Enhanced Transparency for Physical Human-Robot Interaction Using Human Hand Impedance Compensation

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***Abstract*—In a physical human-robot interaction (pHRi) system, improving transparency that allows humans to move as if there is no robot is a challenging topic. In general pHRi, usage of the multiaxial force sensor for robot control is the norm. However, the signal measured from the force sensor contains not only the force applied to the robot by the human motion intention but also the influence of the natural force feedback between the robot and the human hand produced by the robot motion. Therefore, in order to improve the transparency, it is necessary to characterize the dynamics of the human hand as well as the dynamics of the robot. In this paper, an algorithm to improve the transparency is proposed. The proposed algorithm uses only a multiaxial force sensor and compensates the natural force feedback by using the human hand impedance. And it further improves the transparency of the pHRi system, which has a limitation adjusting admittance parameters. In order to verify the algorithm, a device that can measure the impedance of the human hand is introduced, and a system model analysis and experiments using the hydraulic upper limb exoskeleton are carried out.**

***Index Terms*—Hydraulic upper-limb exoskeleton, impedance compensator (IC), physical human-robot interaction (pHRi).**

I. Introduction

PHYSICAL human-robot interaction (pHRi) is an important issue especially in collaborative work between human and robot, learning from demonstration or direct teaching, power amplification, and rehabilitation using robotic exoskeletons [2]–[7]. When compared with robot control using cognitive human-robot interaction (cHRi), such as electroencephalogram or electromyogram, the pHRi has a delay in predicting the human motion intention [8]–[10]. Because, in the most of the pHRi situations, robots are controlled using interaction forces generated between a human and a robot. However, due to the user dependence and the complex interface of cHRi, the practicality of pHRi is much better than cHRi in various applications. Therefore, the research on the improvement of the transparency that makes it possible to move as if there is no robot by minimizing the influence of the robot on the human being in the pHRi condition is challenging.

The most striking difference between pHRi and other methods of robot control, such as haptic, is that the robot and the human are physically connected [11]–[13]. In such a system, humans and robots constantly influence each other. Therefore, in the pHRi system, it is important to improve the transparency so that humans can move naturally with a physically connected robot by accurately predicting the intention of human motion and minimizing the disturbed effect of human operator by the robot. There are several studies on control and dynamic analysis of coupled dynamic systems using hydraulic actuators in high-speed pantographs and pulley/cable actuator for large-scale ball valves [14], [15]. However, dynamic analysis when human and robot are dynamically coupled in pHRi is different. It is because the dynamic characteristics that each person has are different and it is hard to know exactly the motion intention of the person.

For the control of the robot through pHRi, one way is to use force feedback to control the interaction force between the human and the robot to be zero. In the rigid body robot model, however, the negative force feedback within the range of maintaining the stability of the system can reduce the passive physical equivalent mass acted on by the external force up to a half of the original mass [16]. Another widely used method of using a force sensor is to design an admittance to control the robot by translating the force applied by the human hand to the displacement or velocity of the robot end-effector [17]–[20].

However, as will be discussed in Section II, the admittance control has limitations in improving transparency because it cannot overcome distortion of force sensor signal due to natural force feedback caused by human hand impedance. When humans try to control a robot with a force sensor, the measured

Manuscript received October 15, 2017; revised February 16, 2018 and July 1, 2018; accepted September 10, 2018. Date of publication October 12, 2018; date of current version December 13, 2018. Recommended by Technical Editor H. A. Varol. This work was supported by the National Research Foundation of Korea funded by the Korea government under Grant 20162016R1A2B4009858. This paper was presented in part at the IEEE/RSJ International Conference on Intelligent Robots and Systems, Vancouver, BC, Canada, September 2017 [1]. *(Corresponding author: Ja Choon Koo.)*

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Digital Object Identifier 10.1109/TMECH.2018.2875690

force includes not the intended force of the human operator but the influence of the natural force feedback between the robot and the human hand. Even if a human holds a force sensor without any motion intention, when the robot operates, the force sensor measures distorted signal due to natural force feedback. The problem of improving the transparency is a challenging topic due to the difficulties that arise from the contact between the robot and the human in the pHRi situation. In order to overcome this problem, the impedance of human hand should be considered to reduce the influence of natural force feedback. However, most studies have focused on robots rather than humans in pHRi.

Regarding human hand dynamics in pHRi, an algorithm that enables a beginner to perform a smoother welding by compensating for impedance difference using an assistant robot has been studied [21]. The work successfully measures and compares the hand impedance of an expert and a novice during a welding operation. This method reduces hand tremors but needs more power to operate robots. In order to improve the transparency, a study proves benefits of adding inertial measurement unit (IMU) onto the feedback of the human hand's acceleration [22]. And it has shown improved following of the robot and better compensation of the residual error through a state estimator. However, for enhanced precision on the control, both the force sensor and the IMU must be used. In other words, additional sensor is required.

In this paper, a novel algorithm to improve the transparency is proposed. The proposed algorithm uses only a multiaxial force sensor without any other sensors. The contribution of this paper is to reduce the force distortion caused by the natural force feedback due to the contact between the robot and the human hand dynamics. The algorithm can improve the transparency of the pHRi system, which has a limit adjusting the admittance parameters. In order to develop the proposed algorithm, the human hand impedance is measured using a dropping mass device [23].

The estimated impedance of the human hand is used for system model analysis and experiments. And the response of the robot before and after applying the proposed impedance compensator (IC) is compared. The algorithm can improve the transparency by reducing phase lag and increasing magnitude by regulating positions of poles of the system. Finally, the proposed IC is verified with experiments using a three degrees of freedom (3-DOF) hydraulic upper-limb exoskeleton by decreasing the amount of energy required for controlling the exoskeleton.

II. Impedance Compensation Method

The robot control framework at pHRi is shown in Fig. 1. In general, the admittance control algorithm without IC operates a robot by converting the measured force (F_m) between human and robot to the desired velocity (V_d) of the robot. At this time, since the human operator is in contact with the robot, natural force feedback (F_i) due to a motion of the robot and the human hand impedance is generated. Therefore, the force sensor at the contact area between the human and the robot measures not only the motion intended force (F_h) of the human but also the natural force feedback. Then, the measured force ($F_m = F_h - F_i$) is distorted and it makes difficult to improve transparency. Therefore, in this paper, an algorithm is proposed to enhance the transparency by reducing the distorted force through the IC block in Fig. 1. F_c is compensation force. With the proposed IC, the effect of natural force feedback can be reduced and the input force ($F = F_h - F_i + F_c$) of admittance is more accurate human motion intended force. V and X are actual robot velocity and position. The human motion intention block generates motion-intended force (F_h) to operate the robot at the desired velocity (or position) by observing robot states (dashed arrow).

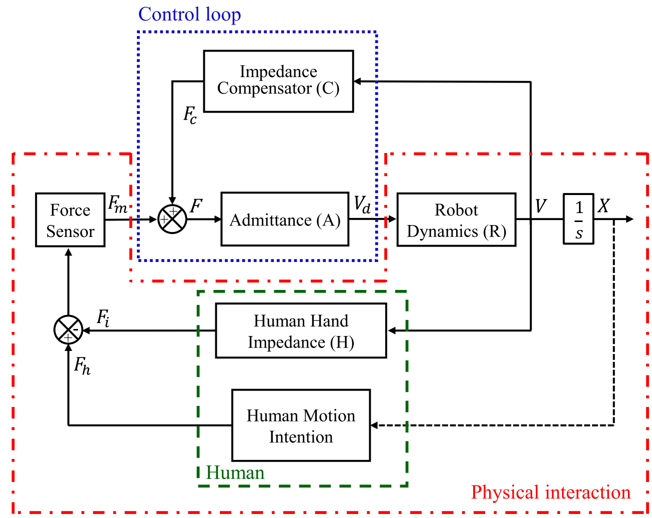

Fig. 1. Block diagram of a human hand impedance compensation control framework.

It is assumed that the admittance (*A*) is a linear mass-damper system that converts measured interaction force between human and robot to desired velocity of robot end-effector. The IC (*C*) and the human hand impedance (*H*) are also assumed as linear mass-spring-damper systems. They can be expressed as follows:

$$A = \frac{V_d(s)}{F(s)} = \frac{1}{m_a s + c_a} \tag{1}$$

$$C = \frac{F_c(s)}{V(s)} = \frac{m_c s^2 + c_c s + k_c}{s} \tag{2}$$

$$H = \frac{F_i(s)}{V(s)} = \frac{m_h s^2 + c_h s + k_h}{s}. \tag{3}$$

The mass and damping parameters of the admittance are represented by m_a and c_a. The mass, damping, and stiffness of the IC are represented by m_c, c_c, and k_c. Also, m_h, c_h, and k_h are mass, damping, and stiffness parameters of the human hand impedance.

Robot dynamics (*R*) is assumed to be 1, for the following two reasons. First, the tracking bandwidth of the human upper-limb is 2–4 Hz [24], [25]. Moreover, in areas such as direct teaching, rehabilitation, and heavy industry, where pHRi is mainly used, tasks are performed in the lower frequency range. Also, the hydraulic upper-limb exoskeleton robot used in this research has enough bandwidth to follow human motion (see Section IV). Therefore, the system performance degradation due to robot can be ignored. Second, the purpose of system modeling and analysis is to clearly show how the parameters of human hand impedance, IC, and admittance, which are outer loop of robot dynamics, affect pHRi. So the robot dynamics is simplified.

The transfer functions of closed loop system with and without IC are expressed as follows:

Without IC

$$G_a = \frac{X(s)}{F_h(s)} = \frac{AR}{1+ARH} = \frac{1}{(m_a+m_h)s^2+(c_a+c_h)s+k_h}. \tag{4}$$

With IC

$$G_{\text{ic}} = \frac{X(s)}{F_h(s)} = \frac{AR}{1+ARH-ARC} = \frac{1}{(m_a+m_h-m_c)s^2+(c_a+c_h-c_c)s+(k_h-k_c)}. \tag{5}$$

To improve the transparency, the parameters of admittance and IC in (1) and (2) should be adjusted so that the system has the desired response characteristics. As transparency is improved, the human operator can control the robot with less force. In other words, the displacement (or the velocity) response of the robot is large as the same force is applied to the robot by the human. As can be seen from the characteristic equation of the transfer function (4) of a system without impedance compensator, adjustment of the admittance parameters cannot reduce an influence of the human hand impedance. Therefore, admittance controller has a limit to achieve the desired response characteristic.

On the other hand, applying the proposed IC enhances the transparency, because the response characteristics of the transfer function (5) can be regulated as desired by adjusting the parameters of the IC. The system response analysis and the design of the IC are described in Section III.

III. IC Design and Analysis

In this section, the design of the IC and the variation of transparency before and after applying to admittance control are investigated. Descriptions of how to estimate the impedance of a human hand and how the proposed algorithm can change the response characteristics of the system using the estimated human hand impedance and the IC are presented.

A. Estimation of the Human Hand Impedance

To analyze the system response and design the proposed algorithm, it is necessary to estimate the impedance of the human hand in the arm movement. Previous studies have measured the dynamics of a human hand with external disturbance force and hand displacement using a robot arm or a dedicated equipment [26]–[29]. However, these devices are difficult to handle and very expensive. In this paper, a simple method with object dropping is used to measure the impedance of a human hand. The main principle of the method, exerting force to the hand and measuring the hand response, is the same as previous researches. But the method does not require actuators and estimates the impedance by measuring the force acting to the hand and the displacement of the hand due to the dropping object.

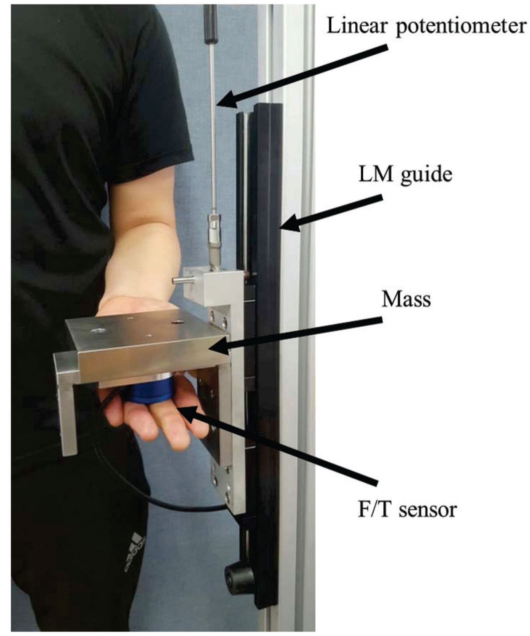

Fig. 2. Experimental setup for human hand impedance estimation.

It is very difficult to obtain an accurate model of the human hand dynamics because the dynamic characteristics of a human hand is different from person to person, and it depends on the posture of the arm, the tension of the muscles, and the state of movement [29], [30]. In this paper, the human hand impedance is estimated in one direction within specific posture because the purpose of this research is to verify the effect of the proposed IC that can enhance the transparency by reducing the influence of natural force feedback, rather than estimating the exact impedance of the hand.

The experimental setup for the hand impedance estimation in a specific state of arm is configured as shown in Fig. 2. The instrument consists of a linear guide, a linear potentiometer, a mass, and a six-axis F/T sensor. Only the data of falling direction measured from the six-axis F/T sensor were used. The linear guide allows the human hand and the mass to move in a perpendicular to the floor. When the assistant is holding the mass at a constant height, the subjects bring their hand to the six-axis F/T sensor, which is under the object and keep the posture naturally not having precaution. Then, without any preliminary signal, the assistant drops the mass. The impedance of the human hand can be estimated from the moving distance of the hand and measured force sensor signal between the hand and the dropped mass.

Eight male and two female participants from the age of 24–32 conduct the experiment three times each. The impedance of the human hand is estimated with signals during 0.2 s immediately after the mass is dropped because the signal shorter than 0.2 s is not enough to perform parameter estimation and the signal

TABLE I
AVERAGE ESTIMATED HAND IMPEDANCE (AVG. ± STD.DEV)

Mass (kg)	Damping (Ns/m)	Stiffness (N/m)
1.5 ± 0.34	7.3 ± 3.1	312 ± 100

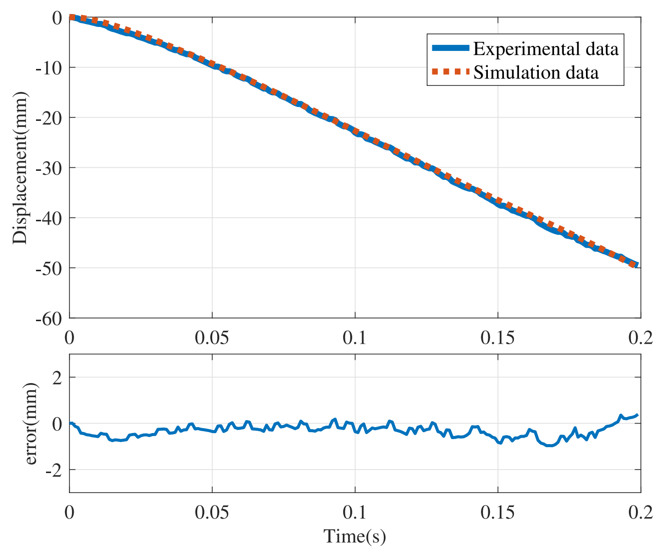

Fig. 3. Comparison of simulation and experimental results.

longer than 0.2 s, the impedance of the hand changes due to the human motion intention [31].

The impedance of the human hand is assumed to be a general mass-spring-damper system as shown in (3). The nonlinear least squares method is used to estimate impedance parameters. The results of the hand impedance estimation are shown in Table I. The mean values of mass, damping, and stiffness were, respectively, estimated to 1.5 kg, 7.3 Ns/m, and 312 N/m. Although the impedance of the human hand is measured by a simple method, similar results are obtained as in previous studies [27], [29]. Therefore, it can be said that the experiment is consistent.

Fig. 3 shows one of the comparison graphs of the experimental results and the simulation results with same external force during 0.2 s to the estimated impedance. The red dotted line represents the simulation result and the blue solid line shows the experimental result. For comparison, both of the starting points are set to zero. As shown in Fig. 3, the displacement obtained from the estimated impedance of the human hand is well matched with the experimental data.

B. Design and Analysis

In this section, the frequency response of the transfer function [(4), (5)], robot displacement (X) from the force exerted by the human on the robot, is analyzed using the impedance of the human hand estimated from Section III-A and the proper admittance parameters. And it is described that how to set IC parameters to improve transparency.

If the pHRi system has a good transparency, the magnitude of the Bode plot becomes large and the phase lag becomes small. For large magnitude, the equivalent stiffness of the system should be small. And to reduce the phase lag, the imaginary part of the pole must be large relative to the real part [32]. From (4), poles of the system without IC are as follow:

$$\sigma_a : -\frac{c_a + c_h}{2(m_a + m_h)}$$

$$jw_a : \pm\frac{\sqrt{4(m_a + m_h)k_h - (c_a + c_h)^2}}{2(m_a + m_h)}. \tag{6}$$

Also, from (5), poles of the system with IC are expressed as

$$\sigma_{\text{ic}} : -\frac{c_a + c_h - c_c}{2(m_a + m_h - m_c)}$$

$$jw_{\text{ic}} : \pm\frac{\sqrt{4(m_a + m_h - m_c)(k_h - k_c) - (c_a + c_h - c_c)^2}}{2(m_a + m_h - m_c)}. \tag{7}$$

As can be seen from (4), (6), and Table I, without IC, it has a limitation to obtain desired system response by adjusting the admittance parameters due to the presence of the human hand impedance. Fig. 4 shows the change of Bode plot according to the parameter values (m_a, c_a) of admittance. As the parameter value increases, the graph moves in the direction of the arrows. Adjusting the admittance cannot change the magnitude of the system. In other words, the admittance control has a limit in improvement of transparency.

By adding the proposed IC, the magnitude and phase can be regulated by adjusting the IC parameters (m_c, c_c, k_c) in (5) and (7).

Fig. 5 presents the frequency response of the transfer function before and after applying the IC. The human hand impedance parameters are set to the average values shown in Table I. The mass and damping of the admittance parameters are set to 2 kg and 15 Ns/m, respectively. These values are the admittance parameters that are applied to the hydraulic upper-limb exoskeleton control in Section IV. To reduce the effect of the human hand impedance and to replace locations of poles within the left half of s-plane, the parameters of the IC should be designed within $m_c < m_a + m_h$, $c_c < c_a + c_h$. Then, the IC decreases the influence of the natural force feedback caused by hand impedance and improve the magnitude and phase performance.

In Fig. 5, the blue solid line represents the response when the admittance control is used without the IC, and the green dotted line shows the response when the proposed IC is applied. The magnitude increases and the phase lag decreases when the IC is applied. As a result, transparency should be improved. Experimental verification of the proposed IC is described in Section IV.

IV. EXPERIMENTAL RESULTS

In this section, the proposed algorithm is verified using a hydraulic upper-limb exoskeleton. As shown in Fig. 6, the hydraulic upper-limb exoskeleton has 3-DOF and consists of two rotary actuators and one linear actuator. The hydraulic actuators (KNR, Inc.) are operated by controlling the flow rate of the hydraulic fluid with a servo valve, which has a bandwidth over 90 Hz (STAR, Inc.). At the end-effector of the exoskele-

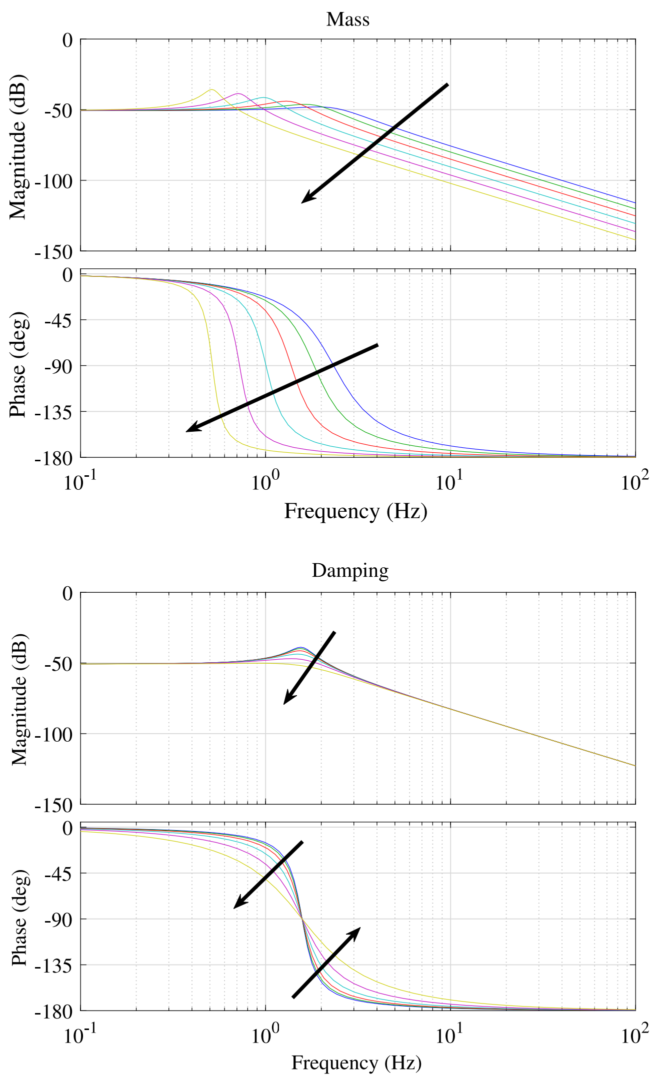

Fig. 4. Bode plot of the admittance control system (G_a) without IC for increasing (the direction of arrows) mass of admittance (upper) and damping of admittance (lower).

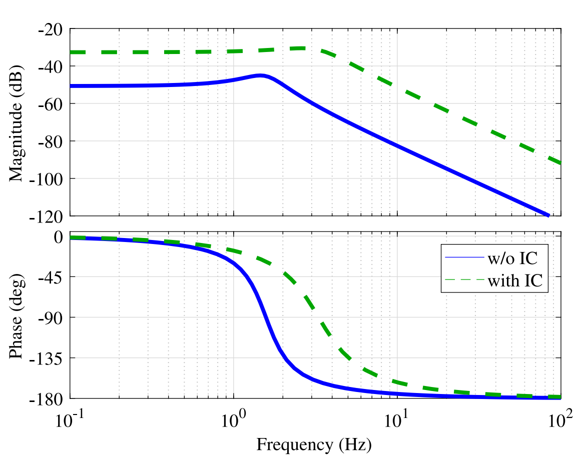

Fig. 5. Bode plots of the systems with and without IC.

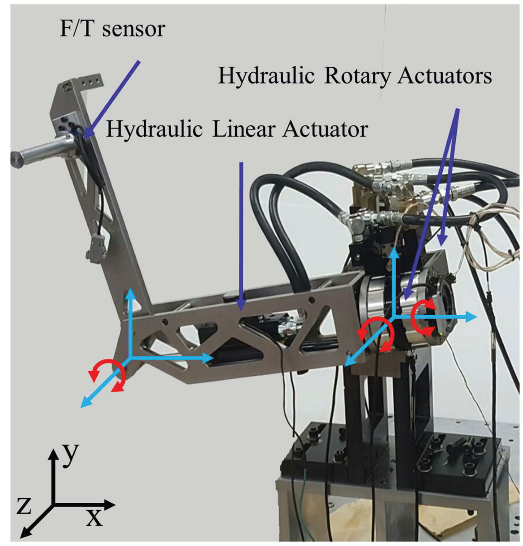

Fig. 6. 3-DOF hydraulic upper-limb exoskeleton.

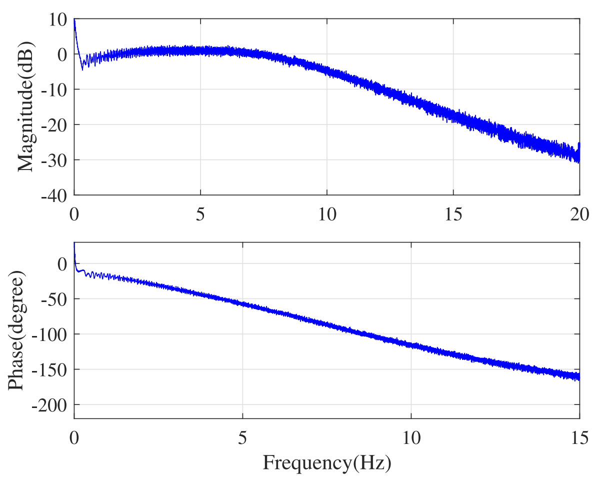

Fig. 7. Frequency response of velocity control of the 3-DOF hydraulic upper-limb exoskeleton in Y-direction.

ton, a six-axis F/T sensor is attached with a handle. The F/T sensor measures the force applied by the human to the robot. The angle of each joint is measured using an encoder (RLS, Inc.) and a potentiometer (Honeywell, Inc.). The exoskeleton is supplied hydraulic oil from a hydraulic power unit (KNR, Inc.), which can supply up to 20 L/min at 200 Bar, and performs velocity control via an internal controller with a sampling rate of 1000 Hz using NI-CompactRIO. The velocity bandwidth of the exoskeleton is measured by applying a chirp signal within the operating range of Y-direction. The amplitude of the chirp signal is 150mm/s determined based on the actuator speed when about 10% of the maximum flow that can be supplied by the servo valve (7 L/min) is supplied. The velocity control bandwidth of the exoskeleton is about 7 Hz, as shown in Fig. 7.

In order to verify the effectiveness of the hand IC, point-to-point experiment is carried out by repeatedly moving a certain section. Seven male and two female participants from the age of

TABLE II
AVERAGE VELOCITY DURING EXPERIMENTS

	velocity (avg.± std. (mm/s))
slow	78.2±4.5
noraml	101.2±5.4
fast	121±6.7

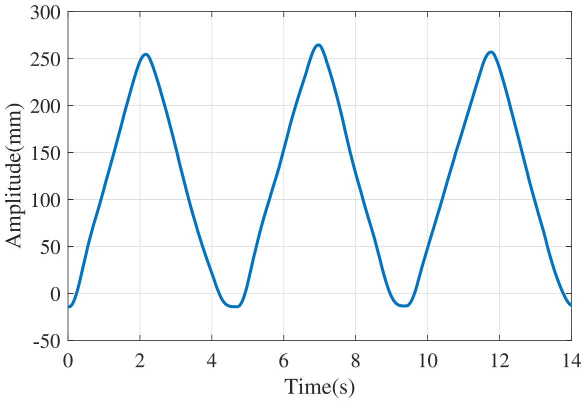

Fig. 8. Three cycles of point-to-point reciprocal experiment.

TABLE III
REQUIRED ENERGY PER UNIT DISTANCE IN POINT TO POINT MOTION

	w/o IC (J/m) avg.± std.	with IC (J/m) avg.± std.	avg. reduction rate
slow	2.91±0.19	2.22±0.13	23.7%
normal	3.79±0.24	2.98±0.22	21.4%
fast	4.44±0.33	3.54±0.32	20.3%

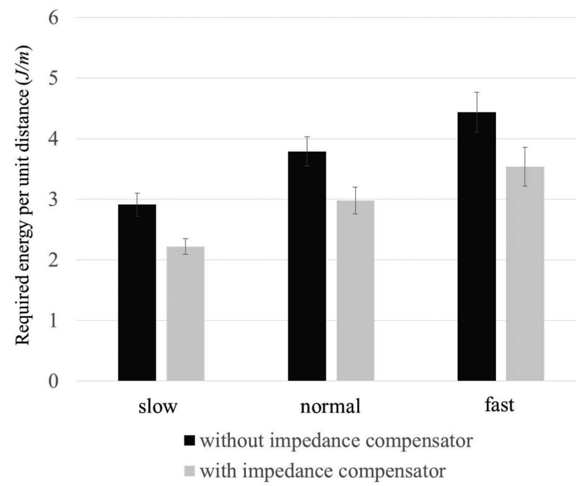

Fig. 9. Required average energy per unit distance and standard deviation in point to point motion.

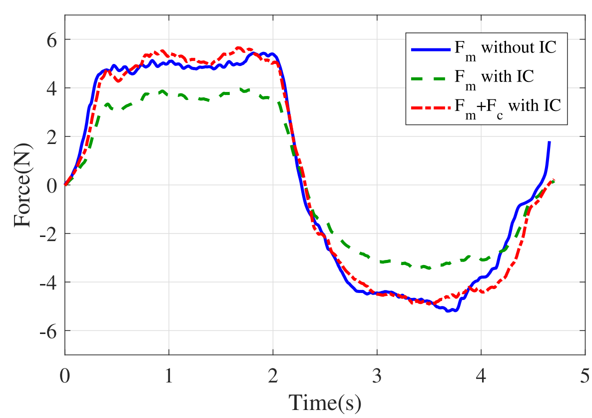

Fig. 10. Interaction force between the human hand and the hydraulic upper-limb exoskeleton in point-to-point motion with and without IC.

24–32 conduct the experiment with an upper-limb exoskeleton. The participants move their hand point-to-point over a defined interval in Y-direction that is perpendicular to the floor same as hand impedance estimation experiment. To get more meaningful results, the experiment is performed in three different velocities (slow, normal, and fast). The metronome, a device that indicates the exact tempo, is used to let participants maintain a steady speed. The average velocity of each temp is shown in Table II. As can be seen from the impedance estimation results in previous section, the estimated impedance of the human hand has a considerable variation from person to person. Also, even for the same person, the hand impedance is varied depending on the dynamic and static state of the hand [30]. If the IC is designed with average estimated hand impedance values shown in Table I, it can cause the stability problem when the poles of system (7) move unstable region depending on operator or in specific motion. Therefore, with trial and error, the IC is designed using the 50% value of the average impedance parameters. Even so, it is sufficient to confirm the improved transparency of the proposed algorithm. Fig. 8 shows three-cycles of reciprocating motion. At this time, it moves in one cycle for eight beats.

As the transparency improves, the human operator can control the robot with less force. In order to evaluate the transparency, the required energy was obtained through the force (F) measured from the F/T sensor and the movement distance of the end-effector while participants conducted the experiment. Because each participants have a different moving distance, the required energy (E) per unit distance is calculated as shown

$$E = \frac{\int_0^s |F| ds}{s}. \tag{8}$$

The results are presented in Table III and Fig. 9. All participants show energy savings of more than 20% at all three different velocities.

Fig. 10 shows the measured force (F_m) from the force sensor with and without the IC during one cycle of reciprocating motion. The dashed green line represents a measured force between the robot and the human with impedance compensation. The dotted red line shows the sum of the measured interaction force and the compensated force (F_c) with impedance compensation. The dotted red line has a similar amplitude to the interaction force without compensation, which is represented by solid blue line. This indicates that IC actually reduces the operating force and improves transparency.

In the previous section, the hand impedance was estimated through the dropping mass experiment in only Y-direction (perpendicular to the floor). In addition, the point-to-point

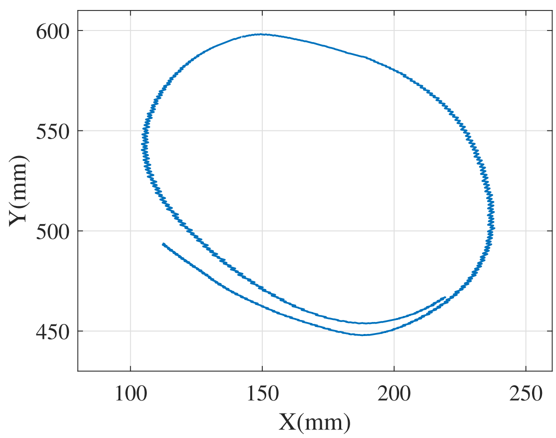

Fig. 11. Trajectory of hydraulic upper-limb exoskeleton end-effector for 4 s in circle motion.

TABLE IV
REQUIRED ENERGY PER UNIT DISTANCE IN CIRCLE MOTION

	E (J/m)
without impedance compensator	8.25
with impedance compensator	6.88

experiment was performed in the same direction. The IC can be scaled up to three axes except the rotation. As described in the impedance parameter ellipses of the research works [29] and [30], the impedance parameters of the hand generally have the largest value in the similar direction of the forearm. In addition, the hand impedance of the two axes perpendicular to which the hand moves are similar [31]. In this paper, the hand impedance was measured in perpendicular direction of forearm. Therefore, the IC would not perfectly compensate the effect of natural velocity feedback, but it can improve the transparency without any problem in stability. Consequently, it can be said that to scale up, the IC in three axes is consistent.

In order to demonstrate the effectiveness of the proposed IC on a plane, an additional experiment, that a human operator draws a circle at a constant speed on a plane perpendicular to the floor with the hydraulic exoskeleton, is carried out. Of course, it does not have to be a circle to verify the performance of the proposed algorithm on a plane. Fig. 11 shows a trajectory of the end-effector during the course of the experiment. The human operator repeatedly moves along a circular trajectory with a diameter of about 120 mm. To verify the performance, the comparison of the required energy per unit distance (E) with and without the IC is shown in Table IV.

When the IC is applied, the required energy per unit distance is reduced about 16.5%. In other words, the experiment confirms that the proposed algorithm is applicable to the extended dimension and improves transparency in pHRi situations.

V. CONCLUSION

In this paper, the IC is proposed to improve transparency. Since the robot and human hand are in contact with each other in the pHRi situation, the force sensor measures not only the force applied to the robot by the human motion intention but also the influence of the robot on the human hand as the robot moves. Due to this natural force feedback, intention of the operator is distorted and transparency is reduced. Therefore, when the human controls the robot in the pHRi situation, it is necessary to consider the dynamics of the human hand in order to predict an accurate human motion intention.

In order to design the IC, a device that is capable of estimating the impedance of human hands by object dropping experiment was used. And the validity of the estimated impedance was confirmed. The proposed IC reduces the influence of the natural force feedback generated from the motion of the robot and the dynamics of the human hand and overcomes the limit of admittance control. The IC is also useful because it uses only one F/T sensor without additional sensors or instruments.

Through the frequency response analysis, the limitation of the admittance control caused by human hand impedance was described. And it was evaluated that the proposed IC can improve the transparency by changing the location of poles. In experiments using the hydraulic upper-limb exoskeleton, the improvement of transparency was verified by considering the energy per unit distance required for the human to control the robot. In one dimension point-to-point experiment with various speed, more than 20% of energy saving was obtained. Nevertheless, the proposed algorithm was effective even in a two dimension plane. Also, although the impedance of the human hand varies depending on the situation, the fixed IC is still effective in improving transparency. As a result, this paper shows how to overcome the limitation of transparency due to natural force feedback caused by the contact between the robot and human in pHRi system through compensation of hand impedance.

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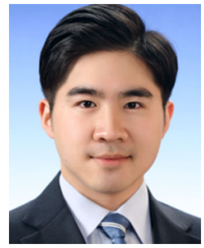

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