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Research Article

Performance Evaluation of a Developed Haptic Device that Presents Sensation Corresponding to the Palm on the Back of the Hand for Robot Hand Teleoperation

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ABSTRACT

We proposed a new tactile presentation device for a palm to tele-operate a robot hand mounted on a rescue robot. The proposed device presents a tactile sensation on the back of the operator's hand rather than the palm to avoid interference. The required specification for the device were determined through subject experiments conducted in our previous studies. In particular, we developed a prototype device through suction stimulation with the required specifications, confirmed that the device can present tactile sensation correctly, and discussed the results.

1. Introduction

After the Great Hanshin-Awaji Earthquake in 1995, there has been an extensive research and development of disaster-response robots in Japan [1]. Disaster-response robots that can gather information and perform tasks have been in demand in recent years [2]. Therefore, disaster-response robots equipped with robotic arms and hands have been developed to achieve human-like characteristics, such as removing obstacles and manipulating valves [3]. Disaster-response robots are moved and operated in unknown and extreme environments; therefore, they are tele-operated by humans in safe areas [4].

It is necessary to provide feedback to the operator on the contact state between the fingers and palms of the robot hand and the object to be grasped for efficient teleoperation with the robot hand. However, in the field of robot teleoperation, there are some systems that provide feedback on the contact state of the fingers [5],[6], but we cannot find systems that provide feedback on the contact state of the palm.

On the other hand, in the field of virtual reality, some researchers have proposed haptic devices for the palm [7],[8]. However, by using them, the device will interference the motion of the opening/closing of the hand. Therefore, Okano et al. have proposed methods of substituting the tactile presentation of the palm to other parts of the body [9]. Their device substituted by the sole the foot for the tactile presentation of the palm.

In this study, the tactile sensation was substituted by the back of the hand instead of the palm to avoid interference between the device and fingers. Moreover, we assumed that the operator could recognize the tactile state more accurately because the tactile sensation is presented just behind the palm.

In our first report [10], the tactile characteristics on the back of a human hand were clarified to obtain the specifications required to develop the proposed device. In the second report [11], we found that tactile sensation

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can be presented as a surface without changing the specifications. In the third report [12], we changed the stimulation method from pressing to suction to make the device small and light. In the fourth report [13], we investigated the relationship between the diameter of the suction pad and correct answer rate, and found that the larger the diameter, the higher the correct answer rate. In the fifth study [14], a prototype of the proposed device was developed based on the results of the fourth report [13]. In this study, its performance was verified and discussed through subjective experiments.

2. Substitute Tactile Presentation Device for the Back of the Hand

Ideally, to correctly convey the state of contact between the robot hand and grasping objects to the operator, the tactile sensation is presented directly to the palm of the hand, as shown in Fig. 1 and our first report [10]. However, when the robot hand is directly tele-operated by the operator's hand, the haptic device may interfere with the fingers, because the robot hand is teleoperated with open-close motion of the operator's hand and the device is mounted on the operator's palm. Therefore, we proposed a method to present the tactile sensation on the back of the hand instead of the palm (Fig. 2).

2.1. *Parameter Identification*

The following parameters are required to design such a back-of-the-hand substituting tactile presentation device.

- Interval between stimulus points (interval: *i*)
- Diameter of the stimulus point (diameter: *d*)
- Force of the stimulus point (force: *f*)

Human skin sensation has well-known characteristics, such as a two-point discrimination threshold. In particular, two close stimulation points are cnsidered as one point. Therefore, we conducted an experiment on the subjects to confirm the characteristics of the tactile sensation on the back of the hand for our proposed device [10]. The combination (*i*, *d*, *f*) = (30 mm, 6 mm, 0.9 kg) had the highest rate of correct answers.

However, to develop a tactile presentation device, suction stimulation is utilized instead of pressure stimulation because the device will becomes significantly large with pressure stimulation. Therefore, we designed the device as shown in Fig. 3. In the third and fourth report [12][13], we verified how well the pressure stimulation position of the palm matched the suction stimulation position of the back of the hand through a subject experiment. We found that the correct answer rate for suction stimulation was highest when (*i*, *d*, *f*) = (30mm, 15mm, 0.9kgf).

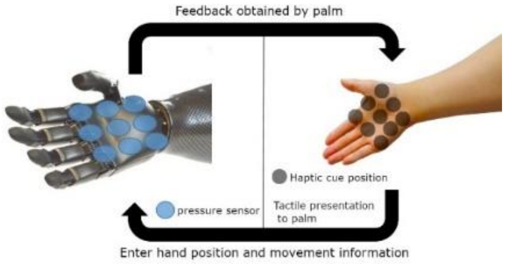

Fig. 1. Ideal method

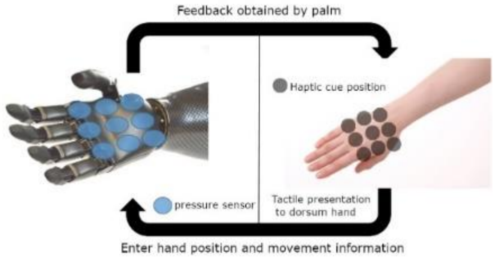

Fig. 2. Proposed method

Fig. 3. Designed device with parameters obtained by experiment

2.2. *Developed prototype device*

The prototype device shown in Fig. 4 was developed based on the specifications determined in our previous studies [12][13]. The device comprises suction pads, suction brackets, and fixtures created by a 3D printer. According to the determined parameters, the diameter of the suction pads was 15 mm and the interval between each pad was 30 mm.

2.3. *Substitutional Tactile Presentation System*

Fig. 5 shows the system configuration of the entire tactile presentation device for the back of the hand, as explained in Section 2.2. The device provides suction stimulation

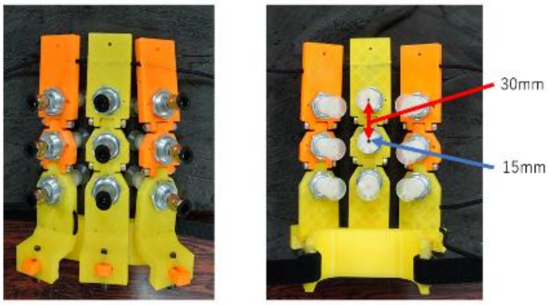

Fig. 4. Prototype device
(Left: Top view, Right: Bottom view)

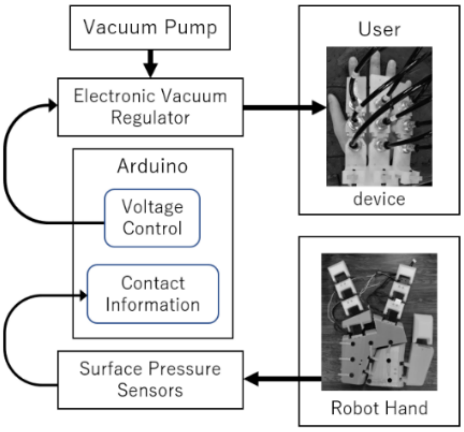

Fig. 5. Overview of the system for the experiment

to the user. The vacuum pump was GCD-051X (ULVAC), and nine regulators for vacuum pressure control were ITV2090 (SMC). The vacuum pressure can be controlled by the input voltage of the regulator, and a micro-computer (Arduino) outputs the input voltage to each regulator. Nine surface pressure sensors were used to convert the contact strengths to voltages, which were read using the Arduino.

3. Performance Verification Experiment of Tactile Presentation Device

3.1. *Experimental Methods*

In this study, we reported the results (correct answer rates) of an experiment in which five operators answered the position of a suction stimulation when it was applied to the back of the operator's hand using the prototype device. Nine points on their backs of the hand are pressed one by one (case 1), twenty points two by two (case 2), and thirty points three by three (case 3). Note that in our previous report [14], the number of subjects and stimulation points were two and one, respectively.

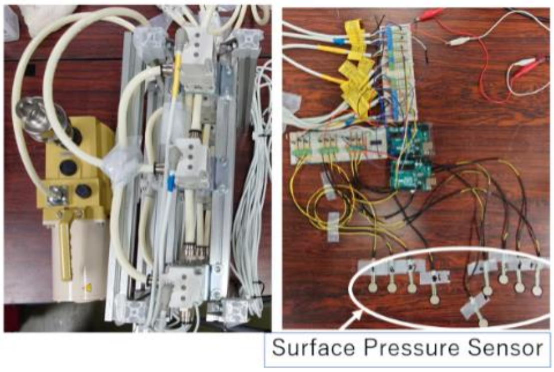

Fig. 6. Experimental scene
(Control side)

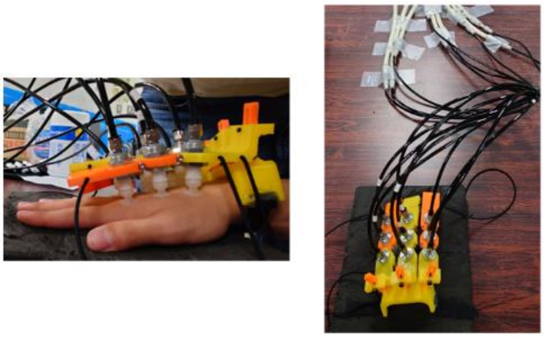

Fig. 7. Experimental scene
(Subject's side)

Fig. 8. Number of stimulation point.

The experimental scenes of the control and subject side are presented in Figs. 6 and Fig. 7, respectively. In this experiment, we sequenced the sensors on the desk instead of the robot hand to simplify the experiment set-up as shown on the right side of Fig. 6. Fig. 7 shows the devices on subject's side. Only the lightweight prototype device was mounted on the operator's hands. The stimulation positions for the experiment are shown in Fig. 8. There is a one-to-one relationship between the surface pressure sensor and sucker. Suction stimulation was applied to the back of the hand in predetermined orders as shown in Tables 1, 2, and 3. Each participant answered the numbers of the stimulation points.

Table 1. Order of stimulus presentation (Case 1).

Order of stimulation	Suction stimulation
1	2
2	7
3	9
4	8
5	5
6	1
7	3
8	6
9	4

Table 2. Order of stimulus presentation (Case 2).

Order of stimulation	Suction stimulation
1	3, 6
2	7, 8
3	1, 5
4	6, 8
5	4, 7
6	2, 5
7	5, 6
8	5, 7
9	2, 3

Table 3. Order of stimulus presentation (Case 3).

Order of stimulation	Suction stimulation
1	2, 5, 8
2	1, 2, 3
3	7, 8, 9
4	3, 5, 7
5	3, 6, 9
6	1, 5, 9
7	2, 3, 6
8	1, 2, 4
9	6, 8, 9

3.2. *Results*

In this experiment, five subjects were introduced to three cases of stimulations as shown in Tables 1, 2, and 3. The total number of collected data was 150. A graph of the results for Cases 1, 2, and 3 are shown in Fig. 9. Average correct answer rates for Cases 1, 2, and 3 are 82.2%, 75.6%, and 73.3%. In this experiment, "correct" means that the combination of stimulation points matched completely.

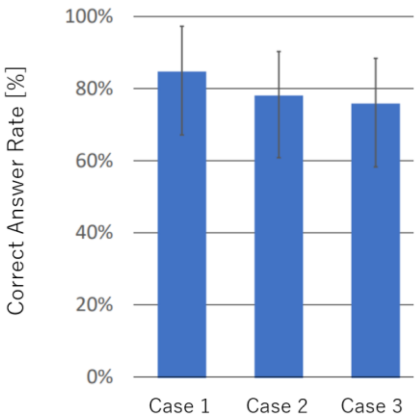

Fig. 9. Correct answer rate of the experiments.

3.3. *Discussion*

In our previous study [8], we found that the correct answer rate of human skin characteristics in the case of one stimulation was 85 %. We believe that the subjects recognized the position of the stimulation points almost correctly even if the proposed device was used because the rate was almost same between with and without the proposed device. Moreover, the incorrectly answered positions were located to above or below correct position. Therefore, we believe that the validity of the proposed method was confirmed.

Additionally, we measured the response time from the start of the stimulus to participant's answer. In most cases, the response was completed within 5 s. Therefore, we believe that the results are reliable because it was confirmed that the subjects answered the position without hesitation.

By comparing the correct answer rates of Cases 1, 2, and 3, it can be observed that the rate decreased slightly. However, because the width of the reduction was not large, the proposed method was applied to multiple stimulations.

In this experiment, the pressure of the vacuum pump is set to constant value (-54 kPa). To improve these results, it may be necessary to change the pressure. We plan to study how to change pressure for appropriate stimulation.

4. Conclusion

In this study, we developed a device according to the specifications determined in our previous studies and then performed subjective experiments to verify its performance. Accordingly, we obtained approximately 80% of the correct answers. Therefore, we believe that this device has the potential to be used in the teleoperation of robotic hands.

In the future, we plan to increase the number of stimulation points. Subsequently, we plan to confirm whether the users can recognize accurately when the pressure of the vacuum pump is controlled. Finally, the proposed device will be applied in the teleoperation task and verify the effectiveness of the proposed method.

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