Effect of Presenting Stiffness of Robot Hand to Human on Human-Robot Handovers

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Abstract

In the present study, we focus on the object handover task as a major example of collaborative work between a human and a robot. To achieve a smooth handover between two different agents, their mutual communication is indispensable for understanding the other's intentions. However, previous research has not dealt with a moment during handover in which a robot takes the object from a human grasp or in which a robot hands the object to the human. It should be noted that the performance during those phases is crucial to the success or failure of the tasks because slight changes in the kinematics of the relationship between hands or fingers and object result in significant changes in grasping status: the human may forcibly pull out the object while the robot is grasping it or drop the object. Therefore, this study aims to realize a smooth handover between a human and a robot, focusing on the moment of object handover. To this end, this paper proposes to present the stiffness of the robot hand to the human. We conducted the subject experiments to investigate the effect of this method on humans in the human-robot interaction. Experimental results show that this presentation method enables the worker to recognize the stiffness of the robot, which is difficult to recognize visually, thereby reducing the workload and allowing the worker to respond seamlessly to changes in the robot's stiffness.

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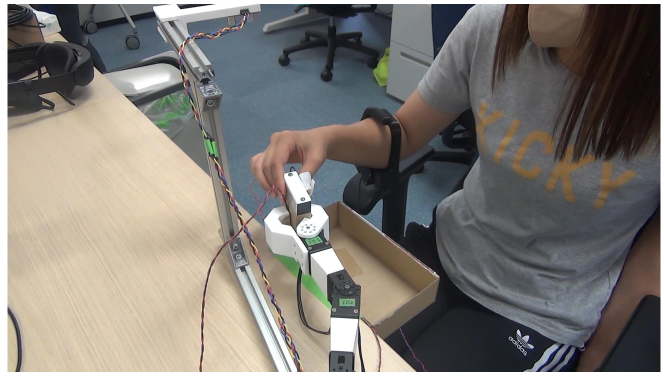

Fig. 1. Experimental setup for human-robot handover. A planar 3-degree-of-freedom robot is a collaborative robot that performs handovers with the human. The tightening device presents the stiffness of this robot's hand as a tightening force on the human forearm.

I. INTRODUCTION

Physical Human-Robot Collaborations have attracted attention, such as collaborative robots [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], rehabilitation robots [12], teleoperated robots [13], supernumerary robotic limbs [14], [15].

Among them, the present study focuses on the object handover task shown in Fig. 1 as a major example of collaborative work between humans and robots. Mutual communication is indispensable for understanding the other's intentions to achieve a smooth handover between two agents. Thus, research studies have been conducted regarding the handover task between a human and a robot considering communication.

For example, research has been conducted on presenting the human state to robots. Choi et al. [1] proposed a method for predicting future handover positions based on the human gaze for indirect handovers in which an object is placed on a desk once. This method minimizes human-robot collisions and shortens the time from when the human places the object to when the robot receives it. Pan et al. [2] propose a method for predicting the future hand-off position based on the trajectory of the object held by the human. This method allows the robot to move to the predicted handover position as soon as the human begins to pass the object. These two research studies focusing on obtaining the goal position of the human hand for generating smooth robot hand trajectory do not deal with a moment during handover in which the robot takes the object from the human grasp or in which the robot hands the object to the human. It should be noted that the performance during these phases is crucial to the success or failure of the tasks because slight changes in the kinematics of the relationship between hands or fingers and object result in significant changes in grasping status: the human may forcibly pull out the object while the robot is grasping it, or drop the object. Costanzo et al. [3] proposed a method in which the robot acquires information about the receiver's grasp of an object using a force sensor when the robot passes the object to the receiver. This method allows the robot to release the object at the moment the human grasps the object. However, it is not applicable when the human passes the object because no information is presented to the human.

Conversely, research is being conducted to present the robot's state to humans. Conventional presentation methods include screens installed in the workspace [4], light signals that indicate the robot's next move [5], and natural language interfaces [6]. Moon et al. [7] proposed a method of presenting the robot's line of sight to the human; this allows the human to reach out to the robot before it reaches the handover position. However, humans need to pay attention to the robot's head. Macciò et al. [8] proposed projecting

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the robot's future position on a head-mounted display in mixed reality. This method is intended for assembly tasks, including object handover position between a human and a robot, and allows the human to know the robot's current position and future position. However, since they all focus on phases related to motion planning and mainly on position control, none of them can display the mechanical state (e.g., grasping force) of grasping an object, even though this is important, as mentioned above.

As described above, many methods have been proposed for smooth handover between a human and a robot, but most focus on reaching the handover position. However, to realize a smooth handover between human and robot, it is important to consider the moment of object handover for information presentation from human to robot as in Costanzo et al. [3], but also from robot to human. In addition, as far as the authors know, studies have focused on only one of the two cases, either the human passing an object to the robot [1], [2] or the human receiving an object from the robot[3], [7], [8], thus no method that can deal with both of them has been investigated. Therefore, this study aims to realize a smooth handover between a human and a robot, focusing on the moment of object handover. It is considered effective to present the dynamical state as in Costanzo et al. [3] to achieve smoothness at the moment of handing over. However, the grasp force acquired by the force sensor provides only current information, and it is challenging to present future information as in Macciò et al. [8]. To this end, this paper proposes to present the stiffness of the robot hand to the human. We conducted the subject experiments to investigate the effect of this method on humans in the human-robot interaction. We hypothesize that our method will help reduce work time and improve the accuracy of object handover between a human and a robot.

In this paper, we first describe the device for presenting the stiffness of the robot hand to humans, the robot used in the experiment, and the experimental design for evaluating the effect of the presentation on the handover in Section 2. Next, we describe the results of the subject experiments in Section 3. Then, we discuss the results of the subject experiments in Section 4. Finally, we summarize this paper and discuss future prospects in Section 5.

II. Method

This section describes a method for presenting the stiffness of the robot hand to the human and evaluating the effect of this presentation on the handover. The stiffness is used to represent hard and soft grasping in object handover. In the following, we describe the presentation device, the robot used in the experiments, and the experimental design.

A. Proposed device

First, the presentation method using the tightening device is described. A schematic diagram of the presentation method is illustrated in Fig. 2. The assumed task is the object handover between a human and a robot, as shown in Fig. 2 (details are described in subsection B). The stiffness input

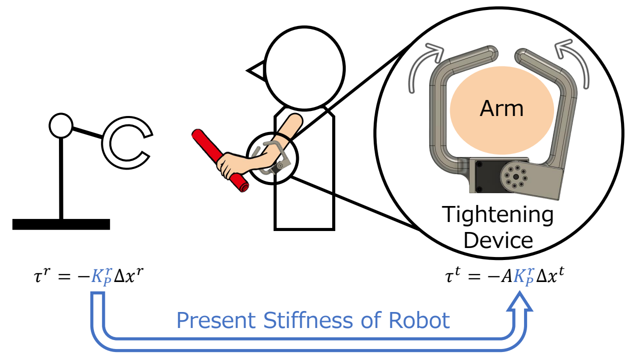

Fig. 2. Schematic diagram of how to present the stiffness of robot to human. K_P^r is the stiffness gain of the robot. Δx is the difference between the current and target angle. A is the variable that is applied to feel the force of the tightening device.

to the motors of the robot hand is also directly input to the motors of the tightening device so that the stiffness of the robot is presented as a tightening force to the human forearm. Reasons for presenting the stiffness in the way of tightening force are, first, that tactile sensation has the shortest response time among visual, auditory, and tactile sensations[16], and second, that it is easy to understand the stiffness of the robot hand intuitively.

Next, the design of the tightening device developed this time is shown on the right side of Fig. 2. It was made of a DC motor and 3D printed parts (material: ABS). The reason for using a 3D printer for the tightening device is that a rigid body is easier to design and control than an elastic body, and the stiffness of the motor can be directly transmitted to the human forearm. The presentation speed of the rubber band was significantly slower than that of the rigid ABS because of the elasticity of the rubber. In other words, a rigid body is thought to be able to present the robot's stiffness faster. The device weighs 160[g], about the same as a wristwatch with a metal band.

The tightening device uses proportional control, which is computationally inexpensive, to present the robot's stiffness with high efficiency. Additionally, a current-controllable motor (XM430-W210-T, Dynamixel) was employed to present the same stiffness as the robot. Assuming that time is t, stiffness gain is $K_P^r(t)$, the current angle of the motor of the tightening device is $\theta_p^t(t)$, and the goal angle of the motor of the tightening devices θ_d^t, the torque of tightening device $\tau^t(t)$ is expressed as in Eq. 1.

$$\tau^t(t) = -AK_P^r(t+\Delta t)(\theta_p^t(t) - \theta_d^t) \quad (1)$$

where the gain A is a constant and is applied so that the force of the tightening device is easily felt. In addition, Δt is added to adjust how many seconds later to present the robot's state. Humans have a phase of cognition between when they perceive external information and when they act on it. The more intuitive the information perceived, the shorter the recognition time, but it is never zero. If the timing of the presentation is inappropriate, the collaborator will be confused, reducing the smoothness of the human-robot collaboration. In addition, related research has shown that presenting cues before the robot moves reduces the mental burden on humans [17]. In addition, the control equation of the tightening device is shown as Eq. 1, but precisely by delaying the robot control by Δt[ms], the robot's Δt[ms] ahead state presentation is realized.

We expect that the presentation of the robot stiffness and the adjustment of the presentation timing will affect the collaborative task objectively and subjectively. Based on this expectation, the following hypotheses were formulated:

H1 : The presentation of robot stiffness by tightening the forearm will help workers recognize the mechanical state of the robot, which is difficult to recognize visually, thus reducing their workload and increasing their work efficiency.

H2 : Accelerating the presentation timing of the robot's stiffness by Δt[ms] reduces the delay in human response to changes in the robot's mechanical state, further improving work efficiency.

To test these hypotheses, we conducted a subject experiment in the handover task, in which changes in the robot's mechanical state are thought to impact performance significantly. Furthermore, we conducted objective evaluations, such as reaction time, and subjective evaluations, such as workload.

B. Experimental Scenario

The scenario of this experiment is a series of handover tasks in which the human passes an object to the robot (Human to Robot, H2R) and receives an object from the robot (Robot to Human, R2H), as shown in Fig. 1. Human-Robot handover is said to consist of three conceptual phases[18]: "Approach," in which one or both parties move to the handover position; "Passing," in which the object is physically transferred from the giver to the receiver; and "Retraction," in which the giver and receiver leave each other. In addition, to focus on the moment of object handover when the robot's dynamical state changes, this paper adds the "Grasp(K^h)" phase, in which the stiffness of the robot hand changes during object grasping. The specific H2R handover and R2H handover scenarios are shown in Fig. 3 and Fig. 4. The stiffness gain K^h of the robot hand is defined in the order of decreasing stiffness from the top as follows:

K^h_{Rel} : Stiffness when the robot is releasing the object

K^h_{Low1} : Stiffness to the extent that the object slips down when the human releases it

K^h_{Low2} : Stiffness to the extent that the object does not drop when the human releases the object and the human can easily pull out the object

K^h_{High} : Stiffness to the extent that the object does not drop when the human releases the object, but the object cannot be easily pulled out by human

The object used in this experiment is rectangular, 90.1[mm] in height, 20.3[mm] in width, 60.0[mm] in length, and weighing 125[g]. In this scenario, the stiffness of this robot hand is indicated by the tightening device ($K^r_P = K^h$). In this scenario, this stiffness K^h is switched as follows:

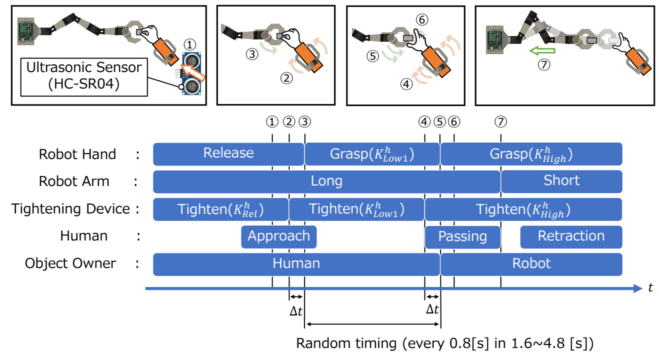

Fig. 3. Experimental scenario for H2R handover. Each scene of H2R handover (top) and state transition diagram (bottom). Random time assumes the robot is not guaranteed to move simultaneously every time.

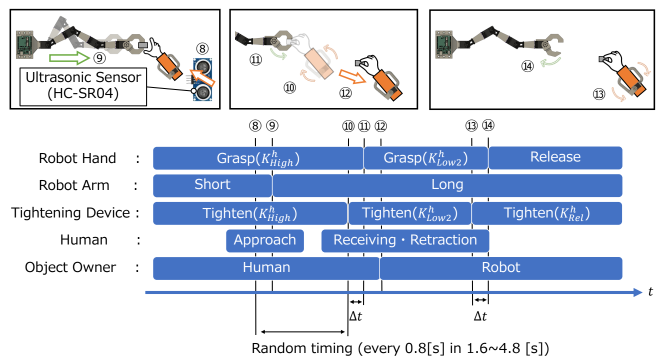

Fig. 4. Experimental scenarios for R2H handover. Each scene of the R2H handover (top) and state transition diagram (bottom). Random time assumes the robot is not guaranteed to move simultaneously every time.

K^h_{Rel} to K^h_{Low1} : About 0.8[s] after the ultrasonic sensor recognizes the human hand

K^h_{Low1} to K^h_{High} : After a random time of about every 0.8[s] in the range of about 1.6 to 4.8[s] after the switch to K^h_{Low1}

K^h_{High} to K^h_{Low2} : After a random time about every 0.8[s] in the range of about 1.6 to 4.8[s] after the ultrasonic sensor recognizes the human hand.

K^h_{Low2} to K^h_{Rel} : After about 4.0[s] after the switch to K^h_{Rel}

Here, the ultrasonic sensor is placed at about the human shoulder as illustrated in Fig. 1, and the hand is recognized when the human hand passes a height within 15[cm] of the ultrasonic sensor. All times are marked with "about" because each time is determined by the number of loops in the program, and the average sampling time of this system is not constant at 38 ± 2[ms]. The random time also simulates that the robot is not guaranteed to move simultaneously every time.

First, H2R handover begins in the "*Approach*" phase; the robot recognizes the hand using the ultrasonic sensor when the human approaches the robot with his/her hand (Fig. 3, 1). Next, in the "Grasp(K^h_{Low1})" phase, the tightening device presents the stiffness K_{Low1} (Fig. 3, 2), and after Δt[ms], the robot grasps the object with K^h_{Low1} (Fig. 3, 3). After a while, moving to the "Grasp(K^h_{High})" phase, the tightening device presents K^h_{High} (Fig. 3, 4), and after Δt[ms], the robot hand changes to K^h_{High} (Fig. 3, 5). Then, when the human recognizes the presentation of K^h_{High} by the tightening device, moving to the "*Passing*" phase, the human releases the object and passes it to the robot (Fig. 3, 6). Finally, 1.28[s] after the robot hand changes to K^h_{High}, moving to the "*Retraction*" phase, and the robot retracts its arm to take the object (Fig. 3, 7), completing the H2R handover.

R2H handover, similarly to H2R handover, begins in the "*Approach*" phase; the robot recognizes the hand using the ultrasonic sensor when the human approaches the robot with his/her hand (Fig. 4, 8), and extends its arm as if to pass the object to the human (Fig. 4, 9). After a while, moving to the "Grasp(K^h_{Low2})" phase, the tightening device presents K_{Low2} (Fig. 4, 10), and after Δt[ms], the robot hand changes to K^h_{Low2} (Fig. 4, 11). Subsequently, when the human recognizes the presentation of K^h_{Low2} by the tightening device, moving to the "*Passing*" and "*Retraction*" phases, the human pulls the object from the robot (Fig. 4, 12). Finally, the tightening device presents K^h_{Rel} (Fig. 4, 13), and Δt[ms] later, the robot hand changes to K^h_{Rel} (Fig. 4, 14), and returns to the initial state, R2H passing is complete.

C. Robot

In this subsection, we briefly describe the robot used in the experiments. For simplicity, we used a 3-DOF planar robot of the shape shown in Fig. 1, which we made ourselves.

The control of the robot is divided into the arm and the hand. Fig. 5 shows the stiffness and arm position of the robot during a series of handovers. x_{Long} is the state in which the arm is extended, as shown in Fig. 4, 9, and x_{Short} is the state in which the arm is retracted, as shown in Fig. 3, 7. Since the arm is controlled by position control of three motors, a motor capable of position control (XL430-W250-T, Dynamixel) was used.

The hand is controlled by proportional control, as in the tightening device. A current controllable motor (XM430-W350-T, Dynamixel) was used to achieve stiffness close to that of a real robot. Assuming time is t, stiffness gain is $K^h(t)$, the current angle of the robot hand motor is $\theta^h_p(t)$, and target angle is θ^h_d, the torque of the robot hand $\tau^h(t)$ is expressed as Eq. 2.

$$\tau^h(t) = -K^h(t)(\theta^h_p(t) - \theta^h_d(K^h)) \tag{2}$$

The variation of the stiffness gain K^h of the robot hand and the tightening device with time t in the series of handover described in subsection A is shown in Fig. 6. The stiffness of the robot hand is gradually changed so that it can grasp the object according to its shape. The stiffness of the tightening device is switched instantaneously because it needs to be presented in a way that is easy for humans to understand.

D. Experimental Design

This study conducted a subject experiment to evaluate the effect of robot hand stiffness presentation on human-robot object handover.

The presentation method of the robot state to participants is the only experimental factor in the present study (method factor, in short), which is composed of the following three levels:

- No : Participants do not wear a tightening device and are not presented with the stiffness of the robot hand
- Current : Participants wear the tightening device and are presented with the current ($\Delta t = 0$[ms]) stiffness of the robot hand
- Future : Participants wear the tightening device and are presented with the future ($\Delta t = 200$[ms]) stiffness of the robot hand

In the No condition, the participant performs the handover with the robot without the tightening device. In the Current and Future conditions , the participant wears the tightening device on his/her forearm to pass and receive the object with the robot. Here, Tanaka et al. [19] pointed out that the reaction time to tactile presentation by humans is 200 $\sim$ 250[ms]. Considering this and the sampling time of this

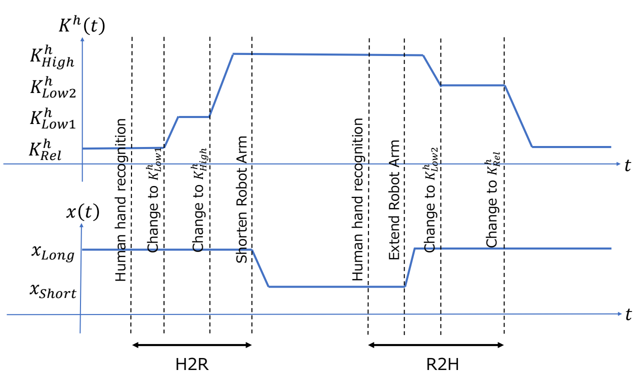

Fig. 5. The variation of the robot handover stiffness gain $K^h(t)$ (top) and the robot arm position $x(t)$ (bottom) against time in a series of human-robot handovers.

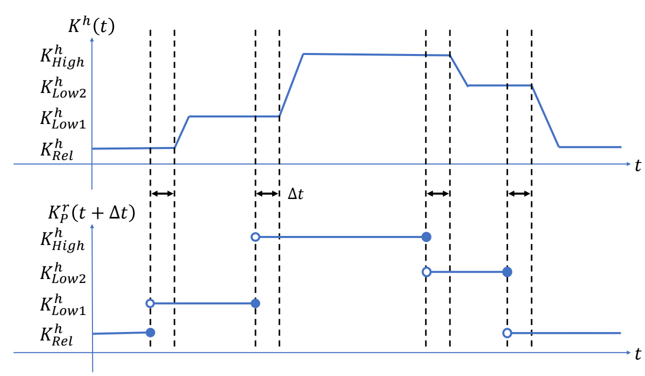

Fig. 6. The variation of the stiffness gains of robot hand (top) and tightening device (bottom) against time in a series of human-robot handovers.

system (38 ± 2[ms]), the Δt of the condition Future was set to 200[ms]. However, when wearing the tightening device, the participant is told whether to do Current or Future and the meaning of the four stiffnesses described in subsection B, but not the specific value of Δt. This experiment was conducted in a within-subjects design, with each participant performing all three experimental conditions. A total of six experiments of the combinations of the order of each experimental condition were conducted, one for each participant, to eliminate the influence of the order of each experimental condition.

To test the hypotheses in subsection A, we evaluated reaction time and success rate, the ease of understanding the timing of handover, subjective smoothness, anxiety about dropping objects, and workload.

E. Evaluation

The evaluation method of reaction time is illustrated in Fig. 7. The $t_{H2Rstart}$ indicates the beginning of H2R reaction time, t_{H2Rend} indicates the end of H2R reaction time, $t_{R2Hstart}$ indicates the beginning of H2R reaction time, and t_{R2Hend} indicates the end of H2R reaction time. H2R and R2H reaction times are defined as follows.

H2R reaction time ($t_{H2Rstart}$ - t_{H2Rend}) :
: The time from when the robot can grasp an object without dropping it to when the human releases the object, i.e., from when the stiffness of the robot hand changes to K^h_{High} to when the pressure sensor value of the human becomes 0[V]

R2H reaction time ($t_{R2Hstart}$ - t_{R2Hend}) :
: The time from when the robot is ready to hand over the object until the object ownership is transferred to the human, i.e., the time from when the stiffness of the robot hand changes to K^h_{Low2} until the pressure sensor value of the robot becomes 0[V]

The evaluation method of success rate is illustrated in Fig. 8. The success and failure of H2R and R2H are defined as follows.

H2R success :
: The case that the human releases the object after the robot's hand stiffness starts to change to K^h_{High} and before the robot retracts its arm

H2R failure 1 (Object drop) :
: The case that the human releases the object when the stiffness of the robot hand is K^h_{Low1}

H2R failure 2 (Object pulling together) :
: The case that the human could not release the object before the robot retracts its arm

R2H success :
: The case that the human was able to pull out the object after the robot hand stiffness finishes changing to K^h_{Low2} and before it starts changing to K^h_{Rel}

R2H failure 1 (Object pulling together) :
: The case that the human forcibly pulls out an object with K^h_{High} before the stiffness of the robot hand changes to K^h_{Low2}

R2H failure 2 (Object drop) :
: The case that the human could not pull out the object before the stiffness of the robot hand changes to K^h_{Rel}

The following six questions regarding the ease of understanding the timing of handover, subjective smoothness, and anxiety about dropping an object were asked for each presentation method and evaluated using a Visual Analog Scale. Scores were defined as 100 for "highly disagree," and 0 for "highly agree" for Q3 and Q6; and 0 for "highly disagree," and 100 for "highly agree" for the others.

Q1. Was the timing of passing the object easy to understand?

Q2. Was it smooth to pass the object?

Q3. Were you worried about dropping the object when passing it?

Q4. Was the timing of receiving the object easy to understand?

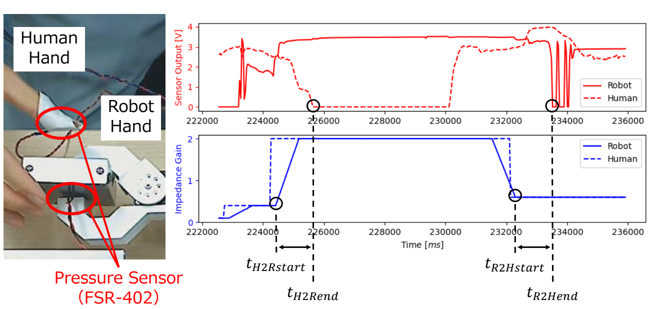

Fig. 7. Method for evaluating reaction time of H2R/R2H handover, where $t_{H2Rstart}$ is the start of H2R reaction time, t_{H2Rend} is the end of H2R reaction time, $t_{R2Hstart}$ is the start of H2R reaction time, and t_{R2Hend} is the end of H2R reaction time. Pressure sensors attached to human and robot fingertips (left) and the measurement data of a series of H2R/R2H handover (right). The red line shows the sensor values of the robot hand (solid line) and the human (dashed line) measured by pressure sensors. The blue lines are the stiffness gains of the robot hand (solid line) and the tightening device (dashed line).

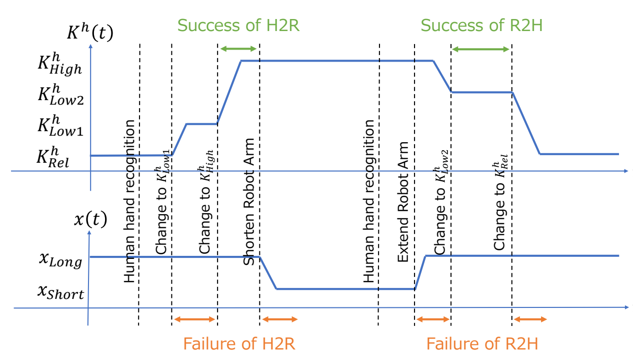

Fig. 8. Method for evaluating success and failure of H2R/R2H handover. H2R handover success if the human releases the object after robot can grasp the object without dropping it and before the robot pulls its arm. R2H handover success if the human pulls the object out after the object is ready to be pulled out of the robot and before the robot releases the object. Handover fails if the human releases or pulls the object out of the robot in any other state.

Q5. Was it smooth to receive the object?

Q6. Were you worried about dropping the object when you received it?

F. Procedure

First, the participants were briefed on the experimental procedure and the data to be collected, and their informed consent was obtained. Then, the four stiffness of the robot hand and the handover task scenario (Fig. 3, Fig. 4) were explained orally. After a 2-minute break, the participants practiced two exercises with pressure sensors attached to their fingertips and a tightening device on their forearms, experiencing the actual change in stiffness of the robot hand. Here, the experimenter changed the stiffness of the robot hand using the keyboard because it was necessary to proceed slowly while re-explaining each step of the scenario. Next, the experimenter demonstrated the handover to the robot using the ultrasonic sensor once, and then the participants practiced for five minutes. Participants wore a tightening device for both exercises and were in their current condition to facilitate familiarization. After a 2-minute break, participants practiced the handover task for 2 minutes. This practice session was conducted before each trial. After the practice, participants performed the handover task 10 times. Reaction times and success rates were recorded for these 10 trials. After the 10 handovers, the participants answered the questionnaire and the NASA-TLX. However, data from only 14 participants were recorded because the questionnaire and the NASA-TLX were conducted in the middle of this experiment. This process, from taking a break to answering the questionnaire, was repeated in all three sessions, using different presentation methods. The total duration of this experiment was one hour.

G. Participants

Eighteen healthy participants (13 males and 5 females) aged 22 - 30 ($Avg = 23.9$, $SD = 3.52$) participated in this experiment after obtaining informed consent. The participants' instructions included a statement that they could stop the experiment anytime and for any reason.

Note that this subject experiment received approval from our university's research ethics board.

III. Results and Discussion

A. Results

The Friedman test was first performed for each of the statistical tests on the result data. If there was a significant difference, a signed Wilcoxon rank test with Bonferroni correction was performed. The significance level for each test was 5%.

The reaction times of H2R and R2H handover for each presentation method are shown in Fig. 9. The average value was used as the representative value for the 10 trials. First, a Friedman test revealed a significant difference in H2R reaction time by a presentation method factor ($p < .001$); however, no significant difference in R2H reaction time by a presentation method factor ($p = .179$). Next, a Wilcoxon signed-rank test revealed that H2R reaction times were significantly faster for Current than No ($p < .001$) and significantly faster for Future than Current ($p = .001$).

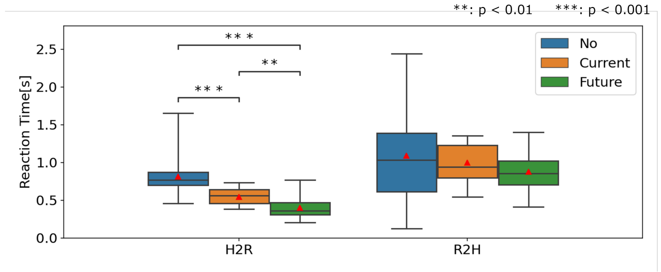

Fig. 9. The results of H2R (left) and R2H (right) handover reaction time.

The success rates of H2R and R2H handover for each presentation method are illustrated in Fig. 10. First, the Friedman test revealed significant differences in success rates for H2R and R2H handover by a presentation method factor (H2R: $p < .001$, R2H: $p < .001$). Next, Wilcoxon's signed rank test showed that the H2R success rate was significantly higher with presentation than without presentation (Future-No: $p = .006$, Current-No: $p = .006$), but there was no significant difference in the H2R success rate between Future and Current ($p = 1.0$). The R2H success rate was significantly higher with presentation than without presentation (Future-No: $p = .008$, Current-No: $p = .008$), but there was no significant difference in R2H success rate between Future and Current ($p = 1.0$).

The results of the questionnaire regarding the ease of understanding the timing of the handover, subjective smoothness, and anxiety about dropping the object for each presentation method are shown in Fig. 11 and Fig. 12. First, the Friedman test revealed significant differences in ease of understanding timing, subjective smoothness, and anxiety about dropping objects for both H2R and R2H handover by a presentation method factor (Q1: $p < .001$, Q2: $p < .001$, Q3: $p < .001$, Q4: $p < .001$, Q 5: $p < .001$, Q6: $p = .011$). Next, the Wilcoxon signed-rank test shows that for Q1, the timing of passing an object with presentation is perceived to be significantly easier to understand than without presentation (Future-No: $p = .004$, Current-No: $p = .004$); however, there is no significant difference in the understandability of the timing of passing an object between Current and Future ($p = .354$). For Q2, the participants with presentation felt

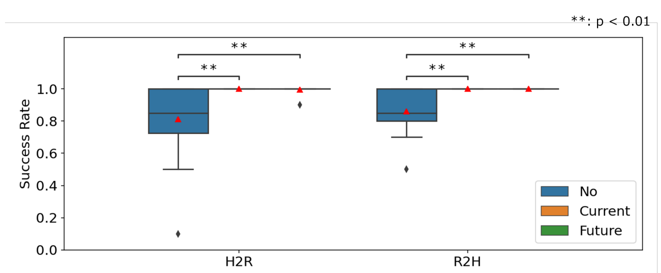

Fig. 10. The results of H2R (left) and R2H (right) handover success rate.

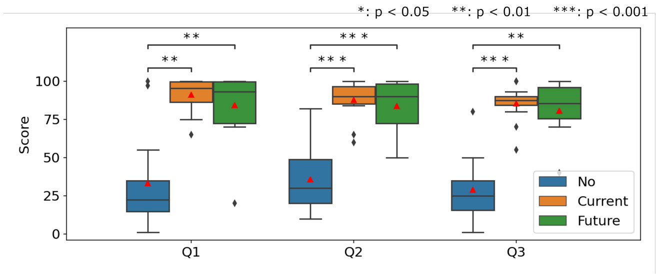

Fig. 11. The questionnaire results on H2R handover: Q1 on ease of understanding when to pass the object to the robot; Q2 on the smoothness of handover; Q3 on anxiety about dropping the object.

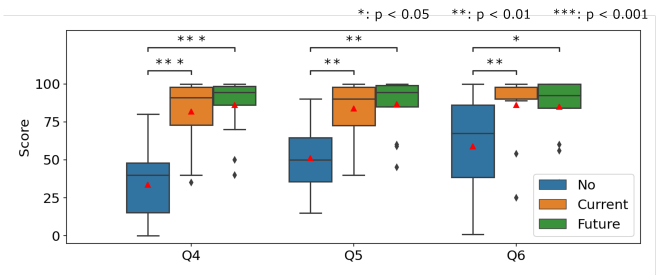

Fig. 12. The results of a questionnaire on R2H handover: Q4 on ease of understanding when to receive the object from the robot; Q5 on the smoothness of handover; Q6 on anxiety about dropping the object.

that they could pass objects significantly more smoothly than those without presentation (Future-No: $p < .001$, Current-No: $p < .001$), but there was no significant difference in the smoothness of passing objects between Current and Future ($p = .761$). For Q3, although participants with presentation felt significantly less anxious about dropping objects in H2R handover than those without presentation (Future-No: $p = .004$, Current-No: $p < .001$), there was no significant difference between Current and Future's anxiety about dropping objects in H2R handover ($p = .464$). For Q4, although participants felt that the timing of receiving an object with presentation was significantly easier to understand than without presentation (Future-No: $p < .001$, Current-No: $p < .001$), there was no significant difference in the ease of understanding the timing of receiving an object between Current and Future ($p = .864$). For Q5, although participants felt that they could receive objects significantly more smoothly with presentation than without presentation (Future-No: $p = .002$, Current-No: $p = .003$), there was no significant difference in the smoothness of receiving objects between Current and Future ($p = .634$). Finally, for Q6, although the participants with presentation felt significantly less anxious about dropping an object in R2H handover than those without presentation (Future-No: $p = .037$, Current-No: $p = .008$), there was no significant difference between Current and Future's anxiety about dropping an object in R2H handover ($p = .810$).

Fig. 13 shows the results of the NASA-TLX WWL scores. First, the Friedman test showed that a significant difference in a presentation method factor existed ($p < .001$). Second,

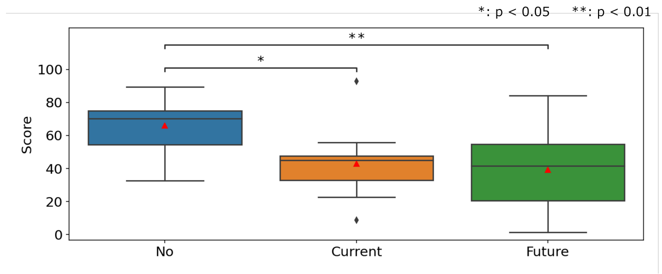

Fig. 13. The results of WWL score on NASA-TLX for human-robot handover.

the Wilcoxon signed rank test showed that the workload was significantly lower with presentation than without (Future-No: $p = .003$, Current-No: $p = .018$), but there was no significant difference in the workload between Current and Future ($p = 1.0$).

B. Discussion

First, the effect of presenting the robot hand stiffness by tightening the forearm is discussed.

The reaction time of H2R handover with presentation was significantly shorter than without presentation, but the R2H reaction time was not significantly different. The fact that the timing of object handover with the presentation was significantly easier to understand than without presentation indicates that the operator was better able to recognize changes in the dynamical state of the robot hand, which is difficult to recognize visually. Therefore, from the overall perspective of the combined H2R and R2H handover, the presentation of the stiffness of the robot hand by tightening the forearm has improved the work efficiency of the human-robot handover.

The results of the WWL of the NASA-TLX showed that workload was significantly reduced with presentation than without presentation; this is thought to be because the handover timing became significantly easier to understand, as well as the reason for the improved work efficiency, as described in the previous paragraph. Therefore, the presentation of the stiffness of the robot hand by tightening the forearm made it significantly easier to understand the timing of object handover, i.e., it was easier to recognize changes in the dynamical state of the robot hand, which is difficult to recognize visually, and thus improved work efficiency and reduced workload. Therefore, hypothesis H1 was proven.

Next, we discuss the effect of the presentation timing on the robot's hand stiffness. The reaction time for H2R handover was significantly shorter for Future than Current. Although there was no significant difference in the reaction time for R2H handover, it can be said that the overall handover efficiency of both H2R and R2H was improved; furthermore, the comparison between with presentation and without presentation. Thus, hypothesis H2 was proven.

In HRC, previous studies [7][9] have shown that presenting the robot's state improves work efficiency and reduces the mental load and that presenting the robot's future state enables it to start moving faster than the robot. However, this study focuses on the motion planning phase up to physical contact with the robot. It does not deal with the phase of physical contact with the robot because the information presented is the future handover position of the robot, and the evaluated time is the time until the robot reaches the handover position. Therefore, the contribution of this study is to show that the presentation of the stiffness of the robot tightened to the forearm "in the phase of physical contact with the robot" improves the work efficiency and reduces the workload of the HRC and that the presentation of the future stiffness of the robot decreases the delay to the change of the robot's dynamical state.

IV. Conclusion

In this study, we proposed a method of presenting the stiffness of a robot as a tightening force on a human forearm so that humans could recognize the robot's stiffness intuitively. To verify the effectiveness of this presentation method, we conducted a subject experiment in the handover task, in which changes in the dynamic state of the robot are considered to have a significant impact on performance. The experimental results showed that, during the phase of physical contact with the robot, presenting the stiffness of the robot by tightening the robot's forearms facilitates the recognition of the robot's stiffness, which is visually challenging for the operator, and reduces the workload and improves work efficiency, and accelerating the timing of the presentation by several hundred milliseconds makes it possible for the human to start moving earlier than the robot. Although this paper deals only with the limited scenario of the moment of handover in the handover task, it is applicable if the control of the collaborative robot has a one-degree-of-freedom term related to the force and the dynamical state to be presented is up to four steps, as in the handover task in this paper. Furthermore, it may be particularly useful in scenarios where the robot's dynamical state changes rapidly or in industrial scenarios where visual or auditory feedback is limited.

Next, we discuss future prospects. In addition, since the present system only presents the robot's state to humans, its feasibility is limited to the above-mentioned tasks. Therefore, it is expected that the robot will be able to estimate the human state and move in accordance with the human, as Costanzo et al. [3] do, which will enable verification in more complex tasks.

References

[1] A. Choi, M. K. Jawed, and J. Joo, "Preemptive motion planning for human-to-robot indirect placement handovers," in *2022 International Conference on Robotics and Automation (ICRA)*, 2022, pp. 4743–4749.

[2] M. K. Pan, E. Knoop, M. Bächer, and G. Niemeyer, "Fast handovers with a robot character: Small sensorimotor delays improve perceived qualities," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2019, pp. 6735–6741.

[3] M. Costanzo, G. De Maria, and C. Natale, "Handover control for human-robot and robot-robot collaboration," *Frontiers in Robotics and AI*, vol. 8, pp. 2296–9144, 2021.

[4] M. C. Shrestha, A. Kobayashi, T. Onishi, E. Uno, H. Yanagawa, Y. Yokoyama, M. Kamezaki, A. Schmitz, and S. Sugano, "Intent communication in navigation through the use of light and screen indicators," in *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, 2016, pp. 523–524.

[5] E. Cha, M. Matarić, and T. Fong, "Nonverbal signaling for non-humanoid robots during human-robot collaboration," in *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, 2016, pp. 601–602.

[6] Z. Gong and Y. Zhang, "Behavior explanation as intention signaling in human-robot teaming," in *2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 2018, pp. 1005–1011.

[7] A. Moon, D. M. Troniak, B. Gleeson, M. K. Pan, M. Zheng, B. A. Blumer, K. MacLean, and E. A. Croft, "Meet me where i'm gazing: How shared attention gaze affects human-robot handover timing," in *Proceedings of the 2014 ACM/IEEE International Conference on Human-Robot Interaction*, ser. HRI '14. New York, NY, USA: Association for Computing Machinery, 2014, p. 334–341.

[8] S. Macciò, A. Carfì, and F. Mastrogiovanni, "Mixed reality as communication medium for human-robot collaboration," in *2022 International Conference on Robotics and Automation (ICRA)*, 2022, pp. 2796–2802.

[9] J. Okimoto and M. Niitsuma, "Effects of auditory cues on human-robot collaboration," in *2020 IEEE 29th International Symposium on Industrial Electronics (ISIE)*, 2020, pp. 1572–1577.

[10] A. D. Dragan, S. Bauman, J. Forlizzi, and S. S. Srinivasa, "Effects of robot motion on human-robot collaboration," in *2015 10th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, 2015, pp. 51–58.

[11] M. Lee Chang, R. A. Gutierrez, P. Khante, E. Schaertl Short, and A. Lockerd Thomaz, "Effects of integrated intent recognition and communication on human-robot collaboration," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2018, pp. 3381–3386.

[12] V. Chambers and P. Artemiadis, "Repeated robot-assisted unilateral stiffness perturbations result in significant aftereffects relevant to post-stroke gait rehabilitation," in *2022 International Conference on Robotics and Automation (ICRA)*, 2022, pp. 5426–5433.

[13] Y. Tanaka, T. Katagiri, H. Yukawa, T. Nishimura, R. Tanada, I. Ogura, T. Hagiwara, and K. Minamizawa, "Sensorimotor control sharing with vibrotactile feedback for body integration through avatar robot," *IEEE Robotics and Automation Letters*, vol. 7, no. 4, pp. 9509–9516, 2022.

[14] B. L. Bonilla and H. H. Asada, "A robot on the shoulder: Coordinated human-wearable robot control using coloured petri nets and partial least squares predictions," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, 2014, pp. 119–125.

[15] F. Y. Wu and H. H. Asada, ""hold-and-manipulate" with a single hand being assisted by wearable extra fingers," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, 2015, pp. 6205–6212.

[16] A. Chan and A. Ng, "Finger response times to visual, auditory and tactile modality stimuli," *Lecture Notes in Engineering and Computer Science*, vol. 2196, pp. 1449–1454, 03 2012.

[17] M. Fujita, R. Kato, and A. Tamio, "Assessment of operators' mental strain induced by hand-over motion of industrial robot manipulator," in *19th International Symposium in Robot and Human Interactive Communication*, 2010, pp. 361–366.

[18] J. R. Medina, F. Duvallet, M. Karnam, and A. Billard, "A human-inspired controller for fluid human-robot handovers," in *2016 IEEE-RAS 16th International Conference on Humanoid Robots (Humanoids)*, 2016, pp. 324–331.

[19] M. Tanaka, K. Ishibashi, and K. Iwanaga, "Reaction time to tactile stimulation by solenoid," *Proceedings of the Annual Conference of the Japan Ergonomics Society*, vol. 48spl, pp. 274–275, 2012.