Recent Advances in Myoelectric Control for Finger Prostheses for Multiple Finger Loss

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Abstract: The loss of one or multiple fingers can lead to psychological problems as well as functional impairment. Various options exist for replacement and restoration after hand or finger loss. Prosthetic hand or finger prostheses improve esthetic outcomes and the quality of life for patients. Myoelectrically controlled hand prostheses have been used to attempt to produce different movements. The available articles (original research articles and review articles) on myoelectrically controlled finger/hand prostheses from January 1922 to February 2021 in English were reviewed using MEDLINE/PubMed, Web of Science, and ScienceDirect resources. The articles were searched using the keywords “finger/hand loss”, “finger prosthesis”, “myoelectric control”, and “prostheses” and relevant articles were selected. Myoelectric or electromyography (EMG) signals are read by myoelectrodes and the signals are amplified, from which the muscle’s naturally generated electricity can be measured. The control of the myoelectric (prosthetic) hands or fingers is important for artificial hand or finger movement; however, the precise control of prosthetic hands or fingers remains a problem. Rehabilitation after multiple finger loss is challenging. Implants in finger prostheses after multiple finger loss offer better finger prosthesis retention. This article presents an overview of myoelectric control regarding finger prosthesis for patients with finger implants following multiple finger loss.

Keywords: finger loss; hand loss; finger prosthesis; hand prostheses; prostheses; myoelectric control; dental implant

1. Introduction

Hands and fingers have a vital role in daily life for various functions and esthetics. The loss of a hand or finger (one or more) may be a result of trauma, disease, or congenital abnormalities. The loss of hands and fingers can lead to psychological problems, functional impairment, and social dysfunction [1]. Various options exist for replacement and restoration after hand and finger loss. For finger loss, the amount of tissue loss, the extent of finger loss (carpel, metacarpal, phalanges), and the number of fingers lost must be considered in treatment planning [2,3]. Prosthetic hand or finger prostheses improve esthetic outcomes and quality of life for patients. Passive hand or finger prostheses are mostly fabricated from silicone retained from adhesive or as implants that are robust and difficult or impossible
regarding movement. Such passive devices may be able to perform limited activities [4,5]; however, a bionic hand substantially improves the functional outcome [6].

There has been considerable development in the biomedical field due to the development of engineering and digital technologies [7–10]. Nowadays, commercial prosthetic hands are becoming advanced and offer a range of individual hand/finger movements. The use of myoelectrical control in hand prostheses to produce different movements is common in the literature [11–13]; however, the precise control of prosthetic hands or fingers is still a problem. Although different methods have been proposed to control a prosthetic hand or finger, the expected function is difficult to achieve. Various methods to command a prosthetic hand include a joystick, push buttons, keyboard, vision, speech, electromyography (EMG), electroencephalography (EEG), and electroneurography (ENG). Among all, electromyographical techniques are most commonly used in prosthetics. EMG is also sometimes called surface EMG (sEMG). This article presents an overview of myoelectric control for hand/finger prostheses in the context of multiple finger loss and the use of implants. In the market, various myoelectric hand prostheses are available but feature limited hand movement, control, and control speed. The motor cortex’s output through corticospinal projection is important in producing individuated hand/finger movements. The use of an implant in a finger bone can aid the retention of a myoelectrically controlled finger or hand prosthesis in producing different movements.

2. Methodology

Available articles on myoelectrically controlled finger/hand prostheses were reviewed from January 1922 to February 2021 using the MEDLINE/PubMed, Web of Science, and ScienceDirect resources in English. The articles were searched using the keywords “finger loss”, “hand loss”, “hand prosthesis”, “finger prosthesis”, “prostheses”, “myoelectric control”, “myoelectrically control”, and relevant articles were selected.

The inclusion criteria of the articles included original research articles and review articles in English from January 1922 to February 2021. The exclusion criteria for articles included case reports and editorial and commentary articles.

3. Signals and Finger Motor Function

Signals are important for the control of the myoelectrical (prosthetic) hands or fingers. Figure 1 shows a myoelectrically controlled hand prosthesis (designed in computer software), a design to collect EMG signals, and the generated signals [14].

The motor and sensory components of the hand provide an individual with high functionality and elegant behavior through a complex integrated system [15]. Human hands can perform numerous actions, varying from handling heavy objects to fine digital movements while directly connecting with the brain. It would ideal if similar movements can be performed by prosthetic hands and fingers. An intelligent interface that controls prosthetic hands and fingers can suggest movement by interpreting a muscle’s electrical activity via the surface EMG signal [16,17]. Figure 2 shows a myoelectrically controlled hand prosthesis, the generation of signals, and EMG channels [6]. The myoelectric activities of the residual limb for the phantom limb movements (PLM) may help for pattern recognition in the context of myoelectrical control [17].

Finger movements require specific stimulation of a group of muscles [18]. Such stimulation is principally controlled by the motor cortex through the corticospinal tract. The motor cortex’s output operates via corticospinal projection, which is important for the movements of the finger. Normally, an action potential propagates and activates a motor neuron which in turn activates the muscle fibers. When the depolarization of the postsynaptic membrane of muscle fiber takes place, the depolarization spreads along the fiber supplemented by the movement of ions and generates an electromagnetic field [19]. Myoelectric or EMG signals are read by microelectrodes and the signals are amplified, from which the muscle’s naturally generated electricity can be measured [16]. The signals are assigned to control the movement of the prosthesis after processing. Specific EMG pulse
sequences are linked to a specific movement of the prosthesis. The predefined movements are controlled by specific signals [20].

**Figure 1.** Myoelectrically controlled hand prosthesis designed in computer software, a design to collect the electromyography (EMG) signals, and sample generated signals [14].

**Figure 2.** Active myoelectrically controlled hand prosthesis, generation of signals, and signals in the electromyography (EMG) [10].
The effectiveness of prosthetic hands can be assessed by user performance when performing functional tasks. Chadwell et al. [21] compared the upper limb activity between myoelectric prosthesis users and normal adults and found that temporal patterns in upper limb activity were present. It was also found that prosthesis users were greatly reliant on their intact limbs for daily activities. There was no significant correlation between the kinematic and the gaze-related performance between myoelectric prosthesis users and normal adults.

Access to the neural control information for an arm is lost during amputation. Hence, improving the function of hands or finger prosthesis poses a challenge. Various invasive methods have been proposed to generate proper signals for myoelectrical prostheses, such as peripheral nerve signal transmission [22], motor cortex [23], or targeted muscle reinnervation (TMR) [24] methods. In TMR, the muscle of the amputee is reinnervated with the residual nerves of the amputated limb. Following the reinnervation, the target muscles produce EMG signals, and these signals can control the prosthetic hand/arm and have promising results [25]. Engdahl et al. [26] studied four types of control for a prosthetic hand (TMR, myoelectric, cortical interfaces, and peripheral nerve interfaces) in upper-limb amputees and found that the participants showed a maximum positive response for the myoelectrical interface, while they showed the least interest for the cortical interface. More skillful individual and combined finger control has not yet been gained [27]. Khushaba et al. [27] investigated the accuracy of individual and combined finger movements using surface EMG signals using Bayesian data fusion in postprocessing for the proper classification of EMG data belonging to different movements. Similarly, Isaković et al. [28] purposed a feedback interface for a myoelectric prosthesis with multiple degrees of freedom that allows proprioceptive and sensory information (i.e., the grasping force). In this method, nine subjects performed a sequential algorithm in a time comparable to that reported when performed by experts and found that amplitudes can be significantly streamlined to a quarter of initial time without reducing the outcome when using prior knowledge in setting the baseline stimulation.

Atzori et al. [20] studied the natural control of robotic hands via sEMG using healthy subjects and amputees. A neural network was used to evaluate the effects of the pre-processing, layer architecture, data augmentation, and optimization. The results show that convolutional neural networks with simple architecture can produce precise results comparable to the average classical classification methods. They also show that several factors (pre-processing, net architecture, and parameters for optimization) are important for the analysis of sEMG data. More accuracy for computer vision and object recognition tasks is seen with larger networks.

Recently, multimodal data acquisition has been applied for the EMG-based detection of hand/finger movement [20,29–31]. Accelerometers can be combined with EMG electrodes to produce excellent capabilities to recognize hand movements [32]. Similarly, convolutional neural networks and deep learning have revolutionized machine learning, computer vision, and speech recognition. Deep learning is used in deep neural network applications and reinforcement learning to maximize the performance of a machine or software agent by itself making errors [33]. The neural networks have been applied to EMG hand movement recognition. The highest accuracy can be seen when combined convolutional neural networks with the retrained network. Table 1 shows the summary of developments in myoelectric finger prostheses and research outcomes.
Table 1. Summary on the developments in myoelectric finger prostheses.

| Year       | Developments                                                                 | Study                                                                 |
|------------|------------------------------------------------------------------------------|----------------------------------------------------------------------|
| 1922       | Passive hooks and shoulder harness were designed by Weimar.                   | [34]                                                                |
| 1948       | The concept of the prosthesis ideally should replace not only mechanical function but also cutaneous and kinesthetic sensation. | [35]                                                                |
| 1948       | Myoelectric control was first implemented by Reinhold Reiter, a physics student at Munich University and patent application. | [36]                                                                |
| 1968       | The first commercial myoelectric hands were available from the middle of the 1960s. | [37]                                                                |
| 1968       | The concept of natural appearance during function “dynamic cosmesis” which contributes to the complexity of design both in terms of segmental trajectories and in terms of mechanical noise is highlighted. | [38]                                                                |
| 1970 onwards | Various advancements in the Myoelectric control prostheses through research and training systems. Availability of advanced commercial limb prostheses, such as the i-Limb from Touch Bionics, BeBionic from RSL Steeper, and Michelangelo by Ottobock. | [11,14,19–21,24,39–42]                                           |

Furthermore, EMG-driven prosthesis performance is influenced by various factors, such as electrode position shifting, varying muscle contraction levels, forearm orientation, and limb position [16]. In addition, Khushaba et al. [16] investigated the combined effect of forearm orientation and muscle contraction levels on the generalizability of EMG pattern recognition. They first verified whether the subjects could produce EMG activity in all different classes of movement at three muscular contraction levels (low, medium, and high) by analyzing the RMS of EMG activity across all channels, orientations, and movements. Figure 3 shows the representative radar plot of the EMG signals RMS values collected from one subject performing wrist flexion (C4) when the wrist was fully pronated. The RMS values from the different channels were then grouped in separate columns for each force level, thereby constructing an RMS matrix. They found a significant difference ($p = 0.003$) between the means of the different force levels. They also mentioned that multiple factors can influence the accuracy of EMG pattern recognition.

![Figure 3](image_url)  

**Figure 3.** The results of root mean square (RMS) of the electromyogram (EMG) signals from six channels through flexion of the wrist at three different levels [16].

There are various myoelectric prostheses available in the market. Some commonly used models are iLimb, Vincent Hand, iLimb Pulse, SensorHand, BeBionic, BeBionic V2,
and Michelangelo [43–47]. Table 2 shows the details of the myoelectric hand/finger prostheses.

| Developed Year | Name          | Producer       | Size                                                                 | Number of Joints | Degree of Freedom | Joint Coupling Method                          | Study |
|----------------|---------------|----------------|----------------------------------------------------------------------|------------------|-------------------|-----------------------------------------------|-------|
| 2009           | i-Limb Touch  | Bionics        | 180–18-mm-long, 80–75-mm-wide, 35–41-mm-thick                       | 11               | 6                 | Tendon linking MCP to PIP                      | [43]  |
| 2010           | Vincent Hand  | Vincent Systems| -                                                                     | 11               | 6                 | Linkage spanning MCP to PIP                    | [44]  |
| 2010           | i-Limb Pulse  | Bionics        | 180–182-mm-long, 80–75-mm-wide, 35–45-mm-thick                      | 11               | 6                 | Tendon linking MCP to PIP                      | [43]  |
| 2011           | SensorHand    | Otto Bock      | Glove sizes                                                          | 2                | 1                 | DC Motor Worm Gear                             | [45]  |
| 2011           | BeBionic      | RSL Steeper    | 198-mm-long, 90-mm-wide, 50-mm-thick                                | 11               | 6                 | DC Motor Worm Gear                             | [46]  |
| 2011           | BeBionic V2   | RSL Steeper    | 190–200-mm-long, 84–92-mm-wide, 50-mm-thick                         | 11               | 6                 | DC Motor Lead Screw                            | [46]  |
| 2012           | Michelangelo  | Otto Bock      | -                                                                     | 6                | 2                 | -                                             | [47]  |

### Table 2. Various myoelectric hand/finger prostheses details.

4. Cosmetic Gloves for Myoelectric Prosthetic Hand or Fingers

Humiliation arising from the use of a prosthetic finger or hand has been considerably reduced because of esthetic improvements. Coverings and gloves have been developed to approximate natural skin tones and they allow visualization of the metallic infrastructure beneath. There are different passive prosthetic gloves available for finger/hand rehabilitation such as electrically powered, activity-specific, body-powered, and hybrid models. A body-powered glove is durable as it is directly driven by body parts (joints and wrist). The cosmetic gloves for myoelectric prosthetic hands can be made from various superelastic rubbers, such as silicone rubber (TSG silicone), a thermoplastic styrene elastomer (TSE), or polyvinyl chloride (PVC) for a realistic appearance and support for flexible motion. Figure 4 shows the silicone prosthesis for finger and hand finger rehabilitation.

![Figure 4. Rehabilitation of finger and hand defects using silicone prostheses: (a) finger prosthesis and (b) hand prosthesis.](image-url)
Yabuki et al. [48] compared TSE, TSG silicone, and PVC gloves for myoelectric prosthetic hands. They found that the differences were small and showed a similar range of motion. The flexible TSE resulted in easy fitting with the lowest fitting time and was hard to break and featured convenient elasticity. Both TSG silicone and TSE gloves showed similar results for grasping objects in pick-and-place experiments. Furthermore, TSG resin is a thermoset material and can be processed at room temperature. Therefore, the TSG silicone material was more suitable for implementing a sensor.

Similarly, Sareen et al. [49] fabricated a prosthetic glove prototype from polylactic acid using 3D printing for hand rehabilitation. The best design prototype was a half-ring servomotor-operated design which is easily adjustable with varying patient finger dimensions. The prototype could produce finger movements using strings attached to servomotors. In addition, this device could be integrated with force-sensitive resistors and controllers for different disability levels; however, the durability of the coverings requires diligent care and adds further costs to the prosthesis.

5. Osseointegrated Implant Retained Myoelectric Prosthesis

Retention is one of the key factors in the success of a myoelectric finger prosthesis for functions such as grasping, carrying, and holding [50]. A friction or adhesive-retained finger prosthesis cannot provide adequate retention. Bone-anchored osseointegration was originally investigated by the Swedish dentist Per-Ingvar Brånemark [51]. An osseointegrated implant retained finger prosthesis offers better retention and helps in different functions [52,53]. Figure 5 shows implants in a finger bone used for the retention of finger prostheses. In two cases, dental implants were placed in the finger bone to retain the silicone prosthesis. In case 1 (Figure 5a,b), a single implant of 5 mm in diameter × 17 mm in length (Osseo Speed, Astra Tech, Molndal, Sweden) was placed in the bone inside the medullary canal with an insertion torque of 40 Ncm for the thumb for single finger loss, whereas in case 2 (Figure 5c,d), three implants of the same size and same insertion were placed on each middle, ring, and little finger thumb for multiple finger loss. Radiographs were taken to verify the position of the implant. Customized metal abutments were fabricated to aid the retention of the silicone prostheses. The mode of retention of the silicone prostheses was friction retained with the metal abutment.

![Figure 5. Implants placed in finger bones for the retention of finger prostheses: (a,c) implants in finger bones in an X-ray and (b,d) implants in finger bone clinically.](image-url)
Finger bone implants also help to reduce the prosthesis failure rate [54]. In addition, osseointegrated implants improve functionality, durability, and freedom of movement in the prosthesis, as well supporting vibrotactile and pressure feedback secondary to osseoperception [55–58]. Osseointegration considers many complications and restrictions inherent to socket-based prostheses, particularly among patients with compromised soft tissue envelopes (e.g., decreased tissue compliance, history of skin grafting, persistent ulceration, or wounds, underlying heterotopic bone, painful neuromas) or a short residual limb [59]. It also eliminates issues related to socket fit and signal transduction between the myositis and the electrodes, improving the efficiency of these devices.

Excellent development in osseointegration arises from the incorporation of motosensory devices into the implant itself [59]. An example of such a device is e-OPRA (Integrum, Sweden), which contains a bidirectional interface using electrodes integrated with the device to improve control of the osseointegrated prosthesis. Currently, clinical trials are being conducted on the e-OPRA device in the USA and are expected to complete by January in 2023 [55]. It has been shown that promising results with more reliability and precision for implanted electrodes than surface electrodes can be found among transhumeral amputees [60,61]. Mastinu et al. [62] studied grip control and motor coordination in three transhumeral amputees with the e-OPRA device. The synergy between bone-anchored devices, advanced neuromuscular interfaces, and targeted muscle reinnervation can significantly improve the sensory and motor function of advanced prostheses.

The main limitation of the above techniques for finger prostheses is that they cannot permit active pronation, supination, flexion, and extension. The use of an implant in the finger bone can aid the retention of myoelectrically controlled finger prostheses regarding finger movements.

6. Discussion

There has been a significant improvement in finger and hand prostheses from passive hooks and shoulder harnesses to myoelectrically controlled prostheses [34,43,45,46]. At present, there are various myoelectrically controlled commercial prosthetic hands in the markets and they offer a range of individual hand/finger movements [11–13]. Some commonly used models include the i-Limb, Vincent Hand, i-Limb Pulse, SensorHand, BeBionic, BeBionic V2, and Michelangelo models [43–47]. Still, the precise control of prosthetic hands or fingers is a problem.

The myoelectric activities of the residual limb for phantom limb movements help for the pattern recognition regarding myoelectric control and intelligent interfaces can control prosthetic hands and fingers, which can suggest finger and hand movement. The signals are assigned to control the movement of the finger/hand prosthesis. The muscle’s electrical activity can be interpreted by the sEMG signal [16,17]. Several factors (pre-processing, net architecture, and parameters for optimization) are important for the analysis of sEMG data. More accuracy on computer vision and object recognition tasks is seen with larger networks [20].

Osseointegrated implants in retained finger prosthesis offer better retention and help in different functions [52]. In addition, osseointegrated implants improve functionality, durability, and freedom of movement in the prosthesis, as well vibrotactile and pressure feedback secondary to osseoperception [54–57]. An example of this is grip control and motor coordination in three transhumeral amputees with the e-OPRA device [60]. The synergy between bone-anchored devices, advanced neuromuscular interfaces, and targeted muscle reinnervation can significantly improve the sensory and motor function of advanced prostheses.

7. Future Perspectives in Myoelectric Prosthesis

Currently, although myoelectrical prosthetic fingers/hands in the market feature advanced mechanics, the control methods are still rudimentary in most cases. Most myoelectrical hand prostheses lack somatosensory feedback and 100% control robustness,
cannot provide sufficient control speed, and are incapable of reproducing various hand movements [20,28]. Hence, they are not sufficient for many real-life applications. The main reason for the lacking robustness is the motion artifacts which typically occur in the low-frequency range [63]. Real-time motion artifact suppression algorithms can be used on an ultra-low-power microcontroller to achieve high robustness.

All myoelectrical control-based prosthetic hands may not have similar operations and exhibit variations in sensing input, deciphering signals, and actuating prosthetic hands [64,65]. The factors that influence myoelectrical fingers/hand prostheses are the shape of the first layer of the network, initial weights of the layers, data augmentation procedures, and the learning rate [20]. The EMG architecture can be made more complex and can be trained with EMG data to produce higher accuracy. Further research and development are necessary for precise control of various prosthetic hand movements with sufficient speed and robust control.

8. Conclusions

Motor cortex output through corticospinal projection is important in producing individuated finger movements. In the market, various myoelectrical hand prostheses are available but feature limited hand movement, control, and control speed. The use of a finger bone implant can aid the retention of myoelectrically controlled finger or hand prostheses regarding the production of different movements. Further research and development are necessary for the precise control of various prosthetic hand movements with sufficient speed and robust control.

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