A Sensory Feedback System
Utilizing Cutaneous Electrical Stimulation
for Stroke Patients with Sensory Loss

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Abstract - Sensory disturbance is very common following stroke and may exacerbate a patient’s functional impairment, even if the patient has good motor function. For instance, patients with sensory disturbances will often grip an object with excessive or underestimated pinch pressure, because they do not receive the appropriate sensory feedback and must rely only on visual feedback. In this study, we developed a sensory feedback system that used cutaneous electrical stimulation for patients with sensory loss. In the system, electrical stimulation is modulated by the strength of pinch pressure and the patients are able to identify their fingertip pinch pressure. To evaluate the efficacy of the system, a clinical case study was conducted in a stroke patient with severe sensory loss. The fluctuation in force control during grasping was gradually decreased as the training progressed and the patient was able to maintain a stable pinch pressure during grasping even without the system following 2 months of intervention. We conclude that the system described in this study may be a useful contribution towards the rehabilitation of patients with sensory loss.

Keywords-component: sensory feedback; stroke; sensory loss; rehabilitation; cutaneous electrical stimulation

I. INTRODUCTION

There are 1.37 million stroke patients in Japan and this number continues to increase [1]. For a significant number of these patients, the upper extremity will be affected, with about 70% of patients experiencing altered arm function and about 40% of patients losing use of the arm. A great deal of time and effort is required to rehabilitate the affected limb and patients are often very focused on recovering as much arm function as possible once they have regained some mobility [2].

In addition to motor deficits such as weakness and inappropriate co-contraction, sensory disturbance is a very common impairment following stroke. Severe sensory loss may inhibit the ability of patients to use the affected hand in daily activities, even when they have good motor function [3]. For example, stroke patients with sensory loss might grip an object with excessive or underestimated force because of inadequate sensory feedback.

However, a review examining 13 interventions for sensory impairment concluded that there is insufficient evidence to support or refute the efficacy of these intervention strategies in improving sensory impairment, upper limb function, or the participants’ functional status and participation [4]. Although preliminary evidence was described for some of these specific interventions, which included mirror therapy, thermal stimulation and intermittent pneumatic compression intervention, the effects were limited to improving sensory impairments such as the detection of light touch, pressure, and temperature pain. Furthermore, the effect on upper limb function was not clear.

Several recent studies have proposed training systems that utilize the visual feedback of hand force during manipulation to improve hand function of stroke patients including, but not limited to, patients with sensory loss [5-7]. For instance, Seo et al. proposed the use of repeated practice of pinch movements coupled with visual feedback of the force direction to improve grip force control in stroke patients. To reduce the excessive grip force of stroke patients, Quancy et al. proposed the use of training incorporating visual feedback of the patient’s actual grip force in relation to a target grip force. Feedback of force information has the potential to improve hand function in patients with sensory loss because it provides additional information that is otherwise unavailable. So far, however, no study has tried to utilize cutaneous feedback to provide information regarding force for patients with severe sensory loss.

In the present study, we propose a pinch pressure feedback system that utilizes cutaneous electrical stimulation, based on the assumption that to recognize force, receiving information through a similar tactile modality may be more natural than receiving this information visually. Another advantage of tactile feedback is that the patient can concentrate on looking at
the shape of the fingers while still receiving information about the pressure. If the pressure is given as a visual display, patients must attempt to simultaneously look at both their fingers and the display during manipulation.

Therefore, in this study we assessed the utility of a system that utilizes cutaneous electrical stimulation in a stroke patient with sensory loss.

II. A SENSORY FEEDBACK SYSTEM UTILIZING CUTANEOUS ELECTRICAL STIMULATION

The system consisted of five major components: (1) force-sensing resistors, (2) a computer, (3) a stimulator, (4) an isolator and (5) surface electrodes for cutaneous electrical stimulation (Fig. 1). Fig. 2 shows a schematic overview of the system. The details of each component are explained as follows.

The force-sensing resistor is a polymer thick film device with a 5.0 mm diameter active area (Standard 400 FSR, Interlink electronics, Camarillo, CA, USA) and can detect from 0.20 to 98.07 N. For this component, the resistance decreases when there is an increase in the force applied to the active area.

For clinical use of the system, the force-sensing resistor can be applied to the tip of the fingers. The pressure is detected at the sampling rate of 1 kHz using the force-sensing resistor and is delivered to the computer through an AD board (ADA16-32/2 (CB) F, Contec, Osaka, Japan). The pressure is averaged over a 150 ms time window and is obtained according to the following equation:

\[ p(nT) = \frac{1}{k} \sum_{m=n-k+1}^{n} |p(mT)| \]

In this equation, \( T \) is the sampling interval, \( TC \) is the average time window and \( nT \) is the time at the \( n \)-th sampling point. Furthermore, \( p(nT) \) is the integrated pressure at time \( nT \), \( p(mT) \) is the rectified pressure at time \( mT \) and \( k \) denotes the number of sampling points in the average time window \( TC \) of 150 ms.

The magnitude of the current is modulated according to the following equation.

\[ \text{stim}(n) = \text{stimL} \quad (ip(n) < ipL) \]

\[ \text{stim}(n) = \frac{\text{stimU} - \text{stimL}}{ipU - ipL} \times (ip(n) - ipL) + \text{stimL} \quad (ipL < ip(n) < ipU) \]

\[ \text{stim}(n) = \text{stimU} \quad (ipU < ip(n)) \]

In this equation, \( \text{stimL} \) is the lower threshold of the stimulation current (defined for each patient as the lowest current at which he or she can feel stimulation), \( \text{stimU} \) is the upper threshold of the stimulation current (defined as the magnitude of current that did not elicit muscle contraction), \( ipL \) and \( ipU \) are the...
minimum and maximum integrated pressures observed when pinching an object, respectively and \( \text{stim}(n) \) is used as the magnification factor of the current at the \( n \)-th sampling. Each of these factors (\( \text{stim}_L \), \( \text{stim}_U \), \( \text{ip}_L \) and \( \text{ip}_U \)) is measured each day prior to the therapy. In the present setting, the actual magnitude of stimulation current at time, \( t \), is calculated according to the following equation:

\[
\text{current}(t) = a \cdot \text{stim}(nT)f(t) \quad nT < t < (n+1)T
\]

In this equation, \( a \) is a constant coefficient, \( f(t) \) is set as a monophasic rectangular pulse sequence at an interval of 20 ms and duration of 300 μs. The stimulation sequence is generated by an electric stimulator (SEN-7203, Nihon Kohden, Tokyo, Japan) and applied to the electrode via an isolator (SS-104, Nihon Kohden). Fig. 3 (a) and (b) show an example of a measured pressure value and stimulation sequence, respectively. The stimulation sequence is modulated in real time by the amplitude of pressure.

Electrical stimulation was applied by using two stimulation electrodes (one anode and one cathode). The shape and size (roughly circular with a diameter of 3 to 5 cm) of the two electrodes was customized for each subject by cutting commercial electrodes (Omron Elepuls, Omron, Kyoto, Japan). The electrode pads for cutaneous electrical stimulation were placed onto skin with preserved sensation, for example, onto the shoulder of the unaffected side.

The signal processing was performed using MATLAB 2007b (MathWorks, Natick, MA, USA).

### III. Experiments

To verify the utility of the system, a stroke patient with severe sensory loss received training. The fluctuation in force control during grasping objects was measured in the patient before and after training.

#### A. Participant

A 66-year old female was recruited into the study. She suffered a right thalamic hemorrhage 27 months previously and developed left hemiparesis (Fig. 4). Her major complaint was that the affected hand was useless in daily activities, although she could move her arm and fingers.

Before conducting any experiments, her motor and sensory functions were assessed. Table I summarizes the results of assessment. Motor function was examined using the Fugl-Meyer Assessment (FMA) [8, 9], which evaluates motor function of the upper extremities. Using FMA, each activity receives a score of 0, 1 or 2, which corresponded to no motion, partial motion or full motion, respectively. The maximum number of points one can achieve with the FMA is 66. In this study, the patient’s score was 60, indicating that the patient’s motor function was relatively intact. Based on the FMA, the patient’s upper extremity impairment was found to be mild, but she was unable to perform manipulation activities such as picking up or grasping.

To examine the patients’ manipulation capabilities, we used the Simple Test for Evaluating Hand Function (STEF) [10]. The STEF, which was developed in Japan, and is a test used for evaluating the patient’s ability to pinch, grasp and transfer objects (Fig. 5). The subject was required, as quickly as possible, to pick up items one by one from a storage space and move them into a target space. The subject performed object-moving tests using 10 objects of different shapes and sizes. The score of each test was calculated according to the time required to perform the object-moving test. The total possible STEF score of ranges from 0 (the poorest) to 100 (the best). In this study, the patient’s total STEF score was only 7, suggesting that she had much difficulty in manipulating real objects.

Her sensory function was also examined using the Semmes-Weinstein monofilament test [11]. A monofilament consisting of thin piece of wire is pressed against the subject’s fingertips until it bends. Without any visual feedback, the subject is asked to report whether he or she feels any pressure. If the subject does not feel anything, the next sized monofilament is tested. This is repeated with larger monofilaments until the subject detects the sensation. In this study, she was unable to detect any sensation in the fingertips even with the largest

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Score/Total Score</th>
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<tr>
<td>Fugl-Meyer</td>
<td>60/66</td>
</tr>
<tr>
<td>STEF</td>
<td>7/100</td>
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<tr>
<td>Semmes-Weinstein monofilament test</td>
<td></td>
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<tr>
<td>Position Sense</td>
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<tr>
<td>Shoulder</td>
<td>Severe loss</td>
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<tr>
<td>Elbow</td>
<td>Severe loss</td>
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<tr>
<td>Hand</td>
<td>Complete loss</td>
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Figure 4. T1-weighted MR image of the study patient. The arrow indicates small low intensity area in the right thalamus.

Figure 5. Simple Test for Evaluating Hand Function (STEF).
monofilament (1.142 mm in diameter). This result, coupled with other clinical physical findings, indicated that she had no touch sensation in the left hand or fingers. In addition, we assessed the position sense of her left upper extremity and found that her hand position sense was completely lost.

Based on these assessments, it was suggested that the lack of sensory feedback was a key factor for non-use of the affected hand in daily activities.

The patient gave written informed consent before participating in the study, which was approved by the local ethics committee of Tokyo Bay Rehabilitation Hospital, Japan.

B. Intervention

The patient was given 1 hour of training using the system 5 days per week for 1 month and then three times a week for 1 month. Alongside the training, the patient also continued with her conventional physical and occupational rehabilitation program, which was conducted for 2 hours, three times per week. The rehabilitation program did not change throughout the study.

Fig. 6 shows an overview of experiment. The force-sensing resistors were applied to the tips of the thumb on both hands (Fig. 7). Two stimulation electrodes (one anode and one cathode) were placed on the shoulder. The patient had severe numbness in left upper extremity due to the thalamic lesion. Therefore, stimulation electrodes were placed on the unaffected side (Fig. 8). The electrical pulse parameters were set at under the muscle contraction threshold.

At the beginning of the experiment, the patient pinched a small block with maximum pressure to allow for stimulus calibration. The maximum stimulation strength (10 mA) was normalized with the maximum pressure value.

At first, the patient could take an object with the unaffected hand to learn its stimulus pattern and intensity, then the patient practiced with the affected hand to generate the same stimulus pattern and intensity while performing the same tasks. The patient practiced pinching or grasping items such as an ellipsoidal can, blocks, a paper cup, fabric balls, sponges and a plastic bottle, and was encouraged to rest at any time during training if she felt tired.

C. Assessment

We measured the voltage values of the force-sensing resistor during a can grasping and lifting task under two conditions, 1) without the system before training and 2) with the system after training. The voltage value changed depending on the pinch pressure value during grasping, and although the relationship between pressure and voltage value was nonlinear, it indicated the features of the patient’s grasping. The sampling rate of the voltage value was 10 kHz and was measured using a data acquisition system (PowerLab 16/30, AD Instruments, Sydney, Australia).

We defined the average rate of change in voltage values as the fluctuation index which indicates the fluctuation in force control during can grasping, although we were not able to refer to the absolute value of the pinch pressure from the force-sensing resistor values directly because of their nonlinear relationship. Before the calculation, the signals were cut out from the onset to offset of motion and were down sampled to 50 Hz. Then, the fluctuation index was calculated by the following equation:

\[ \Delta v(n) = (v(n) - v(n-1))/(1/T) \]  

\[ \text{fluctuation index} = \frac{1}{N-1} \sum_{n=1}^{N-1} |\Delta v(n)| \]  

In these equations, \( v \) is the voltage value of force-sensing resistor, \( T \) is sampling rate (50 Hz), \( \Delta v(n) \) is rate of change at \( n \)-th sample, and \( N \) is total number of sampled data. We calculated the fluctuation index from the data during grasping and lifting task with the system after training. The number of measurements ranged from one to three times each day, and the average plus two standard deviations were also calculated. In
addition, the values from the unaffected hand were also calculated from eleven trials.

IV. RESULTS AND DISCUSSION

A. Results

Before the intervention period, we tested how the unaffected hand grasped an object and lifted it for a period of time. Fig. 9 shows the voltage value of the force-sensing resistor during grasping and lifting. The patient was able to maintain a stable pressure during the task when using the unaffected hand. The voltage value reached a maximum value when the patient lifted up the object (around 1 sec) and it gradually decreased.

On the first day (Day 1), the voltage values of the force-sensing resistor were unstable during the can grasping activity performed with the affected hand, and the fluctuation in force control was unchanged throughout the training. Fig. 10 (a) and (b) show the voltage values without the system before training and with the system after training, respectively. The voltage value was not stable and the patient dropped the can around 8 sec without the system before training. After training, the patient still dropped or nearly dropped the can at around 5, 7, 10, and 15 sec.

We investigated the long-term effects of the intervention. Fig. 11 (a) and (b) show the voltage values without the system before training and with the system after training on Day 63, respectively. The fluctuation of the voltage value led to a decrease compared with the voltage on Day 1 (Fig. 10).

Fig. 12 shows the values of fluctuation index of the affected hand with the system and indicates the change in fluctuation in force control during can grasping across days. The dashed line and gray zone represent the average value and the average plus or minus two standard deviations of the unaffected hand, respectively. The patient was able to keep a stable pressure on Day 53 compared with Day 1. The values of fluctuation index decreased as the training progressed, until the values of fluctuation index observed on Day 53 and Day 63 were almost the same as those observed in the unaffected hand.

B. Discussion

This study describes a novel rehabilitation technique using electrical stimulation. This new training system may be applicable to a wide range of stroke patients with sensory disturbances. In this study, the fluctuation in force control during grasping did not change before and after the training on Day 1. The fluctuation, however, gradually decreased as the training progressed. With the system the patient was able to maintain a stable pressure during grasping on Day 63, which approximately matched the pressure observed in the unaffected hand. In addition, the patient was also able to maintain a stable pressure during grasping even without the proposed system on Day 63. In summary, after about 2 months of training with the system, the patient’s pinch pressure was relatively stable even when the electrical stimulation was absent.

The patient had already received extensive physical and occupational therapy before the experiment. However, her
manipulation capabilities did not change significantly during conventional training. It could be considered that the patient depended excessively on a visual feedback and received too much feedback gain, which might cause unstable force control in manipulation. Our results suggested that force feedback in addition to visual feedback is crucial to improve manipulation capabilities.

Although the long term effect is unclear, it is speculated that effect of training may last for at least several days because the patient was able to maintain stable pressure during can grasping without the system before training on Day 63. The limitations of this study include the small sample size, lack of kinematic analysis and lack of investigation about the real amount of use of the affected hand in daily activities. Therefore, research in a larger cohort of patients is required to properly evaluate the efficacy of the system. Furthermore, the present system is so large that it can be used only in a laboratory or hospital setting, so our aim is to develop a smaller system for use in the home.

V. CONCLUSION

In this study, we developed a sensory feedback system using cutaneous electrical stimulation for stroke patients with sensory loss. This system is very beneficial for patients with sensory loss, because these patients often grasp objects with overabundant or underestimated power because of inadequate sensory feedback. By using the system, patients are able to discern pinch pressure at the fingertip during grasping, because the electrical stimulation modulated by the strength of pinch pressure is fed back to them. To validate the utility of the proposed system, we measured fluctuation in force control during a can grasping task in a stroke patient with sensory loss before and after training with the system. Consequently, after approximately 2 months of training with the system, the patient had a relatively stable pinch pressure whether the cutaneous electrical stimulation was applied or not.

We conclude that because the system is very simple, it may be a valuable contribution to the rehabilitation of patients with sensory loss. In future studies, we aim to increase the number of participants recruited, conduct long-term follow-up, use appropriate clinical assessment measures to evaluate the improvements of manipulation capability and develop a smaller system for use at home to determine whether the effects of this system are generalizable.

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