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Paper:

Bilaterally Shared Haptic Perception for Human-Robot Collaboration in Grasping Operation

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Tactile sensations are crucial for achieving precise operations. A haptic connection between a human operator and a robot has the potential to promote smooth human-robot collaboration (HRC). In this study, we assemble a bilaterally shared haptic system for grasping operations, such as both hands of humans using a bottle cap-opening task. A robot arm controls the grasping force according to the tactile information from the human that opens the cap with a finger-attached acceleration sensor. Then, the grasping force of the robot arm is fed back to the human using a wearable squeezing display. Three experiments are conducted: measurement of the just noticeable difference in the tactile display, a collaborative task with different bottles under two conditions, with and without tactile feedback, including psychological evaluations using a questionnaire, and a collaborative task under an explicit strategy. The results obtained showed that the tactile feedback provided the confidence that the cooperative robot was adjusting its action and improved the stability of the task with the explicit strategy. The results indicate the effectiveness of the tactile feedback and the requirement for an explicit strategy of operators, providing insight into the design of an HRC with bilaterally shared haptic perception.

Keywords: haptics, tactile sharing, human-robot collaboration, bilateral connection, wearable device

1. Introduction

In the fields of manufacturing, welfare, and medicine, human-robot collaboration (HRC) is expected to ensure flexible operations and enhance human abilities [1–3]. In HRC, the communication format of information is an important factor in ensuring the smooth collaboration between a human and a collaborative robot. In addition, there are two types of configurations in HRC, namely unilateral and bilateral configurations.

With respect to unilateral configuration, there are two directions: one is from a human to a robot such that the robot recognizes human actions, and the other is the direction from a robot to a human such that the human recognizes robot actions. In the former direction, the robot is controlled according to the recognized human actions. For instance, in an assembly task, a robot recognizes what a human operator grasps and provides an adequate part of a smooth assembly [4]. Visual information with cameras and depth sensors, and audio information with microphones are useful in monitoring human behavior and voice, including the environment, and tactile-related information such as force [5], vibration [6], and EMG [7, 8] is useful when the target task has blind spots, when a collaborative task requires information that is difficult to recognize using visual and audio information, or when a target task requires the recognition of instantaneous action. When the direction is from a robot to a human, the robot provides sensory feedback to the human operator according to its own actions and states. An alert function can be considered as a representative example. Indeed, with respect to the information from the robot to the human, the information from the human to the robot is often involved (i.e., bilateral) as the robot often needs to recognize certain phenomena derived from human behavior according to the task. For instance, in some studies, intelligent automobiles notify drivers about lateral drift and curve speed using seat vibrations [9]. The presence of tactile feedback has several advantages. The human operator is not required to see the robot, and the feedback information is localized to the target operator, thereby reducing interference to the environment.

The bilateral configuration includes the two aforementioned elements, which induce reciprocal awareness. In other words, a robot can recognize human behavior, and vice versa. Previously, cooperation tasks involving physical interaction between a human and a human/robot have been investigated [10, 11]. In these studies, a human operator and another human/robot grasped and handled an object together. In these cases, there is a direct interaction mediated by the object between the human and the robot when the object is rigid, where the human directly perceives sensory feedback. However, even when there is no direct interaction, the bilateral system promises smooth collaboration. Che et al. proposed a communication system with short vibration feedback, in which a moving robot indicated the intention of the robot to create a path and avoid collisions with the human operator [12]. Accordingly, human operators can strategically determine their behavior according to their perceived feedback. Casalino et al. proposed a reciprocal awareness system in which the assembling robot sends symbolic tactile feedback to a human operator with a wearable vibrator based on recognition of human behavior obtained using a camera, which prompts the human operator to start the next action [13].

Authors have proposed "shared haptic perception," which creates a bilateral haptic connection between humans and robots [14], where the robot recognizes human action via a wearable tactile sensor, and the human operator recognizes the robot action via a symbolic vibrotactile cue with a wearable vibrator. The monitoring of tactile information and giving tactile feedback have the aforementioned advantages (availability for blind and loud environments, instantaneous recognition, and localization), and in previous studies, the symbolic vibrotactile cue was beneficial to human operators in terms of allowing the recognition of instantaneous action, which enables the connection to the next action required as the awareness feedback; however, such a simple symbolic cue may be limited in terms of recognizing the variation of continuous actions such as grasping by robots. In the teleoperation system, force or substitutional sensory feedback has been employed to feed back the force exerted by the robot or the robot's state, such as posture [15–17]. The human operators control the robot, and the feedback directly reflects the action of the human operator owing to a leader-follower relationship. This study focuses on the HRC, in which robots can independently determine adequate actions according to the action of the human operator, and not on the teleoperation system. To the best of our knowledge, the application of continuous information, such as the grasping force for the bilateral haptic connection between humans and robots in HRC, has not been investigated. Findings on the paradigm and effect of the tactile feedback for continuous information in HRC may be beneficial when designing the bilateral configuration, which promotes the cooperative task. Thus, this study aims to investigate shared haptic perception for continuous information in HRC.

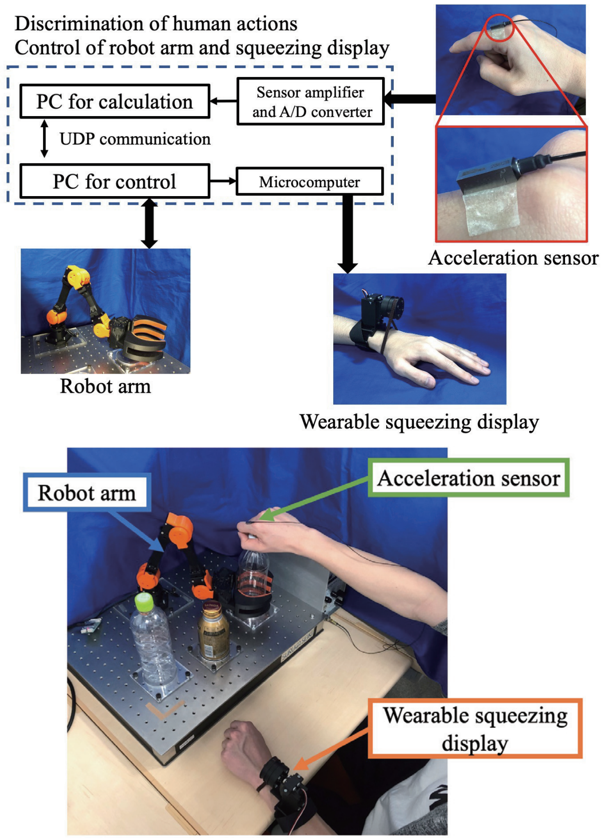


Fig. 1. Configuration of the proposed system. A robot arm controls the grasping force according to the tactile information from the human wearing an acceleration sensor, and the grasping force of the robot arm is fed back to the human with a wearable squeezing display.

The grasping operation of an object is a task that includes continuous information with which humans often engage in daily life; humans often perform these operations using both hands. For example, in a bottle cap opening task or cutting paper with a scissor, one hand manipulates and/or holds the object, while the other hand provides effort for the work. Although humans can easily open the bottle cap even when blindfolded, coordination control between both hands may be required. Therefore, the grasping operation of an object with both hands can be expanded to the HRC. The grasping operation with the HRC is expected to assist people who cannot move one hand well (e.g., stroke patients and amputees) and to augment persons for whom one hand is blocked by other work.

In this study, opening a bottle cap was adopted as the target task for shared haptic perception shown in **Fig. 1**. Here, a human operator rotates a cap and the robot arm grasps the bottle. A robot recognizes the states of the human operator, and accordingly, the robot adjusts the grasping force. A finger-attached acceleration sensor was used to monitor human behavior, and a wearable squeeze display on the wrist was employed as the tactile display that feeds back the grasping force from the robot arm to the human operator. Three experiments were performed. First, the just noticeable difference (JND) in the tactile display was determined in order to investigate the basic capability of feedback perception. Second, a collaborative task with different bottles was conducted under two conditions, namely with and without tactile feedback. Here, the tactile feedback was fed back to the participants, and no explicit strategy was imposed. From this experiment, the feasibility of the proposed HRC system and its improvement with tactile feedback were investigated in terms of its efficiency and other psychological factors. In addition, a collaborative task was conducted using a blindfold under two conditions to investigate the influence of visual information. Third, an explicit strategy was imposed on the proposed HRC system to evoke the effectiveness of the tactile feedback. Based on the results obtained, the effects and limitations of tactile feedback are discussed to provide insight into the design of an HRC with bilaterally shared haptic perception.

The assembled shared haptic system is described in Section 2. In Section 3, experimental methods are provided, and the results obtained from each experiment are presented in Section 4. Section 5 discusses the effects and limitations of the tactile feedback. Finally, Section 6 concludes the paper.

2. Tactile Sharing System with Arm Robot

2.1. Overview of System

The system comprises a tactile sensor attached to the finger, a wearable squeezing tactile display, a robot arm, and laptop computers for control and signal processing. **Fig. 1** illustrates the configuration of the assembled system. The collaborative robot arm, which is an open-source manipulator Mikata arm (ROBOTIS Co., Ltd.), has a four degree-of-freedom (DoF) and a gripper that was designed to grasp the bottles. As the tactile sensor, an acceleration sensor (Showa Sokki, 2302 B; sensitivity: 1.84 pC/(m/s^2); dimension: $4 \times 4 \times 13$ mm) was attached to the upper side of the proximal phalange of an operator's right index finger using double-sided tape (Nitto Denko Corporation, No.5000N). The sensor was stably attached to the finger [18]. The tactile display was worn on the left wrist of a human operator. The tactile information of the human and robot arms is bidirectionally related to the wearable tactile sensor and display.

The acceleration sensor collects tactile information on the index finger derived from the operation and transfers it to a computer for calculation via an amplifier (Showa Sokki, Model1607) and an A/D converter (National Instruments, USB-6218). The computer used for the calculation recognizes the operation state and calculates the torque of the gripper of the robot arm, and the control signal is sent to the other computer via user datagram protocol (UDP) communication, which controls the robot arm using the robot operating system (ROS). The computer for control sends the current torque for grasping to a microcomputer (Arduino UNO), which controls the servomotor of the squeezing tactile display according to the torque.

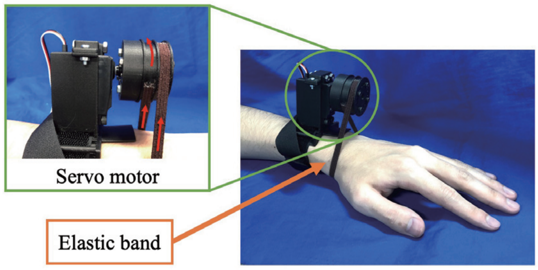


Fig. 2. Wearable squeezing-typed tactile display.

2.2. Wearable Tactile Sensor and Display

The acceleration sensor attached to the finger allows the operator to touch an object directly with the bare fingertip. It is important to maintain natural tactile sensations for the operation of an object as humans normally adjust their movement based on perceived tactile sensations; for example, humans exert a grasping force on an object with a certain margin to avoid slippage [19]. A high-pass filter with a cut-off frequency of 100 Hz was applied to the output from the acceleration sensor, and skin-propagated vibrations were detected [20]. Previous studies have demonstrated that skin-propagated vibrations are available for the identification of texture rubbing [21, 22] and operations [23]. Makino et al. [24] proposed a life log system utilizing a nail-mounted piezo sensor that detects vibrations derived from a finger pad.

Figure 2 presents the assembly of the tactile display, which provides a squeezing stimulation on the wrist with an elastic band that has a 6-mm width, a pulley, and a servo motor (Parallax Standard Servo, Parallax Inc.). Squeezing-type tactile displays have been proposed in previous studies [25, 26]. In the present study, two co-axis pulleys were employed, and the belt was wound to squeeze the wrist according to the rotation position of the servomotor. The rotation position T_θ is determined by the torque of the gripper of the robot arm, which is expressed as

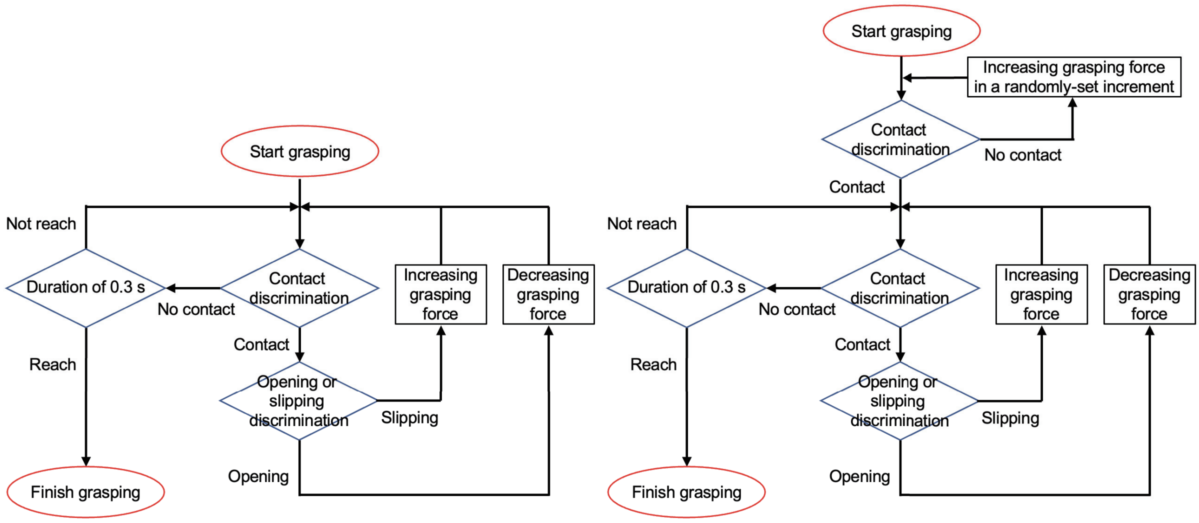
$$T_\theta = 2.45Gr + T_{\theta 0}, \qquad (1)$$

where Gr and $T_{\theta 0}$ indicate the gripper torque of the robot arm and the initial position of the servomotor, respectively. To stabilize the contact, the initial position of the servomotor was the same for all participants.

2.3. Signal Processing

2.3.1. Control Flow

The proposed system was adopted for the bottle cap-opening task. Opening a cap is a dexterous task as it requires the grasping and rotating of the cap; however, although grasping the bottle is simple, the grasping force



(a) Simple mode (b) Strategy mode

Fig. 3. Control flow of the robot arm. Two types were prepared: simple mode and strategy mode.

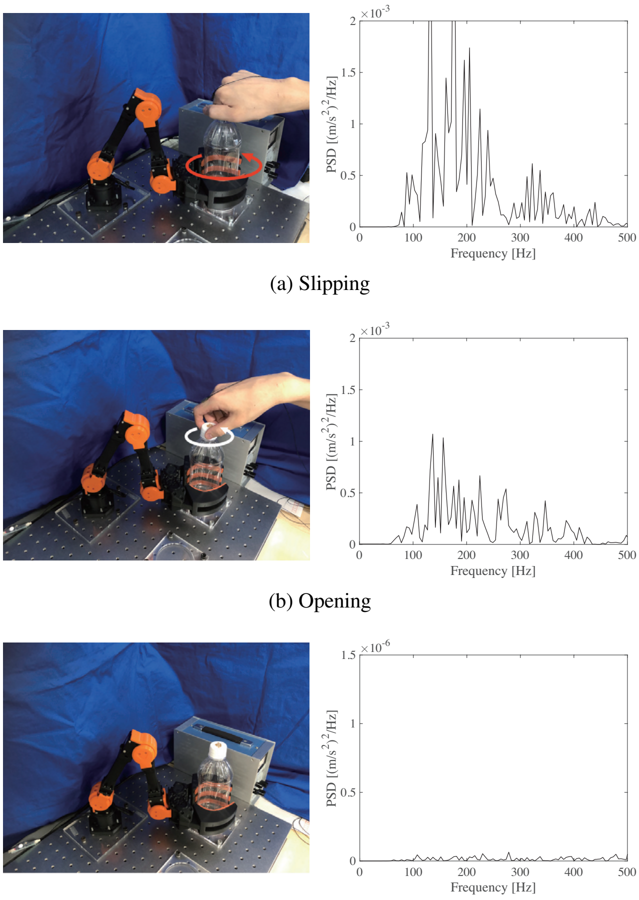
must be adjusted to avoid slipping and bending the bottle. Considering the characteristics of the tasks required by both hands, because the simple control and cooperation initiatives are preferred for the robot arm and human operator, respectively, we designed a co-operation task in which a user was asked to open a bottle cap with his/her right hand with the sensor, while the robot arm grasped the bottle, thereby controlling the grasping force according to human actions.

We prepared two types of control flow of the robot arm for cooperation: the simple feedback mode (simple mode) and the feedback mode with the explicit strategy (strategy mode). **Fig. 3** shows the control flow for both modes. In the simple mode, the grasping torque of the robot arm started with a small value (0.1645 Nm) to make light contact with the bottle, and it was then modified according to human actions. In the strategy mode, the robot arm started to grasp the bottle in one of three increments (0.0041, 0.0082, and 0.0123 Nm) of the grasping torque that was randomly set, and the robot then started to modify the grasping torque according to human actions when the operator started to open the cap. Whereas the tactile feedback is just fed back to operators in the simple mode, the strategy mode requires the operator to estimate the grasping force of the robot arm. However, in the strategy mode, it is expected that the rotation action of the cap by the operator is reduced and stable as an adequate grasping force is initially imposed on the bottle.

First, the robot arm was moved to the bottle until it make contact with the surface of the bottle using the gripper. In this study, the position of the bottle was fixed to control the robot arm automatically. Then, the robot arm collected the tactile information from the human operator and controlled the grasping force with a sampling period of 0.1 s. For the control, we determined three states involved in opening the bottle cap with the human finger: 1) slipping, 2) opening, and 3) no contact. **Fig. 4** illustrates each state with the power spectrum density (PSD) of the sensor output collected for a duration of 0.2 s. No contact indicates the state in which the human does not touch the bottle cap. Slipping indicates the state in which the bottle rotates against the opening motion of the cap by the operator. When the grasping force is insufficient, slippage occurs at the interface between the gripper of the robot arm and the bottle. Opening indicates the state in which the bottle is fixed with a sufficient grasping force, and the cap rotates independently. To strengthen the discrimination, contact discrimination and slipping/opening discrimination were employed separately.

- *Contact discrimination:* Contact discrimination was employed to determine the beginning or ending of the collaborative task. After the contact was determined, slipping/opening discrimination was performed. In particular, for the strategy mode, the robot arm increased the grasping torque until the first contact was determined, and it then controlled the grasping torque using the tactile information from the operator, which is the same as in the simple mode. When no contact was detected after starting the grasping, an assessment of the no-contact condition was performed. When the number of consecutive times reached 3 (i.e., 0.3 s), the robot arm released its gripper from the bottle to finish the task. When the contact was determined, the count returned to 0. This counter method prevents the erroneous recognition of the task end owing to the recognition of the no-contact condition, which is triggered by the temporal termination of the operator's movement even while opening the cap.

- *Slipping/opening discrimination:* Slipping/opening discrimination was employed to adjust the grasping torque. When the slipping was assessed, the torque of the gripper increased at an increment of



(a) Slipping

(b) Opening

(c) No contact

Fig. 4. Each identified state with PSD of the sensor output.

0.0041 Nm for every sample, to increase the grasping force. Alternatively, when the opening task was determined, the torque of the gripper decreased at a decrement of 0.0041 Nm for every sample to reduce the grasping force. The values of the increment and decrement were experimentally determined to be able to adjust the grasping force with sufficient resolution according to the bottles.

2.3.2. Recognition

Each discrimination was conducted using a support vector machine (SVM), which is a type of machine learning method. Principal component analysis (PCA) was adopted to extract features of the output signals from the tactile sensor attached to the operator's finger, which were applied to the SVM. The PSD was calculated for the sensor output collected for each 0.2 s, and the intensity of the sensor output for each range of frequencies was computed as

$$iRMS_i = \log \sqrt{\int_{f_i}^{f_i+50} PSD(f)df}, \quad \ldots \ldots \quad (2)$$

where f_i and $PSD(f)$ represent the i-th frequency for the calculation of the intensity and PSD of the acceleration sensor output at frequency f, respectively. The PSD was divided into eight ranges of 50 Hz each from 100 to 500 Hz, that is, $f_i = 100$, 150, 200, 250, 300, 350, 400, and 450 Hz. The eight $iRMS_i$s were compressed into two-dimensional information via the PCA.

Before the experiment, each participant was asked in a learning session to make the SVM models. Participants were instructed to open the cap of a bottle, which was one of the bottles used in the experiment. The robot arm grasped the bottle and increased the gripper torque in increments of 0.0041 Nm, recording the output signals from the acceleration sensor attached to the participant. When the cap began to rotate independently from the bottle (i.e., opening), participants were instructed to push the keyboard with their left hand as soon as possible to record the time. For durations of 3 s before and 1 s after this time, the sensor output signals were extracted as the training data of the slipping and opening states, respectively. In addition, participants had to push the keyboard again after putting the cap on the table, and then rested their fingers; the sensor output signals of this term were collected with a duration of 1 s as the no-contact phase.

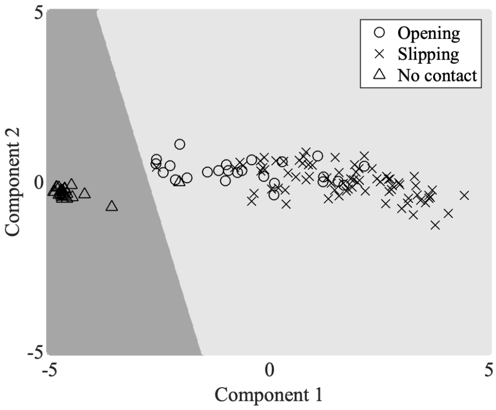
The data collected were divided into samples of 0.2 s, and the intensities of the sensor output were calculated for each sample using Eq. (2). PCA was applied to the intensities, and consequently, the formulations used to compute two features that were utilized in the kernel SVM yielded the following:

$$P_i = \sum_{j=1}^{8} w_{j,i} IRMS_j, \quad \ldots \ldots \ldots \ldots \quad (3)$$

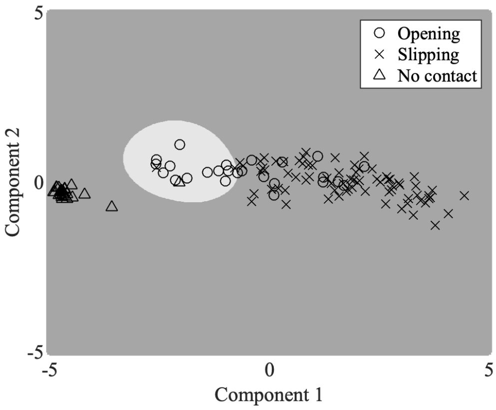
where P_i and $w_{j,i}$ represent the i-th component of the PCA and each coefficient on the i-th component, respectively. The mean cumulative contribution rate for the two components for all participants in this study was 98.2±0.6% (95.8±1.5% and 2.4±1.0% for 1st and 2nd factors, respectively). Therefore, it sufficiently represents the PSD of the sensor output using these two components. Then, two components were labeled as each recorded state, and discrimination models based on the kernel SVM were established for each participant. As above-mentioned, discrimination was conducted between the no-contact and slip or open conditions as the contact discrimination, and between the slip and open conditions as the slipping/opening discrimination, according to the control flow. **Fig. 5** presents an example of the SVM model for each participant. The mean accuracy and its standard deviation for all participants in this study were 98.5±2.1% and 87.7±2.6% for the contact discrimination and the slipping/opening discrimination, respectively. In the experiments, the sensor output with a duration of 0.2 s was extracted every 0.02 s (90% overlap), and was applied to the established SVM model.

3. Experiments

Three experiments were conducted in this study. First, to investigate how participants could discriminate tactile



(a) Discrimination of contact or no contact



(b) Discrimination of slip or open

Fig. 5. Example of the SVM model for one participant.

Fig. 6. Bottles used in the experiments.

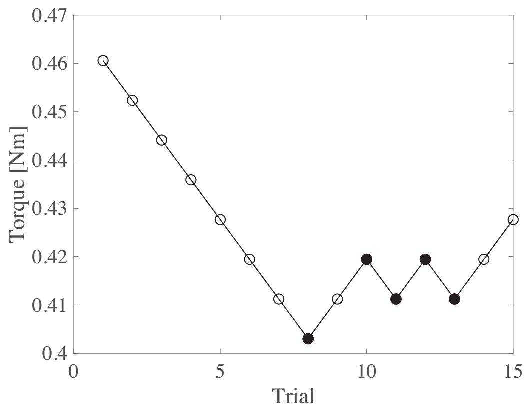


Fig. 7. Example of JND test of tactile display. Filled circles indicate the reversal points that were used to calculate JND.

feedback, a JND was measured when squeezing the wrist with the tactile display (Experiment 1). The bottle cap-opening task was then tested for three different bottles with and without tactile feedback. The second experiment was conducted in the simple mode. The feasibility of the grasping control and the effectiveness of tactile feedback on performance and other psychological factors were investigated (Experiment 2.1). As this experiment had visual feedback (participants could see the bottles), the same task was also conducted with a blindfold to investigate the influence of the visual information (Experiment 2.2). Then, the third experiment was conducted using the strategy mode to evoke the effectiveness of tactile feedback (Experiment 3).

3.1. Samples

Three different bottles were used for the experiments. **Fig. 6** illustrates the bottles used in this study. The bottle cap was closed with the same torque to control the minimum torque required for the opening. The torque was set to be within 0.58–0.62 Nm with an electric torque sensor (Driver Digitorqon Set, TONE). Based on the different surfaces of each bottle, it is expected that the minimum grasping force exerted by the robot arm, which is required to open the cap, would vary for different bottles.

3.2. Participants

Ten healthy adults (eight males and two females, 22–24 years old) participated for Experiment 1, ten healthy adults (nine males and one female, 22–24 years old) for Experiment 2.1, ten healthy adults (ten males, 22–25 years old) for Experiment 2.2, and eight healthy adults (eight males, 20–24 years old) for Experiment 3; some participants participated in multiple experiments. All participants provided informed consent prior to each experiment. The experiments were approved by the ethics committee of the Nagoya Institute of Technology.

3.3. Experiment 1: JND for Tactile Display

The two-alternative forced choice (2AFC) and downward staircase method was adopted to measure the JND [27]. The participants wore a tactile display on their left wrist, as illustrated in **Fig. 2**. **Fig. 7** shows an example of a session for one participant in this experiment.

The downward trial started with a large test stimulus, τ_0, that all participants could perceive. In each trial, a pair of reference τ_r and test τ stimuli were presented to the participants, who were asked to determine whether the two stimuli were identical. If they answered that the two stimuli were different, the test stimulus was decreased, and the decreased stimulus was adopted in the next trial. If they answered that the two stimuli were identical, the test stimulus was increased, and the increased stimulus was used in the next trial. The increment/decrement in the test stimulus between trials $\Delta\tau$ was constant. Participants wore eye masks and headphones that applied white noise to respectively mask the visual and audio senses during the experiment.

In this experiment, three reference stimuli were prepared: $\tau_r = 0.4$, 0.6, and 0.8 Nm. For the first test stimuli $\tau_0 = 0.46$, 0.69, and 0.91 Nm, the increments for each trial $\Delta\tau = 0.008$, 0.012, and 0.016 Nm were set for each reference stimulus of $\tau_r = 0.4$, 0.6, and 0.8 Nm, respectively. These values were determined via preliminary experiments considering the Weber-Fechner law [28].

For each trial, reference and test stimuli were each provided once. The number of trials was 15 for each condition. All reversal points for each condition were extracted to calculate the mean torque, which was determined to be JND τ_{JND}. All participants were given three reference stimuli, and the order of the conditions was randomized for each participant. The ratio of JND to each reference stimulus, K, was computed as the Weber ratio, which is expressed as

$$K = \frac{\tau_{JND}}{\tau_r}. \quad (4)$$

The mean K from all participants was calculated for each reference stimulus.

3.4. Experiment 2: Task Using Simple Mode

3.4.1. Experiment 2.1: Task with Visual Information

The experimental setup is illustrated in **Fig. 1**. The control of the simple mode (**Fig. 3(a)**) was adopted under two conditions: with and without tactile feedback. Half of the participants started from the condition with tactile feedback, and the other half started from the condition without tactile feedback. All participants conducted the experiment in both of the conditions.

Three different bottles were randomly positioned for each trial at the three positions determined beforehand. The participants were instructed to open the cap from the right to the left positioned bottles. At the beginning of the trial, the robot arm stayed in the initial posture and position, and moved to each bottle to start grasping it. After finishing the task (the cap was opened and no-contact was recognized), the robot arm returned to the initial position and initial posture, and it then moved again to the next bottle. Participants were instructed to start rotating the cap immediately after the robot arm started grasping the bottle. To investigate the natural improvement of opening the bottle cap, participants were instructed to rotate the cap at their preferred speed. The participants wore headphones that applied white noise in order to mask the audio stimuli during the experiment.

As mentioned in Section 2.3.2, the SVM model was established for each participant before the experiment. As shown in **Fig. 6**, plastic bottle No.1 was used to establish the SVM model. A total of seven sessions were conducted for each condition, and one session consisted of three bottles. The first two sessions were used for the practice, and the last five sessions were adopted for analysis. Furthermore, a questionnaire on usability was administered after the experiment for each condition. The questionnaire presented in **Table 1** from Q1 to Q5 was designed based on previous human interface research [13, 29]. The Q5 questionnaire was administered only after the tactile feedback. The participants were evaluated on a scale of 1 to 5, which indicated total disagreement and total agreement, respectively.

Table 1. Questionnaire on usability.

No.	Content
Q1	I was able to trust the robot.
Q2	I was able to predict the gripping motion of the robot.
Q3	I was confident that the robot was adjusting the grip.
Q4	It was difficult to carry out this task.
Q5	The tactile feedback was annoying for this task.

For the analysis, the operation time required to complete the opening task for each bottle was measured, and the mean operation time for the five sessions was calculated as an evaluation index. The torque exerted just before the end of gripping each bottle was measured, and the mean torque and the coefficient of variance in the torque (CV) for the five sessions were calculated as other evaluation indexes. The CV was calculated by dividing the variance of the data by the mean value, and the CV in the torque represents the relative dispersion of the grasping force exerted by the robot arm for each condition and each bottle.

Two-way repeated measures analysis of variance (ANOVA) was conducted on different bottles and two conditions for each parameter. When a significant difference was indicated, a post-hoc multi-comparison was applied using paired t-tests with a Bonferroni correction. The resulting questionnaire between the two conditions was also compared in Q1, Q2, Q3, and Q4 using non-parametric Wilcoxon signed-rank tests. The significance level was set to 5%.

3.4.2. Experiment 2.2: Task Without Visual Information

The procedure was similar to that used in Experiment 2.1. In this experiment, the participants were asked to close their eyes as soon as possible when they touched the bottle, and they were asked to open their eyes when each task was completed; the experimenter signaled them by touching their shoulders. The experiment was performed using plastic bottle No.1. They wore a headphone that applied white noise to mask the audio stimuli during the experiment.

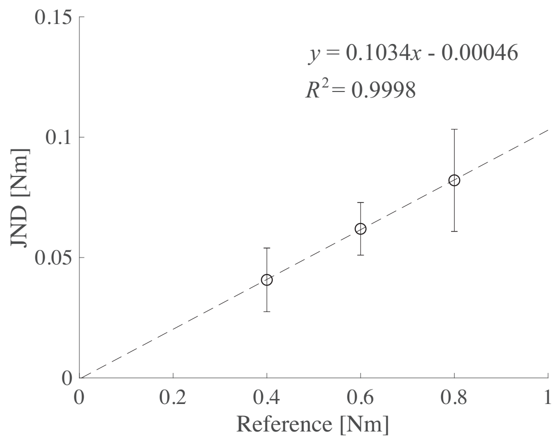
Similar to Experiment 2.1, the experiments were conducted under two conditions, i.e., with and without tactile feedback. Half of the participants started from the condition with tactile feedback, and others started from the condition without tactile feedback. All participants took part in both conditions, and each condition had seven trials. The first two trials were used for the practice, and the last five trials were adopted for the test. The time from when the robot arm made contact with the bottle to when the cap was opened with no contact state, the exerted torque just before the end of gripping, and the CV in the torque were calculated for each participant. The operation time, exerted torque, and CV between the two conditions and between Experiments 2.1 and 2.2 were compared using t-tests.

3.5. Experiment 3: Task Using Strategy Mode

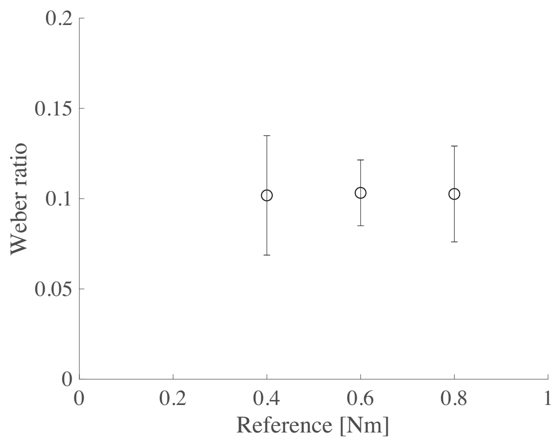
The control of the strategy mode (**Fig. 3(b)**) was adopted for two conditions: with and without tactile feedback. Half of the participants started from the condition with tactile feedback, and the other half started from the condition without tactile feedback. All participants conducted the experiment in both of the conditions.

The procedure was similar to that of Experiment 2.1, but before the experiment with tactile feedback, the participants conducted the task using the simple mode three times for each bottle to remember the tactile feedback derived from the grasping force when the cap was opened. In this experiment, participants were instructed to start rotating the cap when they judged that the robot imposed a sufficient grasping force for each bottle. They had to estimate the grasping force from the visual information of the bottle and the tactile feedback.

Each condition consisted of five trials. The mean torque and CV for each bottle were calculated for each participant and each condition (with or without tactile feedback). Then, two-way repeated measures ANOVA was conducted on different bottles and two conditions for the mean torque and CV. When a significant difference was indicated, a post-hoc multi-comparison was applied using paired t-tests with a Bonferroni correction.



(a) Mean JNDs and their standard deviation for reference stimuli. The fitted line and the coefficient of determination are presented.



(b) Mean Weber ratios and their standard deviation for reference.

Fig. 8. Results of JND measurement for the tactile display.

4. Results

4.1. Experiment 1: JND for Tactile Display

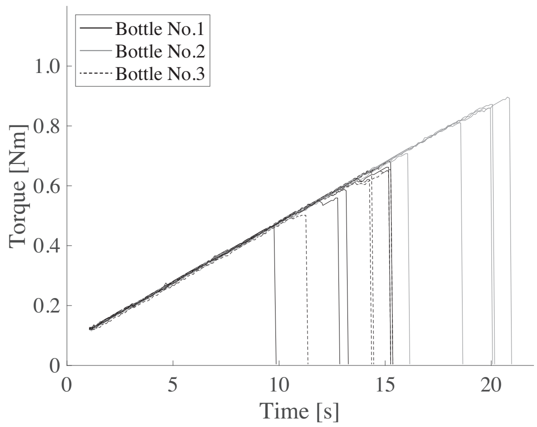
The resulting JNDs and Weber ratios are illustrated in **Fig. 8**, which presents the mean τ_{JND} and K values and their standard deviations. A linear function was fitted to the mean JNDs to determine the Weber ratio. The slope of the fitted line, intercept, and coefficient of determination were 0.1034, -0.00046, and 0.9998, respectively. As the intercept was mostly 0, the obtained results indicated that the Weber ratio was constant in this experiment. As shown in **Fig. 8(b)**, the Weber ratio appears to be constant. Consequently, the mean Weber ratio for all reference stimuli and its standard deviation were calculated as $K = 0.103 \pm 0.026$.

4.2. Experiment 2: Task Using Simple Mode

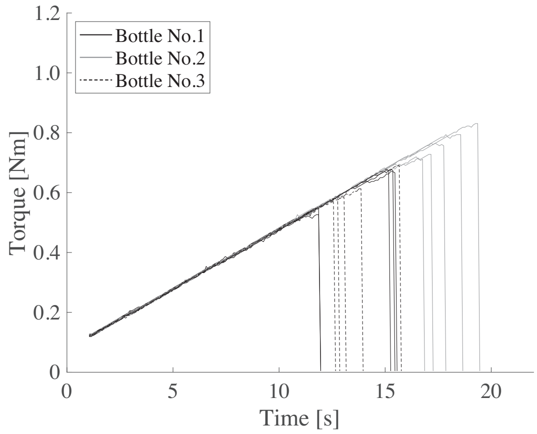
4.2.1. Experiment 2.1: Task with Visual Information

All participants opened the bottle cap throughout the experiment. **Fig. 9** presents an example of the time series of the torque exerted by the collaborative robot. All trials for one participant are illustrated for each condition. It was observed that the torque first increased and then fluttered toward the end of the trial. The trend appeared to be similar between the two conditions. The exerting torques appear different among the bottles.

The resulting operation time, exerted torque, and CV are shown in **Fig. 10**, which presents the mean operation time, mean exerted torque, mean CV for each bottle, and their standard deviations. The two-way repeated ANOVA on the operation time exhibited a significant difference among the bottles ($F(2,18) = 30.6$, $p = 0.2 \times 10^{-5}$). There were no significant differences between the two conditions (with and without tactile feedback) or interaction. A post-hoc multi-comparison between the bottles revealed significant differences between bottles No.1 and No.2 ($t(9) = 5.04$, $p = 0.003$), between bottles No.1 and No.3 ($t(9) = 4.04$, $p = 0.026$), and between bottles No.2 and No.3 ($t(9) = 5.66$, $p = 0.003$). Similar to the operation time, the two-way repeated ANOVA on the torque exhibited a significant difference among the bottles ($F(2,18) = 45.0$, $p = 0.1 \times 10^{-7}$). There were no significant differences between the two conditions (with and without tactile feedback) or interaction. A post-hoc

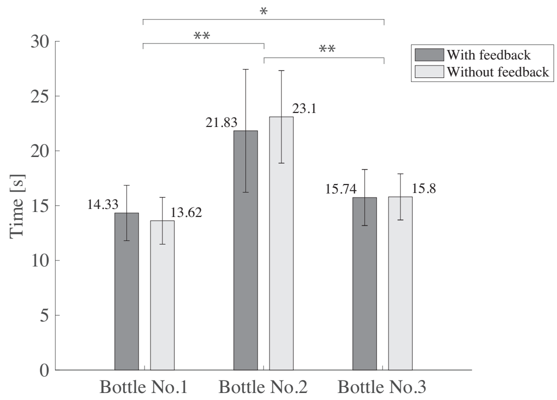


(a) With tactile feedback

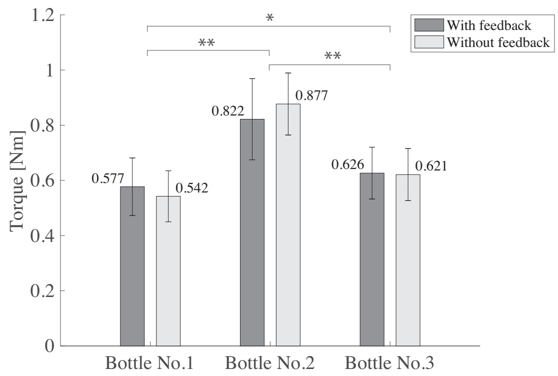


(b) Without tactile feedback

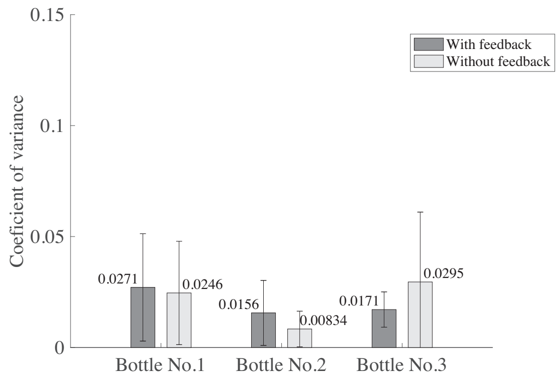
Fig. 9. Examples of the troupe exerted by the robot during trials for each bottle.



(a) Operation time



(b) Exerted torque



(c) Coefficient of variance in torque

Fig. 10. Result of Experiment 2.1 for each bottle on the conditions with and without tactile feedback. Mean values and their standard deviations are presented. * and ** indicate $p < 0.05$ and $p < 0.01$, respectively.

multi-comparison between the bottles revealed significant differences between bottles No.1 and No.2 ($t(9) = 6.78$, $p = 0.0006$), between bottles No.1 and No.3 ($t(9) = 4.06$, $p = 0.026$), and between bottles No.2 and No.3 ($t(9) = 7.08$, $p = 0.0006$). The two-way repeated ANOVA on CV in the torque showed no significant differences among the bottles, between the conditions with and without tactile feedback, or interaction. Therefore, the results showed that tactile feedback did not significantly improve the operation time or torque. The results indicate that bottle No.2 required the largest gripping force and operation time in the other two bottles to open the cap, and bottle No.1 required the smallest gripping force and operation time.

Figure 11 presents the box plots of the resulting questionnaire for each condition. Wilcoxon signed-rank tests demonstrated significant differences in Q2 ($W = 21$, $p = 0.031$) and Q3 ($W = 36$, $p = 0.008$). These experiments indicate that the tactile feedback provided confidence in the control of the gripping force of the robot. In addition, from the Q1 result, it was observed that cooperation trust tends to be stronger with tactile feedback than without tactile feedback ($W = 31$, $p = 0.086$). The median of Q5 value was 2.5.

4.2.2. Experiment 2.2: Task Without Visual Information

All participants opened the bottle cap throughout the experiment. **Fig. 12** presents the mean operation time, mean exerted torque, and CV in the torque and their standard deviations for each condition. The t-test for each parameter exhibited no significant differences between the two conditions. Therefore, the tactile feedback did not improve the operation time and torque in this experiment, even without visual information. In addition, the mean operation time, torque, and CV seem to be simi-

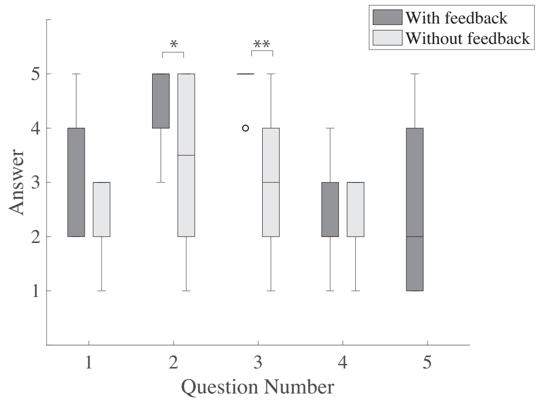


Fig. 11. Questionnaire results for the conditions with and without tactile feedback. * and ** indicate $p < 0.05$ and $p < 0.01$, respectively.

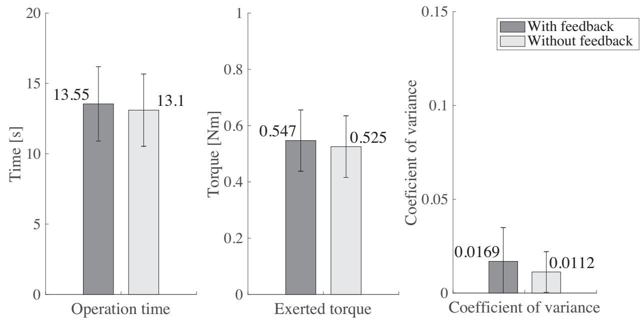
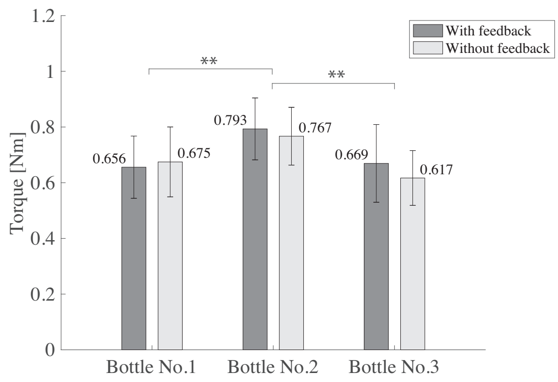
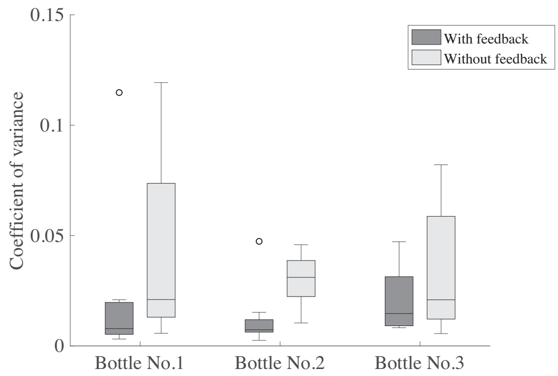


Fig. 12. Result of Experiment 2.2 for the conditions with and without tactile feedback. Mean values and their standard deviations are presented.



(a) Exerted torque



(b) Coefficient of variance in torque

Fig. 13. Result of Experiment 3 for each bottle for the conditions with and without tactile feedback. Mean values and their standard deviations are presented. ** indicates $p < 0.01$. Regarding the CV, there was a significant difference between the conditions with and without feedback ($p = 0.027$) when outliers were excluded.

lar to those obtained in Experiment 2.1. The t-tests between Experiments 2.1 and 2.2 showed that there were no significant differences. We also conducted the same experiment using the other two bottles. The results showed the same tendency that the resulting mean operation time, torque, and CV were at the same level between the conditions with and without the feedback and between Experiments 2.1 and 2.2. These results indicate that visual information does not significantly influence task performance.

4.3. Experiment 3: Task Using Strategy Mode

All participants opened the bottle cap throughout the experiment. The results are shown in **Fig. 13**, which presents the mean exerted torque and CV for each bottle and their standard deviations. The two-way repeated ANOVA on the torque exhibited a significant difference among the bottles ($F(2,14) = 22.0,\ p = 0.4 \times 10^{-4}$). There were no significant differences between the two conditions (with and without tactile feedback) or interaction. A post-hoc multi-comparison between the bottles revealed significant differences between bottles No.1 and No.2 ($t(7) = 4.78,\ p = 0.006$) and between bottles No.2 and No.3 ($t(7) = 7.33,\ p = 0.0005$). These results are similar to those of Experiment 2. Regarding the CV, the results for participant No.5 were outliers ($\chi^2 = 5.9$, $p = 0.015$ for bottle No.1; $\chi^2 = 5.8$, $p = 0.016$ for bottle No.2). Therefore, the results for participant No.5 were excluded from the analysis, and the ANOVA showed a significant difference between the conditions ($F(1,6) = 8.4$, $p = 0.027$). There were no significant differences between the bottles or interaction. This result indicated that the variance of the torque by the robot was smaller in the condition with the tactile feedback than in that without the tactile feedback.

5. Discussion

The Weber ratio of the tactile display was about 0.1, resulting in the JND varying from 0.04 to 0.08 Nm for the reference ranged from 0.4 to 0.8 Nm. Considering the torque exerted in Experiments 2 and 3, this result indicates that participants could perceive the variance of the torque with the tactile feedback.

Experiments 2 and 3 demonstrated that the assembled system helped the human operator open the cap. The robot exerted different grasping forces according to the different bottles. Bottle No.2, which required the largest forces, had a smooth surface, and Bottle No.1, which required the smallest forces, had an uneven surface; hence, the experimental results were consistent with the properties of the bottles. The results of the operation time in Experiment 2 showed the same trend as the torque. This is caused by the control flow, in which the torque for the grasping increases at a constant increment according to the discrimination.

Regarding the comparison between the conditions with and without tactile feedback, no significant result was obtained for the operation time, torque, and CV in the torque in Experiments 2.1 and 2.2. Because Experiment 2.1 included visual feedback for both conditions, Experiment 2.2 was conducted without visual information. Nevertheless, the results were mostly the same between the two conditions. Thus, the results of Experiment 2 indicate that tactile feedback did not significantly influence the performance of the task when the grasping torque was just fed back to the operators. This might be attributed to the construction of a relationship such as a leader and follower, despite the independent relationship. The robot adjusted its grasping forces based on the actions of the human operator. Therefore, the participants were not required to pay attention to the robot. Consequently, the participants may not have altered their rotation action on the cap.

In a tele-operative robot, the robot is just an agent for humans, and the motion of the human is reflected directly on the robot. Therefore, sensory feedback reflecting the movement of the robot according to the operator's movement is inherently available to establish the original sensory-motor control of the human operator. With respect to the cooperative task in this study, the human operator and robot can move independently based on their decisions. They have independent bodies with a sensory-motor control system for each. Basically, both hands are independently controlled with sensory-motor control for each. Therefore, explicit coordination between the human and the robot might improve the performance of the task. In other words, human operators must have a strategy to utilize the robot operation for their own actions. A few previous studies on HRC with tactile feedback have demonstrated the effectiveness of tactile feedback [13, 14]. In these studies, the robot decides the next action according to the action of the human operator, and the operator then continues to decide the next action according to the robot's action. Therefore, to determine the next action for each, the human and robot inevitably need to engage in a two-way exchange of information between themselves. Human operators clearly had the motivation to change their behavior according to tactile feedback.

The psychological evaluation in Experiment 2.1, which was obtained from the questionnaire, indicated that tactile feedback is effective in recognizing the robot's action. However, as the tactile feedback was just fed back to the participants and the HRC control was not designed under an explicit strategy, operators could not utilize the feedback for the operation. Q2 indicates that participants made a prediction, which supports the idea that an explicit rule can be used to improve the performance of the task.

Experiment 3 with the explicit strategy demonstrated that the CV in the torque was smaller with the tactile feedback than without feedback, indicating that the explicit strategy improved the stability of the task in HRC. Against different bottles and various increments of grasping torque of the robot arm, the continuous information based on the tactile feedback induced participants to open the cap using adequate timing and provided stable operation. The explicit strategy required the human operator to learn the adequate grasping force of the robot via training; however, the coordination provided stable operation, reducing the rotation operation by operators. Thus, the experimental results demonstrated the effectiveness of the continuous tactile feedback and the requirement for an explicit strategy to evoke the effect of feedback in bilaterally shared haptic perception in HRC.

6. Conclusion

This study investigated bilaterally shared haptic perception to promote HRC. The bottle-cap opening task was adopted because continuous information is required for the adjustment of the grasping force, not alert information. The system was composed of a robot arm, a wearable acceleration sensor, and a wearable squeezing display. A human operator wearing the acceleration sensor opens a bottle cap, and the robot recognizes three states: slipping, opening, and no contact. Then, the robot arm controls the grasping force according to the tactile information from the human, and the grasping force is fed back to the human with a wearable squeezing device. The results showed that the assembled system worked well with significantly different grasping forces for different bottles. However, the tactile feedback that was just fed back did not improve the performance of the task, whereas it provided confidence that the cooperative robot adjusted the grasping force. The results indicated the requirement for the explicit strategy of humans for the feedback as the coordination between the human and the robot is not within the original sensory-motor control of the human. The experiment with the explicit strategy demonstrated that the grasping force was stable as participants could start to rotate the bottle by recognizing that the robot arm provided adequate grasping forces for each bottle. Thus, the results indicated the effectiveness of the tactile feedback in the stability of the task and the requirement of explicit coordination for an HRC with bilaterally shared haptic perception on the continuous information. In future work, we will improve the proposed HRC system for applications in various other operations in daily life.

Acknowledgements

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