Myoelectric motor execution and sensory training to alleviate chronic pain and regain movement in a paralyzed arm after an arm replantation: a case study

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Abstract

Background

Following upper limb amputation, surgeries such as arm transplantation or replantation might be an option to restore function. After such surgeries, rehabilitation of the arm is needed. However, conventional rehabilitation is dependent on some volitional movement of the arm. If there is no or minimal movement of the arm, conventional rehabilitation might not be successful. The purpose of this study is to evaluate a novel combination of myoelectric motor execution (MME) and sensory training to reduce pain and improve upper limb function in a person with a highly impaired replanted arm.

Methods

The participant, a 72-year-old male, had his right arm replanted after a traumatic accident. No functional recovery was achieved following conventional rehabilitation and chronic neuropathic pain developed post-surgery. The participant then received 18 sessions of MME in which intended movements were decoded from the replanted arm's myoelectric signals using machine learning and real-time feedback was provided on a screen. Nine sessions included sensory training using tactile grids where the participant discriminated different sensations.

Results

The participant regained active extension of the thumb (4 degrees), and regained active wrist movement (flex: 6 degrees, extend: 10 degrees), both of which were completely paralyzed prior the MME interventions. He also regained sensation in the thumb and fingers, and had a reduction in pain (weighted pain distribution 2.47 to 1.7)

Conclusion

MME is a novel virtual rehabilitation treatment which provides feedback using virtual limbs and serious games. MME combined with sensory training is a potential rehabilitation treatment for individuals with highly impaired arms which might ameliorate chronic neuropathic pain.

Introduction

After a major upper limb amputation, there are different options for restoring the function of the lost arm and hand. Traditionally, prosthetic devices can be fitted to the residual limb, but the abandonment rate is around 50% (1), and most prosthetic hands only offer one grasping function (single degree of freedom). An alternative solution is to replant the amputated limb. Replantation is possible if the amputated limb has not been severely crushed and not exposed to prolonged normothermic ischemia time (2). When a traumatic amputation has occurred, replantation should always be considered. An experienced hand surgeon with microsurgery skills can determine if replantation is feasible considering the prognosis of function, pain, and sensibility.

The benefit of limb replantation over a prosthesis is that sensory feedback, including proprioception, is possible and the replanted hand is usually more functional than a prosthetic one (2). Furthermore, cosmesis is preserved with a replantation and there is no discomfort from wearing a prosthesis. Recent reviews found that patients who had the arm replanted were more satisfied and had higher patient reported outcomes, such as upper limb function, compared to patients who received a prosthesis (3, 4). However, the limb replantation surgery is complex and post-surgical
rehabilitation is lengthy. Furthermore, hand function and sensation is not guaranteed and since the nerves are severed and then surgically repaired, there is a risk that chronic neuropathic pain will develop (5).

Neuropathic pain is also common among individuals with upper limb loss. In this population, the pain is often referred to as phantom limb pain (PLP), which is pain felt in the lost limb. Similarly to the neuropathic pain experienced by arm replantation patients, the pain is often chronic and difficult to treat. To date, there is no treatment that effectively relieves PLP in the various existing cases, but a recent treatment called Phantom Motor Execution (PME) has shown promise in clinical trials (6, 7). PME uses myoelectric pattern recognition to decode the movement of the phantom limb by classifying patterns of electromyographic activity from the residual limb. The output of the pattern recognition algorithm is used to control a virtual limb on a screen or to control video games. PME showed a reduction of about 50% after 12 sessions in patients with chronic intractable upper limb PLP, who suffered it for an average of 10 years. The cause for PLP is unknown, but several hypotheses exist (8). The stochastic entanglement is a recent hypothesis based on dynamical systems theory and states that severe impairment of the sensorimotor system can perturbate the somatosensory circuitry into a pathological state in which pain is processed despite the lack of noxious stimuli (6). Alleviating pain thus requires that the affected sensorimotor circuitry is purposefully and sufficiently engaged in the absence of pain to weaken their pathological and joint processing. We hypothesize that the origin of chronic pain caused by arm replantation is similar to that of PLP and can therefore be treated in an analogous manner.

Another treatment which has been explored to alleviate PLP is sensory training (9). Sensory training (ST) improves the participant's ability to discriminate different spatial and temporal somatosensory stimuli. According to the stochastic entanglement hypothesis, the combination of PME with mindful sensory training should be superior to PME alone, as both motor and sensory processing are targeted (6).

In this single-case design study, we combine a novel PME-like treatment with sensory training, named Myoelectric Motor Execution (MME) to treat chronic pain and restore function in a patient who had an arm replantation. The patient had his arm replanted at Sahlgrenska University Hospital, Sweden. After surgery, the patient reported pain which became chronic, and he had no function in the replanted hand and wrist. Following revision surgeries, the patient underwent extensive rehabilitation, but no improvement in pain or function were achieved. We therefore decided to investigate if MME and sensory training could alleviate pain and potentially improve the function in the paretic arm and hand, given that guided motor execution would be continuously attempted as part of the interventions. The research questions of this study were directed to the possibility of using MME and sensory training to 1) alleviate pain and 2) improve function of a highly impaired replanted arm.

Methods

Participant

The participant was a 72-year-old male who had the right arm amputated above the elbow joint due to trauma. Subsequently, the participant had the arm replanted. Following surgery, the participant had almost no sensation in the arm and poor hand and wrist function. To achieve grip function, a free gracilis muscle was surgically attached, but the vessels clotted, and the resulting wrist movement was limited. In a revision surgery, a tendon transfer of brachioradialis was performed. The brachioradialis was transferred to the wrist and a passive thumb by tenodesis of the flexor pollicis longus to the radius. The aim was to obtain better wrist and grip function. The brachioradialis muscle was weak (Medical Research Counsil scale of 3) and the patient had to go through release of massive adhesions and tenolysis due to the previous operations. This resulted in a poor outcome of the last surgery. Osteoarthritis in the wrist was observed. Given the lack of somatosensory feedback in the hand, the patient reported to experience a phantom hand sometimes disassociated to the replanted one. Due to a combination of age, diabetes, and vascular disease, it was
decided not to perform any additional revision surgeries. All surgeries were performed at Sahlgrenska University Hospital in Mölndal, Sweden.

Neuropathic pain was one of the major issues after the first surgery. Pain management, physiotherapy, and sensory training were extensively done from the first surgery. The participant was given Gabapentin, Paracetamol, and Oxycontin to reduce pain. The participant went through 12 weeks of physio- and occupational therapy but did not regain any function. The replanted arm would sometimes swell, which was treated with elastomull bandages wrapped around the limb to provide compression.

The current study was approved by the Swedish Ethics Authority (Dnr.: 2020–07150). The participant was informed about the study and signed informed consent prior enrolment.

Intervention

Training protocol

The treatment consisted of 20 sessions. Session 1 and 20 were assessment only, and no training was performed. Sessions 2 to 10 were MME only and sessions 11 to 19 consisted of MME and sensory training. In sessions 11 to 19, 75% of the time was spent on MME and the remaining time on sensory training. Sessions 6, 11 and 20 started with the monofilament test to assess sensory acuity (see outcome measures). In general, the participant had two sessions per week, but there were periods where the participant was not available, so there were weeks with one or no sessions. There were 84 days between the first and the last session. Each session took approximately two hours including breaks.

Myoelectric Motor Execution (MME)

MME was based on PME (7, 10), but here the patient attempted to move the affected physical limb instead of a phantom limb. Electrodes were placed in the affected limb to record the attempted muscular contractions. The resulting myoelectric signals were analyzed using a pattern recognition algorithm that inferred the intended movement (see decoding of movement intend). MME entails four steps:

1. The electrodes, up to eight pairs, are placed on the skin surface above the muscles in the affected limb.
2. The movements that are going to be trained are selected.
3. The participant performs a recording session, where the participant attempts to execute the selected movements while observing a virtual limb performing the same movement. Myoelectric signals are recorded during this process and used to train the pattern recognition classifier.
4. Training activities such as freeform virtual limb control, match testing, or gaming are performed with the participant in control. The quality of the control depends on the signals recorded during the recording session.

The participant started with movement such as pronation, supination, and flexion and extension of the wrist. Only one degree of freedom (DoF) was performed at a time. Pronation and supination were trained specifically to strengthen the brachioradialis muscle. The participant would sometimes perform movements bilaterally, to aid movement of the replanted arm. In later sessions, thumb extension was trained. Due to the surgeries, the participant needed to learn how to contract the brachioradialis to extend the thumb. The therapist guided the participant to achieve this with radial deviation performed bilaterally. In later sessions opening and closing of the hand was trained since the participant reported he could perform this movement with his phantom.

Sensory training (ST)
For sensory training, we employed a device with two tactile displays each consisting of 16 tactors arranged in a 4x4 grid with an inter-tactor distance of one cm which is strapped around the affected limb. Each tactor can be pushed towards the skin, allowing for different stimulation patterns (11). In addition, each grid can vibrate up to 250 Hz. During sensory training, the participant performs different activities:

- **Familiarization**: The participant was stimulated by different vibrotactile modalities without being asked to discriminate between them.

- **Sensory tasks**: In the sensory discrimination tasks, the participant was presented with different small quizzes where the participant must discriminate between two types of stimuli. An example is “Fast or Slow” where the participant is given a slow vibrating stimulus, a fast-vibrating stimulus, and then a stimulus without label, and is then tasked with identifying whether the unlabeled stimuli was fast or slow. The participant can repeat the slow, fast, and unlabeled stimuli as many times as desired. Similar discrimination tasks exist for touch patterns, where an example could be that the participant must identify which column of tactors were activated.

- **Vibration game**: In the vibration game, the participant was presented with a vibration which must be identified on a scale from slow to fast of at least four possible vibrations. The participant can feel the target vibration and all the vibrations on the scale as many times as they want.

- **Memory Game**: In the memory game, the participant was presented with up to 12 cards depending on the difficulty level. The cards are presented face down and the participant must find the matching pair. Every time a card is turned, a sensation is felt (can be vibration or touch). When the participant turns two cards after each other that give the same sensation, they are considered a match and are removed. The game ends when all matching pairs have been found. The participant in this study played the easy and medium difficulty levels with 8 and 12 cards respectively.

Initially, the tactile grids were placed below the elbow with a grid on the radial and ulnar side of the forearm (see Fig. 1). In later sessions, a grid was placed on the palmar side of the thumb. Since the participant reported pain from light touch (allodynia), there was concerns about sensory training being painful. However, the participant did not perceive pain and found sensory stimuli provided by the tactile displays to be pleasant like a massage. Sensory training was performed with the device described in (12).

**Decoding of movement intend**

To decode movement intend, eight channels of myoelectric signals were recorded at 1 KHz and transmitted wirelessly to a laptop computer using the ADS_BP4 (13). The signals were filtered and overlapping time windows with a window length of 200 ms with an increment of 50 ms were extracted. The features mean absolute value, wavelength, zero crossings, and slope-sign changes were calculated for each window and used to train a linear discriminant analysis classifier. This method can decode movement intend in individuals who have almost no voluntary movement of the limb.

**Outcome measures**

For tracking changes related to pain the Q-PLP questionnaire was filled in after every session. Q-PLP was designed specifically to track phantom limb pain and was chosen as the patient reported some phantom phenomena (7). All questions related to prosthetic use or residual limb pain were skipped. The level of pain was also recorded using the Weighted Pain Distribution (WPD) (10). The WPD captures the percentage of time spend in six pain levels (scale none to excruciating, 0 to 5) by adding up six weighted portions with higher pain levels being weighted higher.
At every assessment session, the ROM was measured using a goniometer. For tracking changes in sensory perception, the Semmes-Weinstein monofilament tests (14) was used in an exploratory fashion. Commonly, starts by stimulating the participant with the smallest probe and increase the probe size until the participant reports sensation in the stimulated location. However, the participant had referred sensations from the stimulation and it was decided to continue to increase the probe size to see if it had an effect on the referred sensation.

Results

Weighted Pain Distribution and Numeric Rating Scale

The Weighted Pain Distribution (WPD) fluctuated throughout the study, but decreased at the final session. See Fig. 2. The Numeric Rating Scale (NRS) of current pain fluctuated to a higher extent than the WPD and had not decreased at the final session. See Fig. 2. For both measures an initial increase was observed, which has been observed with PME (10)

Range of motion

ROM increased in all measured joints of the affected arm. Note that some joints initially had no active motion but gained active motion at later sessions. See Table 1.

Table 1
Active and passive ROM of the wrist and thumb in degrees for the affected hand.

<table>
<thead>
<tr>
<th></th>
<th>Session 6</th>
<th>Session 11</th>
<th>Session 20</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wrist</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flex</td>
<td>36</td>
<td>73</td>
<td>73</td>
</tr>
<tr>
<td>Extend</td>
<td>34</td>
<td>33</td>
<td>35</td>
</tr>
<tr>
<td>Active</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flex</td>
<td>0</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Extend</td>
<td>0</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td><strong>Thumb</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flex</td>
<td>22</td>
<td>27</td>
<td>34</td>
</tr>
<tr>
<td>Extend</td>
<td>26</td>
<td>27</td>
<td>56</td>
</tr>
<tr>
<td>Active</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flex</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Extend</td>
<td>0</td>
<td>0</td>
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</tr>
</tbody>
</table>

Monofilament
The results from the monofilament test are shown in Fig. 3 and Table 2. Note how the application site and the location of the sensation vary widely (e.g. applications at the proximal part of the forearm were felt in the hand). There was considerable variability between the assessments. Referred sensations moved from the dorsal side of the hand to the palmar side in between assessments (e.g. purple area Fig. 3), and hardly any point from the first assessment was found in the last assessment. Stimulations in the green area were initially only felt in one location of the hand (Fig. 3A), but later also felt in multiple locations of the hand, arm, and stimulated area (Fig. 3B) and finally only in the stimulated area (Fig. 3C) meaning that referred sensations were replaced with expected sensations. Sensations also developed in the hand (e.g. yellow area) and thumb (i.e. blue area).

### Table 2

| Minimal detectable monofilament for each application site following the colors used in Fig. 3. NS = No sensation. |
|---|---|---|
| Session 6 | Session 11 | Session 20 |
| Orange | 4.93 | 4.56 | 4.17 |
| Purple | 4.93 | 4.08 | 4.56 |
| Green | 5.18 | 4.31 | 4.08 |
| Pink | 4.93 | 4.74 | 3.84 |
| Petroleum green | 4.56 | 5.46 | 4.31 |
| Blue | NS | 5.07 | 4.56 |
| Yellow | NS | NS | 4.56 |

However, the minimal detectable stimulation with a monofilament decreased for most sites which indicates that sensory perception improved during the treatment.

**Discussion**

In this study, we found that MME modestly reduced pain and allowed for the participant to regain movement in joints that were paralyzed after arm replantation, where conventional physio- and occupational therapy had no effect. One benefit of MME is the provision of real-time feedback, even in the absence of limb movement. Artificially presented bio-feedback is especially important for participants who have little or no limb movement, as they receive limited somatosensory feedback from their own limb. Feedback might help these participants to become mindful of their limb and movement capabilities. MME is therefore especially suited for cases such as the one presented in this study, namely, highly impaired. In future studies, we aim to treat other sensorimotor impairments in larger samples and with appropriate control groups.

Sensory training in this study was primarily applied for pain alleviation and as a supplement to improvements in ROM. While the participant commented that he felt temporary alleviation directly after sensory training, the contribution of sensory training to the results cannot be established since no trend in pain measures was observed after its introduction in session 11. However, the participant did improve on the monofilament test and could detect smaller monofilaments after training. This indicates that sensory training improved sensory acuity, but not enough to impact pain or function in this particular case.

MME led to improved ROM for the participant in this study, especially for the thumb which was initially paralyzed but later mobile. However, the achieved ROM was not sufficient for using the replanted arm in activities of daily living.
Nevertheless, the improvements in ROM might be sufficient for using an assistive device which can provide grip function. Grip function would presumably allow the participant to use the replanted arm in activities of daily living as a support for the non-affected arm. One such activity could be playing golf, which was his favorite hobby before the accident. Furthermore, if the replanted arm can support the non-affected arm, the strain on the non-affected arm will reduce. Reducing the strain on the non-affected arm could reduce the risk for musculoskeletal complications arising from overuse of the non-affected arm, which is seen in one-handed individuals (15).

In future work, we intend to make the implementation of MME intuitive and user friendly to such a degree that participants could conduct training by themselves after a short introduction. This will allow for rehabilitation for individuals with sensorimotor impairments in the home setting, which in turn might increase training exposure along with the possibility of long-term improvements. As many countries are faced with an ageing population (16) and thereby increasing the need for rehabilitation therapists, digitally-enabled therapies like the one presented here might reduce strain on healthcare resources.

The limitations of this study are the lack of qualitative assessments, follow-up, and the inherent limitations of a study with one participant.

Declarations

Ethics approval and consent to participate
The current study was approved by the Swedish Ethics Authority (Dnr.: 2020-07150). The participant was informed about the study and signed informed consent prior enrolment.

Consent for publication
Consent for publication of anonymized data was obtained from the participant as part of the informed consent form that was signed prior enrolment.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

MB and MOC are inventors in a pending patent related to the technology used in this study. No conflicts of interest have been reported by the remaining authors.

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Author’s contribution

Conception: CR, MOC. Design: MBK, MMN, MB. Acquisition, interpretation of data, analysis of data: MBK, MMN, MB, ME. Drafting of the article: MBK. All authors approved the final version. All authors agree to be accountable for all aspects of the work.

References
Figures

Figure 1

Left: The participant during MME playing a serious game. Right: The participant during sensory training.
Figure 2

Left: Weighted Pain Distribution. Bars shows the percentage of time the participant was in different levels of pain as indicated by the color distribution of the bars. The WPD is plotted as a line. Right: Change in pain measured with the Numeric Rating Scale (NRS).

Figure 3

Raw data from the monofilament test from the affected arm from the ventral and dorsal side. Circles refer to application site and crosses of the same color appertain to the location of the referred sensation from stimulation to that application site (e.g. green crosses represents the referred location from stimulation in the green circle). Numbers refer to monofilament thickness in millimeters. Grey circles refer to application sites which did not have a sensation. Data is
from a) session 6, b) session 11 and c) final assessment session. Note that no sensory training occurred between session 6 and 11.