2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
October 14-18, 2024. Abu Dhabi, UAE

Effect of Tactile and Deep Sensory Feedback Synchronized with the Manipulation of Myoelectric Hand on Body Recognition

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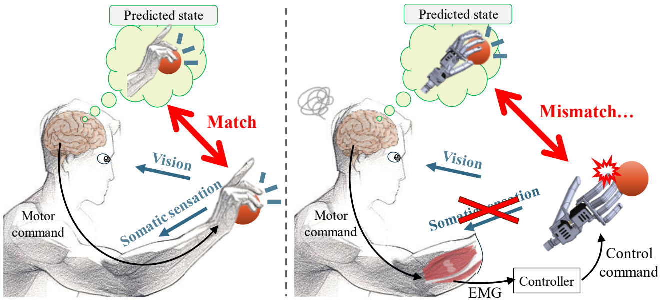
Abstract— **Currently, myoelectric prosthetic hands are not recognized as part of the body due to the lack of sensory feedback (FB). To address this issue, it is necessary to investigate the factors that influence body recognition. Most existing research focuses on stationary prosthetic hands, such as in the rubber hand illusion, and discusses two concepts: sense of ownership (SO) and sense of agency (SA). SO refers to the feeling that a body part belongs to one's own body, while SA refers to the feeling that one is in control of the movements of one's own body parts. In this study, we developed a wearable and operable prototype myoelectric prosthetic hand equipped with tactile and deep sensory feedback, rather than a stationary prosthetic hand. Furthermore, we investigated the effect of tactile and deep sensory feedback on body recognition through psychophysical experiments. The results indicated that tactile feedback improved body recognition and deep sensory feedback improved SO; however, no effect was observed on SA.**

I. INTRODUCTION

A prosthetic hand is intended to “replace a lost hand" and "be recognized as a part of the user's body." Currently available prosthetic hands include cosmetic prosthetic hands that resemble healthy hands in appearance, active prosthetic hands that operate using trunk movements, and myoelectric prosthetic hands that operate based on the myoelectric potential of the residual limb. A myoelectric prosthetic hand has an appearance similar to that of a normal hand and intuitive movements, which makes it similar in form and function to a human hand. However, current myoelectric prosthetic hands are not necessarily recognized as body parts because of their clumsy movements and lack of sensation. There are major differences between a myoelectric prosthetic hand and a human hand (Fig. 1). For example, when a person intends to grasp a ball, the human hand receives feedback (FB) from somatic sensations, such as tactile and deep sensations, in response to the actual action, and this feedback match the sensory predictions in the brain. In addition, myoelectric prosthetic hands are not only controlled indirectly via a controller but also lack somatic sensation. This tends to cause a mismatch between the prediction of the user's brain and actual state of the hand, indicating that the prosthetic hand is not recognized as a part of the user's body. To solve this problem, it is necessary to investigate the factors affecting the body recognition of myoelectric prosthetic hands.

Research regarding the body recognition of prosthetic hands, such as that focusing on the rubber hand illusion [1], has mainly been conducted using static prosthetic hands. Body recognition has been discussed in terms of two concepts: sense of ownership (SO) and sense of agency (SA), and the mechanism has been explained using a comparator model [2]. SO is "the feeling that a body part belongs to one's own body," and is said to occur through the integration of the following three: an intended state in the brain, predicted state including sensory FBs, and actual sensory FBs. SA is "the feeling that one is in control of the movements of one's own body parts," and is said to occur when the intended state in the brain matches the forward model. Previous studies have used this concept to investigate the influence of factors such as the appearance of the prosthetic hand [3], [4] as well as temporal and spatial synchronization of passive tactile FB [5] on body recognition. However, because these studies were conducted on a static prosthetic hand, the factors unique to myoelectric prosthetic hands, such as active movement and sensory FB associated with movement, remain unknown. However, research on body recognition targeting myoelectric prosthetic hands has been conducted in recent years. Specifically, research focusing on tactile FB and deep sensory FB has shown that body recognition may be improved by applying mechano-tactile stimulation corresponding to fingertip



(a)Human hand (b)Myoelectric hand

Figure 1. Differences between human hand and myoelectric hand

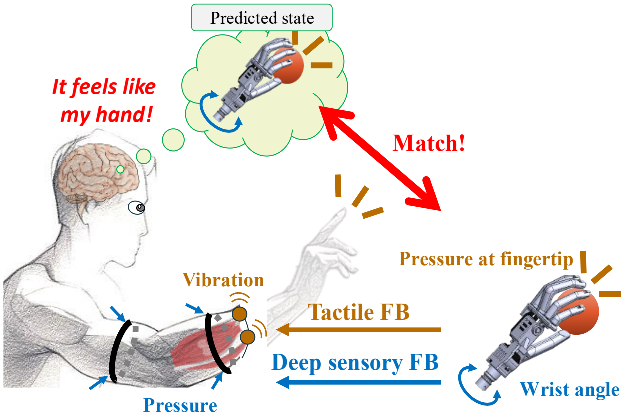


Figure 2. Overview of the approach

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pressure of a myoelectric prosthetic hand as a tactile FB [6], [7]. Regarding deep sensory FB, the embodiment of an artificial sixth finger has been demonstrated in healthy individuals. This method uses a deep sensory FB with pressure stimulation corresponding to the bending angle of the sixth finger [8]. However, few studies have focused on deep sensory FB and body recognition in myoelectric prosthetic hands. Since the myoelectric prosthetic hand is similar to the sixth finger in that it is an artificial limb, it is possible that body recognition could be improved by providing deep sensory FB in the myoelectric prosthetic hand as well. Thus, there are few studies on the effect of sensory FB on the body recognition of prosthetic hands. Therefore, this study aimed to clarify the influence of tactile FB and deep sensory FB on the body recognition of myoelectric prosthetic hands through psychophysical experiments.

II. EVALUATION OF BODY COGNITION WHEN USING MYOELECTRIC PROSTHETIC HAND WITH SENSORY FB

In this study, we established the following two hypotheses to investigate the influence of tactile and deep sensory FB.

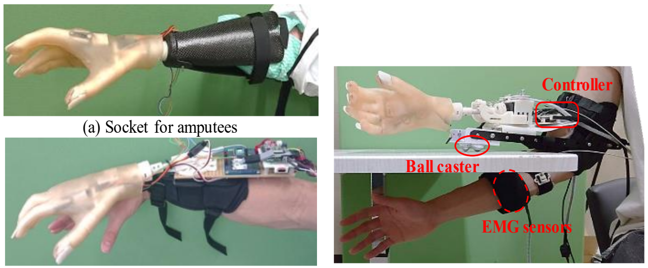
1) Tactile sensation is active mainly when grasping an object, and deep sensation is active mainly when reaching for an object.

2) Tactile FB and deep sensory FB improve the prediction of state of the prosthetic hand and improve its body recognition.

Based on this hypothesis, we divided body recognition in two tasks (grasping and reaching) using a myoelectric prosthetic hand equipped with tactile and deep sensory FB (Fig. 2). By comparing two conditions—with and without tactile FB in the grasping task, and with and without deep sensory FB in the reaching task—we investigated the effect of each on body recognition. Body recognition was subjectively evaluated using a questionnaire.

A. *Myoelectric Prosthetic Hand with Sensory FB Function*

In this study, we developed a prototype myoelectric prosthetic hand with tactile and deep sensory FB functions and used it for investigating influence of tactile FB and deep sensory FB. The myoelectric prosthetic hand consisted of a myoelectric sensor, controller, robotic hand, mounting socket, and cosmetic glove. The robotic hand, which has two servo motors working as actuators, is a 2-degree-of-freedom prosthetic hand that can open and close at a speed of 80 deg./s and rotate about the wrist at a speed of 36 deg./s. A pattern recognition method using a 3-layer feedforward neural network (24-dimensional input, 32-dimensional intermediate, and 3-dimensional output layers) was adopted as a control method for the myoelectric prosthetic hand. This method recognizes three motion classes: grasping, opening, and resting (during grasping tasks) or wrist pronation, supination, and resting (during reaching tasks). Surface myoelectric potential was measured using three myoelectric sensors placed circumferentially around the forearm (12 bits, sampling rate of 2000 Hz). A fast Fourier transform was applied, and the power was calculated for each of the eight frequency bands in the range of 20–330 Hz, which was used as a 24-dimensional input to neural network. This was implemented on a microcontroller and used as a controller. The frequency of control cycle was 250 Hz, and the system motion delay was approximately 200 ms. Here, the motion delay was the time period from when the healthy hand wearing the sensor started to move until the actuator of the prosthetic hand started operating. According to previous research, body recognition is triggered when the motion delay of the CG hand is 200 ms or less [9], and this requirement is satisfied by developed prosthetic.



(a) Socket for amputees

(b) Socket for able-bodied (Grasping task)

(c) Socket for able-bodied（Reaching task ）

Figure 3. Sockets for amputees and able-bodied subjects

To attach this robotic hand to the body, forearm amputees use a brace called a socket (Fig. 3(a)). In this study, we will evaluate not only forearm amputees but also able-bodied people simulating forearm amputees; therefore, it is necessary to apply the prosthetic hand to able-bodied people. However, it has been shown that the misalignment of the position and angle of the prosthetic hand impairs body recognition [10]. Therefore, we developed a socket for able-bodied people that allows the robot hand and healthy hand to overlap when viewed by the operator, and it was placed such that the robot hand does not come into contact with the healthy hand (Figs. 3(b), (c)). To prevent damage to body image, the socket was covered with the sleeve of a lab coat, and the hand of the able-bodied subject was hidden under a cloth or below a desk. During the reaching task, the robot hand moved by following the operator's arm movements (internal/external rotation and flexion/extension of the shoulder) by attaching ball casters to the contact surface between the socket and the desk.

B. *Sensory FB System*

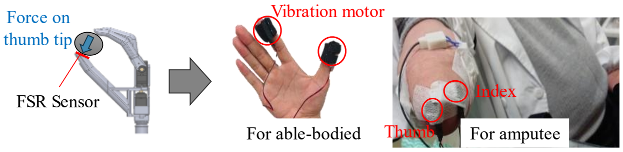
In previous research, the following two requirements were listed for intuitive sensory FB: 1) somatosensory matching, which requires that the location at which the target sensation should be felt matches the location stimulated by the sensory FB, and 2) modality matching, which requires that the sensation modality (type of sensation) targeted by sensory FB matches the stimulus modality [11]. Therefore, we prototyped a tactile FB system that returns a constant vibration when an object is grasped and a deep sensory FB system that transmits the wrist angle of the prosthetic hand to the forearm and upper arm by pressure stimulation.

The haptic FB system measures fingertip pressure using an FSR sensor (FSR 402, Interlink Electronics) placed on the thumb pad of the prosthetic hand, and when the pressure exceeds a threshold, two vibration motors (FM34F, Tokyo Parts Industrial, φ12×t3.4 mm) placed on the operator's skin vibrate (Fig. 4(a)). If the operator is a forearm amputee, vibration motors are placed at the stump where the phantom limb of the thumb and index finger is felt; in the case of an able-bodied person, they are placed on the pads of the thumb and index finger. This satisfies somatosensory matching between the prosthetic hand and operator. However, modality matching is not satisfactory because the fingertip pressure of the prosthetic hand is fed back by vibration. However, in this experiment, sensory substitution was reduced by vibrating the object to be grasped. The vibration motors vibrate at 200 Hz when the force P_{thumb}[N] applied to the thumb pad exceeds the threshold P_{th}, and do not vibrate at otherwise. At this time, P_{th} is set to a value sufficiently smaller than P_{thumb} when the prosthetic hand is grasping the object. This ensures that a vibration stimulation is generated when grasping an object.

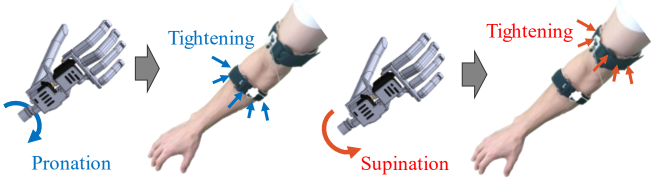
Deep sensory FB system provides FB on wrist position sense by applying tightening pressure. This tightens around the pronator teres muscle during pronation and around the triceps brachii muscle during supination. Thus, we aimed to achieve somatosensory matching. Sensory substitution occurs because the position sense originally felt by muscle spindles is transmitted by pressure sense, and modality matching is therefore not fully satisfied. However, based on a study [8] that demonstrated the possibility of embodiment through pressure FB of the position sense of the sixth finger, we expected the proposed method to similarly improve body recognition. In the FB system, the wires are pulled by a pin fixed to the wrist rotation axis of the prosthetic hand, which tightens the cuffs wrapped around the forearm and the upper arm in proportion to the wrist angle. The forearm cuff was tightened when pronating, and the upper arm cuff was tightened during supination (Fig. 4(b)). At this time, the wires pulled during pronation and supination operated independently. The initial tension of each wire was calibrated by winding the pulley. During the experiment, adjustments were made for each subject. The initial tension was adjusted so that the subject felt a change in tightening pressure when the wrist angle of the prosthetic hand changed from 0 deg. to ±30 deg. The tension of each wire and pressing force at the representative point with respect to the wrist angle of the prosthetic hand are shown in Fig. 5. This measurement was performed for one subject (male, forearm circumference 240 mm, mid upper arm circumference 230 mm) and was repeated five times. Tension was measured by connecting a load cell (USM-50N, UNIPULSE, rated load 50 N) attached to the cuff of each forearm and upper arm and an amplifier (HX711, Spark Fun) to a microcontroller (Arduino UNO). The resolution of the measurement system was 10 mN and the sampling frequency was 10 Hz. The pressing force was measured by connecting the FSR sensor to a microcontroller. The representative points were near the pronator teres muscle of the forearm cuff and the triceps brachii muscle of the upper arm cuff.

C. Assessment of Body Recognition

To evaluate the influence of tactile and deep sensory FB on body recognition, we conducted a subjective evaluation using a questionnaire (Table 1) comprising 12 questions, regarding the SO, SA, and control items that are not used for direct evaluation [12]. The answers were marked on paper on a 7-point Likert scale. The indicators of SO and SA are the average values of answers to questions 1 to 3 and 7 to 9, which are called illusion scores; high scores indicate high SO and SA. The participants were allowed to view and correct their answers at any time during the experiment. In the experiment, all participants used Japanese as their native language; therefore, the questionnaire items were translated into Japanese.

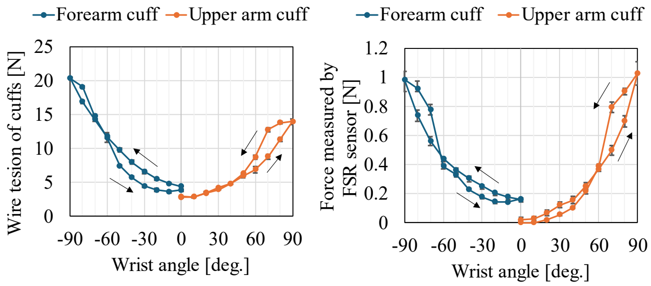


(a)The tactile feedback system



(b)The deep sensory feedback system

Figure 4. Stimulation methods of the sensory FB systems



(a) Wire tension vs wrist angle (b) Pressing force vs wrist angle

Figure 5. Wire tension and pressing force of the deep sensory FB system

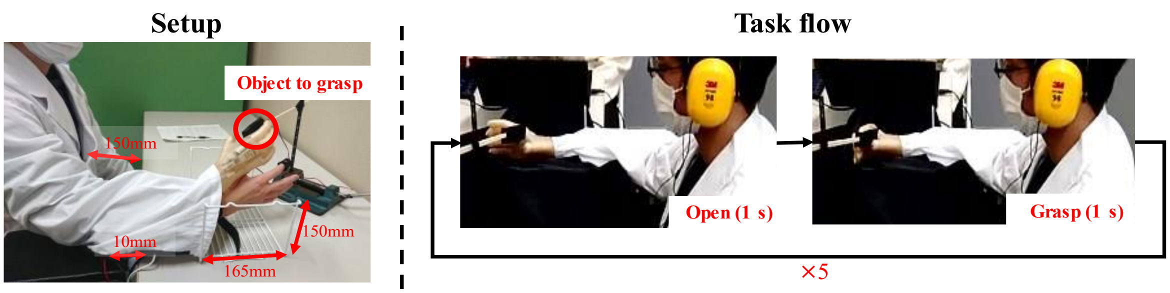
TABLE I. STATEMENTS USED IN THE EXPERIMENT TO MEASURE THE SENSE OF OWNERSHIP AND AGENCY

Sense of ownership	1	I felt as if I was looking at my own hand
	2	I felt as if the rubber hand was part of my body
	3	I felt as if the rubber hand was my hand
Sense of ownership control	4	It seems as if I had more than one right hand
	5	It felt as if I had no longer a right hand, as if my right hand had disappeared
	6	I felt as if my real hand was turning rubbery
Sense of agency	7	I felt as if I could cause movements of the rubber hand
	8	I felt as if I could control movements of the rubber hand
	9	The rubber hand was obeying my will and I can make it move just like I want it
Sense of agency control	10	I felt as if the rubber hand was controlling my will
	11	It seemed as if the rubber hand had a will of its own
	12	I felt as if the rubber hand was controlling me

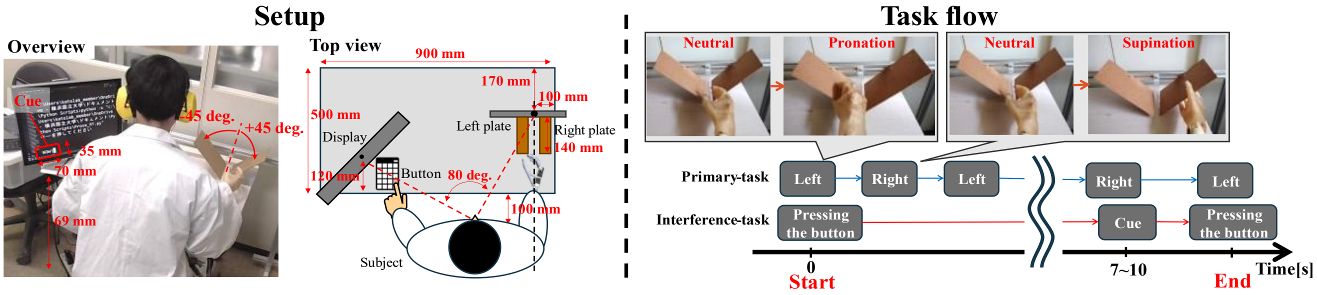
D. Task Design

To evaluate the effects of tactile FB on body recognition, we performed an object-grasping task in which a constantly vibrating object was grasped five times (Fig. 6(a)). The subject wore a prosthetic hand through a socket, but the position of the forearm was fixed such that all four fingers other than the thumb could be used to operate the prosthetic hand. In addition, wearing earmuffs prevented the motor drive noise from inhibiting body recognition. This task was performed alternately for four trials under two conditions, with and without tactile FB, and a questionnaire was completed after each trial.

We performed a reaching task to evaluate the effects of deep sensory FB on body recognition. In this task, we aimed to limit visual perception and increase focus on the deep sensory FB by using a dual-task method. In this method, subjects simultaneously perform a main task and an interference task. At this time, considering that humans have a finite ability to deal with cognitive load, it became impossible to allocate visual cognition solely to the main task. Therefore,



(a) Setup and task flow of grasping task



(b) Setup and task flow of reaching task

Figure 6. Experiment setup and task flow of grasping and reaching task

it was possible to indirectly quantify the visual cognitive load used in the main task based on the performance score of the interference task. The main and interference tasks in the dual task were set as follows (Fig. 6(b)):

Main task: Grasp two plates (fixed in front of the subject) alternately on the left and then on the right as many times as possible within the specified time limit.

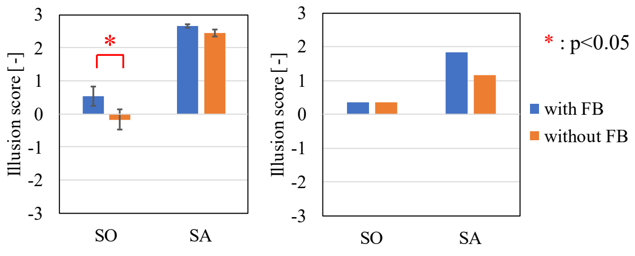
Interference task: Press a button as quickly as possible in response to a cue that appears randomly on the display (placed on the left side of the subject) within 7–10 seconds of the start of the task.

The evaluation index for the main task was the total number of times the plate was grasped, from the start of the interference task until the button was pressed. The evaluation index for the interference task was the time from when the cue was displayed at the bottom left of the display (2007FP, DELL, 20.1") until the button was pressed, minus the baseline value for each subject. The baseline was the average reaction time to the cue when the subject performed only the interference task for five trials, without performing the main task. During the task, the subject wore a prosthetic hand through a socket; however, the movements of the healthy hand were limited to pronation and supination of the wrist and movement of the arm parallel was limited to the desktop. The index finger of each participant's left hand was placed on a button. This task was performed alternately in five sets of 10 trials under two conditions, with and without deep sensory FB, and a questionnaire regarding body recognition was administered after each set.

III. RESULTS AND DISCUSSION

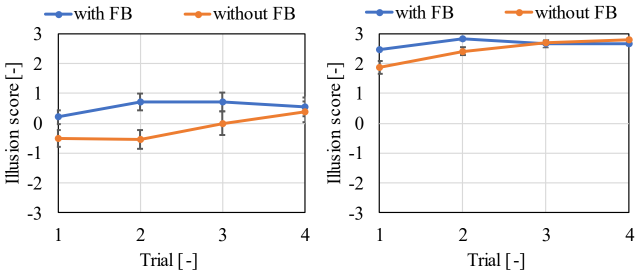
A. Grasping Task

This task involved eight able-bodied subjects (four males, four females, mean age 21±1.3 years) and one forearm amputee (male, right arm amputee, using a myoelectric prosthesis daily for more than three years).



(a)Able-bodied (b)Amputee

Figure 7. Illusion score for conditions with and without tactile FB



(a) Sense of ownership (b) Sense of agency

Figure 8. Illusion score vs trial on able-bodied

To compare the degree of body recognition with and without tactile FB, Fig. 7 shows the average illusion scores of the four trials of SO and SA under each condition. Fig. 7(a) shows the average illusion score for able-bodied subjects, and Fig. 7(b) shows the average illusion score for a forearm amputee. As shown in Fig. 7(a), the illusion score for the SO in healthy subjects was 0.71 higher in the condition with tactile FB than in the condition without FB ($p=0.045$, t-test). In addition, the illusion score for SA was 0.18 higher in the condition with tactile FB than in the condition without FB, and no significant difference was observed ($p=0.13$, t-test). Thus, it can be said that in able-bodied subjects, the tactile FB used in this study improve SO, and tactile FB may improve SA.

However, Fig. 7(b) shows that the illusion score of the SO in forearm amputees with and without tactile FB was 0.37. The illusion score for SA was 0.67, which was higher in the condition with tactile FB than in the condition without FB. The reason for this was that this subject had been using a myoelectric prosthetic hand for over three years, which resulted in similar predictions about the prosthetic hand for both the conditions, with or without FB. For a more detailed investigation, the long-term application of sensory FB and comparison with the results of other forearm amputees are required. Therefore, tactile FB did not change the SO in forearm amputees in this study, but the SA showed improvement.

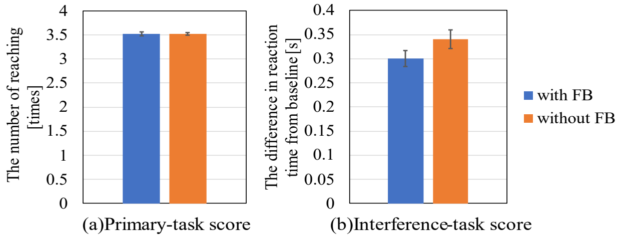
In addition, Fig. 8 shows the changes in body recognition for the trials in able-bodied participants. Fig. 8(a) and Fig. 8 (b) show the SO and SA illusion scores for each trial, respectively. Fig. 8(a) shows that the illusion score in the no-tactile FB condition tends to increase with successive trials. In particular, the score for the fourth trial was 0.88 higher than that for the first trial (p=0.0016, t-test). Therefore, in the object-grasping task of this study, even in the condition without tactile FB, body recognition improved with repeated trials, and the difference between the conditions with and without tactile FB decreased. This may be because the vibration of the actuator transmitted through the socket for able-bodied subjects was substituted for tactile FB while performing the same motion periodically during the task. The use of actuator vibration as a sensory FB has been reported in existing research as an incidental FB [13], and it is believed that repeating the task makes it easier to match the predictions of the subject's sensory FB.

B. Reaching Task

The subjects for this task consisted of seven able-bodied subjects (five males and two females, mean age 22.8±1.1 years). Among these, five participants completed the questionnaires.

To present a comparison of the visual cognitive load with and without deep sensory FB, Fig. 9 shows the average scores from the 2nd to 5th sets of the main and interference tasks. As shown in Fig. 9(a), the average score on the main task was 0.0036 higher in the condition with deep sensory FB than in the condition without FB, and no significant difference was observed (p=0.47, t-test). Hence, it can be considered that the difference in the score of the interference task depending on the condition with or without of deep sensory FB affects the visual cognitive load. In addition, as shown in Fig. 9(b), the average score on the interference task was 0.040 higher in the deep sensory FB condition than in the FB condition, and no significant difference was observed (p=0.065, t-test). This suggests that the visual cognitive load may have been reduced by the deep sensory FB between the second and fifth sets.

Fig. 10 shows the change in the score of the interference task for the trial set. Focusing on the difference in scores depending on the condition with or without deep sensory FB, the third set had the largest difference, with the condition without the FB being significantly higher by 0.090 s than the FB condition (p=0.047, t-test). However, the difference in the score was the smallest in the 5th set, where the condition with the FB was 0.012 s higher than the condition without the FB.



(a)Primary-task score (b)Interference-task score

Figure 9. Dual-task score for with/without deep sensory FB

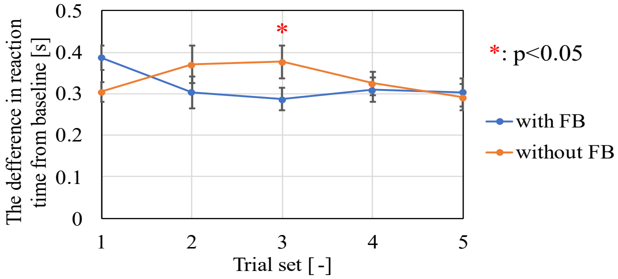
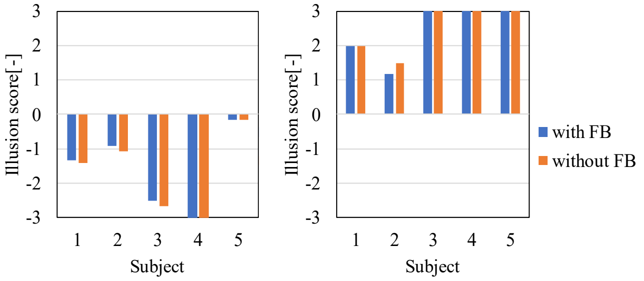


Figure 10. Interference task score for with/without deep sensory FB vs trial set

There are two possible reasons: subjects learned the correspondence between the deep sensory FB and the wrist angle of the prosthetic hand, or they learned to predict the motion speed of the prosthetic hand. Regarding the former, because the subjects performed the task while learning the correspondence between the strength of the cuff tightening and the wrist angle of the prosthetic hand using a deep sensory FB, it is possible that the deep sensory FB was not used effectively in the first trial set. From the second trial set onward, it is thought that the score stabilized around 0.3 s because the subject learned a model that predicted the wrist angle of the prosthetic hand from deep sensory FB. However, regarding the latter, learning does not enable the prediction of wrist angle of the prosthetic hand using deep sensory FB, but rather the prediction of the motion speed and angle of the wrist of the prosthetic hand based on the output of the subject's myoelectric potential. Because the main part of the reaching task was always to move back and forth at the same wrist angle, it was easy to learn how long the myoelectric potential should be output to reach the object as the task progressed. It is thought that this learning occurs constantly from the 1st to the 5th set, but the effect of learning is particularly evident in the part where the reaction time decreases from the 3rd to the 5th set. For the 1st to 3rd sets, conditions with and without deep sensory FB were implemented alternately, which may have resulted in inaccurate predictions and higher scores. These results indicate that deep sensory FB may reduce visual cognitive load in specific trial sets. In addition, by showing a reduction in the visual cognitive load due to deep sensory FB, it can be said that the subjects concentrated on the deep sensory FB during the task.

To present a comparison of the degree of body recognition with and without deep sensory FB, the average illusion score for each subject from the 2nd set to the 5th set is shown in Fig. 11. Fig. 11(a) shows the illusion score for SO and Fig. 11(b) shows the illusion score for SA. Fig. 11(a) shows that subjects 1, 2, and 3 had higher illusion scores in the condition with deep sensory FB than without FB. The difference in scores between subjects with and without FB was 0.083 for subjects 1 and 0.17 for subjects 2 and 3, respectively. However, for Subjects 4 and



(a)Sense of ownership (b)Sense of agency

Figure 11. Illusion score for with/without deep sensory FB

5, scores did not show variation with the presence or absence of deep sensory FB. In addition, all the subjects had negative illusion scores. These results suggest that, although an SO did not occur with respect to the prosthetic hand in this experiment, it is possible that a deep sensory FB facilitates the generation of an SO. There are two main reasons for this. The subject trusts the deep sensations of the healthy hand more than the deep sensory FB system of the prosthetic hand, and the motion speed of the prosthetic hand is 36 deg./s, which is slower than that of the healthy hand. In particular, in a verbal questionnaire administered after completing the task, subjects reported that they were more conscious of the deep sensations in their normal hand and felt that the motion speed of their prosthetic hand was lower than the subjects' intentions. This created a discrepancy between the predicted sensory FB and the actual sensory FB, making it difficult for the subject to feel the SO.

In addition, as shown in Fig. 11(b), subject 2's illusion score was 0.33 higher in the condition without deep sensation FB than in the condition with FB. For the other subjects, it did not change with or without deep sensation FB. Illusion scores were positive for all participants, regardless of whether they had FB. Therefore, it can be said that although the subjects felt an SA with their myoelectric prosthetic hand in this experimental setting, a deep sensory FB may have slightly reduced their SA. One possible reason why SA did not change with the presence or absence of deep sensory FB is that in this experimental setting, sufficient SA occurred even in the absence of deep sensory FB. Subjects 3, 4, and 5 had a maximum illusion score of 3 in the condition without deep sensation FB; therefore, it can be said that they already had sufficient SA. Subject 2 said that the cause of the slight decrease in the SA due to deep sensory FB was that “it felt like the tightening of the cuff was inhibiting muscle movement.” This suggests that stimulation methods may need to be improved to avoid user discomfort and reduce their SA. Thus, it can be said that deep sensory FB, which stimulates the wrist angle with pressure, has the potential to improve the SO. Further, if sufficient SA has already been generated, it may have little effect.

IV. CONCLUSION

In this study, we investigated the effects of tactile FB during the grasping motion and deep sensory FB during the reaching motion on the body recognition of the myoelectric prosthetic hand. The following conclusions were drawn:

1) Haptic FB, which transmits the fingertip pressure of a prosthetic hand through vibration stimulation, improves body recognition; however, incidental FB, such as actuator vibration, may also have the same effect.

2) Deep sensory FB, which conveys the wrist angle of the prosthetic hand by tightening the pressure, may slightly improve the SO. However, to investigate this effect in more detail, it is necessary to consider the deep sensations of the operator's forearm.

The practical implications of this research are that by demonstrating the effect of sensory FB on body recognition of a prosthetic hand, it can assist in prosthetic design guidelines, contribute to improving user satisfaction with prosthetic hands, and reduce the cognitive burden when using a prosthetic hand. However, there are two issues with this study. The first is that there was only one amputee subject, so the results may differ for other forearm amputees. Furthermore, in able-bodied subjects, the presence of the natural hand may have hindered body recognition. The second issue is that the evaluation in this study was solely subjective. Therefore, we plan to conduct similar experiments with more forearm amputees and investigate the effects of tactile FB and deep sensory FB by combining them with brain activity measurements, which provide an objective evaluation.

ACKNOWLEDGMENT

This study was supported by JSPS KAKENHI (grant number: JP21H03300).

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