a prosthetic hand is crucial to obtain natural use of the device. The hand requires this because sensation enhances situational movements involving fine motor control. With the natural use of a hand, adaptability causes these fine motor movements to be precise with each use. Parameters such as the angle of the finger joints and fatigue of the muscles are automatically and unconsciously regulated by sensory feedback (Kumar et al., 2019). Without this, users need to rely on visual feedback which is more difficult to manipulate and mentally exhausting. Other methods of feedback may be implemented to lessen this burden. Auditory feedback from a prosthetic device can provide an additional marker for manipulation to enhance accuracy (Kumar et al., 2019). For this reason, a mechanism of sensory feedback is key to the functionality of the prosthetic hand.

There are several methods of sensation that can be implemented in a prosthetic hand. These include both features that are natural to the human hand and other feedback mechanisms such as auditory feedback. The sensations that must minimally be included for accurate control are pressure, slippage, and touch (Kumar et al., 2019). Additional methods of detection such as temperature sensors, tactile sensors, or angle sensors are also implemented. Moreover, these sensors need adjustment in terms of the distance between them and their placement in relation to muscles in the hand, which involves choosing correct materials and miniaturizing sensors (Kumar et al., 2019). Sensory feedback to the user for quick recognition can be incorporated by invasive methods such as direct nerve stimulation or non-invasive methods such as electro-tactile or mechano-tactile feedback (Shehata et al., 2020). Limitations to non-invasive methods include the accuracy of the feedback signal being delivered to the user. It is important to consider both the neural communication with a prosthetic hand and sensory feedback to enhance the efficiency and use of the device.

TYPES OF PROSTHETICS

Passive Prosthetics

There are several types of hand prosthetics that have been used to perform hand functions. Active prosthetics use an internal mechanism, while passive prosthetics use external mechanisms (Maat et al., 2017). Passive prosthetics come in various forms with the main categories being prosthetic hands and prosthetic tools, as shown in Figure 2. Prosthetic hands resemble the natural hand and are most often used for cosmetic purposes. This prosthetic type has psychological advantages related to self-confidence since it can be used to heighten self-image in social situations (Maat et al., 2017). Prosthetic tools do not resemble a hand and have increased functionality since they are used to perform certain tasks. They are commonly referred to as activity-specific prosthetic hands, since their main purpose is to perform specific mechanical movements. Prosthetic hands and prosthetic tools can be classified as static or adjustable. Static prosthetics do not allow for movement, while adjustable prosthetics may allow for motions such as grasping (Maat et al., 2017). Passive prosthetics are generally easier to control than active prosthetics due to their low complexity and maintenance. For this reason, infants and young children often have passive prosthetics to allow for basic hand movements and grasping objects (Eshraghi et al., 2020).

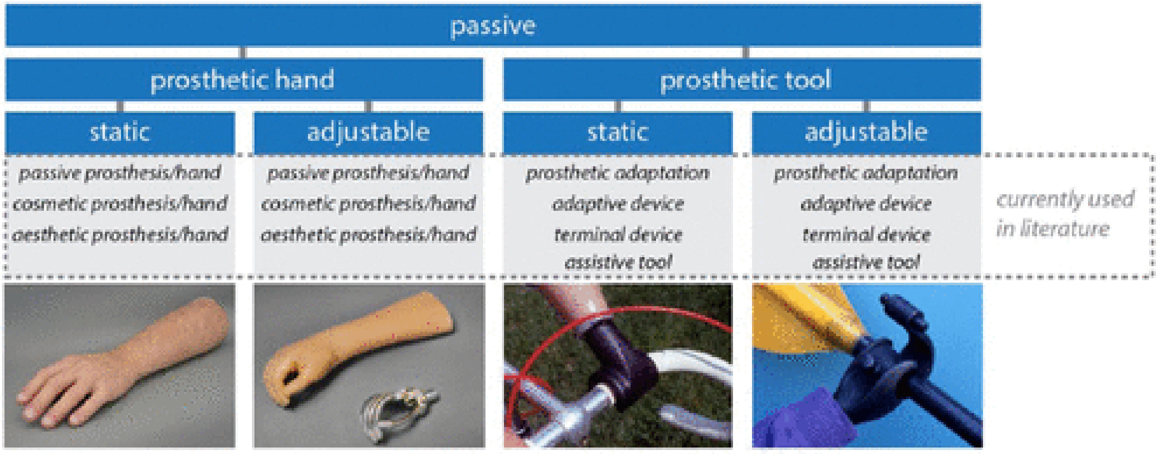


Figure 2. Passive Prosthetic Devices. Passive prosthetics include either static or adjustable prosthetic hands and prosthetic tools. Prosthetic hands emphasize cosmetics of the natural hand, while prosthetic tools are more assistive for the user. Figure taken from (Maat et al., 2017).

Researchers in a study presented a design for a passive prosthetic hand that was low-cost and easy to manufacture (Romero et al., 2020). This model was created to be used as a reference for other passive prosthetics related to upper limb amputations. Since prosthetic hands which incorporate microprocessors and other technology may be difficult to manufacture on a larger-scale, this prosthetic hand was designed to be passive and incorporates materials which can be easily printed and assembled. Researchers then performed a mechanical feasibility test to ensure the prosthetic hand met the everyday needs of users. This test revealed that the passive prosthetic hand design did not undergo plastic deformation and could be mechanically viable for its users (Romero et al., 2020).

Activity-Specific

Activity-specific prosthetic hands are passive prosthetic tools used for athletics and recreational activities. These include prosthetic tools designed to hold sports equipment such as golf clubs and tennis rackets (Maat et al., 2017). Other activity-specific prosthetics may be used for musicians to grasp drumsticks or play guitar (Maat et al., 2017). A common prosthetic tool used for recreational activities is the prosthetic hook since it permits grasping and easy control.

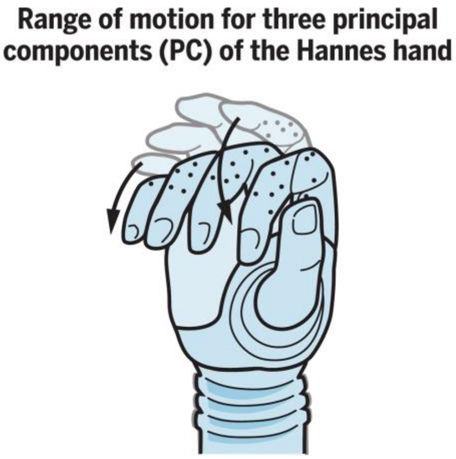
Myoelectric Prosthetics

Myoelectric prosthetic hands use electrical signals from the user's muscles, process the signals, and amplify them to allow for movement of the device. Myoelectric signals can be adjusted to control parameters such as the position of fingers and amount of force used to grasp (Castellini & van der Smagt, 2009). Although this is an active prosthetic, it may be designed similar to passive prosthetics to offer comfort and be cosmetically appealing. Myoelectric prosthetic hands use surface electromyography (EMG) to detect muscle activity and sense what the user commands the prosthetic to do. This prosthetic type uses an electric motor that is powered externally such as by a battery. Surface EMG is a non-invasive method of acquiring myoelectric signals from upper limbs and using this to control a prosthetic hand. They are preferred by many users due to their pain-free implementation and ease of use. Myoelectric prosthetic hands include a processor to acquire the surface EMG signal and create a command to mechanically control the device (Prakash et al., 2019). Myoelectric prosthetic hands acquire various sources including the desired EMG signal, electromagnetic noise, and motion artifact (Prakash et al., 2019). For this reason, compact surface EMG sensors are favorable for prosthetic hands since they have increased sensitivity and signal-to-noise ratio (SNR)

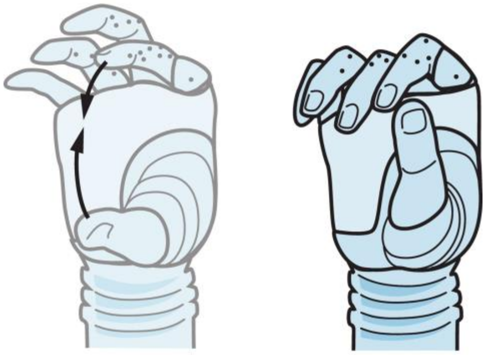
(Prakash et al., 2019). These features allow the sensor to acquire EMG signals even from weak muscle activity, while decreasing the inaccuracy due to noise interference.

There are a range of functional myoelectric prosthetic hands which have been designed to allow for closer movements to the natural hand using more joints and degrees of freedom. i-Limb is a prosthetic hand designed with five fingers and two electrodes, permitting fingers to open and close (Wang et al., 2017). A more complex prosthetic hand, Smarthand, has five fingers and 40 electrodes to both control the hand and provide sensory feedback to the user, a feature that is highly beneficial to the functionality of the device (Wang et al., 2017).

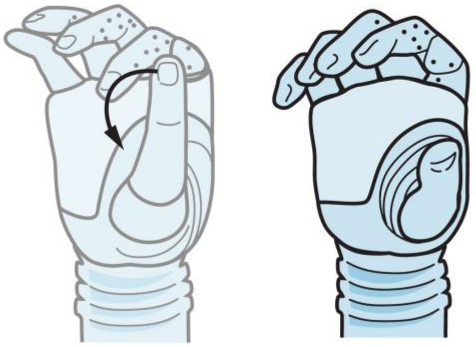
The Hannes hand is a myoelectric prosthetic hand designed to provide high functionality while giving the appearance of a natural hand (Nazarpour, 2020). Hannes hand was modeled after the natural joint kinematics of the hand to allow for seamless control while grasping objects (Nazarpour, 2020).



PC1 Closing the four fingers.



PC2 Partial adduction of the thumb.



PC3 Partial rotation of the thumb.

Figure 3. Hannes Hand Movements. The Hannes hand performs opening and closing movements similar to a natural human hand. Four fingers can be closed (PC1) and the thumb can be adducted (PC2) or rotated (PC3). Figure taken from (Nazarpour, 2020).

One distinguishing feature of this prosthetic hand is its ability to perform a full grasp (Nazarpour, 2020). As shown in Figure 3, the prosthetic is able to close four digits, adduct the thumb, and rotate the thumb to provide for means of gripping objects. The design of the Hannes hand considers several factors that have caused users to previously abandon their prosthetic hand devices, including appearance, weight, speed, size, and force. To model the temporal and spatial control of the hand's joints and muscle movements, principal component analysis was performed based on various hand positions during grasping (Laffranchi et al., 2020). This allows a large amount of motor variables from the hand to be divided into principal components which allow for easier representation by the Hannes hand (Laffranchi et al., 2020).

The SoftHand Pro (SHP) is a myoelectric prosthetic hand that allows for all degrees of freedom that the natural human hand has (Godfrey et al., 2018). This prosthetic is easy to control by the user since it has only one motor. The SoftHand Pro was designed to allow for easy grip control, but grasping small objects requires additional training as compared to body-powered prosthetic hands.

Implantable Myoelectric Sensors

Implantable myoelectric sensors (IMES) control prosthetic hands similarly to myoelectric sensors that use surface EMGs in that they both use myoelectric signals to perform hand movements. Implantable myoelectric sensors are implanted in specific limb muscles to collect the myoelectric signals more directly from the muscle and relay this signal wirelessly to the prosthetic hand (Pasquina et al., 2015). This allows for increased fine motor control and a more accurate signal. Figure 4 shows implantable myoelectric sensors to be of small size and dynamic.

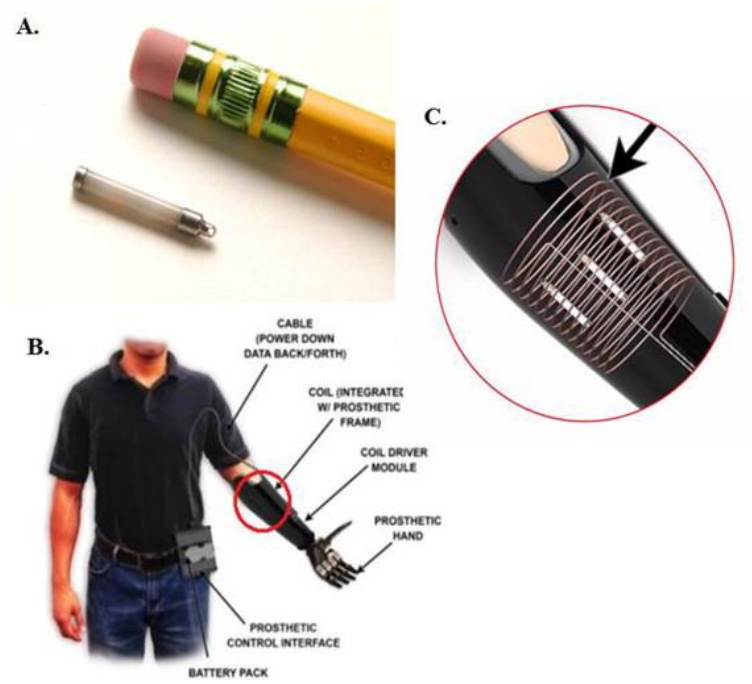


Figure 4. Implantable Myoelectric Sensors. The IMES system (B) includes an IMES electrode (A) and coil (C) to collect EMG signals. Note the size of the electrode and implementation in the prosthetic device. Figure taken from (Pasquina et al., 2015).

Although background noise is still present, the use of implantable myoelectric sensors reduces artifact as compared to surface EMG controlled myoelectric prosthetic hands (Pasquina et al., 2015). Surface electrodes may be inaccurate due to poor contact with the user’s skin from sweating, causing the electrode to move its position. These surface EMGs may also pick up myoelectric signals from other muscles near the electrode. This key difference has caused users with upper limb amputations to abandon prosthetic hands which use surface EMGs (Pasquina et al., 2015). In addition, surface electrodes only allow for signal detection from superficial muscles, while implantable myoelectric sensors permit signals to be recorded from deep muscle groups as well. This has allowed users to perform more complex movements with increased accuracy (Pasquina et al., 2015). Improvements with implantable myoelectric sensors for hand control are still applicable. A study comparing implantable myoelectric sensors to surface electrodes in individuals with trans-humeral amputations revealed the increased controllability provided by implantable electrodes (Mastinu et al., 2019). Moreover, implantable sensors permitted reliable control of the grip force when holding objects. However, control of a prosthetic hand with an implantable myoelectric sensor system still relied heavily on visual feedback to aid with sensory control of the device (Mastinu et al., 2019).

Body-Powered Prosthetics

Body-powered prosthetic hands are passive prosthetics which use the user's body movement to grip objects (Huinink et al., 2016). One of the most widely used body-powered prosthetic tools is in the form of a hook attached to a cable that permits it to open and close to perform grasping movements. This body-powered prosthetic involves a cable connected to the hook or hand on one end and the user's upper limb on the other end. A harness attaches to the upper limb to allow the prosthetic to stay in place. This system works by moving the upper arm or shoulder to allow the cable to perform open and closed hand movements when gripping objects (Huinink et al., 2016). In this manner, the movement of the prosthetic tool is controlled by the user's body rather than myoelectric signals. Since this is a passive prosthetic tool, it is favored by users for its simplicity and ease of use (Huinink et al., 2016). Although it provides a basic function of the hand, control of body-powered prosthetics have lower precision and do not allow for fine motor control.

To provide increased functionality in body-powered prosthetic hands, various models of body-powered prosthetic fingers have been designed. One body-powered prosthetic finger uses a pulley-cable, similar to typical body-powered prosthetic hands, to move the finger based on a grasping command (Smit et al., 2013). Hydraulic cylinder body-powered prosthetic fingers are also underactuated and move by pulling a master cylinder (Smit et al., 2013). Both prosthetic devices are shown in Figure 5 below. To compare, pulley-cable prosthetic fingers require 74% more energy than hydraulic cylinder prosthetic fingers (Smit et al., 2013). For this reason, hydraulic cylinder prosthetic fingers are more efficient for use in body-powered prosthetic hands.

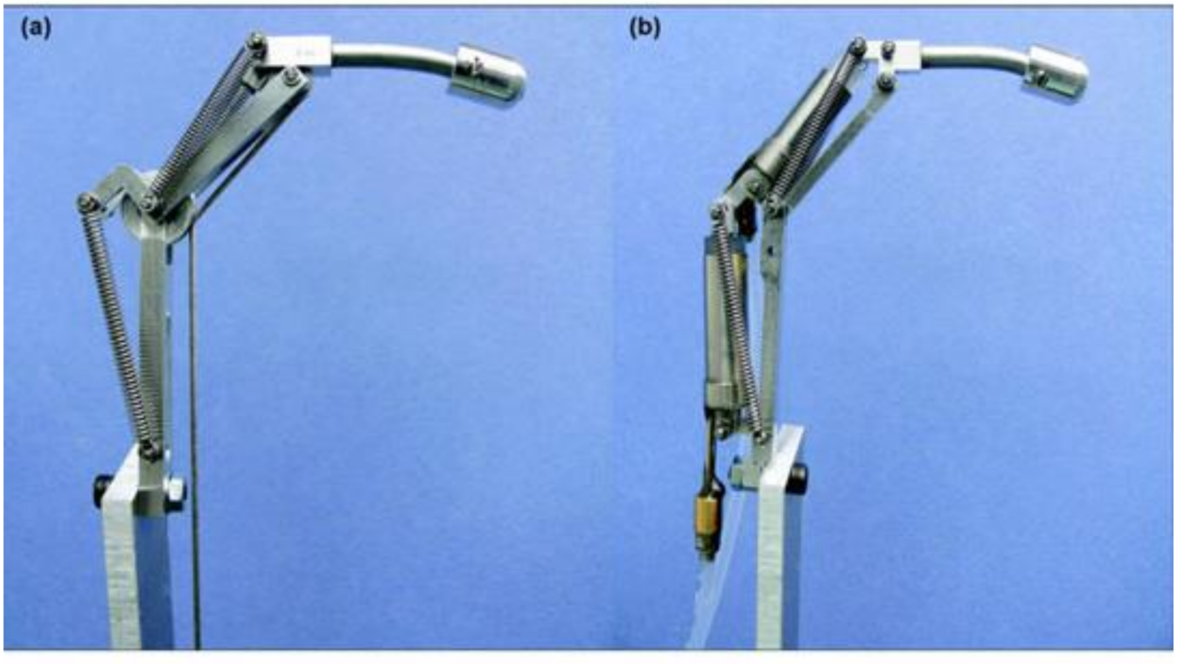


Figure 5. Body-Powered Prosthetics. Body-powered prosthetic fingers with two different systems are shown. One prosthetic (a) functions by a pulley-cable system to extend the finger. The other prosthetic (b) uses a hydraulic cylinder to extend the finger. Both prosthetics have the same springs allowing the device to extend. Figure taken from (Smit et al., 2013).

Human ECoG

Prosthetic hands have been developed which incorporate a brain-machine interface using human electrocorticography (ECoG). Electrocorticography records the brain’s activity using electrodes that are placed directly on the cerebral cortex. ECoG signals from sensorimotor areas in the brain have provided a framework for decoding certain hand gestures based on these signals (Hotson et al., 2016). ECoG has also been useful to understand how the hand controls grasping and certain finger movements. Since higher functioning prosthetics require individual control of fingers, ECoG signals related to specific finger movements and hand gestures have been mapped out to provide a reference for the control of a prosthetic hand (Schroeder et al., 2017). Implanting a brain-machine interface allows signals that control the prosthetic hand to be taken directly from the brain. There is still a need for strong sensory feedback in this brain-machine interface (Schroeder et al., 2017).

Adaptive Prosthetics

Adaptive prosthetic hands allow for control of the device based on the task performed, such as grasping. In passive adaptive prosthetic hand models, fingers are able to simply adjust to the shape of an object being held based on the size of the object (Xu et al., 2019). Since this is a passive model, the prosthetic does not require an electric source to perform this movement. Prosthetic hands may also have adaptive mechanical sensors and are therefore active prosthetic hands (Xu et al., 2019).

Prosthetic hands with an adaptive mechanical sensor allow for adjustments to be made based on the need for specific finger movements to perform tasks. A prosthetic finger with multiple degrees of freedom was proposed in a study with an adaptive mechanical sensor to be incorporated in a prosthetic hand (Wu et al., 2021). The prosthetic was able to adapt to grasping commands and adjust the angle of the joints on the fingers based on the shape of objects to better move each finger in relation to the edges of the object. Another approach to a prosthetic hand with an adaptive mechanical sensor is related to the arch on the palm of the hand. Since the palm of the hand is involved in grasping movements, it is important to consider this when designing a functional prosthetic hand. This approach does not use the degrees of freedom of the fingers to create a grasping motion. Rather, it focuses on how the carpometacarpal joint allows for the thumb and palm to make an arch and grasp objects (Xu et al., 2019). For this reason, implementing an arch function to the prosthetic hand has allowed for the hand to grasp in a more natural and seamless movement, avoiding the multi degree of freedom approach (Xu et al., 2019). As shown in Figure 6, this implemented prosthetic hand is composed of four passive adaptive fingers and an active thumb with two motors, allowing it to move by flexing, extending, adducting, and abducting to control grasping (Xu et al., 2019).

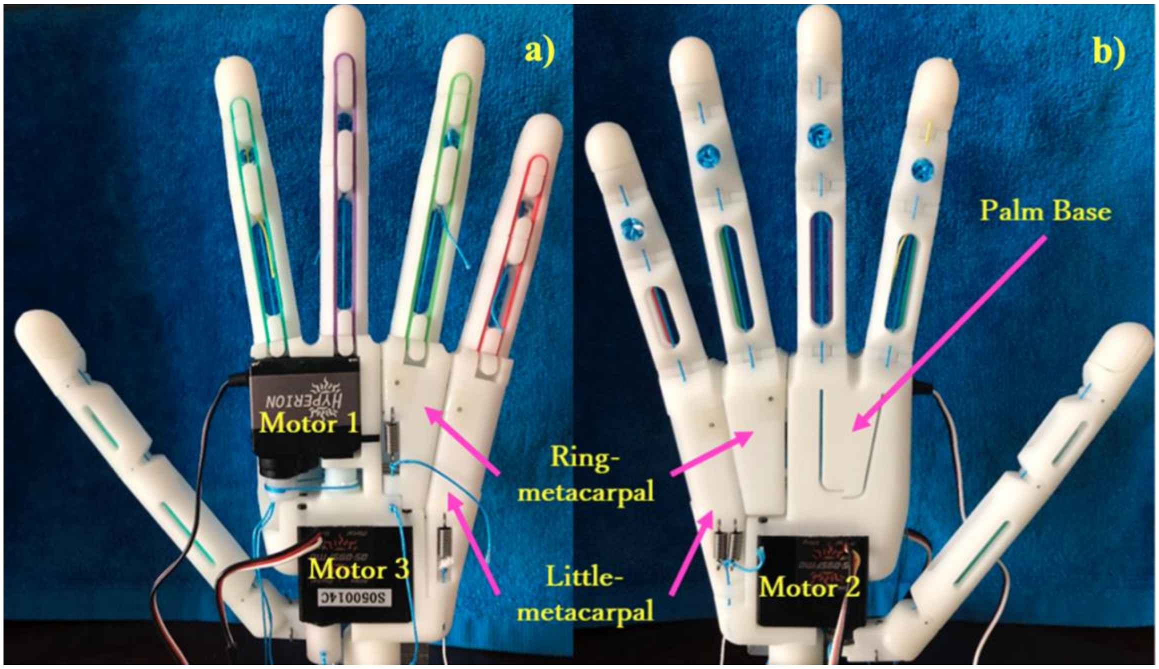


Figure 6. Adaptive Mechanical Sensor Prosthetic Hand. The posterior side (a) of the prosthetic hand includes motor 1, which flexes and extends the four fingers, and motor 3, which adducts and abducts the thumb. The anterior side (b) of the prosthetic hand is composed of motor 2 on the palm of the hand to flex and extend the thumb. Figure taken from (Xu et al., 2019).

The arch mechanism for this prosthetic hand involves two stages. In the load stage, the thumb is adducted and metacarpals are passively extended, causing the object to be grasped (Xu et al., 2019). In the no-load stage, the thumb and palm form an arch to prepare for grasping. This design is beneficial for adaptive control during grasping, but still lacks a sensory feedback mechanism for the user.

Sonomyographic Prosthetics

Sonomyography can be used to sense muscle activity for the purpose of prosthetic hands (Akhlaghi et al., 2016). Ultrasound imaging can reveal mechanical deformation of muscles. Databases for ultrasound recordings of certain hand gestures and movements have been created to provide a system of information to design prosthetic hands (Akhlaghi et al., 2016). Ultrasound can show muscle activity for the main forearm muscle groups involved in grasping. These include the anterior flexors, medial flexors, lateral extensors, and posterior extensors (Akhlaghi et al., 2016). The use of ultrasound allows for recording of the active contraction and passive relaxation of specific muscles when a certain hand gesture or movement is made. Taking note of these changes in muscle activity has allowed translation to a prosthetic hand that uses this model to function.

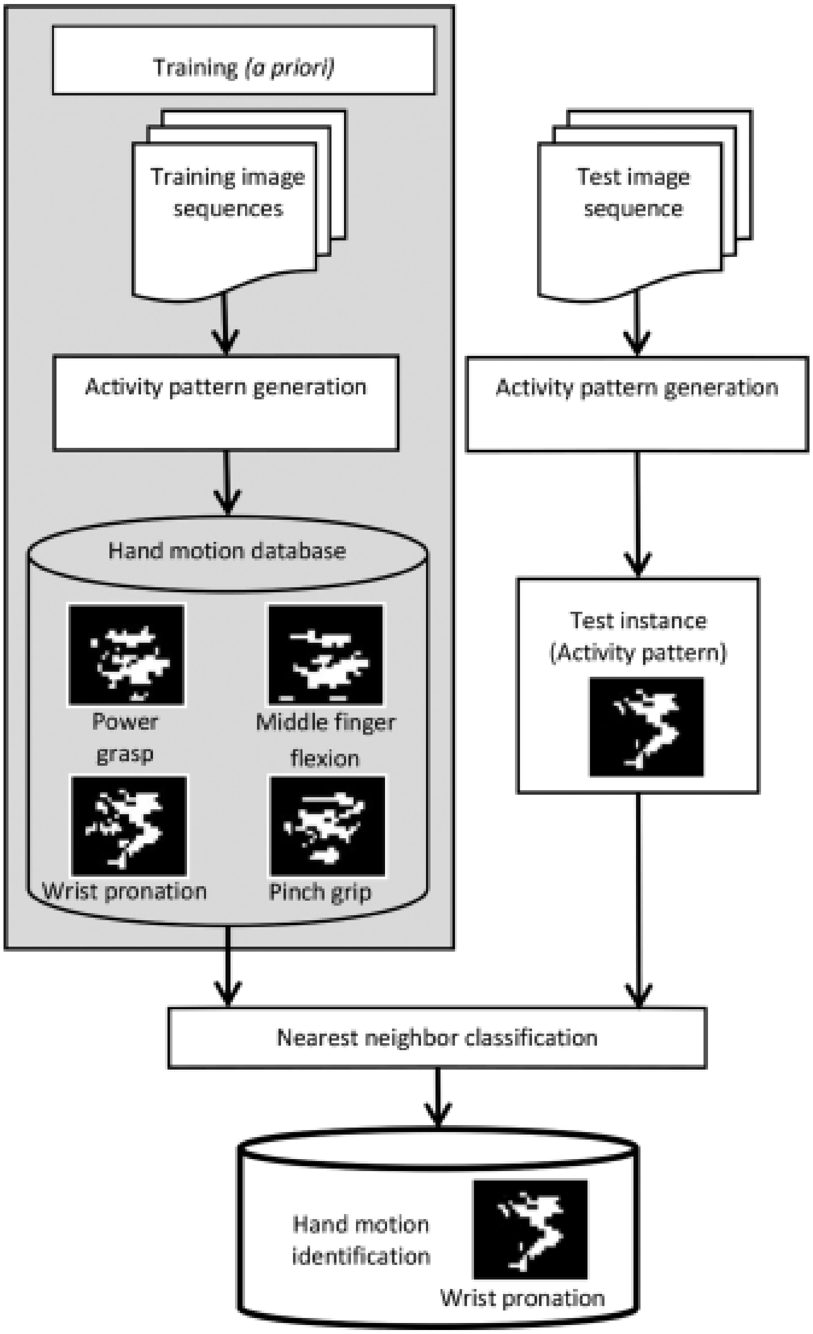


Figure 7. Algorithm For Hand Gestures. During training, activity patterns are collected and added to a hand motion database. Nearest neighbor classification involves classifying a motion instance based on the training database. Figure taken from (Akhlaghi et al., 2016).

As shown in Figure 7, a database is created from hand gestures recorded by individuals during a training period. From the mechanical muscle movements by the hand gestures, muscle activity patterns are recognized. Hand motions are identified based on the closest muscle activity pattern recognized in the hand motion database. Prior to any prosthetic hand implementation, virtual hands have been used by individuals to observe the possible hand gestures obtained from the database.

Use of surface EMGs only allows for signal detection from superficial muscles, while sonomyography can demonstrate muscle activity from both superficial and deep muscles (Akhlaghi et al., 2016). For this reason, sonomyography can allow for increased control and accuracy with prosthetic hand movements. In addition, surface EMGs have a low signal-to-noise ratio, causing significant background noise which interferes with the myoelectric signal transduction (Akhlaghi et al., 2016). Ultrasound imaging provides for enhanced specificity as compared to surface EMG recording, improving the accuracy of muscle activity detection for prosthetic hands. In addition, sonomyographic prosthetic hands may be favored by individuals over implantable myoelectric sensors as they are noninvasive and require significantly less training time. It is important to consider training time when comparing prosthetic hand devices, since this is a factor contributing to abandonment of complex prosthetic devices by users.

Limitations of sonomyography for prosthetics are related to the novelty of the models tested; one degree of freedom prosthetics have been tested with sonomyographic control (Dhawan et al., 2019). However, multiple degrees of freedom are required for a prosthetic hand with high functionality. Individuals who tested the prosthetic hand also relied on both proprioceptive and visual feedback. Incorporating mechanisms of sensory feedback to the device is necessary to increase functionality. Although an ultrasound-based model for prosthetics is relatively new, a study has shown that sonomyographic control of the hand can be implemented in commercially available prosthetic hands (Dhawan et al., 2019).

NEURAL CONTROL AND SENSORY FEEDBACK

Overview

Passive prosthetic hands use external mechanisms to control and move the device, while active prosthetics use internal mechanisms. Myoelectric prosthetic hands use surface EMGs to detect muscle signal and implantable myoelectric sensors use implantable EMGs to detect muscle signal. Electrocorticographic prosthetic hands use ECoG signals directly from the brain to control a prosthetic hand. Depending on the mechanisms of adaptive prosthetics, their neural control differs. Sonomyographic prosthetic hands use ultrasound to detect muscle activity and perform hand movements.

Efferent neurons carry motor signal from the brain to the peripheral nervous system in a natural hand to perform a movement. Afferent neurons will carry sensory information from the peripheral nervous system to the brain for sensation. For this reason, it is crucial to consider both neural control and sensory feedback in all prosthetic hand models to optimize functionality for the user.

Control and Feedback in Various Prosthetic Designs

Passive prosthetic hands do not receive neural input and are controlled manually or by a residual limb. Since an internal mechanism of control does not exist for passive prosthetics, the user must rely on external methods to perform a movement with the prosthetic hand. Given the external mechanism of control for passive prosthetic hands, there is no internal sensory feedback mechanism. For this reason, the user must rely solely on visual feedback to sense the prosthetic’s orientation and location in space.

Activity-specific passive prosthetic hands may allow the user to have increased sensory feedback, depending on the type of prosthetic tool. For activity-specific prosthetic hands which are used to play instruments, auditory feedback may be beneficial for the user to obtain sensory feedback from the device.

Myoelectric prosthetic hands receive neural input through surface electrodes on the user's skin. These surface electrodes receive muscle activation potentials and the processor determines the force that will be performed as shown in Figure 8 (Fang et al., 2015). There are three main layouts for surface electrodes of myoelectric prosthetics: muscle-targeted layout, low-density surface electrode layout, and high-density surface electrode layout. Table 1 compares muscle-targeted and low-density surface electrode layouts. Accuracy of each electrode layout varies with EMG channel number and features of each configuration. Muscle-targeted layout focuses on specific muscles (Fang et al., 2015). For low-density surface electrode layout, electrodes are placed evenly on the surface of the skin in patterns, while high-density electrodes are more closely spaced (Fang et al., 2015).

Table 1. EMG Electrode Layouts. [1]EMG channel. [2]Muscle-targeted layout. [3]Low-density layout. [4]Hand motion. [5]Hand motion and rest motion. Table taken from (Fang et al., 2015).

Electrode	Motion[4]	Accuracy (%)
1[1]/MT[2]	4	90.7
2/MT	10	87.8
2/MT	6	96.7

2/MT	6	97.5
2/MT	8	83.3
2/MT	6	97.5
2/MT	4	92.7±3.3
4/MT	6	95.2±3.0
4/MT	7	92.0
4/MT	5	92.0
4/MT	6	91.0±1.9
6/LD[3]	8	98.0/80.3
8/LD	9	77.5/94.4
6/MT	9	85.9±8.34
6/LD	18	73.5±8.3
7/LD	5+1[5]	95.0
8/MT	11	95.9
8/MT	6+1	94.7
10/LD	7	89.0±79.0
8/LD+4/MT	4	92.6
32/LD	10+1	84.4±7.2
32/LD	12	>98.0
19/LD	6	~90

Many commercial prosthetic hands involve a pair of electrodes placed on a flexor and extensor muscle to allow for both movements. Sensation of myoelectric prosthetic hands can be obtained from visual or auditory feedback, as mentioned previously. Auditory cues can alert the user of the extent of grasping motion or force applied by the prosthetic device. Additional methods of sensory feedback include mechano-tactile and electro-tactile feedback. Electro-tactile sensory feedback involves electrical stimulation of nerves through surface electrodes incorporated by myoelectric prosthetic hands (Pamungkas & Caesarendra, 2018). With electro-tactile sensory feedback, the user can be haptically alerted of movements made by the prosthetic and other markers such as location and orientation of the device.

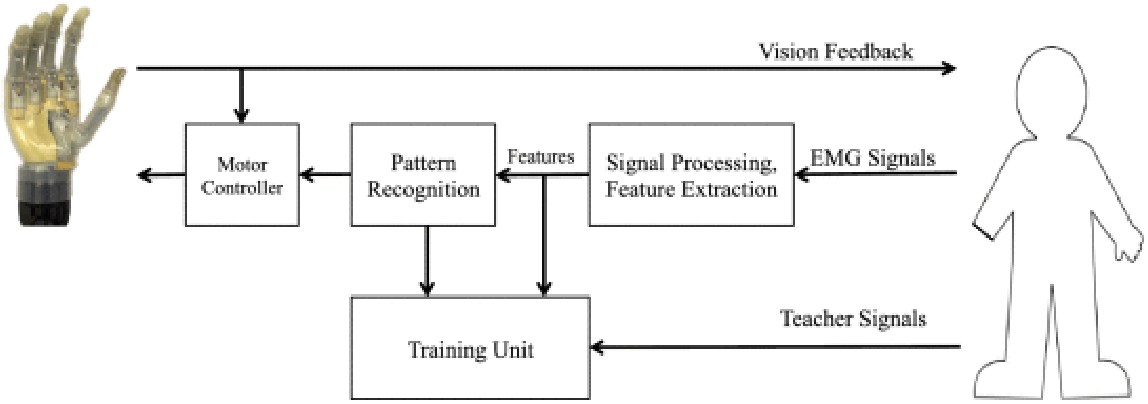


Figure 8. Control of Prosthetic Hand. Prosthetic hand motion is derived from EMG signals which are processed, recognized, and transmitted to a motor to allow for movement. Visual feedback aids the user to perform commands and control the device. Figure taken from (Fang et al., 2015).

Mechano-tactile sensory feedback involves a mechanical stimulation to the user which alerts them of the location or ownership of their prosthetic hand (Shehata et al., 2020). This mechanism of feedback is efficient since it permits the user to receive sensory feedback while performing tasks. There are several methods of delivering mechano-tactile sensory feedback to the user via a prosthetic hand. A mechano-tactile sensory feedback study was performed to determine the most efficient method of delivery for a prosthetic hand in both passive and active conditions (Shehata et al., 2020). During this study, tapping and brushing sensory feedback methods were tested on individuals using three mechano-tactile tactors. Each method was tested in synchronous, without delay, and asynchronous conditions. During the passive conditions, synchronous stimulation caused higher prosthetic hand displacement as compared to asynchronous, but differences between brushing and tapping were not statistically significant (Shehata et al., 2020). For active conditions, asynchronous feedback resulted in lower agency than synchronous. Given that individuals in this study used simulated prosthetic hand devices, proprioceptive drift of the prosthetic may be different for active and passive conditions during prosthetic hand use.

Prosthetic hands with implantable myoelectric sensors receive neural feedback similar to myoelectric prosthetic hands through EMG directly from a muscle. Since the sensors are implanted near the muscle, this signal is more directly available. Implantable myoelectric sensors then wirelessly transfer the signal recording to the prosthetic hand. This is typically done via an electromagnetic coil that is in the prosthetic hand socket (Pasquina et al., 2015). Following this, the samples are transmitted to a prosthetic control interface (PCI), which further filters the signal (Pasquina et al., 2015). The implantable myoelectric sensor system was developed to mimic myoelectric prosthetic devices that use surface electrodes to be implemented in commercially available devices (Pasquina et al., 2015). Figure 9 shows the pathway of EMG signal processing from the implantable myoelectric sensor to the prosthetic control interface. Following signal filtering and processing, the prosthetic receives a control signal which allows for a gesture or movement to be made.

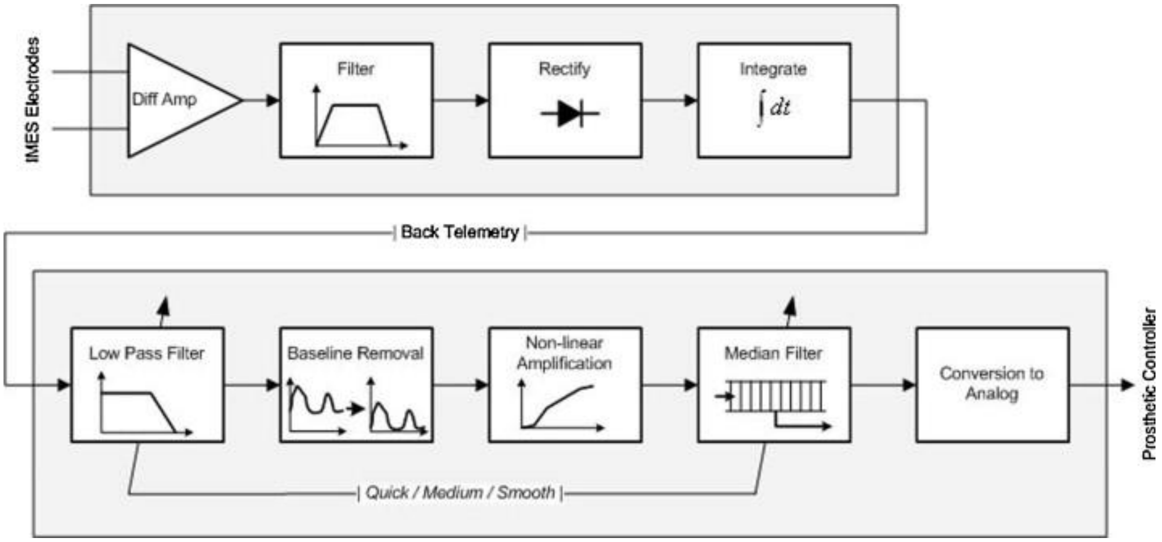


Figure 9. Signal Processing For Implantable Myoelectric Prosthetics. IMES sensors collect EMG signal which is filtered, rectified, integrated, and amplified. The signal is then converted to an analog signal to allow for prosthetic hand control. Figure taken from (Pasquina et al., 2015).

Sensory feedback of implantable myoelectric sensor prosthetic hands involves visual, auditory, and tactile feedback mechanisms. In addition to these mechanisms, osseoperceptive feedback may also be used, depending on the prosthetic hand. Implantable myoelectric prosthetic hands that are osseointegrated, such as the e-OPRA implant system, allow for osseoperceptive feedback (Mastinu et al., 2019). Osseointegrated prosthetics are implanted to the user's bone to provide an osseoneuromuscular interface (Mastinu et al., 2019). Osseoperception provides the user with a sense of location and interaction of their prosthetic hand. However, visual, auditory, tactile, and osseoperceptive sensory feedback mechanisms are still insufficient for the user to have a natural grasp and movement with an implantable myoelectric prosthetic hand (Mastinu et al., 2019).

Body-powered prosthetic hands use a cable or harness attached to the body to create movement. These prosthetics are passive prosthetics and therefore do not receive neural input since they are manually controlled. Body-powered prosthetic hands rely on visual feedback for sensation.

Electrocorticographic prosthetic hands receive neural input directly from the brain in the form of ECoG signals. These prosthetic hands rely on visual feedback for sensation and thus, there is a need for proprioceptive and touch feedback to be implemented. A model for intracortical microstimulation (ICMS) as a form of sensory feedback for prosthetic devices has been explored (Schroeder et al., 2017). ICMS of the primary somatosensory cortex causes a tactile stimulation that may permit the user to perform brain-machine interface tasks, such as with a prosthetic hand (Schroeder et al., 2017). This stimulation is invasive, but can allow for enhanced sensory feedback as compared to other mechanisms, since it reports a signal directly to the brain. In addition, ECoG electrode implant is a highly invasive procedure as shown in Figure 10.

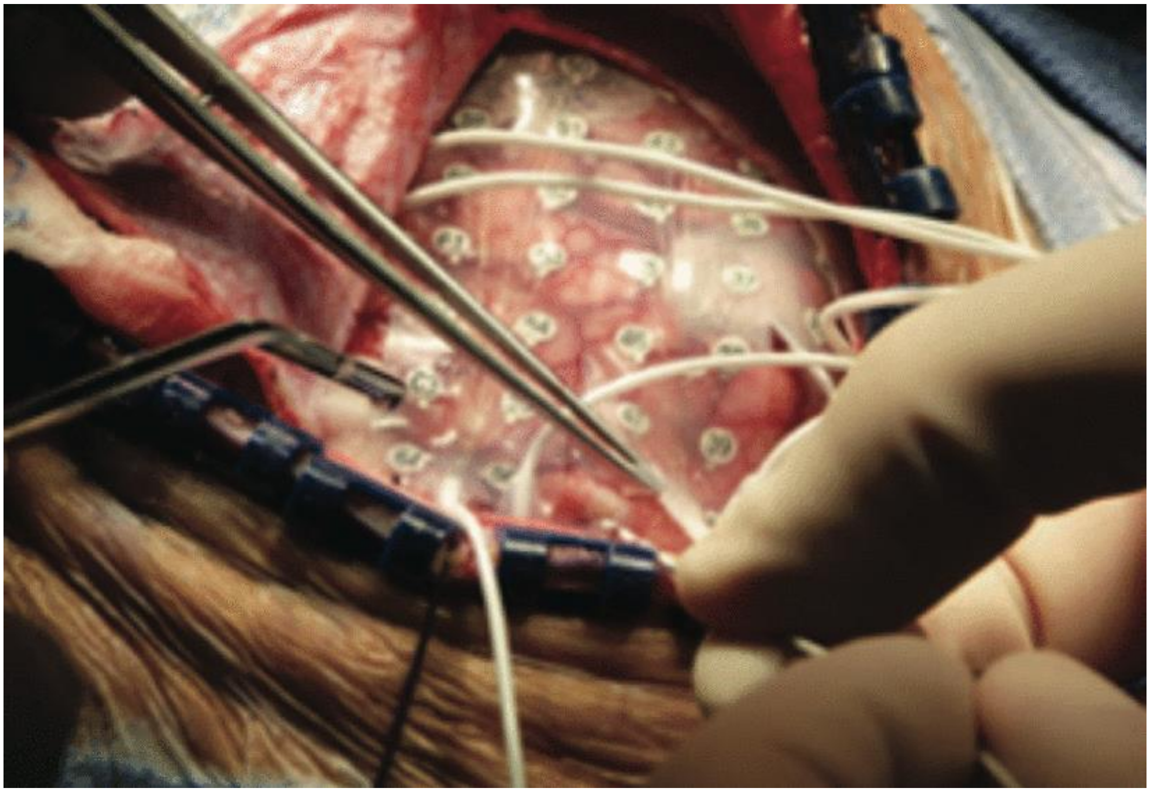


Figure 10. ECoG Electrode Placement. Electrodes are placed on the cerebral cortex to record ECoG signals for hand gesture database. Database can be used to control prosthetic hand device. Figure taken from (Fang et al., 2015).

Adaptive prosthetic hands allow for control of the prosthetic hand to be adjusted based on the movement made or object being grasped. Neural control depends on whether the device is controlled via an internal or external mechanism since there are both passive and active adaptive prosthetic hands. Passive adaptive prosthetic hands will be manually controlled by the user and will not have an internal mechanism of neural control. Active adaptive prosthetic hands will detect the size of an object being grasped and therefore have an internal mechanism of neural control. Visual feedback is available and necessary to users of adaptive prosthetic hands.

Sonomyographic prosthetic hands use sonomyography to collect mechanical movement of residual muscles to control the device. Their mechanism of control involves detection of muscle activity using ultrasound signals. The control of the prosthetic is then dependent on proprioception (Dhawan et al., 2019). Similar to other prosthetic hand designs, this model has visual feedback available for the user. In addition, sonomyographic prosthetic hands can use proprioceptive feedback and intuition from residual muscles, providing a sense of ownership over the device (Dhawan et al., 2019). Since sonomyographic prosthetic hands are more intuitive than myoelectric prosthetic hands, they may be favored by users and have reduced abandonment rates.

BIOMATERIALS

Biomaterials used for prosthetic hand influence the practicality and functionality of the device for the user. It is important to consider the use of materials that provide comfort to the user, whether it is related to the weight of the materials, size of the prosthetic hand, or fit of the socket. Other considerations are related to durability of the device. An efficient prosthetic hand should be durable and require low maintenance to compare to a natural hand. A functional prosthetic hand will allow for flexibility when needed for increased range of motion and hand movements. Ultimately, it is important to consider the biocompatibility of the biomaterial used in the device with the human body. This is especially significant if the device requires implantable materials, such as implantable myoelectric sensors. Materials that are not biocompatible may cause a significant immune response in the body, requiring further intervention. Practical features such as cost of the biomaterials and training also need to be considered.

Appropriate biomaterials need to be chosen for each component of a prosthetic hand, including the custom socket, prosthetic hand, and sensors. In addition, some prosthetic hands may be designed with additional components such as cosmetic gloves. Cosmetic gloves provide a psychological advantage for prosthetics in that they appear similar to a natural hand with appropriate biomaterials.

Prosthetic hands have been developed with a range of materials to optimize functionality and appearance. Iron was used in early prosthetics, but is no longer used due to limitations in weight (Soriano-Heras et al., 2018). New materials have been created to allow for enhanced use of prosthetic hands. Plastics and metal composites permit low weight prosthetics that are stronger in nature (Soriano-Heras et al., 2018). Certain materials can be used to perform specific movements. For example, materials such as shape-memory-alloy (SMA) allow for increased flexibility and movement (Soriano-Heras et al., 2018). Shape-memory-alloy can deform and return to its original shape and form when heated. In addition, this material is advantageous since it is lightweight and thus can be used instead of conventional actuators in prosthetic devices. It is also important to consider that not all shape-memory-alloys are biocompatible; nitinol is a biocompatible shape-memory-alloy that has medical uses and therefore can be incorporated in a prosthetic hand (Soriano-Heras et al., 2018).

Joints of the natural hand can be represented in prosthetic hands by creation of a joint assembly or use of a biomaterial which mimics joint movement. Table 2 reveals that flexible thermoplastic polyurethane (TPU) is a polymer with low flexural modulus, meaning the material can withstand large deformation under stress (Deng & Tadesse, 2021). In addition, TPU can be 3D printed, allowing for ease of manufacturing prosthetic hands with this material (Deng & Tadesse, 2021). Given these characteristics of TPU, it is suitable for use in joints of a prosthetic hand, since it permits flexion of joints with its ability to bend.

Table 2. Material Characteristics of Thermoplastic Polyurethane. Table taken from (Deng & Tadesse, 2021), (Shi et al., 2020).

Material	Flexural Modulus	Tensile Strength	Elongation at Break
Thermoplastic polyurethane (TPU)	25.6 MPa	41.7±0.2 MPa	558.2±19.9%

A joint assembly involves parts made of biomaterials which when assembled, allow for a joint to perform its function. Compliant rolling-contacts elements (CORE) joints provide the functions of flexion and extension and thus, can be used for interphalangeal joints of the hand (Catalano et al., 2014). There are two types of CORE joints which perform the same movements, shown in Figure 11. These joints include a metallic or elastic band set across the joint and two passive cylinders (Catalano et al., 2014).

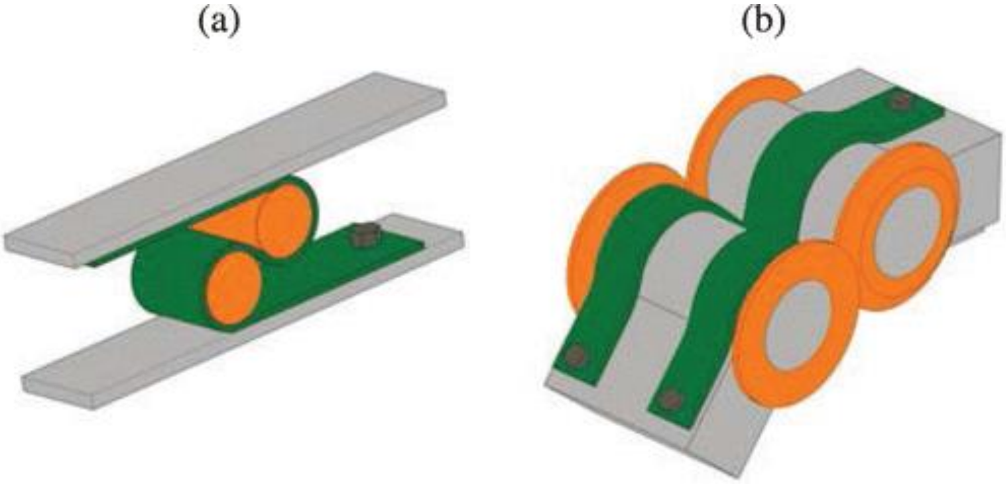


Figure 11. CORE Joint. Compliant rolling-contacts elements joint. (A) Rolamite joint and (B) Hillberry joint, which involves two cylinders and a metallic band in contact between the structures. The designs are compliant during flexion and rigid with traction. Figure taken from (Catalano et al., 2014).

MERO Hand is a mechanically robust anthropomorphic prosthetic hand that uses modified CORE joints (Liu et al., 2019). This prosthetic hand proposes joints that has multi-directional compliance and involves a two ligaments, a tendon, a distal link, and a base link (Liu et al., 2019). Figure 12 shows this modified CORE joint for the MERO hand. In this model, the tendon and ligaments were both designed with elastic strings to be flexible with movement of the hand. When the tendon of this joint is pulled, the distal link rolls on the base link, similar to the cylinders of the original CORE joint.

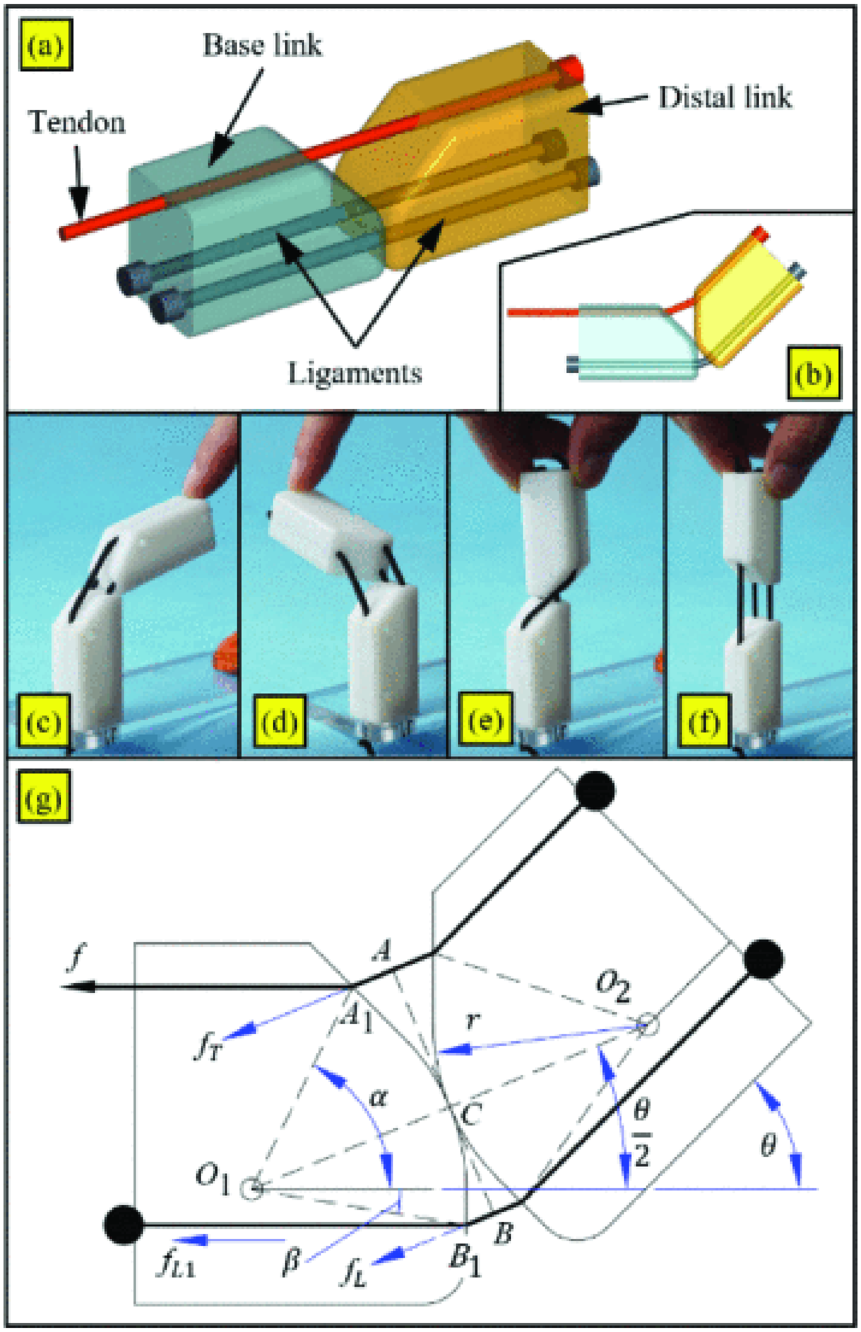


Figure 12. MERO Hand's CORE Joint. Variation of the CORE joint in this prosthetic model allows for increased flexibility with the same motions: (a) extension, (b) bending, (c) backward bending, (d) side bending, (e) twisting, and (f) dislocation. (g) is a model of the modified CORE joint with force diagram. Figure taken from (Liu et al., 2019).

Prosthetic hand tools such as hooks are typically made with metal biomaterials such as stainless steel, titanium, and aluminum (Geethanjali, 2016). Table 3 reveals the characteristics of these common biomaterials. Stainless steel is strong, but has a greater weight. Aluminum has low weight and strength. Titanium has less weight and high strength (Geethanjali, 2016). For this reason, it is important to consider the function of the prosthetic tool when considering which metal to use. In addition, composite metals may be created to reinforce certain characteristics of two or more metals.

Table 3. Characteristics of Prosthetic Hand Materials. Table taken from (Scholz et al., 2011), (Kim & Jhang, 2015).

Material	Young’s Modulus	Strength
Stainless steel	206 GPa	High
Aluminum	71.8±0.7 GPa	Low
Titanium	118 GPa	High

Materials designed for prosthetic hand sockets must avoid complications related to the use of impractical plastics in many models. Prosthetic sockets often increase heat production and cause sweating and irritation of adjacent skin (Rezvanifar et al., 2020). These issues have contributed to abandonment of prosthetic hand devices. To avoid these disadvantages, a material which can regulate skin temperature or provide cooling to the skin is advantageous to individuals. The use of phase change materials (PCM) can allow for this cooling effect given their high latent heat (Rezvanifar et al., 2020). PCM liners can be incorporated with silicone sockets to allow for cooling. Moreover, cooling channels have been designed for temperature regulation of prosthetic sockets, which involves a hollow space between two channels which permits air to circulate and absorb excessive heat in the socket, as shown in Figure 13 (Rezvanifar et al., 2020).

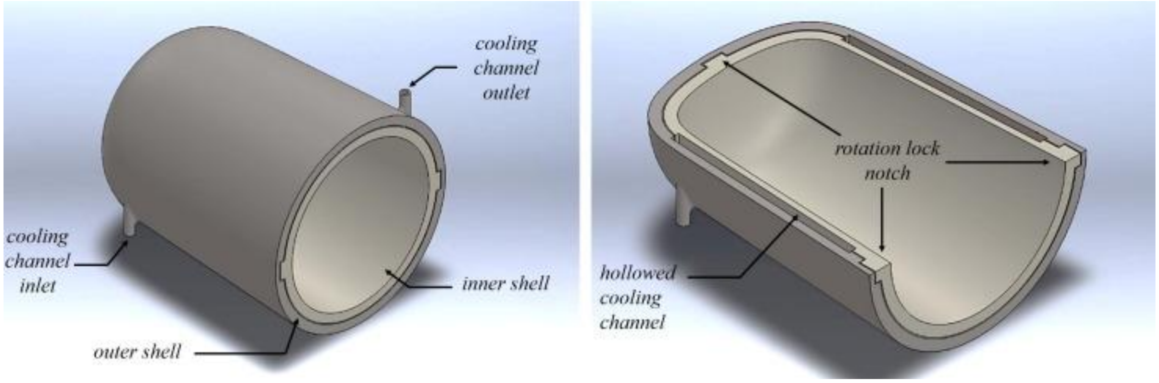
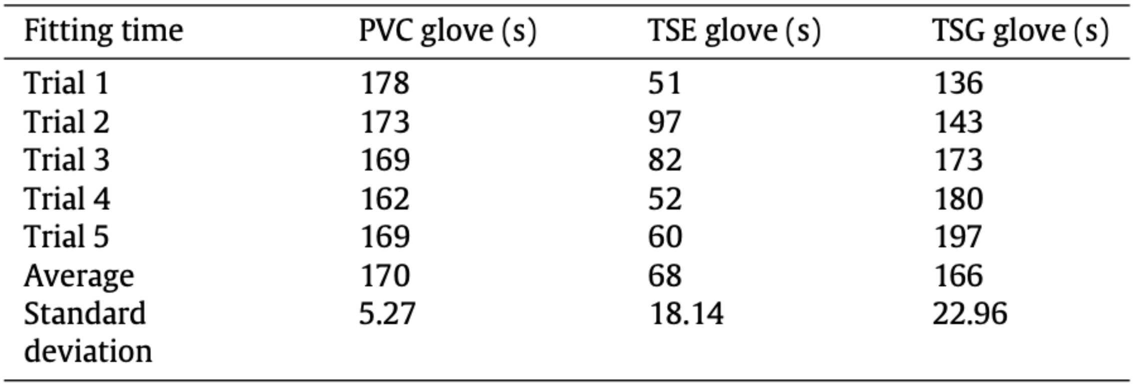


Figure 13. Prosthetic Hand Socket Design. Introducing cooling channels in prosthetic hand sockets allows for increased air circulation and temperature regulation. Figure taken from (Rezvanifar et al., 2020).

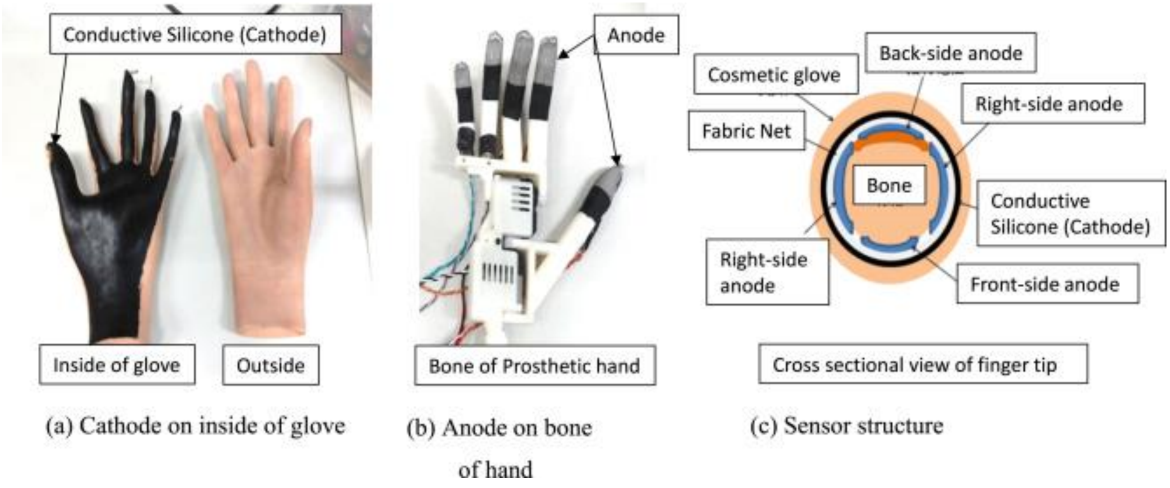
Consideration of biomaterials for cosmetic gloves is crucial since use of inappropriate materials may negatively impact the mechanical functionality of a prosthetic hand. Silicone and polyvinyl chloride (PVC) are commonly used materials for cosmetic gloves. PVC is more stiff than silicone and easier to stain, negatively affecting its cosmetic appearance (Smit & Plettenburg, 2013). This staining can be avoided by applying surface coating to the PVC glove, a process that requires maintenance (Smit & Plettenburg, 2013). Silicone is more flexible than PVC, but is also a more expensive material. In addition to the high cost of silicone, its production is also more expensive than PVC production, which is considered a drawback related to its manufacturing (Smit & Plettenburg, 2013). New cosmetic gloves incorporate silicone and thermoplastic styrene elastomer (TSE), giving the gloves a superelastic rubber material (Yabuki et al., 2019). As compared to PVC, the combination of silicone and TSE improves the appearance of the gloves by enhancing wrinkles, fingerprints, and nails (Yabuki et al., 2019). This combination can also withstand more strain before breakage than PVC alone. The amount of time it takes the user to fit the glove, or average fitting time, is also lower for TSE silicone cosmetic gloves, 68 seconds, as compared to PVC, 170 seconds, in Table 4 due to the increased flexibility (Yabuki et al., 2019).

Table 4. Fitting Times of Silicone and PVC Gloves. Table taken from (Yabuki et al., 2019).



Fitting time	PVC glove (s)	TSE glove (s)	TSG glove (s)
Trial 1	178	51	136
Trial 2	173	97	143
Trial 3	169	82	173
Trial 4	162	52	180
Trial 5	169	60	197
Average	170	68	166
Standard deviation	5.27	18.14	22.96

Silicone can better accommodate insertion of sensors for sensory feedback of the prosthetic hand. This is because the flexibility and thinness of silicone allows for sensors to be inserted within a small space of the cosmetic glove. Figure 14 shows a pressure sensor in a TSE silicone cosmetic glove. The flexibility of the silicone gloves allows easy fitting on the prosthetic device, while incorporating the necessary sensor.



(a) Cathode on inside of glove (b) Anode on bone of hand (c) Sensor structure

Figure 14. Silicone Cosmetic Glove. The silicone cosmetic glove incorporates a pressure sensor. Its flexibility allows for low fitting time on the prosthetic hand. Figure taken from (Yabuki et al., 2019).

Cosmetic gloves also affect the electric current related to the EMG prosthetic hand system. Maximum electric currents were measured for TSE silicone gloves and PVC gloves and PVC required a higher electric current to both stabilize and move the hand (Yabuki et al., 2019). For this reason, TSE silicone is more efficient in terms of energy consumption than PVC.

Cosmetic gloves are useful for the user in terms of cosmetic appearance. As added benefits, the gloves may have other functions, depending on the materials used. The gloves can be used to protest the prosthetic device from water damage or dirt (Smit & Plettenburg, 2013). In general, it is important to consider that cosmetic gloves impose forces on the prosthetic hand regardless of the material and will require the user to expend additional energy (Smit & Plettenburg, 2013). It is also important to ensure that a cosmetic glove does not interfere with the intended function of the prosthetic hand. The user will still need to use additional force as a result of the presence of a cosmetic glove to use the hand. However, the cosmetic glove must not prevent the user from grasping an object or performing deliberate hand gestures. They may typically only be used for comfort and psychological advantages.

TESTING

Testing of prosthetic hands is necessary to ensure adequate functionality and consistency with use. It is also important to consider the availability of materials and manufacturing of prosthetic hand designs. Many methods of testing prosthetic hands, prosthetic hand sockets, and cosmetic gloves are available. One of the most common tests uses the Activities Measure for Upper-Limb Amputees (AM-ULA) (Mohammadi et al., 2020). This test establishes the main functionalities required for a certain prosthetic hand model. Table 5 below shows the items tested by the AM-ULA for X-limb, a soft myoelectric prosthetic hand (Mohammadi et al., 2020). During this study, 18 common tasks are given to the prosthetic hand users and the use of the prosthetic to perform each task is measured. Individuals are required to rate their ability to perform a task on a scale of 0-4; higher scores are correlated to increased functionality. The scores are given based on task completion, independence, skillfulness, time required, and quality of movement (Mohammadi et al., 2020). AM-ULA involves 11 bimanual and seven monomanual tasks, but individuals are permitted to complete bimanual tasks with one hand (Mohammadi et al., 2020). Required grasps are listed for each task to be performed. A pinch grasp involves abduction of the thumb meeting with the second digit. A power grasp involves all fingers positioned near the palm. During a tripod grasp, the thumb, second digit, and third digit meet. Testing using these parameters and tasks assumes that the three grasp types encompass all activities required for a functional prosthetic hand.

Table 5. AM-ULA Measurements for X-limb. [1]Percent the prosthetic performs the specific activity. Table taken from (Mohammadi et al., 2020).

#	Task	Using Prosthesis[1] (%)	Required Grasp
1	Attach end of zipper and zip	63.6	Pinch
2	Tie shoe laces	50.0	Pinch
3	Fold bath towel	43.1	Pinch
4	Use hammer and nail	42.2	Power/Pinch
5	Use scissors	35.0	Tripod
6	Button shirt	16.7	Pinch/Tripod
7	Put on T-shirt	11.5	Pinch/Tripod
8	Remove T-shirt	11.5	Pinch/Tripod
9	Use phone	6.8	Power
10	Use fork	6.6	Power
11	Use spoon	6.6	Power
12	Write name legibly	6.6	Tripod
13	Drink from paper cup	5.1	Power
14	Put on socks	3.4	Power
15	Brush/comb hair	1.6	Power
16	Pour soda/water	-	Power
17	Door knob	-	Power
18	Reach overhead	-	Power

In addition to functionality, force of the grasps must be tested to ensure efficient gripping. Grasp force testing was performed on several myoelectric prosthetic hand designs including i-Limb Pulse, i-Limb Ultra, BeBionic, SoftHand Pro, MANUS-Hand, Smart Hand, Remedi Hand, Fluid Hand III, Michelangelo, Sensor Hand, and X-Limb (Mohammadi et al., 2020). This was done using a force-sensitive resistor sensor in contact with two plates to measure both pinch and power grasp forces. As shown in Figure 15, the plates were placed either between the thumb and second digit for the pinch grasp or between the thumb and four fingers for the power grasp.

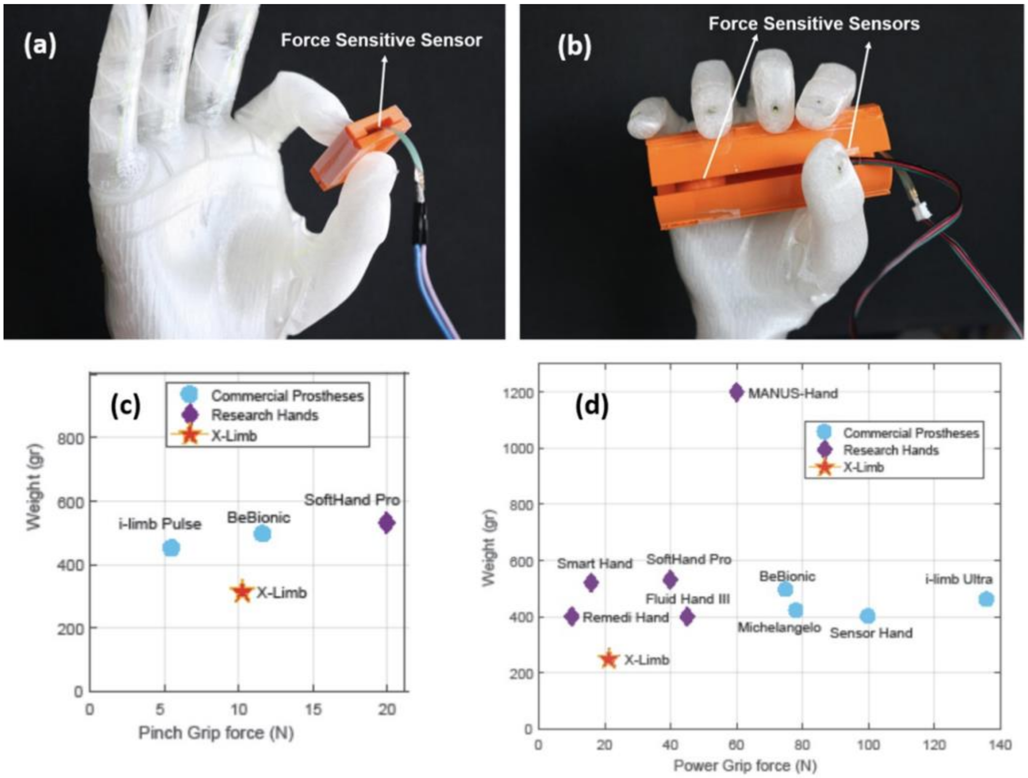


Figure 15. Grasp Force Testing. (a)-(b) Force-sensitive resistor sensor must be in constant contact with orange plates to provide an accurate reading. Pinch and power grip forces were measured for several commercial prosthetic hands, research prosthetic hands, and X-Limb. Figure taken from (Mohammadi et al., 2020).

There are many methods for testing prosthetic devices for different measures. Each test evaluates different parameters including functionality, force, feedback, and fitting time. Prosthetics currently in the market have been abandoned by users due to lack of control and feedback, diminishing functionality (Vujaklija et al., 2016). For this reason, new methods to control prosthetic hands are widely studied, either by enhancing commercial myoelectric designs or evaluating methods of obtaining control with sonomyography or electrocorticography. Prosthetics have been abandoned due to fragility and lack of flexibility, creating a burden on upper limb amputees and reducing efficiency (Vujaklija et al., 2016).

CONCLUSIONS

Currently, prosthetic hands face high abandonment rates resulting from several factors, including discomfort, training time, and functionality. This review evaluates the types of prosthetic hands: passive, surface and implantable myoelectric, body-powered, electrocorticographic, adaptive, and sonomyographic. In addition, an assessment of the methods of neural control and sensory feedback, two separate features, is important to recognize how the design of a prosthetic hand contributes to its functionality by the user. Biomaterials that compose a prosthetic hand relate to its comfort and use, promoting its abandonment or success. Finally, testing a prosthetic hand ensures its consistency and ease-of-use. Reviewing these characteristics highlights the important features of an optimal prosthetic hand, which would be designed to maximize functionality and comfort and minimize training time.

Lack of intuitive sensory feedback in prosthetic hands has also contributed to abandonment since relying solely on visual feedback is mentally tiring. For this reason, implementation of sensory feedback mechanisms including auditory, proprioceptive, mechano-tactile, and electro-tactile feedback is necessary to improve current models. Providing the user with electrical or pressure stimuli allows real-time feedback which improves efficiency and compatibility with everyday tasks.

Methods of neural control and sensory feedback can be further developed in future approaches to be more similar to the sensation of a natural hand. With these features in mind, an optimal prosthetic hand can be developed to meet the needs of individuals with upper limb amputations.

Nonetheless, it is important to note the reasons for abandonment of prosthetic hands. An ideal prosthetic considers these drawbacks of current prosthetic hand designs and users must evaluate comfort above all.

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