Improvement of Performance of Sensory Feedback System for Myoelectric Prosthetic Hand

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***Abstract*—In this paper, a control system of the sensory feedback device for myoelectric prosthetic hand users, which was developed in our previous study, was improved to express the hardness of an object continuously. The sensory feedback device is worn on user's upper arm. When the finger of the myoelectric prosthetic hand grabs the object, a contact force on the object is detected by a pressure-sensitive sensor attached on a finger cushion of the myoelectric prosthetic hand. Moreover, the hardness of the object is calculated. According to the hardness of the object, a reference input to realize the corresponding winding speed of the belt is generated by a reference input generator. Then, the motor of the feedback device is controlled to track the reference input by using the self-tuning Proportional-Integral-Derivative (PID) control technique, taking parameter variation into account. Thus, the belt of the feedback device is wound by the motor and tightens the user's upper arm, so that the user can feel a tactile sense. Finally, confirmation tests are conducted to verify the effectiveness of the improved control system. As a result, the hard object and the soft object are able to be distinguished with an average accuracy of 92.5%.**

***Index Terms*—sensory feedback, myoelectric prosthetic hand, self-tuning PID control, identification of hardness**

I. Introduction

Myoelectric prosthetic hand is an electric prosthetic hand that is controlled by distinguishing the movements using electromyogram signals, which is called myoelectricity and is recorded from the muscles. Myoelectric prosthetic hand is operated freely by will of the user, because it is made to improve the kinetic functions of hands. However, there is a flaw that there are no senses. In nonhandicapped persons, the confirmation of the state of the thing that a person is holding is a role of the senses. Therefore, the myoelectric prosthetic hand that cannot obtain tactile sense places an additional burden on the user because a user must only control with the visual feedback and hold the object by watching the myoelectric prosthetic hand. For this reason, study of sensory feedback devices conveying tactile information of the myoelectric prosthetic hand to a user has been conducted before. However, such devices cannot be used for practical applications yet.

Under these circumstances, various methods have been purposed as the method to convey senses to human. For example, Ref. [1] shows that force sense is conveyed to train the artificial hand by using an artificial hand of the magic hand type. Ref. [2] proposes the sensory feedback method, which combined electrical stimulation with vibratory stimulation by using a vibration motor and an electrode. Ref. [3], [4] show that tactile sense is conveyed through vibration created by a motor, and Ref. [5] investigates stimulation patterns for sensory feedback using electrodes. As a method using auditory sense, Ref. [6] shows that users can distinguish between objects by representing contact forces using multi-frequency auditory signals. Ref. [7] proposes a device that presents a sense of motion by rotational stretch of user's skin. Ref. [8] proposes the device that has two feedback methods force and vibratory feedback to cope up with both portability and functionality. Specifically, force sense is conveyed by converting the rotating movement of the motor to vertical movement to press a plunger to a human arm by using the screw, and vibratory sensation is conveyed using a vibration motor. Ref. [9] proposes a multifunction device that presents touch, pressure, vibration, shear force, and temperature to the skin of user.

However, in the case where the tactile sense is displayed using vibration and electrical stimulation, it is difficult for a user to understand this tactile information intuitively because this is different from original tactile sense. In addition, when a malfunction occurs such as a runaway of the device motor due to the breakdown of the device controller, safety countermeasures are not considered.

Therefore, in Ref. [10], we developed such a sensory feedback (hereafter, *FB device*) that is small and has the safety mechanism to reduce the user's load. The FB device is worn to the upper arm of the user and conveys the holding power of the prosthetic hand by winding a belt onto upper arm using a motor. Contacts with objects are detected with a pressure sensor installed in the fingertip of the prosthetic hand, and differences in object hardness are expressed by changing the speed of tightening the belt.

However, in the control system, there was a problem that the object hardness expressed by the FB device has only three phases, hard object, soft object, and medium

Manuscript received November 17, 2015; revised January 17, 2016.

doi: 10.18178/ijpmbs.5.1.44-51

object, because the object hardness is conveyed in stages by changing the desired value of the controller.

Accordingly, the purpose of this study is to improve the control system of the FB device to express the hardness of various objects by enabling continuous handling of object hardness.

Specifically, reference input signal providing the winding speed of the belt corresponding to hardness is generated from the hardness of the grasped object calculated from the measured value by a sensor installed in the fingertip of the prosthetic hands. Moreover, human arm has uncertainties such as nonlinearity because there is an individual difference such as deformation volume and hardness. Ref. [11] proposed a self-tuning PID controller in which PID gain is adjusted by successively calculating each gain in the system depending on the control object condition. Accordingly, this control method is employed and force sense is conveyed to the user by controlling the winding amount of FB device belt to follow reference input.

Finally, an identification experiment of the hardness was conducted to verify the effectiveness of the proposed control system.

II. Equipment

A. Summary of Sensory Feedback Device (FB Device)

Fig. 1 shows the FB device developed in Ref. [10]. The operating principle is as follows. One end of the belt is installed in device, and the other end is fixed on main shaft. When a contact force with the object is detected by sensors installed in the finger of the prosthetic hands, the motor rotates. The main shaft is linked to the motor with two gears a 1:1 gear ratio. Thus, the rotation of the motor is transmitted to main shaft, and user's arm is tightened with belt wound onto main shaft.

Actually, Fig. 2 shows a state worn at upper arm of the user. The device is worn at the upper arm of the hand on which the artificial arm is worn so that the user can feel the force feedback intuitively. The device is fixed on the arm by tightening two belts of the top and bottom sides of the device.

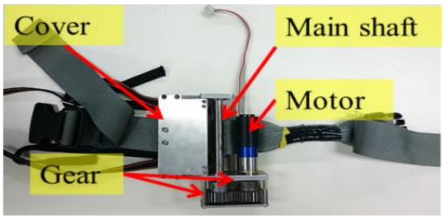

Figure 1. Sensory feedback device (FB device).

Figure 2. Worn state of FB device.

B. Myoelectric Prosthetic Hand

In Ref. [12], the prosthetic hand shown in Fig. 3 was developed, and this prosthetic hand is used in this study. The myoelectric prosthetic hand comprises a motor and a wire, and has the structure which bends a finger by winding a wire.

When a user held an object using the myoelectric prosthetic hand, there are three main movements: opening a finger, closing a finger, and keeping a state of grasping the object. The myoelectric prosthetic hand used in this study only has the thumb and index finger. For simplification, the object was held by bending the proximal interphalangeal (*PIP*) joint of the index finger. Thus, the movement of the index finger is determined by measuring the surface electromyograms (SEMG) of the flexor digitorum superficialis muscle (ch1) and extensor carpi radialis longus (ch2), and the PIP joint of the index finger is controlled. Fig. 4 shows the positions of electrodes to detecte the SEMG.

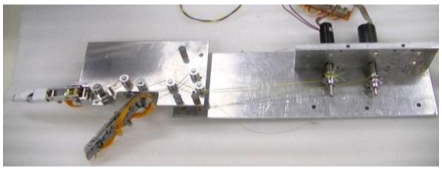

Figure 3. Myoelectric prosthetic hand.

Figure 4. Position of electrodes.

C. Control Method of Myoelectric Prosthetic Hand

Ref. [13] proposes the prosthetic hand control method, and this control method is adopted in this study. Specifically, the intended finger movement is identified using an integrated electromyogram (*IEMG*), which is said to reflect a muscular activity state. A support vector machine (*SVM*) is used as a classifier to identify between movements.

IEMG is the value that integrated SEMG measured by an electrode and is calculated in the next equation.

$$IEMG_i = \int_{t-\Delta t}^{t} |SEMG_i| \, dt \; (i = 1\sim2), \qquad (1)$$

where $SEMG_i$ are the measurements of *SEMG* of each electrode measured for every sampling time. i (=1~2) represents the channel corresponding to the measurement position. Δt expresses the interval of integration and means substantially number of samples. Ref. [13] sets 256 as number of samples, and 0.256 s as the interval of integration. Thus, the same value is used in this study.

1) Identification movement

In this paper, two types of movements, which are flexure and extension of operator's four fingers expect for the thumb, are determined as identification movements. Fig. 5 shows the two types of movements. Then, the prosthetic hand's index finger is controlled to be extended when extension of operator's four fingers is identified, and the prosthetic hand's index finger is controlled to be flexed when flexure of operator's four fingers is identified. Although the operator moves four fingers in reality, an index finger alone is moved in the case of the prosthetic hand.

When IEMG value exceeds a certain threshold, identification of the finger movement is executed. The result identified by SVM is expressed as SVM_{out}, and SVM_{out} represents the next three movements; flexure of four fingers for SVM_{out} = 1, extension of four fingers for $SVM_{out} = -1$, and the state in which no finger is moved for SVM_{out} =0.

$SVM_{out} = 1$ $SVM_{out} = -1$

Figure 5. Finger movements for identification.

2) Learning and control

Flexure and extension of four fingers are executed five times each to let the SVM learn, and a total of ten characteristic vectors are created as learning data. The learning of SVM is executed using the tool box released in Information: Signals, Images, Systems (ISIS) and spline is used in a kernel matrix.

In the control of the prosthetic hand, a target angle is set on the basis of the time when a user maintains muscular strength. Consequently, the user is able to voluntarily operate the angle of the prosthetic hand finger. $1/K_1$ [sec] is determined as time from a state in which the prosthetic hand finger is extended to a state in which the finger is bent to the limit. The target angle, θ_{ref}, of the prosthetic hand finger is calculated by the following equation.

$$\theta_{ref} = \frac{\pi}{2}\int_{t-\Delta t}^{t} K_1 \cdot SVM_{out}\, dt. \qquad (2)$$

In other words, K_1 is a constant that expresses the movement speed of the finger.

The motor driving a finger is controlled by PI controller so that the angle of the prosthetic hand finger follows the target angle given by (2).

III. Calculation of Hardness

A. Calculation of Hardness Parameter (Spring Constant)

The hardness of the object is calculated by the reaction force obtained from a grabbed object. The reaction force is obtained with pressure sensor (FSR402 Short Tail) made in Interlink Electronics Company and installed in the finger cushion of the prosthetic hand's index finger. Thus, the spring constant (hereafter, *hardness parameter, K*) [N/m] is calculated in the following equation by using Hooke's law.

$$K = \frac{F}{x}, \qquad (3)$$

where F [N] is a reaction force and x [m] is the fingertip displacement.

B. Measurement of Reaction Force

Conversion equation is found experimentally by conducting the following preliminary experiment to obtain the reaction force from a measured value (voltage value) of the pressure sensor.

Water was poured into the PET bottle so that the weight of the PET bottle becomes 300, 400, 500, 800, 900, and 1000 g. PET bottle was arranged to apply load to the center of the pressure sensor, and the pressure sensor value was measured. Thereafter, an equation of relation between the measurement voltage V [v] and reaction force F [N] was obtained as linear function by using least squares method. Conversion equation of the following equation was found by experimental results.

$$F = 9.81 \times 483.51 \times V \times 10^{-3} \qquad (4)$$

According to the above results, the reaction force is obtained from the measured value of pressure sensor by using (4).

C. Measurement of Fingertip Displacement

The fingertip displacement x [m] is calculated with following equation as shown in Fig. 6.

$$x = l\sin\theta, \qquad (5)$$

where θ [rad] is the bending angle of the PIP joint, and l = 0.03 m is the distance from the PIP joint to the center of the sensor. Furthermore, θ is calculated as follows by using experimental equation obtained from a measured value of the encoder of the motor driving PIP joint.

$$\theta = 67.553\theta_{en}^{\ 6} - 395.55\theta_{en}^{\ 5} + 871.77\theta_{en}^{\ 4} - 881.87\theta_{en}^{\ 3} + 368.16\theta_{en}^{\ 2} + 46.037\theta_{en}, \qquad (6)$$

where θ_{en} is the measured value of the encoder of the motor driving PIP joint.

According to the above results, the hardness parameter K is calculated by (3).

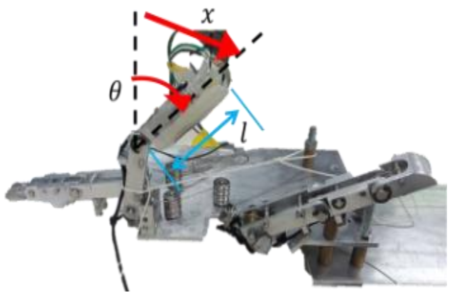

Figure 6. Displacement of fingertip.

IV. Reference Input Generator

A. Constitution of Reference Input Generator

It is necessary to change the speed of tightening the belt of the FB device according to the object hardness to achieve the purpose of this study. Specifically, the belt is wound quickly when a hard object was grabbed, and the belt is wound slowly when a soft object was grabbed. Therefore, the reference input generator is decided to be comprised by a step input and primary delay filter, as shown in Fig. 7.

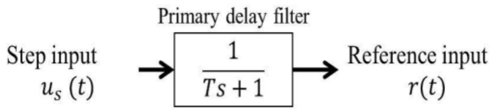

Figure 7. Reference input generator.

In this figure, u_s (t) is step input and r (t) is reference input to the FB device.

The following relational equation is obtained from Fig. 7:

$$R(s) = \frac{1}{Ts+1} U_s(s). \tag{7}$$

If the time constant of the primary delay filter is small, reference input in which the rise time is quick, e.g., T = 0.1 in Fig. 8 is generated. Moreover, if the time constant of the primary delay filter is large, reference input in which the rise time is slow, e.g., T =2 in Fig. 8 is generated. Consequently, the time constant T (K) [sec] of primary delay filter is adjusted according to the value of hardness parameter K. Then, the motor winding a belt is controlled so as to follow the reference input given by (7).

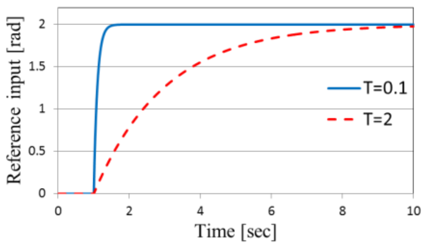

Figure 8. Examples of reference input.

B. Relationship between Time Constant and Hardness Parameter

A function to connect hardness parameter K with the time constant T is derived. The output range of the pressure sensor is $0 \leq V$ [v] ≤ 5. To determine a time constant range, preliminary experiments were conducted. As results, the output diverged at $0.1 > T$ [sec] and T [sec] > 2 was not realistic in practice because the response time from holding the object by the prosthetic hand to conveying tactile sense to the user was too long. Consequently, the time constant range is set to $0.1 \leq T$ [sec] ≤ 2. In addition, for the displacement of the fingertip, the range is set to $0.5 \times 10^{-3} \leq x$ [m] $\leq 40 \times 10^{-3}$, assuming that the PIP joint of the finger of the prosthetic hand rotates in the range of maximum flexural angle 110 deg from 1 deg.

Moreover, using the above-mentioned settings, such a scaling that the amplitude range of the hardness parameter fits into the time constant range was conducted. In addition to the scaling, increase and decrease is reversed so that the time constant is large when the hardness parameter is small and the time constant is small when the hardness parameter is large. The range of the hardness parameter K from 2000-4000 is significant because hardness of many objects lies in this range.

The function arctangent was chosen so that a difference in the hardness of the object can be felt easily, and the following relational equation was determined by trial and error.

$$T = \tan^{-1}(-K \times 0.0012 + 3.1) \times 0.67 + 1.14 \tag{8}$$

Fig. 9 shows the relationship between the hardness parameter K and the time constant T based on (8).

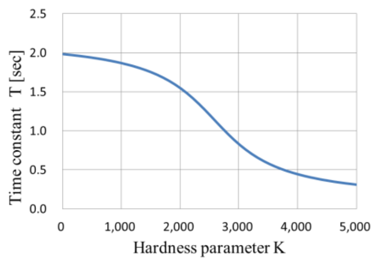

Figure 9. Relationship between time constant and hardness parameter.

C. Verification of Reference Input Generator

Verification of the reference input generator was conducted by numerical simulation. In the verification, the reference input generated by the reference input generator was confirmed for the hardness parameter K increased 1000 each from 1000 to 5000. Fig. 10 shows the result.

Fig. 10 shows that the rise time becomes early with increase of the hardness parameter. In addition, a large change of the rise time is seen in a range of K = 2000-4000. Therefore, the reference input expressing difference of the hardness was generated effectively in the range of K = 2000-4000.

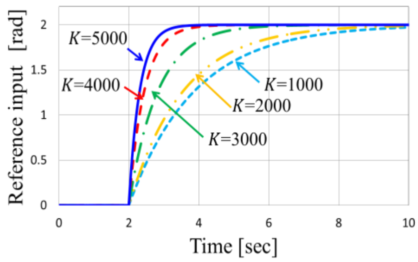

Figure 10. Generated reference inputs.

D. Discretization of the Reference Input Generator

Eq. (7) is discretized using bilinear transform because discrete-time controlled algorithm is conducted in the FB device control explained in the next section, and is converted into the following equation.

$$r(k) = \frac{T_s}{2T+T_s}u_s(k) + \frac{T_s}{2T+T_s}u_s(k-1) + \frac{2T-T_s}{2T+T_s}r(k-1) \quad (9)$$

where k is the number of steps, T_s is the sampling time, and T is the time constant.

V. Control of FB Device

The motor winding the belt of the FB device is controlled with a PID controller. The FB device coheres with the user's arm to convey the tactile sense by pressing user's upper arm. However, velocity of the arm deformation and arm hardness are different for individual user because the arm of each person has individual differences in the quantity of fat and muscle. Furthermore, even in the same person, the parameter fluctuates because the hardness of muscle changes according to the condition of the muscle. Accordingly, an adaptive control, in which the controller gain is adjusted according to an unknown controlled object, is adopted. Specifically, in Ref. [11] Yamamoto and others proposed a self-tuning PID controller, and this controller is employed in this study.

The control purpose of the FB device is to determine the control input $u(k)$ so that the output angle $y(k)$ follows reference input $r(k)$. However, Ref. [11] considers that there exists dead time L in a controlled object. Thus, the control purpose of the FB device is to determine the control input $u(k)$ so that the output angle $y(k + L)$ follows the reference input $r(k)$. The control algorithm such that output $y(k + L)$, including dead time, follows $r(k)$ is obtained from the following equation by using the minimum-variance control approach.

$$\hat{y}(k+L|k) = r(k), \quad (10)$$

where $\hat{y}(k + L|k)$ is the optimal prediction value of $y(k + L)$.

On the other hands, the PID control algorithm is described in the following equation by using a transfer function expression.

$$G_c = K_c\left(1 + \frac{1}{T_I s} + T_d s\right), \quad (11)$$

where K_c is gain, T_I is integral action time, and T_d is derivative action time. Eq. (11) is rewritten as a discrete time velocity-type PID Control algorithm, and Eq. (12) is obtained.

$$\begin{aligned} u(k) = u(k-1) &+ K_p\{y(k-1) - y(k)\} \\ &+ K_I\{r(k) - y(k)\} \\ &+ K_d\{2y(k-1) - y(k) - y(k-2)\}, \end{aligned} \quad (12)$$

where each parameter is $K_p = K_c - K_I/2$, $K_I = K_c\,(T_s/T_I)$, $K_d = K_c\,(T_d/T_s)$.

Moreover, define $d(k)$ as $d(k) = u(k) - u(k-1)$, and $\Phi(k)$ as the following equation by assuming $K_I \neq 0$.

$$\Phi(k) \triangleq a_1 d(k) + a_2 y(k) + a_3 y(k-1) + a_4 y(k-2), \quad (13)$$

where

$$\begin{cases} a_1 = \frac{1}{K_I} \quad a_2 = \frac{K_p + K_I + K_d}{K_I} \\ a_3 = -\frac{K_p + 2K_d}{K_I} \quad a_4 = \frac{K_d}{K_I}. \end{cases} \quad (14)$$

Then, Eq. (12) is able to be expressed as the following equation.

$$\Phi(k) - r(k) = 0. \quad (15)$$

An iterative least square technique is employed to connect (10) obtained by the minimum-variance control with (15) obtained by the PID control algorithm. Furthermore, by estimating each parameter a_i of $\Phi(k)$ so as to satisfy (16), it is considered that $\Phi(k)$ becomes the optimal prediction value of $y(k + L)$.

$$\Phi(k) \to y(k+L). \quad (16)$$

However, in this study, it is considered that dead time hardly exists because the controlled object is a motor. Consequently, the dead time L was chosen as $L = 1$.

The estimated parameter vector $\hat{\boldsymbol{\theta}}(k)$ and regressor vector $\boldsymbol{\varphi}(k)$ are defined in following expressions.

$$\begin{cases} \hat{\boldsymbol{\theta}}(k) = \left[\hat{a}_1(k)\ \hat{a}_2(k)\hat{a}_3(k)\hat{b}(k)\right]^T \\ \boldsymbol{\varphi}(k) = [d(k)y(k)y(k-1)\varepsilon(k)]^T, \end{cases} \quad (17)$$

where $\varepsilon(k) = y(k + 1) - \hat{y}(k + L|k)$ is the estimated error. Therefore, instead of the above iterative least-square technique, it is needed to employ an extended least squares method, because the estimated error $\varepsilon(k)$ is included in (17). The algorithm of the extended least squares method is shown as follows:

$$\begin{cases} \hat{\boldsymbol{\theta}}(k) = \hat{\boldsymbol{\theta}}(k-1) + \boldsymbol{H}(k)\varepsilon(k) \\ \boldsymbol{H}(k) = \frac{\boldsymbol{P}(k-1)\boldsymbol{\varphi}(k-1)}{1+\boldsymbol{\varphi}^{\boldsymbol{T}}(k-1)\boldsymbol{P}(k-1)\boldsymbol{\varphi}(k-1)} \\ \boldsymbol{P}(k) = \boldsymbol{P}(k-1) - \boldsymbol{H}(k)\boldsymbol{\varphi}^{\boldsymbol{T}}(k-1)\boldsymbol{P}(k-1) \\ \varepsilon(k) = Y(k) - \hat{\boldsymbol{\theta}}^{\boldsymbol{T}}(k-1)\boldsymbol{\varphi}(k-1) \\ Y(k) = y(k) - \{1 - \hat{a}_2(k-1) - \hat{a}_3(k-1)\}y(k-3) \end{cases} \quad (18)$$

Furthermore, the PID gain is calculated as follows by using the estimated parameter $\hat{a}_1(k)$, $\hat{a}_2(k)$, and $\hat{a}_3(k)$:

$$\widehat{K}_p(k) = \frac{2\hat{a}_2(k) + \hat{a}_3(k) - 2}{\hat{a}_1(k)},\ \widehat{K}_I(k) = \frac{1}{\hat{a}_1(k)}, \quad \widehat{K}_d(k) = \frac{1 - \hat{a}_2(k) - \hat{a}_3(k)}{\hat{a}_1(k)} \quad (19)$$

In addition, the control input is obtained from the following equation by using the gains given in (19).

$$\begin{aligned} u(k) = u(k-1) &+ \widehat{K}_p(k)\{y(k-1) - y(k)\} \\ &+ \widehat{K}_I(k)\{r(k) - y(k)\} \\ &+ \widehat{K}_d(k)\{2y(k-1) - y(k) - y(k-2)\} \end{aligned} \quad (20)$$

In the above-mentioned calculation, the problem that the PID gain becomes negative values is expected. However, in this study, this problem is coped with by adjusting the initial value without using a constraint condition to simplify the application of the control algorithm to the FB device. The initial values to obtain positive PID gains were set as follows by trial and error:

$$\boldsymbol{P}(0) = 0.0004\boldsymbol{I}_{4\times 4}$$
$$\hat{\boldsymbol{\theta}}(0) = [80\ 20.1 - 20\ 0.1]^T. \quad (21)$$

VI. Verification Experiment

A. *Operation Check Experiment of FB Device*

There are two purposes of this experiment.

1) To confirm that it is possible to generate reference input corresponding to object hardness using a reference input generator by holding objects of different hardness.

2) To confirm that FB device motor is able to follow the reference input which is generated by the reference input generator.

The experimental method is as follows: Objects of three different hardnesses (hard, medium, and soft) were grasped by the myoelectric prosthetic hand in a state in which the FB device is not worn to the user's arm. The response of the FB device motor is then compared to the reference input generated for each hardness. The subject is an adult male in his twenties.

Hard objects are defined as a thing that does not deform easily even if a person pushes with a finger, and a rubber baseball was chosen. Soft objects are defined as a thing that deforms easily if a person pushes with a finger, and soft tennis ball was chosen. Medium hardness objects are defined as a thing that has intermediate hardness between hard objects and soft objects, and a colored toy ball used in sports was chosen.

The hardness parameter K was calculated by (3) to (6). The experimental procedure is as follows:

1) The electrodes were installed in the forearm of the subject, and the subject practiced operation of the myoelectric prosthetic hand.

2) The subject operated the index finger of the prosthetic hand and held the object with the prosthetic hand.

Fig. 11 shows the result when the rubber baseball was held, Fig. 12 shows the result when the soft tennis ball was held, and Fig. 13 shows the result when the colored ball was held. In addition, Table I shows the values of PID gain that were calculated by (19). The test was conducted five times for each hardness, and the result closest to the average waveform is shown because all results showed similar waveforms.

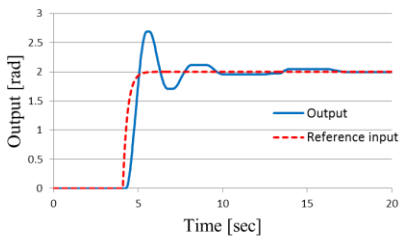

Figure 11. Result of rubber baseball.

From Table I, in the reference input, a clear change of the time constant was shown. From Fig. 11 to Fig. 13, it was confirmed that the intended reference input was generated for each of hard, soft, and medium hardness object. In the tracking of the motor, lag was observed in the rise time of the output waveform. Moreover, overshoot was observed for the hard object. However, it was confirmed that the motor was able to follow the reference input.

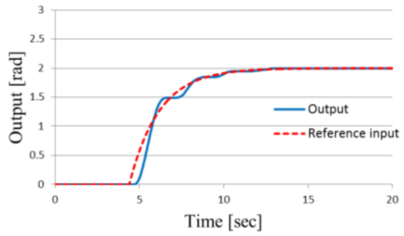

Figure 12. Result of soft tennis ball.

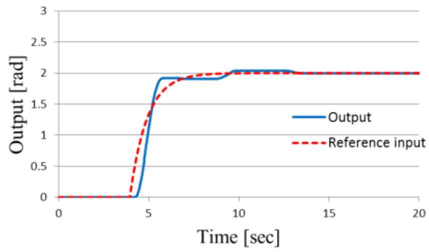

Figure 13. Result of the colored ball.

TABLE I. Self-Tuned PID Gains

Object	Time constant T [s]	PID gain		
		$\hat{K}_p(k)$	$\hat{K}_I(k)$	$\hat{K}_d(k)$
Rubber baseball	0.26	0.228331	0.0125	0.010694
Soft tennis ball	1.77	0.227356	0.0125	0.011346
Color ball	0.92	0.227638	0.0125	0.011157

B. *Identification Experiment of Hardness*

The purpose of this experiment is to verify that the user can identify the object hardness using the FB device. To simplify the experiment, two types of the objects, which are hard and soft objects, were used to identify the hardness. As well as former experiment, the rubber baseball was chosen as hard object and the soft tennis ball was chosen as soft object. The experimental procedure is as follows:

1) The electrodes were installed in the forearm of the subject, and the subject practiced operation of the myoelectric prosthetic hand.

2) In order to understand relationship between object hardness and the behavior of the FB device, the subject tested the FB device.

3) The subject held either rubber baseball or soft tennis ball chosen by a third paty in the state where the subject cannot see the object.

4) The subject judged the hard or soft object from the behavior of the FB device. This was performed ten times.

Fig. 14 shows the experimental setup.

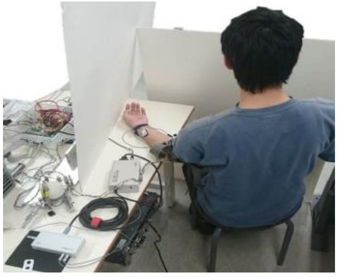

Figure 14. Experimental setup.

Identification experiment of the hardness was conducted for four adult males in their twenties. Table II summarizes the accuracy rate for identification of hardness obtained by the number of correct answers within the ten repetitions. From Table II, it was confirmed that a high average accuracy rate of 92.5% was obtained.

TABLE II. RESULTS OF EXPERIMENT FOR HARDNESS IDENTIFICATION

Subject	Accuracy rate for identification of hardness [%]
A	100 (10/10)
B	100 (10/10)
C	90 (9/10)
D	80 (8/10)
Average	92.5

C. Consideration

From the results of the operation check experiment of the FB device, time-lag was observed in rise time of the output waveform. This is because the processing time to calculate the hardness parameter K was long. In addition, overshoot was observed concerning the hard object. However, in identification experiment of hardness, the influence of the overshoot did not interfere with the user's hardness identification. Therefore, it is considered that the influence of the overshoot can be disregarded in practical use of the FB device

In this experiment, although the experiment was conducted with only three types of hardness objects, it is considered that the FB device would be able to express numerous types of hardness because object hardness can be continuously handled by introducing the reference input generator.

From the result of identification experiment of the hardness, it was confirmed that the FB device worked normally using the self-tuning PID controller, and conveyed force sense corresponding to the object hardness to the user.

However, there are some results that the FB device showed incorrect action in the experiment several times because of contact failure between pressure sensor and the object. As a result, identification failed because of this problem. As a future problem, it is necessary to improve the measurement accuracy of the object hardness so as not to cause the contact failure between the pressure sensor and the object.

VII. CONCLUSION

In this study, the control system of the sensory feedback (FB) device was proposed. The control system can express the hardness of various objects by introducing the reference input generator. The reference input generator generates reference input providing the winding speed of the belt in FB device according to the hardness of the grasped object. Then, such a control system that the output angle of the FB device motor follows the reference input was constructed using the self-tuning PID controller. Therefore, object hardness was conveyed by fast winding of the belt when the hard object was grabbed and slow winding when the soft object was grabbed.

Verification experiments were carried out to confirm the effectiveness of the proposed control system. As a result of the operation check experiment of the FB device, the intended movement of the FB device was verified. In addition, as a result of the hardness identification experiment, the hard object (rubber baseball) and soft object (soft tennis ball) could be distinguished with the accuracy of 92.5% on average.

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