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Development of Thin Vibration Sheets Using a Shape Memory Alloy Actuator for the Tactile Feedback of Myoelectric Prosthetic hands*

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Abstract— **Because the current myoelectric prosthetic hand does not have a tactile function, the user must always check the condition of the prosthetic hand. Various studies on sensory feedback have been conducted to address this problem, but several devices used in them cannot be integrated with artificial limbs, and wearing the devices is a burden on the user. To solve this problem, we developed thin vibration stimulation sheets using shape memory alloy (SMA) actuators. We then conducted an experiment on the effect of the change in shape at the contact part between the sheet and the skin on perception and confirmed that it would be easier to perceive vibration when the skin was deformed in a wider range. In addition, we investigated the number of distinguishable stimulus intensity levels and identification of stimulus positions. According to the results, the stimulus presented by the developed vibration sheet could be identified in three stages without learning about the stimulus, and the stimulation position by the vibration sheet could be identified with the same or higher accuracy as that of the disk-type vibration motor used in the existing research, although the accuracy decreased when vibrations were presented simultaneously.**

I. Introduction

A myoelectric prosthetic hand is a type of electric artificial limb whose action is determined by an electrical tension generated when a muscle contracts [1]. The electrical signal is measured by a myoelectric sensor placed in a socket where the user inserts the step end of the arm. The control method of a prosthetic hand allows it to be operated more voluntarily than an active prosthesis. However, although some attempts have been made, a prosthetic hand which is commercially available doesn't have a tactile function, and the user must always visually confirm the state of the device such as whether he or she is holding an object. Therefore, it's difficult for the user to perform another action while operating the artificial hand.

To solve this problem, research is being conducted to feed back the sensation of the myoelectric prosthetic hand to the user [2]. This approach presents information such as the force of holding an object or the angles of the fingers by stimulating the skin of the user's remaining arm. The main feedback method used in these studies was the presentation of pressure [3] or vibration [4]. However, the stimulus presentation device used in most studies has certain problems that the device has an excessively large volume or that the presented stimulus becomes an artifact for myoelectricity. Therefore, the user must wear the stimulator at a position away from the myoelectric sensor as a device separate from the artificial of placing it in the socket, which increases the effort to wear the prosthetic hand.

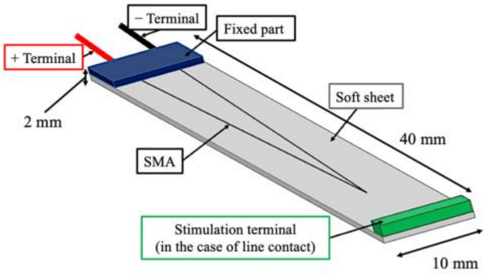

Figure 1. Mechanism diagram.

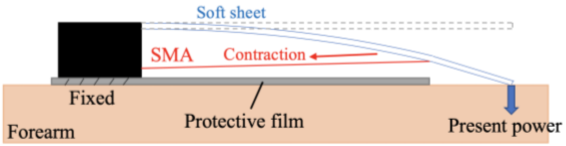

Figure 2. Structural diagram.

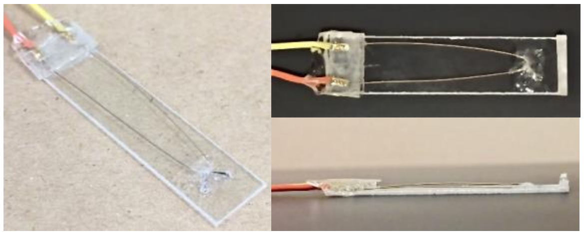

Figure 3. Actual device.

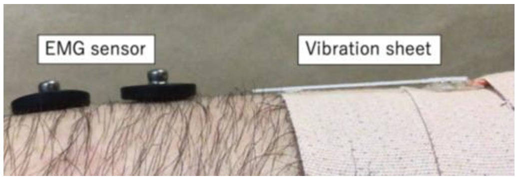

Figure 4. Forearm with EMG sensors and a vibration sheet.

In addition, as small skin stimulators that can be placed in a narrow space, devices using shape memory alloy (SMA) actuators have been studied in recent years [5], [6]. The stimulators created in these studies are thin, presenting stimuli that tighten the skin and are thought to have little effect on myoelectricity. However, in this method, there is a time lag between the presentation of the stimulus and the perception, and as a result, the movement and sensation of the artificial limb are separated.

Therefore, the purpose of this study was to develop thin vibrating sheets that operate by vibrating thin plates at high

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speeds owing to the contraction of shape memory alloy actuators. The device was small enough to be installed in the socket of an artificial hand and presented a vibration stimulus to the skin that did not easily create a time gap between the presentation of the stimulus and the perception. We then investigated the effect of the change in shape at the contact part between the sheet and the skin on perception, the number of steps of distinguishable stimulus intensity, and the identification of the stimulus position.

II. DEVELOPMENT OF THE VIBRATION SHEET

A. *Description of the Shape Memory Alloy Actuator*

We used a small and lightweight SMA wire (BioMetal Fiber, BMF) as an actuator to realize a stimulator that can be placed in the socket of a myoelectric prosthetic hand. This is a fibrous material that contracts with a strong force when energized and naturally expands to its original length when the current is stopped. The rate of practical kinetic strain is defined as the amount of change from the natural length. By using this characteristic, it is possible to create an oscillating state by repeatedly switching ON/OFF, in which current flows at high speed to heat and cool [7].

Fig. 1 illustrates how the vibrating sheet stimulates the skin. The SMA and a soft sheet are joined, and when the SMA wire contracts, the sheet bends. This allows the stimulation terminal to come into contact with the skin and present stimulation to the user of the artificial hand. The movement of the vibrating sheet can be approximated by the bending deformation of a cantilever with a rectangular cross section.

B. *Structure and Control Method of the Vibration Sheet*

Fig. 2 demonstrates the structure of the proposed thin vibration stimulation sheet, and Figs. 3 and 4 describe the actual device. The stimulator dimensions were 10 mm in width, 40 mm in length, and 2 mm in thickness. The vibration stimulator was constructed to join the polystyrene sheet (thickness: 0.3 mm) and SMA wire (diameter: 0.15 mm, length: 60 mm). This vibrating sheet is sufficiently thinner than the dry myoelectric sensor (thickness: 6 mm), which is commercially available and placed in the socket of a myoelectric prosthetic hand.

The SMA wire contracted and expanded by repeating heating by energization and cooling by natural heat dissipation. The current was controlled using pulse width modulation (PWM). In this method, a pulse is used to control the energized state and the non-energized state by applying a voltage. The parameters which were set so that the self-heating of SMA didn't cause discomfort to the wearer when driving it were a drive voltage of 5 V, the power consumption of 0.039 W, PWM parameter (duty ratio) of 5%, and a practical kinetic strain rate of 4%.

C. *Determining the Stimulus Terminal Shape*

When the shape of the stimulus terminal of the vibrating sheet changes, the ease of perceiving the presented stimulus also changes. Therefore, we investigated the effect of the change in shape at the contact area between the thin vibrating sheet developed in this study and the skin on the perception of stimuli. In this experiment, three healthy subjects (female: 1, male: 2, age: 21–23) were included.

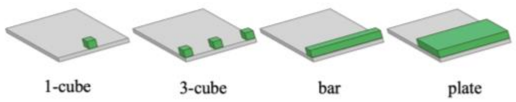

Figure 5. Four types of terminal shape candidates.

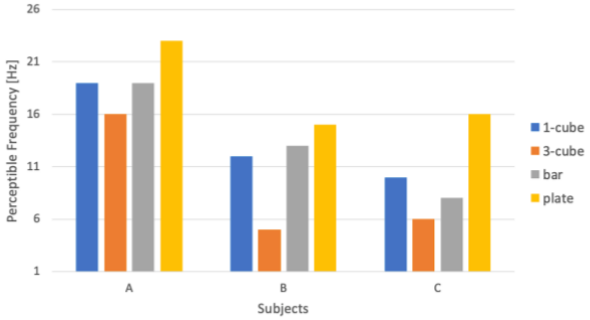

Figure 6. The perceptible frequency ranges.

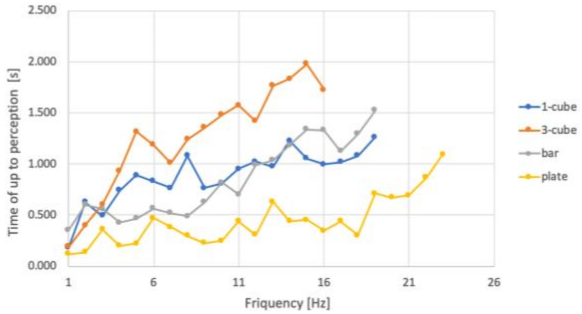

Figure 7. The time gap from the presentation of vibration to the perception (subject A).

In this experiment, four types of stimulation terminal shape candidates, as depicted in Fig. 5, were prepared: one-point contact (1-cube), three-point contact (3-cube), line contact (bar), and surface contact (plate). The area of the stimulation terminal in contact with the skin was 1 mm^2 (one-point contact), 3 mm^2 (three-point contact), 10 mm^2 (line contact), and 30 mm^2 (surface contact). One type of stimulation terminal was joined, and a vibration stimulator was placed at a position where the terminal contacted the skin at a position 10 cm from the elbow joint on the back of the right forearm. In the measurement, the vibrator was vibrated at 1 Hz. When the subject could perceive the vibration, the frequency was increased by 1 Hz. This step was repeated, and the maximum frequency at which the vibration could be perceived was measured three times. The same measurement was performed for each stimulus terminal. In this experiment, when the vibration was presented, the time until the subject perceived the vibration was measured, and they were compared among the stimulation terminals.

Fig. 6 presents the perceptible frequency range of the stimulator with each stimulus terminal. Notably, the range of perceptible frequencies increased in the order of three-point contact, line contact, and surface contact. Similarly, it was confirmed that the range of perceptible frequencies expanded in the order of three-point contact and one-point contact. It was presumed that the cause of this was that the amount of skin deformation had changed. In the former, the contact area increased, and in the latter, the pressure to push the skin was higher. This caused the skin to deform more extensively, making it easier to perceive vibrations. Therefore, the range of perceptible frequencies was considered to be determined by the size of the contact area between the vibrating sheet and the skin and the amount of pressure that the sheet exerted on the skin. In addition, it was observed that the result of subject A was clearly higher than that of subjects B and C. This was because of the difference in the temperature when the experiment was conducted. The temperature when subject A conducted the experiment was 23 °C, while the temperature when the other subjects conducted the experiment was 17 °C. Therefore, it was presumed that the skin sensations of subjects B and C were dull owing to the influence of the temperature.

Fig. 7 shows the time gap from the presentation of vibration to the perception of subject A. This result confirmed that the time lag was the shortest for surface contact, almost the same for line contact and one-point contact, and the longest for three-point contact. In addition, it was noted that the higher the frequency was at all stimulation terminals, the longer it took to perceive. This was because the amplitude of vibration became smaller as the frequency increased, which hampered the perception of the vibration.

III. EXPERIMENTS ON THE IDENTIFICATION OF THE STIMULUS INTENSITY AND POSITION

We investigated the identification of the number of steps of distinguishable stimulus intensity and the identification of the position where the stimulus was presented using the thin vibration sheet developed in this study. The experiment was conducted on three healthy subjects (female: 1, male: 2, age: 22–23). In both experiments, the shape of the stimulation terminal of the vibrating sheet was surface contact because the perceptible frequency range was the widest in the aforementioned experiments.

A. Identification of the Number of Distinguishable Stages of Stimulation

When performing sensory feedback, it is desirable to identify the stimulus intensity presented by the device in multiple stages without learning about the stimulus. In this experiment, using the developed vibration sheet, we investigated the number of steps the stimulus intensity could be identified in a state where stimulus learning was hardly performed.

In this experiment, a vibrating sheet was placed such that the stimulation terminal was in contact with the skin at a position of 10 cm from the elbow joint on the back of the right forearm. The vibration stimulator was vibrated only once at a frequency of 1 to 10 Hz. Then, the vibration of a certain frequency was presented, and the subject was requested to identify that frequency. For the vibration, each frequency of 1 to 10 Hz was randomly presented five times, and the ratio of the answers was calculated.

Tables I, II, and III present the rate of answers for each subject. The numbers in the table indicate that the darker the color is, the higher is the percentage. From this, it was confirmed that the percentage of the frequencies answered tended to increase at 1 Hz, 3–4 Hz, and 6–9 Hz in all subjects. Therefore, it was considered that individual differences had almost no effect on the bias of the response rate when there was almost no learning about vibration. In addition, it was observed that as the frequency increased, the response rate to the presented frequency was distributed over a wide range of frequencies. Therefore, considering that the amplitude of the developed vibration stimulation sheet decreased as the frequency increased, it was considered that the vibration identification was more affected by the change in amplitude than the change in frequency.

TABLE I. RATE OF ANSWER (SUBJECT A)

Subject A		**Answer [Hz]**									
		1	2	3	4	5	6	7	8	9	10
Presentation [Hz]	1	1	0	0	0	0	0	0	0	0	0
	2	0	0.8	0.2	0	0	0	0	0	0	0
	3	0	0	0.6	0.4	0	0	0	0	0	0
	4	0	0	0.2	0.2	0.4	0	0.2	0	0	0
	5	0	0	0	0.4	0.4	0	0.2	0	0	0
	6	0	0	0	0	0.2	0.8	0	0	0	0
	7	0	0	0	0	0.2	0	0.2	0.6	0	0
	8	0	0	0	0	0	0.2	0.4	0.4	0	0
	9	0	0	0	0	0	0	0.6	0.2	0.2	0
	10	0	0	0	0	0	0	0.2	0.6	0.2	0

TABLE II. RATE OF ANSWER (SUBJECT B)

Subject B		**Answer [Hz]**									
		1	2	3	4	5	6	7	8	9	10
Presentation [Hz]	1	0.8	0.2	0	0	0	0	0	0	0	0
	2	0	0.2	0.6	0.2	0	0	0	0	0	0
	3	0	0	0.4	0.4	0.2	0	0	0	0	0
	4	0	0	0	0.2	0.2	0.2	0.2	0.2	0	0
	5	0	0	0	0	0	0.4	0.4	0	0	0.2
	6	0	0	0	0	0	0	0.8	0	0.2	0
	7	0	0	0	0	0	0	0.2	0.6	0.2	0
	8	0	0	0	0	0	0	0	0.4	0.4	0.2
	9	0	0	0	0	0	0	0.2	0.6	0.2	0
	10	0	0	0	0	0	0	0	0	0.2	0.8

TABLE III. RATE OF ANSWER (SUBJECT C)

Subject C		**Answer [Hz]**									
		1	2	3	4	5	6	7	8	9	10
Presentation [Hz]	1	0.8	0.2	0	0	0	0	0	0	0	0
	2	0	0.4	0.4	0.2	0	0	0	0	0	0
	3	0	0	0	0.2	0.8	0	0	0	0	0
	4	0	0	0.2	0.6	0.2	0	0	0	0	0
	5	0	0	0	0	0	1	0	0	0	0
	6	0	0	0	0.2	0	0.4	0.2	0	0.2	0
	7	0	0	0	0	0	0.2	0	0.4	0.4	0
	8	0	0	0	0	0	0	0.4	0	0.6	0
	9	0	0	0	0	0	0	0	0	0.8	0.2
	10	0	0	0	0	0	0	0	0.2	0	0.8

When the data presented in Table I were analyzed using the k-means method and the elbow method, it could be divided into three clusters. In other words, it was confirmed that the vibration intensity could be identified in three stages when the developed vibration sheet was vibrated at 1 to 10 Hz with little learning for the stimulus. Considering that the number of human short-term memories that can be memorized is 4 ± 1 [8], it is considered that the developed vibration sheet could present 3 stages of vibration, although more detailed investigation on the characteristics of the stimulator is needed.

B. Identification of the Position of Stimulation

When performing sensory feedback using multiple stimulators, it is desirable to identify the stimulator that is presenting the stimulus. Therefore, we investigated whether it was possible to identify the stimulator that was operating when multiple stimulators were placed on the arm. In this experiment, the disk-type vibration motor used in the existing study and the vibration sheet developed in this study were used as the vibration stimulator.

In this experiment, five vibrating sheets or five disc-shaped vibrating motors were placed concentrically on the forearm at intervals of 20 mm. The vibration motor or the stimulation terminal of the vibration sheet was brought into contact with the skin at a position of 10 cm from the elbow joint of the right forearm. First, the five oscillators were individually vibrated and a subject was requested to remember the position where the vibration was presented and the oscillator number. Next, two adjacent oscillators were vibrated simultaneously and the subject was instructed to remember the positional relationship of the vibrations in the same manner. After performing this process three times each, individual vibrations or simultaneous vibrations were randomly presented, and the correct answer rate was calculated by requesting the subject to identify the device that was vibrating. The frequencies of the vibrations presented were 5 Hz for the vibration sheet and 70 Hz, 140 Hz, and 210 Hz for the vibration motor.

Tables IV, V, VI, and VII present the rate of correct answers for subject A. The brown cells in the figure indicate the percentage of correct answers, and the darker the color is, the higher is the percentage. From these results, it was confirmed that irrespective of the type of the vibrating device, the correct answer rate decreased when two vibrations were generated simultaneously as compared to the case where each vibration was generated individually. This was because, in the case of simultaneous vibrations, a phantom sensation phenomenon occurred in which even if two or more stimuli were presented, it was recognized as only one stimulus. In addition, the correct answer rate was approximately the same as that of the vibrating motor (210 Hz), and it was confirmed that the correct answer rate of the vibrating sheet tended to be higher when the frequency of the vibrating motor decreased. This was because of a decrease in the amount of information presented by one stimulator. If the amount of information presented by each stimulator was larger than the amount of information presented by the phantom sensation, each vibration could be recognized with a high accuracy even if an illusion occurred. However, as the frequency decreased, the amount of information presented by one vibration stimulator decreased, making it difficult to identify individual oscillators.

Consequently, it was considered that the stimulation position by the developed vibration sheet could be identified with the same or higher accuracy as that of the disk-type vibration motor used in the existing study, although the accuracy decreased with simultaneous vibrations.

TABLE IV. RATE OF CORRECT ANSWERS (SUBJECT A, VIBRATION SHEET, 5 HZ)

Vibration sheet (5 Hz)		**Answer (position number)**									
		1	2	3	4	5	1,2	2,3	3,4	4,5	5,1
Presentation (position number)	1	0.8	0	0	0	0	0	0	0	0	0.2
	2	0	1	0	0	0	0	0	0	0	0
	3	0	0.2	0.8	0	0	0	0	0	0	0
	4	0	0	0	1	0	0	0	0	0	0
	5	0	0	0	0	1	0	0	0	0	0
	1,2	0.4	0	0	0	0	0.6	0	0	0	0
	2,3	0	0.2	0	0	0	0.2	0.6	0	0	0
	3,4	0	0	0	0	0	0	0	1	0	0
	4,5	0	0	0	0.2	0	0	0	0	0.8	0
	5,1	0.2	0	0	0	0	0	0	0	0	0.8

TABLE V. RATE OF CORRECT ANSWERS (SUBJECT A, VIBRATION MOTOR, 210 HZ)

Vibration motor (210 Hz)		**Answer (position number)**									
		1	2	3	4	5	1,2	2,3	3,4	4,5	5,1
Presentation (position number)	1	1	0	0	0	0	0	0	0	0	0
	2	0	1	0	0	0	0	0	0	0	0
	3	0	0.2	0.8	0	0	0	0	0	0	0
	4	0	0	0	1	0	0	0	0	0	0
	5	0	0	0	0	1	0	0	0	0	0
	1,2	0.2	0	0	0	0	0.8	0	0	0	0
	2,3	0	0.2	0	0	0	0	0.8	0	0	0
	3,4	0	0.2	0	0	0	0	0.2	0.6	0	0
	4,5	0	0	0	0.2	0	0	0	0.2	0.6	0
	5,1	0	0	0	0	0	0	0	0	0	1

TABLE VI. RATE OF CORRECT ANSWERS (SUBJECT A, VIBRATION MOTOR, 140 HZ)

Vibration motor (140 Hz)		**Answer (position number)**									
		1	2	3	4	5	1,2	2,3	3,4	4,5	5,1
Presentation (position number)	1	1	0	0	0	0	0	0	0	0	0
	2	0	0.8	0	0.2	0	0	0	0	0	0
	3	0	0	0.8	0	0	0	0.2	0	0	0
	4	0	0	0	1	0	0	0	0	0	0
	5	0	0	0	0	0.6	0	0	0	0.4	0
	1,2	0.2	0.6	0	0	0	0.2	0	0	0	0
	2,3	0.2	0.4	0.2	0	0	0	0.2	0	0	0
	3,4	0	0	0	0	0	0	0	1	0	0
	4,5	0	0	0	0.2	0.2	0	0	0	0.6	0
	5,1	0	0	0	0	0	0	0	0	0	1

TABLE VII. RATE OF CORRECT ANSWERS (SUBJECT A, VIBRATION MOTOR, 70 HZ)

Vibration motor (70 Hz)		**Answer (position number)**									
		1	2	3	4	5	1,2	2,3	3,4	4,5	5,1
Presentation (position number)	1	0.6	0	0	0	0	0.4	0	0	0	0
	2	0	0.8	0.2	0	0	0	0	0	0	0
	3	0	0	0.8	0	0	0	0	0.2	0	0
	4	0	0	0	1	0	0	0	0	0	0
	5	0	0	0	0	0.8	0	0	0	0.2	0
	1,2	0.4	0.2	0	0	0	0.4	0	0	0	0
	2,3	0	0	0.6	0	0	0	0.2	0.2	0	0
	3,4	0	0	0.2	0	0	0	0.2	0.6	0	0
	4,5	0	0	0	0.2	0	0.6	0	0	0.2	0
	5,1	0	0	0	0	0.4	0	0	0	0	0.6

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