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Sensory Feedback Device for Myoelectric Prosthetic Hand

Chiharu Ishii

Abstract

In this work, a sensory feedback device for myoelectric prosthetic hand was developed to enhance the quality of life (QOL) of myoelectric prosthetic hand users. Two types of sensory feedback, namely, force sense feedback and temperature sense feedback, were proposed. As for the feedback device of force sense, the device is mounted on the user's upper arm and provides hardness of the object onto the upper arm by winding a belt using a motor. On the other hand, as for the feedback device of temperature sense, the device is mounted on the user's upper arm and presents temperature of the object onto the upper arm using a Peltier element. Finally, two-sensory feedback devices were united, and a two-sensory feedback device was built.

Keywords: sensory feedback device, myoelectric prosthetic hand, force sense, temperature sense

1. Introduction

A myoelectric prosthetic hand is an electrically driven artificial hand that is controlled based on biosignals generated by muscle movement. Therefore, the myoelectric prosthetic hand can be moved freely as intended by the user. However, the user cannot feel sensations when he/she touches an object using the prosthetic hand. Healthy person uses the tactile sense and temperature sense to check the state of the object that he/she touched. A myoelectric prosthetic hand cannot produce any sensations. Therefore, the user has to operate the prosthetic hand only based on visual information. Thus, the user needs to watch the object constantly. This is a burden to the user. To solve this problem, sensory feedback which provides sensation to the user has been studied. Sensory feedback systems for an upper limb prosthesis in

the initial stage have been reported in [1]. Summary of studies involving sensory feedback in upper limb prosthetics is listed in [2].

A method of providing a sense of touch realized by vibration stimulation was proposed in [3], and a method of sensory feedback realized by the combination of vibration stimulation and electric stimulation was proposed in [4], respectively. On the other hand, Otsuka et al. [5] developed a device that perceives the temperature when an object was touched by a myoelectric prosthetic hand using a hot and cold pad. Morimitsu and Katsura [6] examined transfer of temperature sense using the Peltier element.

In this study, two types of sensory feedback device were developed to enhance the quality of life (QOL) of myoelectric prosthetic hand users. First, a compact feedback device of force sense (hereinafter referred to as FFB device) with a safety mechanism was developed. The FFB device is mounted on the user's upper arm, and when a prosthetic hand holds an object, a belt in the device is winded by a motor to present the holding force to the user's arm. Besides, the winding speed of the belt is changed according to the hardness of the object held by the prosthetic hand. In the control system of the FFB device, a reference input creation model creates reference input signals according to the hardness. A self-tuning proportional-integral-derivative (PID) control method proposed by [7] was employed to adjust the gain of the PID controller based on the state of a target object and control the belt-winding speed of the FFB device following the reference input. For the verification of the effectiveness of the control system for the FFB device, a myoelectric prosthetic hand made by [8] was combined with a control method proposed by [9], and experiments to distinguish among five kinds of springs of different hardness were conducted.

Second, a feedback device of temperature sense (hereinafter referred to as TFB device) was developed by using a Peltier element to present an object temperature when the user touches the object by a prosthetic hand. A temperature prediction algorithm was proposed to shorten the temperature measurement. Besides, the temperature sense differs at each body site. Therefore, the TFB device developed in this study transfers temperature sense felt by the fingertip to the upper arm based on the result of the experiment on temperature sense investigation. Furthermore, experiments to distinguish among five different temperatures were performed to verify the effectiveness of the TFB device. Finally, two-sensory feedback devices were united, and a two-sensory feedback device was built.

2. Myoelectric prosthetic hand

In this study, the myoelectric prosthetic hand made by [8] shown in **Figure 1(a)** is used. The prosthetic hand consists of motors and wires, and the fingers are bent by winding the wires. A pressure sensor is attached to a finger cushion on the prosthetic hand's index finger, and a temperature sensor is attached at the fingertip of the prosthetic hand's middle finger.

The myoelectric prosthetic hand used in this study only has three fingers, namely, the thumb, index finger, and middle finger. Therefore, the prosthetic hand grasps an object by bending
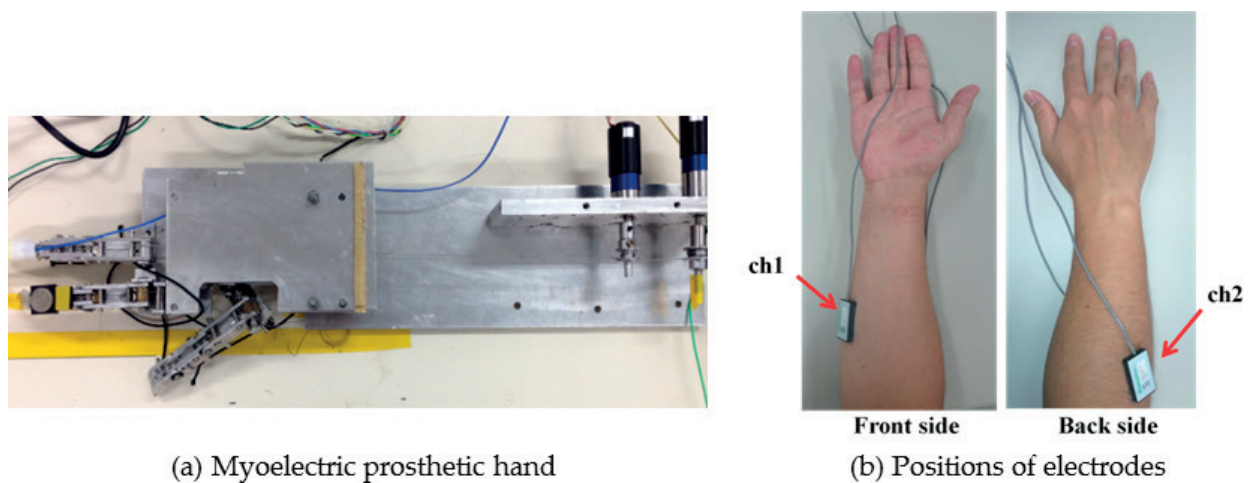
(a) Myoelectric prosthetic hand   (b) Positions of electrodes

Figure 1. (a) Myoelectric prosthetic hand. (b) positions of electrodes.

the index finger for contact force feedback case and bending the middle finger for temperature sense feedback case. The motion of the index finger and the middle finger is identified by measuring the surface electromyogram (SEMG) of the flexor digitorum superficialis (ch 1) and extensor carpi radialis longus (ch 2) shown in **Figure 1(b)** to control the proximal interphalangeal (PIP) joint of the prosthetic hand's index finger and middle finger.

3. Feedback device of force sense (FFB device)

3.1. Design concept

In this study, amputees who lost the lower half of a single forearm were chosen as subjects, and electrodes were placed on the upper half of the forearm to operate a prosthetic hand. To let prosthetic hand users recognize the sense more intuitively, the sense of pressure was given to the prosthetic hand users when they grasp an object. The sense of pressure was presented by the tightening force of a belt on the upper arm of the users.

The difference of the contact force according to the hardness of the object is expressed as the winding speed of the belt. The pressure value added to the finger and displacement of the finger are measured, and they are used to estimate the object hardness. Then, the winding speed of the belt is changed to present the estimated hardness. Namely, the high winding speed is for a hard object, and the low winding speed is for a soft object.

3.2. Overview of FFB device

3.2.1. Equipment

Figure 2 shows the developed FFB device and its attached state on the user's upper arm. The working principle is described as follows. Contact force between an object and a finger is measured by the pressure sensor attached to the finger cushion on the prosthetic hand's
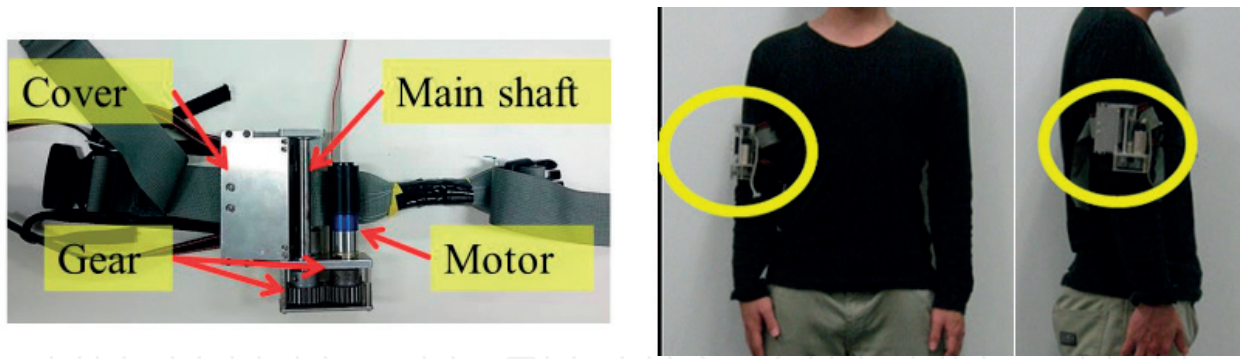
Figure 2. FFB device and its attached state.

index finger. The main shaft for winding the belt and the motor are connected through two gears. When the prosthetic hand grasps the object, namely, when the contact force is sensed, the motor rotates. Therefore, the main shaft is also rotated by the rotation of the motor. Thus, the belt is winded and tightens the upper arm.

The device is small with the dimensions 97 mm (width), 117 mm (depth), and 39 mm (height).

3.2.2. Safety mechanism

A safety measure against the motor's failure or other emergent case needs to be taken. In the case of emergency, the belt is released by simply opening the cover, and then the device is released from the arm.

3.3. Control method of prosthetic hand

In this study, a control strategy proposed in [9] is used for the operation method of the myo-electric prosthetic hand. It is well known that an integrated electromyogram (IEMG) reflects muscle activity. Hence, the IEMG is employed to identify the input motion for the operation of the prosthetic hand, and a support vector machine (SVM), which is one of the techniques of the machine learning, is used as an identifier. For the control of the prosthetic hand, a target angle of the finger of the prosthetic hand is set based on how long the user keeps the muscle force. This allows the user to arbitrarily control the finger angle.

3.4. Measurement of hardness

A pressure sensor "FSR402 Short Tail" made by Interlink Electronics was attached on the fingertip to measure the reaction force F [N] from the grasped object. The displacement of the fingertip [m] is measured from the encoder attached on the driving motor of the finger. Then, the spring constant K [N/m], hereinafter referred to as the hardness parameter, can be calculated from Hooke's law:

$$K = \frac{F}{x} \tag{1}$$

A preliminary experiment was conducted in [10] to derive a conversion formula from the pressure (voltage V [v]) measured with the pressure sensor to the reaction force F [N]. The resulting conversion formula is the following:

$$F = 9.81 \times \{(8.01 \times 10^{-3}) V^6 - (9.79 \times 10^{-2}) V^5 + (4.52 \times 10^{-1}) V^4$$
$$- (9.49 \times 10^{-1}) V^3 + (8.56 \times 10^{-1}) V^2 - (1.37 \times 10^{-1}) V\} \tag{2}$$

With Eq. (2), a reaction force is calculated from the measurement value obtained with the pressure sensor. Thus, one can calculate the hardness parameter from Eq. (1).

3.5. Control of FFB device

3.5.1. Configuration of reference input creation model

For the purpose of this study, the winding speed of the belt in the FFB device needs to be adjustable according to the hardness of the grasped object. A reference input creation model is defined as shown in **Figure 3**, in which a reference input $r(t)$ is obtained by a step input $u_s(t)$ passing a primary delay filter.

The following relation is obtained from **Figure 3**:

$$R(s) = \frac{1}{Ts+1} U_s(s) \tag{3}$$

A small time constant of the primary delay filter produces a rapidly rising reference input, and a large time constant produces a gradually rising reference input. The time constant T [s] of the primary delay filter is adjusted in accordance with the hardness parameter, K, to control the belt-winding motor to follow the reference input. Thus, T is denoted as $T(K)$.

For safety reason, the FFB device is configured so that up to 10 mm of the belt is wound up.

3.5.2. Relation between time constant and hardness parameter

A function of the time constant $T(K)$ related to the hardness parameter K was derived in [10], which was determined as follows by trial and error:

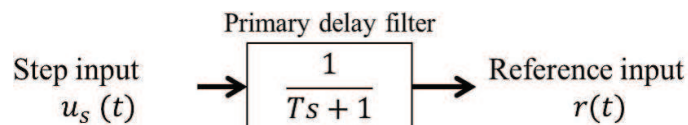$$T(K) = \tan^{-1}(-K \times 0.000734 + 2.1) \times 0.705 + 1.202 \tag{4}$$

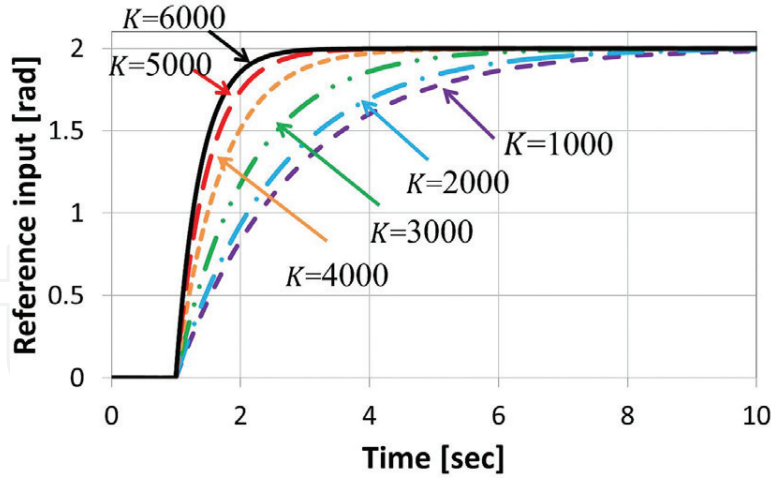**Figure 3.** Reference input creation model.

Figure 4. Reference inputs.

3.5.3. Verification of reference input creation model

Numerical simulation was performed to verify the reference input creation model. In the verification, the hardness parameter was increased from 1000 to 6000 for each 1000, and the reference input derived from the reference input creation model was checked. The result is shown in **Figure 4**.

Figure 4 shows that the rise of the curve becomes rapid as the hardness parameter increases. This result indicates that the reference input could be efficiently created so that the user can feel a difference of the hardness.

3.5.4. Self-tuning PID control

The FFB device gives feedback of the force sense by pressing the upper arm of the user. The amount of fat and muscle of the human arm differs from person to person, and the arm hardness could also change depending on how much the user strains the arm. Thus, the arm hardness has a nonlinear characteristic. Therefore, an adaptive control is used for the control of the belt-winding motor of the FFB device. To this end, the self-tuning PID control proposed by [7] is used. Since the self-tuning PID control scheme is based on a discrete time control, Eq. (3) is discretized by a bilinear transformation to design a controller of the FFB device.

The control aim is to determine the control input $u(k)$ so that the output angle $y(k)$ of the FFB device follows the reference input $r(k)$. The detail of the derivation of the control input is described in [10]. The PID gain can be calculated by using the estimation parameters $\hat{a}_1(k)$, $\hat{a}_2(k)$, and $\hat{a}_3(k)$ as follows:

$$\hat{K}_p(k) = \frac{2\,\hat{a}_2(k) + \hat{a}_3(k) - 2}{\hat{a}_1(k)}, \quad \hat{K}_i(k) = \frac{1}{\hat{a}_1(k)}, \quad \hat{K}_d(k) = \frac{1 - \hat{a}_2(k) - \hat{a}_3(k)}{\hat{a}_1(k)} \tag{5}$$

Here, k is the number of steps. Then, the control input is given by the following equation:

$$u(k) = u(k-1) + \hat{K}_p(k)\{y(k-1) - y(k)\} + \hat{K}_i(k)\{r(k) - y(k)\}$$
$$+ \hat{K}_d(k)\{2y(k-1) - y(k) - y(k-2)\} \tag{6}$$

3.6. Operation check of FFB device

For the verification of the functions of the whole system, the prosthetic hand was operated based on the SEMG of a subject, and the hardness of an object that was grasped by the hand was estimated. Then, how the FFB device controlled by the self-tuning PID could follow the reference input created from the estimated hardness was examined.

Five kinds of springs with different hardness were chosen as objects to grasp. **Table 1** shows the physical properties of the springs.

The subject was an adult male in 20s. The results in which each of the springs was grasped once are shown in the following figures and tables. **Figure 5** shows how the FFB device followed the reference input. **Table 2** shows the results of the hardness estimation. **Table 3** shows self-tuning PID gains and the time constant calculated from the estimated hardness.

Figure 5(a) and **(b)** shows a time delay of about 0.2 s in the response of the FFB device for any spring. However, the device clearly followed the reference input. Although a small error between the estimated value and the real value of the hardness parameter is seen in **Table 2**, the time constant was successfully calculated for all of the springs as shown in **Table 3**. Therefore, it was confirmed that the reference input could be created according to the estimated hardness of the grasped object. In addition, the belt-winding action of the FFB device under the control of the self-tuning PID controller followed the reference input obtained from the estimated hardness. Thus, it was verified that the system worked properly.

3.7. Hardness identification experiment

The usefulness of the FFB device with the proposed system implemented is objectively verified with a psychophysics experiment method. Five kinds of springs, shown in **Table 1** in the previous section, were used as the target of the hardness identification.

No.	Spring constant K [N/m]	Diameter [m]	Length [m]
S_1	990	14×10^{-3}	25×10^{-3}
S_2	1800	8×10^{-3}	25×10^{-3}
S_3	2980	10×10^{-3}	30×10^{-3}
S_4	4390	13×10^{-3}	25×10^{-3}
S_5	5340	7×10^{-3}	25×10^{-3}

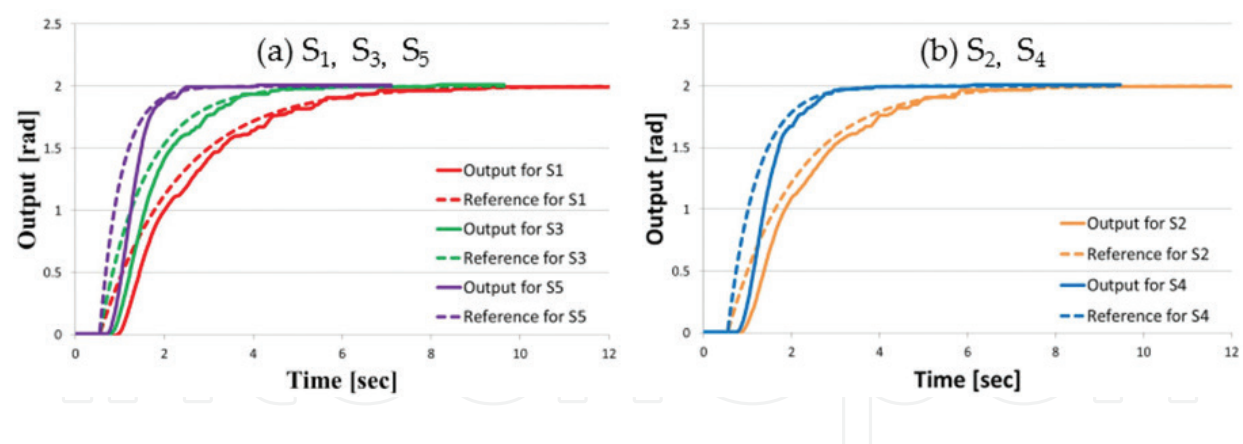**Table 1.** Physical properties of springs.

Figure 5. Reference input and output of the FFB device.

Spring	Force [N]	Displacement [m]	Estimated hardness parameter [N/m]	Real hardness parameter [N/m]
S_1	5.23	3.76×10^{-3}	1390	990
S_2	5.27	2.56×10^{-3}	2060	1800
S_3	5.66	1.80×10^{-3}	3150	2980
S_4	5.15	1.27×10^{-3}	4060	4390
S_5	4.96	0.99×10^{-3}	5030	5340

Table 2. Estimated and real hardness parameter.

Spring	Time constant T [s]	PID gain		
		$\hat{K}_p(k)$	$\hat{K}_i(k)$	$\hat{K}_d(k)$
S_1	1.78	0.22706	0.0125	0.01154
S_2	1.58	0.22707	0.0125	0.01154
S_3	1.06	0.22713	0.0125	0.01150
S_4	0.69	0.22710	0.0125	0.01151
S_5	0.49	0.22717	0.0125	0.01147

Table 3. Time constant and self-tuned PID gains.

3.7.1. Overview of the experiment

In the experiment, the myoelectric prosthetic hand was not used, but the spring constant of each spring was input directly to a computer, and then the hardness identification experiment using the FFB device was conducted.

The experiment was conducted by following the procedure of a constant method. The hardness of a brass spring (K = 2980) was used as standard stimulation, and the hardness of five springs, including the brass spring, was used as comparative stimulation. The experimental procedure is described as follows:

1. FFB device is attached on the upper arm of the subject.

2. The subject is trained so that he can recognize the behavior of the FFB device.

3. The standard stimulation is given to the subject.

4. A 4-second interval is taken.

5. The comparative stimulation is given to the subject.

6. The subject answers which stimulation is harder or whether the two are the same.

7. 25 sets of operations [(3)–(6)] are conducted. In the operations, all the comparative stimulations are used five times in random orders.

8. The operations [(3) and (5)] were replaced, and 25 sets of the operations [(3)–(6)] are conducted again.

The experiments were performed for five healthy subjects in their 20s. In the operations, a 1-min break was taken every five sets to prevent the subject from getting tired.

3.7.2. Results

Table 4 shows the results of experiments. The bold numbers show the ratio of correct identification of the stimulations.

From the results on the hardness identification experiment, one can see that the proposed method of presenting different varying hardness levels by using different belt-winding speeds was effective to identify the hardness of the five kinds of objects.

Stimulation	Rate of the subject's answer [%]		
	Hard	Equal	Soft
S_1	4	12	**84**
S_2	16	16	**68**
S_3	24	**46**	30
S_4	**78**	22	0
S_5	**88**	12	0

Table 4. Identification results of hardness.

4. Feedback device of temperature sense (TFB device)

4.1. Temperature sense

A combination of cold and warm sensations is called a temperature sense. The temperature sense differs at each body site even when an object of the same temperature is touched. In addition, when the skin is exposed to extreme heat or cold, the pain along with the risk of burns arises. Therefore, it is necessary to regulate the temperature of the TFB device.

4.2. Peltier element and thermocouple

The Peltier element is an electronic device that enables both cooling and heating by applying a voltage on the basis of the Peltier effect, and temperature is adjustable by regulating the voltage. The TFB device has a Peltier element; thus, the temperature sense is transferred to the user. The Peltier element used in the TFB device is "TEC1-12708" made by HB Electronic Components.

A thermocouple is a temperature sensor on the basis of the Seebeck effect. The thermocouple is attached to the silicone finger mounted on the fingertip of the myoelectric prosthetic hand to measure temperature of an object when the fingertip touches the object. A K-type thermo-couple "AD-1214" made by T&D Corporation is used in this study.

4.3. Overview of TFB device

Figure 6 shows the developed TFB device and its attached state on the user's upper arm. The Peltier element is attached to the inside of an aluminum board, and in order to raise a heat dissipation efficiency, a radiation sheet and a heat sink are attached to the other side of the aluminum board. The TFB device is attached on the upper arm of the user in contact with the user's skin, and the temperature sense that is corresponding to the temperature detected by the temperature sensor at the fingertip is transferred in the upper arm of the prosthetic hand user.

The device is small enough with the dimensions 50 mm (width), 60 mm (depth), and 17 mm (height).

When the TFB device is used for a long period, the accumulated heat causes a high temperature of the TFB device. Therefore, the continuous operating time of the TFB device is limited to 5 s.
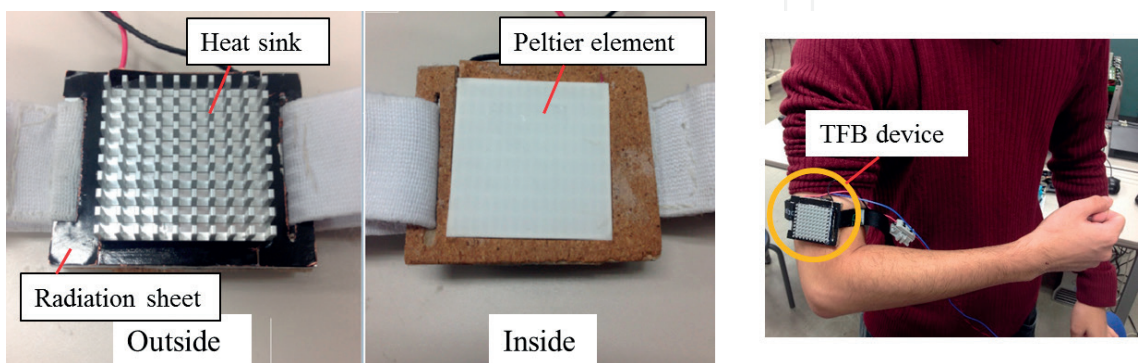

Figure 6. TFB device and its attached state.

When the TFB device decreases the temperature, it enables refrigeration of surface temperature to a minimum of 15°C for 5 s. On the contrary, when the TFB device increases the temperature, it enables heating of surface temperature exceeding 50°C. Hence, the temperature of the TFB device is limited to 40°C for safety.

4.4. Temperature prediction

After the myoelectric prosthetic hand contacts with the object, the temperature sensor needs a long time for measuring the temperature. Therefore, a temperature prediction is performed to shorten the measurement time.

Let relationship between a sensor output $y(t)$ and a temperature variation $u(t)$ be given by the following equation in transfer function expression:

$$Y(s) = G(s)U(s) \tag{7}$$

To determine the transfer function $G(s)$, the parameter identification was performed. Furthermore, let ΔT denote the predicted temperature variation and $\hat{y}(t)$ denote the estimated output, and then the estimated output is calculated as follows using the identified transfer function:

$$\hat{Y}(s) = \frac{0.89\,s^3 + 0.66\,s^2 + 0.49s + 0.06}{s^4 + 2.54\,s^3 + 1.7\,s^2 + 0.8s + 0.06}\Delta T \tag{8}$$

Let $\varepsilon(t)$ denote the error between the estimated output $\hat{y}(t)$ and sensor output $y(t)$, which is presented by $\varepsilon(t) = \hat{y}(t) - y(t)$. The predicted temperature variation ΔT is updated by using $\varepsilon(t)$ as follows in each sampling period:

$$\Delta T_{new} = \Delta T_{old} + K \cdot \varepsilon(t) \tag{9}$$

where ΔT_{old} is the predicted temperature variation one step before, ΔT_{new} denotes an updated predicted temperature variation, and K is an arbitrary constant, which was chosen as $K = 70$.

Let T_0 denote the room temperature, and then predicted temperature T is given as follows:

$$T = \Delta T_{new} + T_0 \tag{10}$$

The predicted temperature is updated to reduce the error when the sensor detected a temperature variation; thus, the temperature when reached to the equilibrium state is given by Eq. (10). As a result, the sensor can detect the temperature of the object in a short time.

The verification experiment was performed to verify an effectiveness of the proposed temperature prediction algorithm. In the experiment, under the room temperature of 26°C, the sensor touched an object of 40°C. Then, the temperature was predicted by the proposed algorithm. **Figure 7** shows the result.

The result showed that prediction of the temperature in a short time is possible by using the proposed temperature prediction method.
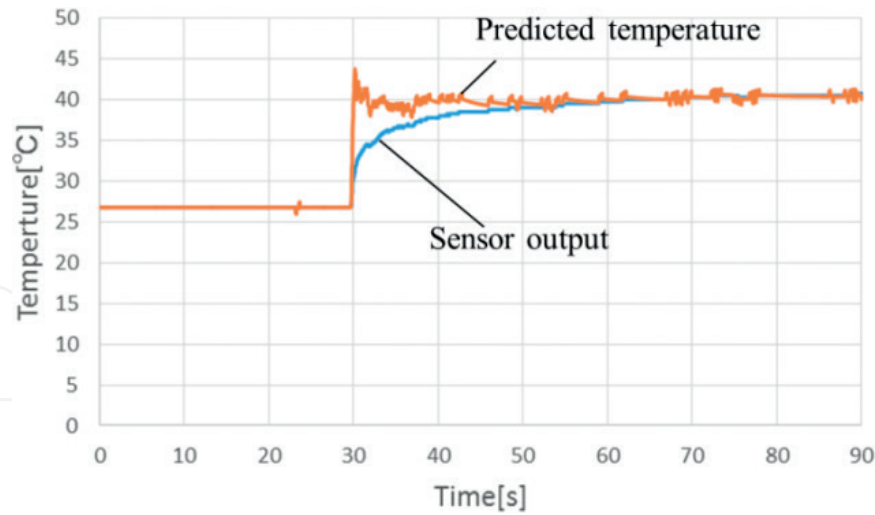
Figure 7. Result of the temperature prediction for the object of 40°C.

4.5. Temperature sense investigation

The temperature sense of an individual differs at each body site. For example, the temperature senses when an object with the same temperature is touched with a finger and with the upper arm are different. Therefore, in order to investigate the difference in the temperature sense between the fingertip and the upper arm, a temperature sense investigation was performed. Thus, the temperature experienced by the upper arm which is equivalent to the temperature experienced by the fingertip was determined as feedback temperature to the upper arm.

The temperature which should be presented at the upper arm and the voltage which should be applied to the TFB device were determined in [11] as follows. The relationship between the temperatures experienced by the fingertip and by the upper arm was interpolated. Then, the relationship between the predicted temperature at the fingertip T and the target temperature in the upper arm T_t and the relationship between the predicted temperature at the fingertip T and the input voltage to the TFB device V were approximated as shown in Eqs. (11) and (12), respectively, by using the least squares method:

$$T_t = 0.00008\, T^4 - 0.006\, T^3 + 0.1841\, T^2 - 1.1439T + 16.902 \tag{11}$$

$$V = 1.578 \times 10^{-7}\, T^6 - 2.135 \times 10^{-5}\, T^5 + 1.122 \times 10^{-3}\, T^4$$
$$- 2.894 \times 10^{-2}\, T^3 + 0.3819 \times T^2 - 2.543T + 8.743 \tag{12}$$

4.6. Closed-loop control system

4.6.1. Construction of the control system

In the previous section, the developed TFB device was controlled in an open-loop system, in which the constant voltage computed from Eq. (12) was applied to the TFB device. In the case where the voltage is continuously provided to the TFB device, the temperature keeps increasing

or decreasing. Hence, it is impossible to maintain the temperature using this control system. Therefore, the continuous operating time of the TFB device was limited to 5 s.

To use the TFB device continuously, a closed-loop control system was constructed. For this purpose, another temperature sensor was additionally attached on the surface of the Peltier element of the TFB device. The target temperature in the upper arm T_t corresponding to the predicted temperature at the fingertip of the myoelectric prosthetic hand T is determined by Eq. (11). Then, the input voltage to the TFB device is determined by a PID controller. The PID gains were determined by trial and error and chosen as $K_P = 1$, $K_I = 0.05$ and $K_D = 0.01$.

4.6.2. Operation check of TFB device

In order to verify the effectiveness of the closed-loop control system with PID controller, experiment was performed. In the experiment, the target temperature is suddenly decreased from 40 to 15°C. The transition of the temperature of the TFB device and the input voltage to the TFB device are shown in **Figure 8**.

As shown in **Figure 8**, the results showed that the constructed closed-loop system enabled the adjustment of the temperature of the TFB device according to the temperature change and also enabled a long-time continuous operation of the TFB device.

4.7. Temperature identification experiment

In order to verify the performance of the TFB device controlled in the closed-loop control system, a temperature identification experiment was performed. The usefulness of the TFB device controlled by the closed-loop system is objectively verified with a psychophysics experiment method.

4.7.1. Overview of the experiment

In this experiment, the myoelectric prosthetic hand was not used, but each temperature was input directly to a computer, and then the temperature identification experiment using the TFB device was conducted.

The temperature of 30°C was used as standard stimulation, and five kinds of temperature, 28, 29, 30, 31, and 32°C, were used as comparative stimulation. The following describes the experimental procedure:

1. TFB device is attached on the upper arm of the subject.

2. An experimenter inputs the standard stimulation (30°C) to the computer, and standard stimulation is presented to the subject by the TFB device.

3. An experimenter inputs the comparative stimulation that is randomly selected from the five kinds of temperatures to the computer, and comparative stimulation is presented to the subject by the TFB device.

4. The subject answers which temperature is higher or whether the two are almost same.

5. 25 sets of the operations [(2)–(4)] are performed.

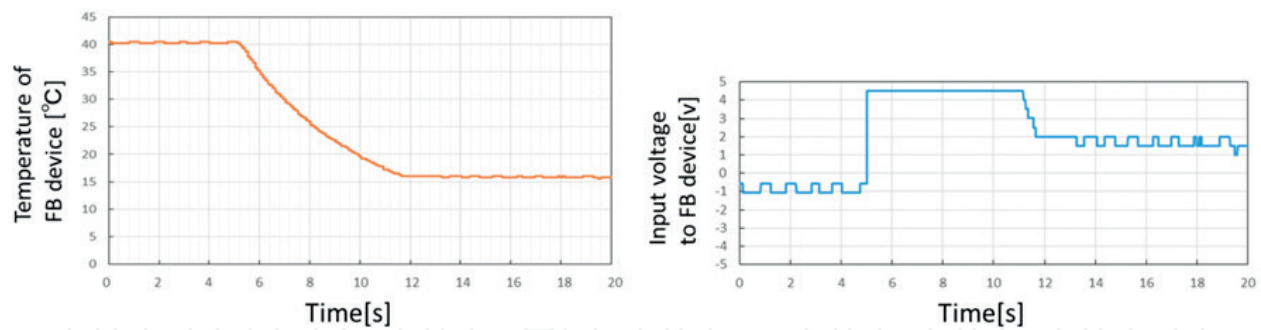6. The operations [(2) and (3)] were replaced, and 25 sets of the operations [(2)–(4)] are performed.

Figure 8. Temperature of the TFB device and input voltage to the TFB device.

Temperature of comparison stimulus [°C]	Rate of the subject's answer [%]		
	Hot	Equal	Cold
28	0	14	**86**
29	4	36	**60**
30	6	**82**	12
31	**60**	34	6
32	**86**	10	4

Table 5. Identification results of temperature.

In the operations, all the comparative stimulations were used 10 times in random orders. The experiments were performed for five healthy subjects in their 20s.

4.7.2. Results

Table 5 shows the results of experiments. The bold numbers show the ratio of correct identification of the stimulations.

From the results on the temperature identification experiment, one can see that the proposed method of presenting temperature by the TFB device controlled in the closed-loop control system was effective to identify the five kinds of temperatures.

5. Integration of the sensory feedback devices

5.1. New myoelectric prosthetic hand

To improve the operability of the myoelectric prosthetic hand, a new myoelectric prosthetic hand was designed and built by imitating the commercial prosthetic hand, which is shown in **Figure 9**. The pressure sensor and the temperature sensor were attached to the fingertip of the

thumb and index finger of the prosthetic hand, respectively. Thus, this myoelectric prosthetic hand makes it possible to detect the force and temperature when the prosthetic hand holds an object.

5.2. Two-sensory feedback device

Finally, the FFB device and the TFB device were united, and a two-sensory feedback device was built, which is shown in **Figure 10**. The dimensions of the device are 75 mm (width), 82 mm (depth), and 34 mm (height).
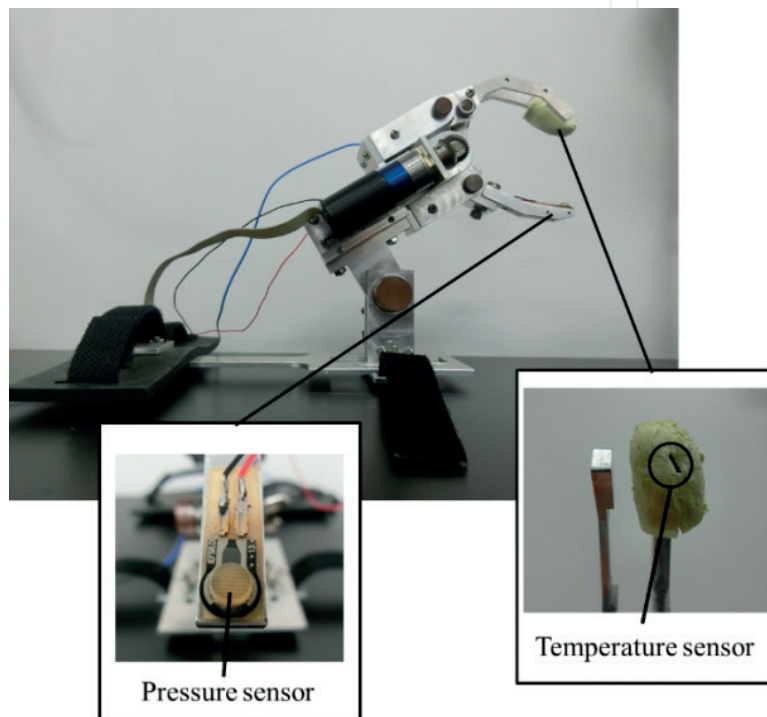

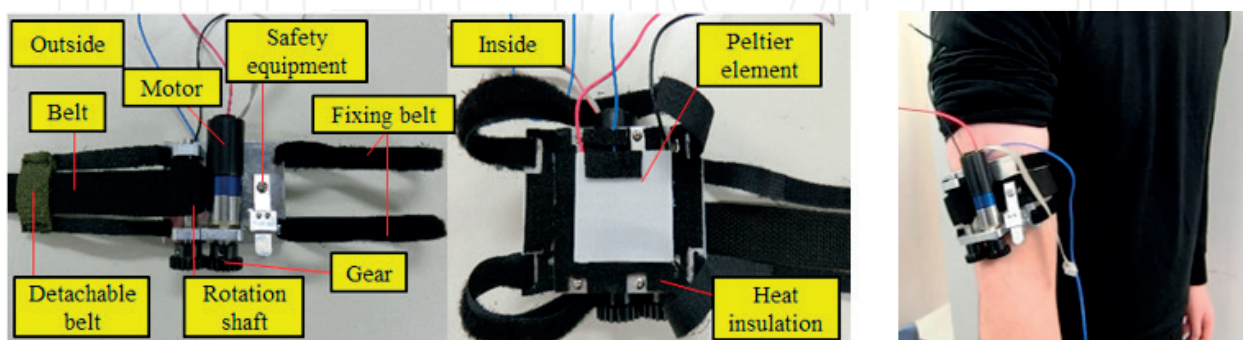**Figure 9.** New myoelectric prosthetic hand.

Figure 10. Two-sensory feedback device and its attached state.

6. Conclusion

In this study, force feedback device (FFB device) and temperature feedback device (TFB device) were proposed and built. When a user of a myoelectric prosthetic hand grasps an object, the FFB device provides pressure to the user's upper arm by winding a belt using a motor, and the TFB device presents the temperature sense to the user's upper arm using the Peltier element.

In the FFB device, the hardness of the object was estimated by a pressure sensor attached on the fingertip of the myoelectric prosthetic hand, and a reference input was produced by a reference input creation model according to the hardness. In addition, a self-tuning PID controller was employed to control the FFB device so as to make the motor's output angle follow the reference input. Furthermore, the hardness of the grasped object was presented by the winding speed of the belt. Hardness identification experiment to distinguish among the five kinds of springs of different hardness was carried out. The experimental results on the hardness identification experiment showed that the proposed method was effective to identify the hardness of the five kinds of objects.

In the TFB device, a temperature prediction algorithm was proposed for short-time temperature detection. Then, based on the results of the temperature sense investigation, the corresponding temperature sense when the object was touched by a fingertip was transferred to the user's upper arm by the TFB device. However, it was difficult to operate the TFB device continuously because this device was controlled in an open-loop control system. To solve this problem, a closed-loop control system was constructed for the TFB device and was tested for sudden change of the temperature. Temperature identification experiment to distinguish among five different temperatures was carried out to verify the effectiveness of the TFB device controlled in the closed-loop control system. The experimental results on the temperature identification experiment showed the sufficient capability of the TFB device controlled in the closed-loop control system.

In addition, a new myoelectric prosthetic hand was built to improve the operability of the myoelectric prosthetic hand. Finally, two-sensory feedback devices were united, and a two-sensory feedback device was built.

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