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Research Article

Myoelectric Prosthetic Hand with Sensory Feedback that Generates Discomfort

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ABSTRACT

The aim of this study is to develop a new tactile feedback method for myoelectric prosthetic hands. The sense of touch can be reproduced such as by vibrating actuators based on information from a sensor attached to the fingertip of the myoelectric prosthetic hand. This paper attempted to use delayed vibration feedback to create discomfort as a corresponding sensation to pain since a prior study has found that a time lag between sensory input and stimulation can cause discomfort. In the experiment carried out, we first examine the relationship between the delay time D and sensation in vibration stimulation. The experimental results indicated that discomfort occurs between D = 0.25 seconds and 0.65 seconds. Furthermore, to verify whether the proposed feedback method can be used to discriminate between normal objects and dangerous objects such as knives, we applied it to the haptic feedback of a prosthetic hand controlled by myoelectric signals. The results showed that the participant could recognize the difference in feedback and distinguish between the two types of objects with an accuracy of 95.0 ± 0.1%.

1. Introduction

Myoelectric prosthetic hands are capable of simulating human hand movement by discriminating electromyogram (EMG) signals, such as intended movements and force information, therefore, they can compensate for the lost functions of upper limb amputees. Yang and Liu proposed deep learning based multi-DOF wrist movement discrimination and achieved accurate and complex control of various robotic platforms [1]. In order to create a myoelectric prosthetic hand that resembles a human arm, it is necessary to consider the construction of a multi-degree-of-freedom robot hand and its control method, and several studies on pattern classification to estimate motions from myoelectric signals. Various methods have been proposed to realize movements that more closely resemble human hand movements [1], [2], [3], [4], [5], [6]. These include complex motion discrimination and continuous motion recognition, and in terms of intuitive control using EMG signals that can be measured from the human as a control input, it can be said that a prosthetic hand that closely resembles an actual human hand is being realized.

Although there are various studies on structures and control methods of myoelectric prosthetic hands, to create a truly human prosthetic hand, it is necessary not only to realize control that mimics human hand movement, but also to equip the prosthetic hand with a means of obtaining sensory information such as the tactile sensation that is inherent in the human arm. One of the reasons why there are so few myoelectric prosthetic hand users, despite the development of various advanced prosthetic hands, is that there is little sensory feedback to the user.

To solve this problem, research has been conducted to feed back the information obtained when the prosthetic

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hand comes in contact with an object to the operator. For sensory feedback, it is important to develop sensors and control methods to imitate the human sense of touch [7], [8], [9], [10], [11], [12], and to reproduce the sense of touch using various actuators [13], [14], [15], [16], [17]. For example, BioTac tactile sensor [7] can detect contact force, micro-vibration and thermal fluxes. In this paper, how to reproduce the sensation to a human is mainly discussed.

Feedback for myoelectric prosthetic hands can be divided into invasive and non-invasive methods, among which it is important to know what kind of stimuli to use and how to use them. Various types of stimuli such as vibration [13], [14], temperature, pressure [15], [16] and electrical stimulation [17] have been studied as possible feedback. On the other hand, there is research that uses electrical stimulation to present the pain of a localized strong stimulus, and research that combines image recognition to present the texture of an object, and phantom limb stimulation [18]. Pain, for example, may be useful for presenting contact with objects that should not be touched with a prosthetic hand, such as hot or sharp objects, but it is usually difficult to provide direct feedback of pain to the user. To present pain sensation, we have investigated the relationship between the timing of vibration stimuli and human sensation based on the effects of stimulus latency on human sensation [19]. [20]. The previous study revealed that the time-delay of approximately 0.4 s from the timing of contact with an object could cause discomfort to the user [21]. However, we have not introduced the previously proposed feedback method to the myoelectric prosthetic hand.

This paper proposes a myoelectric prosthetic hand with discomfort feedback. The proposed prosthetic hand aims to create a sensation of discomfort that corresponds to pain, and simulates such sensation through delayed vibration stimulation when touching an object with the prosthetic hand.

The rest of the paper is organized as follows: Section 2 describes the concept of the proposed prosthetic hand with a sensory feedback system, and Sections 3 and 4 show experiments using the proposed system. Section 5 finally concludes the paper.

2. EMG-based prosthetic hand with discomfort feedback

Fig. 1 shows the proposed myoelectric prosthetic hand with a sensory feedback system that simulates sensations

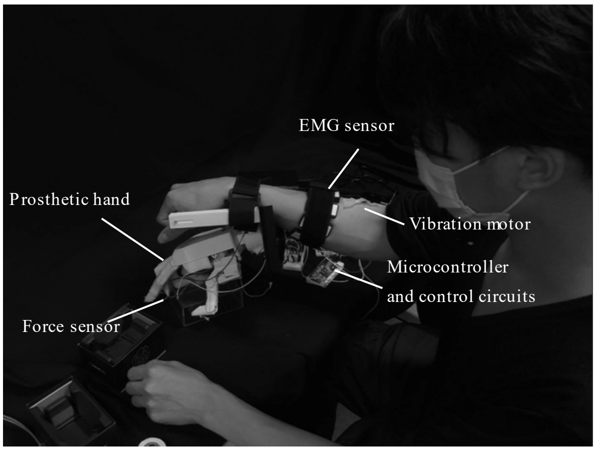

Fig. 1. Overview of the myoelectric prosthetic hand feedback system. The proposed prosthetic hand can be controlled by myoelectric signals, and tactile information can be presented by controlling a vibration motor using information obtained from a sensor attached to the fingertip.

corresponding to pain. The proposed prosthetic hand consists of a sensor for measuring myoelectric signals, a microcontroller for estimating the user's intention from the measured signals and controlling each motor of the myoelectric prosthetic hand, and a force sensor. The detailed information about the proposed prosthetic hand is described in the following subsections.

2.1. *Structure*

The structure of the proposed prosthetic hand is based on OpenHand (see Fig. 1). A geared DC motor with an encoder is used to control each finger, and a servo motor is also used to control the base joint of the thumb. The prosthetic hand control system consists of a Raspberry Pi Zero WH (Raspberry Pi) with a high precision ad/da board (onboard ADS1256 and DAC8552) and DRV8835 motor drivers. A membrane force sensor (diameter: 10.2 mm, ALPHA) is also attached to the fingertip of the prosthetic hand, and the voltage value corresponding to the magnitude of the force is measured by the microcontroller via the AD board. Additionally, it is equipped with a small eccentric motor, and tactile feedback is possible by controlling the magnitude and timing of vibrations via the motor driver.

Thus, the proposed prosthetic hand proposed hand can acquire contact information from the external environment, and can be controlled like the hand itself by controlling the motors of each finger. Next, the control method of the proposed prosthetic hand is explained.

2.2. *EMG-based control*

Although various sensors are available for acquiring EMG signals, a Myo Gesture Arm Band (Thalmic Labs.) is used in this paper. Eight pairs of stainless electrodes (L = 8) are attached to the forearm, and measured signals are imported to the microcontroller via Bluetooth LE communication (sampling frequency: f_s=200 Hz). The signals are then full-wave rectified, smoothed using a second-order Butterworth low pass filter (f_c=1 Hz), and normalized as the maximum value of each channel is 1 using the maximum value for each channel and the average value for each channel at rest obtained in advance. After that, the normalized value with the sum of all channels as 1 is defined as a feature vector $\boldsymbol{x}(t) \in \Re^L$ for classification, and the average value of all channels is defined as force information $F(t)$ for determining motion occurrence.

A multi-layered perceptron with the terminal learning is used to discriminate the user's intended motions. Feature vectors ${}^{(m)}\boldsymbol{x}(t)^{(n)}(m = 1, \dots, M; n = 1, \dots N_m;$ M is the number of motions and N_m is the number of samples for motion *m*) are used to train the network, and when new feature vector $\boldsymbol{x}(t)$ is input to the trained network, the network outputs posterior probabilities of each motion. The motion with the highest probability value is judged as the motion performed by the user if the force information $F(t)$ is greater than the pre-set value $F_{\text{th}}(F(t) \geq F_{\text{th}})$. Otherwise, motion discrimination is not performed ($F(t) < F_{\text{th}}$).

According to the motion discrimination result, the motor of each finger is selected and controlled via PWM modulation. The maximum equilibrium angle $\Theta_i(i = 1, \dots I;$ I is the number of joints for control) is determined in advance, and the target angle at each time is calculated by solving the equation of motion according to the force information. Then, by determining the amount of traction on the wire for each finger and adjusting the rotation speed of the motor, each finger can be controlled voluntarily using EMG signals.

2.3. *Sensory feedback*

Here, when performing a grip or pinch motion and coming into contact with an object, the magnitude of force applied to a fingertip can be obtained as a voltage value $C(t)$ via a force sensor. In this paper, we assume that the pain when coming into contact with a sharp object is fed back as a feeling of discomfort, and the feedback vibration is changed depending on whether or not the $C(t)$ exceeds a preset threshold.

The time taken for the sensory stimuli to be recognized as contacting an object is approximately 50 to 300 [ms]. In a music game, the timing of the button operation and its feedback was varied, and the results were evaluated by questionnaire, and the larger the deviation from the operator's expected timing, the greater the discomfort. Therefore, when the force sensor value exceeds the object contact judgment threshold C_{th} and the threshold value C_{th} during the contact judgment time S, the vibration stimulus is given after the delay time D [s] from the end of the contact judgment time S in this paper.

3. Verification of the effect of vibration feedback delay time on tactile sensation

3.1. *Method*

In order to verify the optimal delay time D for expressing pain as discomfort using the proposed method, an experiment was conducted on a healthy university student whether the operator feels discomfort against the unexpected stimulus. In the experiment, the participant initiated feedback at his timing, and after a random delay of $D = [0.1, 0.8]$ s (16 total in 0.05 s increments), a 2.0 s vibration stimulus was generated. In this experiment, the participant was asked to evaluate how much discomfort he felt by a questionnaire with a 10-point scale. The experiment consisted of 80 trials (each delay time was presented randomly five times), with one trial consisting of the process of the participant pressing a button to generate a delay time feedback and answering a questionnaire.

3.2. *Results and discussion*

Fig. 2 shows the results of the experiment. The vertical axis is the evaluation value of the questionnaire, and the horizontal axis is the delay time D. From the graph, although there are variations from each trial, it can be seen that the results change in a quadratic manner. When the delay time is small, it is felt as normal vibration feedback, and when the delay time is large, it is felt as a vibration stimulus with a different timing than the strength of the discomfort. However, when the delay time is around 0.25-0.65 s, the vibration stimulation starts with a slight delay from the timing of contact, so the

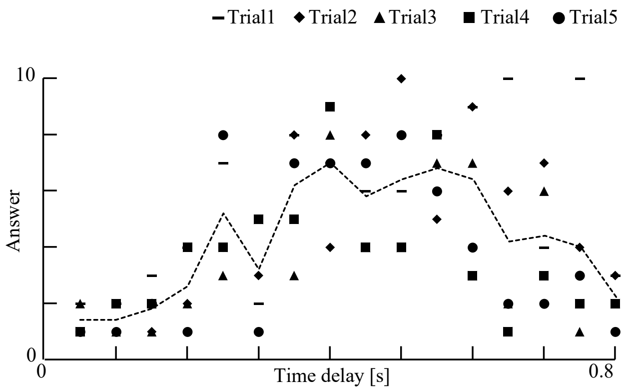

Fig. 2. Relationships between delay time of vibration and tactile sensation.

participant feels a sense of lag, similar to the time lag between video and audio in a video conference.

From these results, the optimal delay time for expressing discomfort by vibrotactile feedback can be estimated at around 0.4 s.

4. Object discrimination experiment

4.1. *Method*

In order to verify the effectiveness of the proposed tactile feedback method, object discrimination experiments were performed using the developed EMG-based prosthetic hand with tactile feedback.

The number of as intended timing during the experimen discrimination motions was set as M = 4 (opening, grasping, wrist flexion, and extension) and EMG signals were measured from L = 8 pairs of electrodes. F_{th} is set as $F_{\mathrm{th}} = 0.2$ and the participant was asked to perform opening/grasping motion t.

Fig. 3 shows the experimental scene. The participant performs a grasping motion using the prosthetic hand while the prosthetic hand is not visible. In the experiment, contact with the object was detected by a force sensor attached to the fingertip ($C_{\mathrm{th}} = 2.0$), feedback with or without a delay of 0.4 s (determined from the previous experiment) was randomly presented 20 times. The participant was asked to answer whether the object was intended to be a normal object (non-delayed feedback) or a sharp object such as a knife (discomfort presentation with delayed feedback).

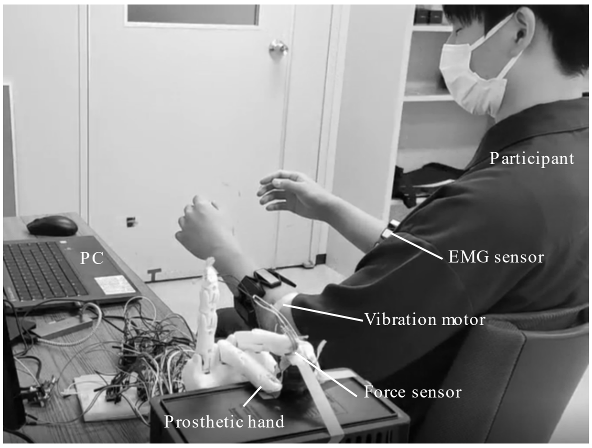

Fig. 3. Experimental scene. The fingertips of a myoelectric prosthetic hand can be opened and closed by discriminating EMG signals measured from the participant's skin surface. The system detects contact between the prosthetic fingertip and an object and

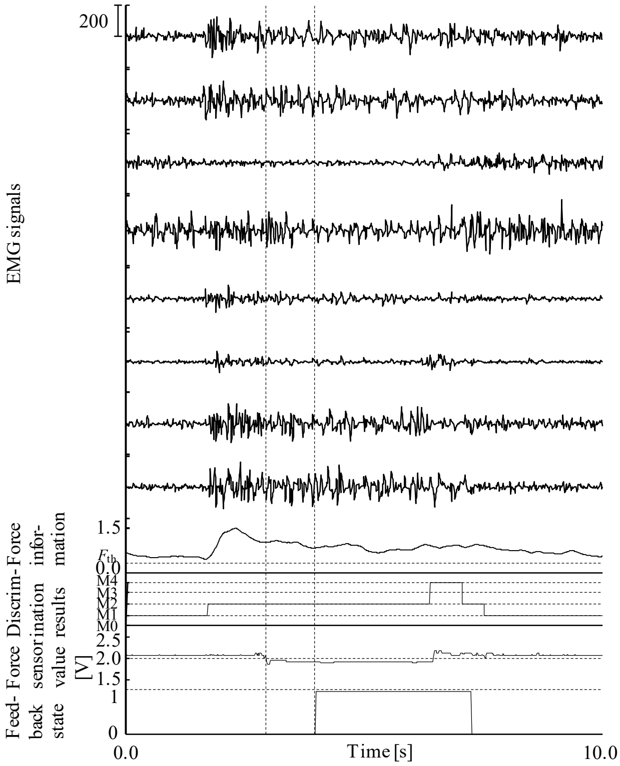

Fig. 4. An example of experimental results (trial 5). After contact with an object is detected by a sensor attached to the fingertip of the prosthetic hand, delayed vibration feedback is provided.

4.2. *Results and discussion*

Fig. 4 shows an example of experimental results, representing EMG signals, force information calculated using EMG signals, discrimination results, force sensor value, and vibrotactile feedback information, from the top. From the result, the participant performs an opening motion to open the prosthetic hand, and then performs a grasping motion to try to grasp an object. In this trial, by using delayed feedback assuming a sharp object, note that there is a delay in the start of vibration after contact with the object due to discomfort feedback. In this way, the prosthetic hand can be controlled by EMG signals, and information can be fed back when it touches an object. The object discrimination rate was 95.0 ± 0.1 %.

The participant was able to recognize the differences between objects through vibration feedback, and the proposed prosthetic hand was able to accurately obtain this information in situations where the prosthetic hand was supposed to be in danger, such as touching a sharp object.

5. Conclusion

In this paper, we proposed a myoelectric prosthetic hand with a sensory feedback system that can provide discomfort to the user based on the time delay of tactile stimulation. The proposed prosthetic hand measures EMG signals from electrodes attached to the forearm and enables voluntary control by using the differences in signal characteristics for each motion to discriminate them. Additionally, the proposed system can detect contact with an object by a tactile sensor and then apply a vibration stimulus at a timing according to the magnitude of the contact. In the experiments performed, we first evaluated the time delay between vibration feedback after contact determination and feedback. The start time of the feedback by vibration stimulation was varied in 16 steps in 0.05-second increments between 0.1 and 0.8 seconds and presented randomly. The time delay that caused the most discomfort to the participants was 0.4 seconds. Furthermore, we also conducted prosthetic hand control and object discrimination experiments using the developed EMG-based prosthetic hand with discomfort feedback function. Experimental results showed that vibrotactile feedback with and without time delay was presented randomly and the participant was able to discriminate between two types of objects with an accuracy of 95.0 ± 0.1%. However, although this paper could evaluate the effect on sensation due to the temporal gap between contact and vibrotactile stimulation, the system was not able to accurately provide the sensory information to the user possessed by the human fingertips, such as the texture of an object, and participants were only able to recognize the gap in vibration onset time. While the authors do not consider that it is necessary to directly feedback sensations corresponding to pain, it is necessary to consider how information including the texture of objects can be given to users to make the prosthetic hand more similar to a human hand.

In future research, we would like to increase the number of subjects and conduct experiments, as well as propose a new feedback method for myoelectric prosthetic hands that utilizes illusions.

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