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Bilateral Control of Elbow and Shoulder Joints Using Functional Electrical Stimulation Between Humans and Robots

YUU HASEGAWA [1], **TOMOYA KITAMURA** [1], **SHO SAKAINO** [2,3], **AND TOSHIAKI TSUJI** [1]

[1]Department of Electrical and Electronic Systems, Saitama University, Saitama 338-8570, Japan
[2]Department of Intelligent Interaction Technologies, Graduate School of Systems and Information Engineering, University of Tsukuba, Tsukuba 305-8577, Japan
[3]Japan Science and Technology Agency (JST), Precursory Research for Embryonic Science and Technology (PRESTO), Tsukuba 332-0012, Japan

Corresponding author: Yuu Hasegawa (y.hasegawa.470@ms.saitama-u.ac.jp)

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ABSTRACT Robotic remote-control technologies have a wide field of applications. Bilateral control is a type of remote-control technique. Most of the existing bilateral control techniques require complicated force transmission mechanisms in the master systems. Therefore, operators feel discomfort due to a sense of restraint by the exoskeleton-type robot arms. We attempted to solve this problem by incorporating functional electrical stimulation into the master system. In this study, bilateral control was proposed between a human and a three-joint robot with three degrees of freedom using functional electrical stimulation for shoulder and elbow joints. The experiment consisted of extracting a block of Jenga using the slave robot. The proposed method was compared to unilateral control in which the master moves freely without feedback to the master.

INDEX TERMS Bilateral control, elbow control, functional electrical stimulation, oblique coordinate control, shoulder control.

I. INTRODUCTION

Robotic remote-control technologies are used in several domains, such as the medical field and extreme environments like the space [1], [2]. Bilateral control is a type of remote-control technique that can transmit force information between the master and slave-sides of the device [3]. By transmitting the force information, the contact status of the slave can be conveyed to the master [4], [5]. Therefore, the operation at the master side can be simulated to mimic real-world working conditions.

Many research works have been reported on bilateral control using human arms. Sen et al. developed an exoskeleton-type master unit to imitate a human elbow and hand movements via bilateral control [6]. Rebelo et al. constructed a bilateral control system that could imitate six degrees of freedom including the shoulder, elbow, and wrist joints of the human bodies [7]. However, most of the existing bilateral control techniques require complicated force transmission mechanisms in the master systems. Therefore, the operators feel discomfort due to a sense of restraint by the exoskeleton-type robot arms.

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Also, functional electrical stimulation (FES) has been used to restore motor functions in permanently paralyzed limbs, resulting from upper motor neuron disorders such as spinal cord injury and stroke, by providing electrical stimulation [8]. FES has originally been studied in the field of rehabilitation. Recently, FES has also been used in applications for healthy people. It is also well known that humans-sense physical contact through cutaneous and deep sensations [9], [10]. FES can provide a richer tactile sensation because the deep sensations can be transmitted through it. Thus, we attempted to solve this problem by incorporating FES into the master system [11]–[13].

Some studies have reported the use of FES for human motion control. Tamaki et al. controlled fingers via FES. They showed that FES can help in playing a musical instrument by controlling the fingers [14]. Leonardis et al. measured the electromyogram of an arm in real time and reproduced the estimated grasping force with an exoskeleton-type robot hand [15]. In a previous study, we proposed the bilateral control of an elbow joint using FES [11]. We showed that a reaction force can be induced in finger motions using bilateral control for the thumb and middle finger of two subjects using FES [12]. These studies indicate that human motion can be controlled and reaction force can be transmitted using FES.

When a bilateral control system is constructed between a human, who is controlled by FES and acts as a master, and a robot (slave), the reaction force received by the robot can be transmitted while the human feels lesser restraint. Conventional studies have proposed bilateral control between humans and robots using FES in the hand, elbow joint, and foot [16]–[18]. It is more useful in the master system with multiple degrees of freedom (DoF) such as shoulders and fingers, because mechanical structures to display multi DoF reaction force is almost impossibly difficult. However, the shoulder muscles are intricately overlapped. It is difficult to apply electrical stimulation to specific muscles. Therefore, bilateral control for shoulder movements using FES has not been reported. However, our research suggests that changing the stimulation frequency can distinguish between shoulder muscles that are stimulated [19].

To the best of knowledge, bilateral control between humans and robots in the shoulder joint using FES has not been proposed in the conventional studies, and the three-dimensional motion has not been demonstrated. Therefore, in this study, we propose bilateral control with three DoF between a human and a three-joint robot using FES for shoulder and elbow joints. However, when bilateral control is performed between a human and a robot, the control input is easily saturated owing to the difference in the movable range. This problem causes the robot to run away and has a fatal impact on the safety and control aspects. To avoid this problem, we propose the implementation of the angle response limiting method using oblique coordinate control [20]. Consequently, the saturation of the control input can be suppressed and the robot can realize stable operation.

The remainder of this paper is organized as follows. Section 2 describes bilateral control. Section 3 describes FES. Section 4 describes master and slave. Section 5 describes angle limitation using oblique coordinate control, and the system of bilateral control. Section 6 demonstrates the effectiveness of the proposed method through experiments. Section 7 concludes this paper.

II. BILATERAL CONTROL

Bilateral control, a remote-control technique [21], is illustrated in Fig. 1. The operator side is called "master" and the operated side is called "slave." Unilateral control is a control method of sending a command value in one direction from a master to a slave. In contrast, bilateral control is a control method of sending a command value in bi-direction between a master and a slave. Accordingly, the master can feel the external force applied to the slave, thereby simulating the sensation that the master's body has become the slave [13], [22]. In this study, we used position-symmetrical bilateral control because its control system is simple, stable, and does not require a force sensor [23].

III. FUNCTIONAL ELECTRICAL STIMULATION

FES has been illustrated in Fig. 2. FES delivers electrical stimulation to peripheral nerves using an external power source to excite them, thereby enabling the human joints to flex and extend.

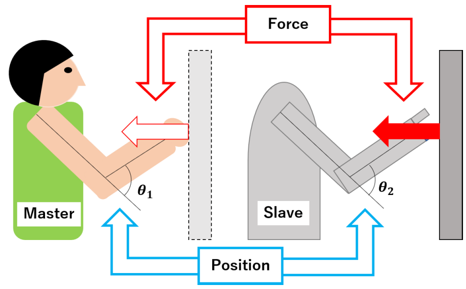

FIGURE 1. Conceptual diagram of bilateral control.

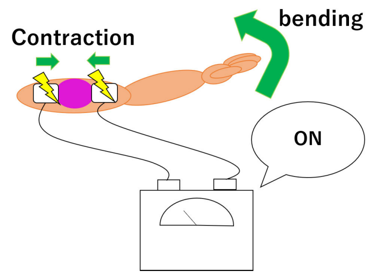

FIGURE 2. Conceptual diagram of FES.

There are two representative methods of delivering the electrical stimulation to the muscles.

- Stimulation using invasive electrodes implanted in muscles [24].
- Stimulation from the body surface using an electrode pad without implanting electrodes in the body [25].

In this study, electrical stimulation was delivered to the upper arm and shoulder using adhesive pads considering safety and convenience.

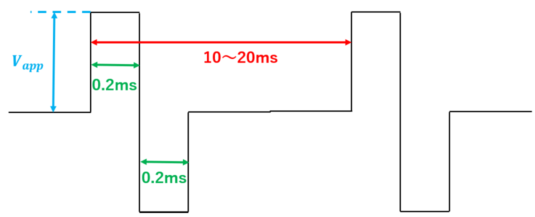

FIGURE 3. Waveform of electrical stimulation.

Figure 3 shows the stimulation waveform. We used a bipolar pulse wave. Table 1 lists the names and functions of the muscles that were electrically stimulated to move the elbow and shoulder joints. The flexor muscle works in the direction that bends the elbow and shoulder, and the extensor muscle works in the direction that extends the elbow and shoulder. The adductor muscle works in the direction that rotates the shoulder forward, and the abduction muscle works in the direction that rotates the shoulder backward. Figure 4 shows the locations of the pads and names of the muscles. The arrangement of these electrode pads was identified using

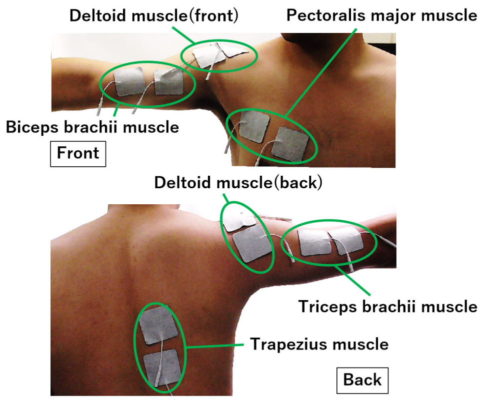

FIGURE 4. Location of the pads.

TABLE 1. Names and functions of the muscles.

Muscle	Joint	Function
Biceps brachii muscle	Elbow	Bending
Triceps brachii muscle		Extension
Deltoid muscle(front)	Shoulder	Bending
Deltoid muscle(back)		Extension
Pectoralis major muscle		Horizontal adduction
Trapezius muscle		Horizontal abduction

TABLE 2. Value of electrical stimulation device.

Supply voltage	50 V
Output voltage (Instantaneous value)	30 V
Output voltage (Effective value)	20 mA

a motor point pen (COMPEX). The electrical stimulation device used in the experiments was created in accordance with the Japanese Industrial Standard (JIS) for low-frequency therapy devices and is designed to have a maximum output current, which is less than the effective value of 20 mA. Moreover, to ensure operator safety and reduce their discomfort, we restricted the stimulation voltage up to 30 V. The input and output values of the electrical stimulation device are presented in Table 2.

IV. MASTER AND SLAVE

In this study, the human body, whose reaction force is presented by FES, is the master. Three DoFs, i.e., two DoFs of horizontal adduction / horizontal abduction and flexion / extension at the shoulder joint and one DoF of the elbow joint, were driven by the FES. The measurement standard for the angles of elbow and shoulder joints are shown in Fig. 5, where EJA denotes elbow joint angle and SJA denotes shoulder joint angle. Perception neuron (Noitom) was used as an angle measuring device. Perception neuron was a motion captured with a dynamic range of 360°, resolution of 0.02°, and max output rate of 120 fps. Figure 6 shows the wearing state.

In contrast, Geomagic Touch (3D systems) was used as the slave robot. It is a three-axis manipulator, with a momentary maximum exertable force of 3.3 N. Figure 7 shows the state of slave robot in this experiment. The directions shown by the

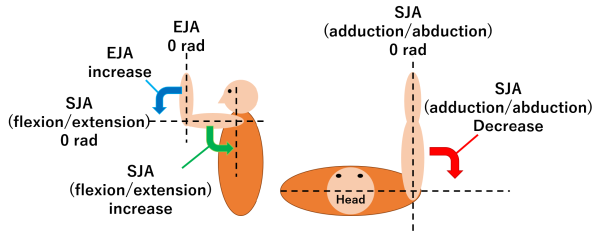

FIGURE 5. Measurement standard of joint angles.

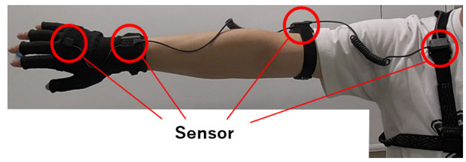

FIGURE 6. State of wearing sensor.

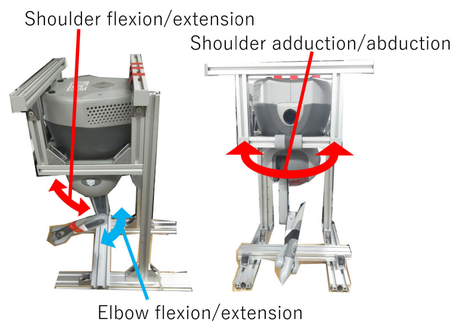

FIGURE 7. State of slave robot in experiments.

red and blue arrows in Fig. 7 move in synchronization with the human shoulder and elbow joints, respectively.

V. ANGLE LIMITATION USING OBLIQUE COORDINATE CONTROL AND SYSTEM OF BILATERAL CONTROL

A. OBLIQUE COORDINATE CONTROL AND ANGLE LIMITATION

The slave robot, used in these experiments, has a limited movable range. The slave ran out of control when a command value beyond the movable range of the slave was given as input. Thus, it is necessary to set a limit on the command value input for the slave robot. Accordingly, we proposed to use oblique coordinate control that can implement a given variety of tasks only by defining the coordinate transform (task Jacobian matrix) [20], [26]. In this method, θ_m that a real angle of master, and $\hat{\theta}_m$ that a virtual angle, were defined as follows.

$$\theta_m = g(\hat{\theta}_m) \tag{1}$$

$$\theta_m = \begin{cases} (\theta_{min}-\alpha)(1-e^{-\gamma(\hat{\theta}_m-\alpha)})+\alpha & (\theta_m \leq \alpha) \\ \hat{\theta}_m & (\alpha < \theta_m < \beta) \\ (\theta_{max}-\beta)(1-e^{-\delta(\hat{\theta}_m-\beta)})+\beta & (\beta \leq \theta_m). \end{cases} \tag{2}$$

Here, θ_{max} and θ_{min} denote the upper and lower limits, and α, β, γ, and δ are the adjustment parameters with the following

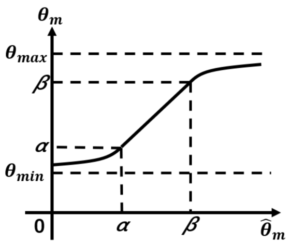

FIGURE 8. Angle limited coordinates.

relationship.

$$g(\alpha) = \alpha \tag{3}$$

$$g(\beta) = \beta \tag{4}$$

$$\gamma = \frac{1}{\theta_{min} - \alpha} \tag{5}$$

$$\delta = \frac{1}{\theta_{max} - \beta}. \tag{6}$$

Figure 8 illustrates this relational expression. From Fig. 8, it was confirmed that θ_m is a coordinate system that is always mapped to the restricted range irrespective of the value of $\hat{\theta}_m$. The greater value of $|\theta_{min} - \alpha|$ and, $|\theta_{max} - \beta|$ indicate that the system is more conservative. Further, from the above equation, the virtual angle $\hat{\theta}_m$ can be defined as follows.

$$\hat{\theta}_m = g^{-1}(\theta_m) \tag{7}$$

$$\hat{\theta}_m = \begin{cases} (\theta_{min}-\alpha)\ln\dfrac{\theta_{min}-\theta_m}{\theta_{min}-\alpha}+\alpha & (\theta_m \leq \alpha) \\ \theta_m & (\alpha < \theta_m < \beta) \\ (\theta_{max}-\beta)\ln\dfrac{\theta_{max}-\theta_m}{\theta_{max}-\beta}+\beta & (\beta \leq \theta_m). \end{cases} \tag{8}$$

By inputting $\hat{\theta}_m$ into the control system, the actual angle response value can be obtained within the limit range even if the response value exceeds the limit in the control system.

Using this relational expression, torque conversion and dynamics conversion were also performed in the angle-limited coordinate system; however, the details are left to reference [20].

B. CONTROL SYSTEM

A bilateral control system with one DoF for the elbow joint and two DoFs for the shoulder joints was implemented, assuming that the control system has little interference between each joint. In addition, the joint angular velocity response was determined by pseudo-differentiation.

The controller on the master side implemented a high order sliding mode control using the super-twisting algorithm as a position controller [27]. The super-twisting algorithm is described in the following equations.

$$\begin{cases} u = -\lambda|S|^{\rho}\mathrm{sgn}(S) + u_a \\ \dot{u}_a = -W\mathrm{sgn}(S). \end{cases} \tag{9}$$

The sliding surface was set as follows.

$$S = \dot{\theta}_s - \dot{\hat{\theta}}_m + \lambda(\theta_s - \hat{\theta}_m). \tag{10}$$

Here, λ, ρ, and W are the predetermined positive constants, determined on the bases of the results of conventional research [28]. Subscripts m and s represent the master and slave, respectively. The electrical stimulation voltage applied to the human body V_{app} was determined using the minimum voltage V_{th} that exerts muscle strength as follows.

$$V_{app} = \begin{cases} u + V_{th} & (u > 0) \\ 0 & (u = 0) \\ -u + V_{th} & (u < 0). \end{cases} \tag{11}$$

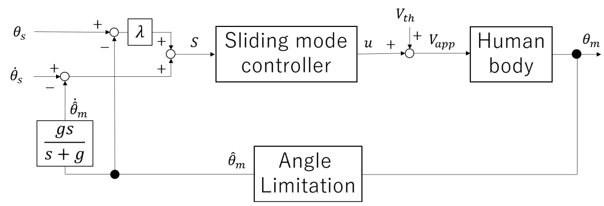

FIGURE 9. Block diagram of master system.

Figure 9 shows a block diagram of the master system. In contrast, the controller on the slave side implemented a proportional differential (PD) controller as a position controller. In addition, a disturbance observer (DOB) was used to improve the disturbance suppression performance [29], [30]. The control algorithm is described in the following equation.

$$\tau_{ref} = \frac{J}{2}\{K_p(\hat{\theta}_m - \theta_s) + K_d(\dot{\hat{\theta}}_m - \dot{\theta}_s)\}. \tag{12}$$

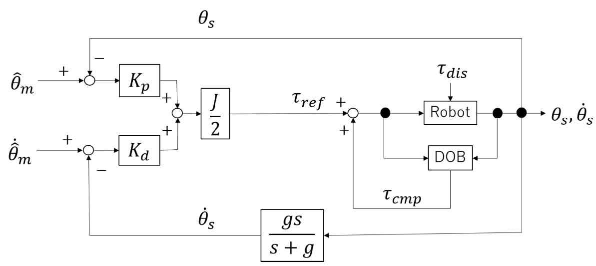

FIGURE 10. Block diagram of slave system.

where J is the moment of inertia of the robot, K_p is the position feedback gain, K_d is the velocity feedback gain, τ is the torque, and the subscripts *ref*, *dis*, and *cmp* denote the reference value, disturbance, and compensation value, respectively. The disturbance is due to the friction and gravity. The compensation value is due to the DOB. A block diagram of the slave system is shown in Fig. 10. Here, g represents a cut-off frequency. Table 3 lists the values of the parameters. Here, the subscripts 1, 2, and 3 indicate the parameters related to the motion in the horizontal adduction/horizontal abduction direction of the shoulder joint, flexion/extension direction of the shoulder joint, and the motion of the elbow joint, respectively.

Figure 11 shows a block diagram summarizing the master and slave system. The output values from the master system

TABLE 3. Identified system parameters.

	Parameter	Value
λ_1	positive constant 1	3.0
λ_2	positive constant 2	5.0
λ_3	positive constant 3	6.0
W_1	positive constant 1	0.30
W_2	positive constant 2	0.50
W_3	positive constant 3	0.60
ρ	positive constant	0.50
K_p	Position feedback gain	100.0
K_d	Velocity feedback gain	20.0
J_1	Inertia 1 [mNm]	4.0
J_2	Inertia 2 [mNm]	8.21
J_3	Inertia 3 [mNm]	3.43
g	Cut-off frequency [rad/sec]	40.0

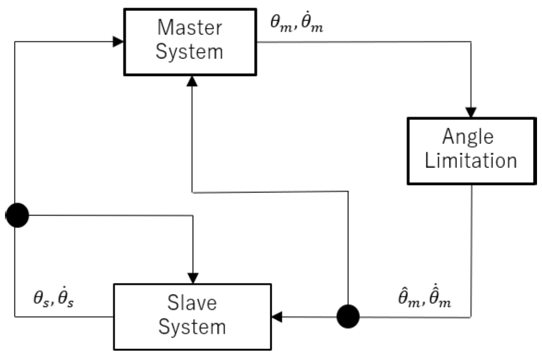

FIGURE 11. Block diagram of bilateral control system.

TABLE 4. Correspondence table between the muscles of each subject and the frequency of the electrical stimulation.

Subject	Muscle	Frequency [Hz]
A	Biceps brachii muscle	50
	Triceps brachii muscle	50
	Deltoid muscle(front)	50
	Deltoid muscle(back)	100
	Pectoralis major muscle	50
	Trapezius muscle	100
B	Biceps brachii muscle	50
	Triceps brachii muscle	50
	Deltoid muscle(front)	50
	Deltoid muscle(back)	100
	Pectoralis major muscle	50
	Trapezius muscle	50
C	Biceps brachii muscle	50
	Triceps brachii muscle	50
	Deltoid muscle(front)	50
	Deltoid muscle(back)	50
	Pectoralis major muscle	50
	Trapezius muscle	100

θ_m and $\dot{\theta}_m$, are given as input to an angle limitation function using oblique coordinate control. The output values from the angle limitation, $\hat{\theta}_m$ and $\dot{\hat{\theta}}_m$, become the angle command values suppressed within the limit range of the slave. Then, the output values from the slave system, θ_s and $\dot{\theta}_s$, and those from the angle limitation, $\hat{\theta}_m$ and $\dot{\hat{\theta}}_m$, are given as input to the master system to determine the voltage value applied to the human body.

VI. EXPERIMENT

This section demonstrates the effectiveness of the proposed method via experiments. In this study, three healthy men in their twenties were chosen as subjects. The contents and purpose of the experiments were explained to them in advance, and the experiment was performed after obtaining informed consent. We also obtained permission from the ethics committee of the Saitama University and the system information research ethics committee of University of Tsukuba for this experiment. We found that shoulder joints can be driven by selecting appropriate stimulation frequencies according to subjects and muscles [19]. Table 4 lists a correspondence table between the muscles of each subject and the frequency of the electrical stimulation.

FIGURE 12. State of slave robot in the task.

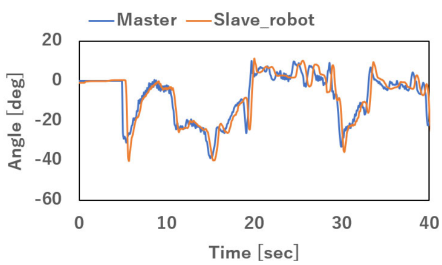

FIGURE 13. Proposed method in SJA(adduction/abduction) in subject A.

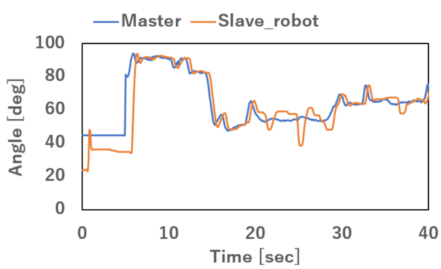

FIGURE 14. Proposed method in SJA(flexion/extension) in subject A.

Figure 12 shows the state of slave robot in the task. In this experiment, the task was to extract a block of Jenga using the

TABLE 5. Result of experiment: (✓)(success), ×(failure).

Times			1	2	3	4	5	6	7	8	avg
Subject A	Proposed	Success	(✓)	(✓)	(✓)	(✓)	(✓)	-	-	-	-
		Time[sec]	21.15	29.1	20.5	9.0	15.05	-	-	-	18.96
	Conventional	Success	×	(✓)	×	(✓)	(✓)	(✓)	(✓)	-	-
		Time[sec]	-	33.1	-	52.7	84.7	10.55	27.5	-	41.71
Subject B	Proposed	Success	(✓)	(✓)	(✓)	(✓)	(✓)	-	-	-	-
		Time[sec]	48.0	20.15	8.85	21.15	23.2	-	-	-	24.27
	Conventional	Success	(✓)	(✓)	(✓)	(✓)	(✓)	-	-	-	-
		Time[sec]	54.0	19.45	43.7	47.05	11.7	-	-	-	35.18
Subject C	Proposed	Success	(✓)	(✓)	(✓)	(✓)	(✓)	-	-	-	-
		Time[sec]	19.50	11.15	21.35	9.2	7.15	-	-	-	13.67
	Conventional	Success	(✓)	×	(✓)	(✓)	×	(✓)	×	(✓)	-
		Time[sec]	36.75	-	33.75	36.6	-	16.9	-	15.45	27.89

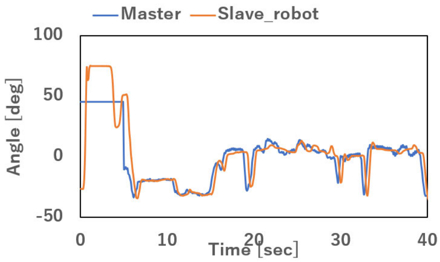

FIGURE 15. Proposed method in EJA in subject A.

FIGURE 16. Conventional method in SJA(adduction/abduction) in subject A.

FIGURE 17. Conventional method in SJA(flexion/extension) in subject A.

slave robot. The proposed method was compared to unilateral control in which the master moves freely without feedback to the master. In the experiment, the conventional and proposed methods were alternately performed to eliminate the influence of experience. The task was repeated until the conventional and proposed methods were successful five times. The results of the experiments with unilateral control and bilateral control are shown in Figs. 13–18. Figures 13–15 show the implementation of bilateral control by the proposed

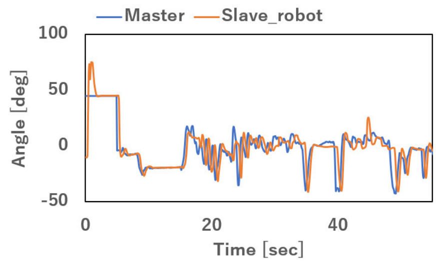

FIGURE 18. Conventional method in EJA in subject A.

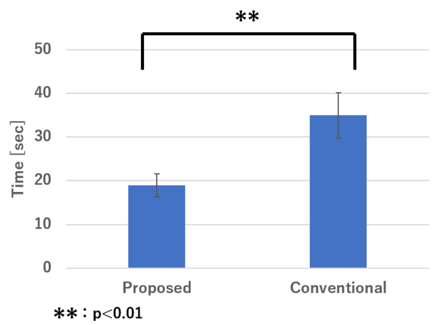

FIGURE 19. Statistical comparison of average time.

method using FES and Figs. 16–18 show the conventional method by unilateral control for each joint in subject A. In Figs 13–18, the blue line represents the master response and the orange line represents the slave response. Table 5 presents the success or failure of the task and the time required to achieve it.

Figs 13–18 show that there were no significant differences between the conventional and the proposed methods, and a good position response was obtained in both cases. Table 5 demonstrates that the conventional method had a poorer rate of success for the task and took longer time than the proposed method because there was no feedback to the master; therefore, the operator could not recognize the contact state correctly and could not perform an operation suitable for searching and extracting the Jenga block. In contrast, by using the proposed method, subjects could maintain a stable contact, which resulted in a more careful and faster extraction of the block. This is owing to the feedback to the master by using FES. In addition, significant differences were calculated from the time required to achieve the tasks in the conventional method and that in the proposed method in all subjects by the paired t-test. The calculation of t-test showed that the proposed method was significant at the $p = 0.0018 < 0.01$ level. Also, Fig. 19 reveals that the proposed method was statistically superior. Therefore, the effectiveness of bilateral control using reaction force presentation by FES was demonstrated from these experiments.

VII. CONCLUSION

In this study, we proposed a bilateral control technique between humans and robots in the shoulder and elbow joints using reaction force presentation by FES. To the best of knowledge, bilateral control between humans and robots in the shoulder joint using FES has not been proposed in the conventional studies, and the three-dimensional motion has not been demonstrated. When bilateral control is implemented between humans and robots using FES, the control input tended to be saturated due to the difference in the movable range of the joint between them, which raised a problem. This problem caused the robot to run away and had a fatal impact on the safety and control aspects. Therefore, we attempted to eliminate this problem by limiting the joint angle by the master using oblique coordinate control. In the experiment, we compared the task of extracting a block of Jenga using the proposed method and unilateral control. Consequently, unilateral control was found to have a poorer rate of success of the task and required longer time for completion than the proposed method. The calculation of t-test showed that the proposed method was significant. These results demonstrated the effectiveness of bilateral control using reaction force presentation by FES. In future, we will confirm the effectiveness of more advanced tasks through bilateral control including fingers movements.

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YUU HASEGAWA received the B.E. degree in electrical and electronic systems engineering from Saitama University, Saitama, Japan, in 2018, where he is currently pursuing the M.E. degree with the Department of Electrical and Electronic Systems. He is involved in research on motion control and mechatronics.

TOMOYA KITAMURA received the B.E. and M.E. degrees in electrical and electronic systems engineering from Saitama University, Saitama, Japan, in 2015 and 2017, respectively. He is currently pursuing the Ph.D. degree with the Department of Electrical and Electronic Systems. His research interests include mechatronics and biomedical engineering. He has been a Research Fellow (DC2) of Japan Society for the Promotion of Science, since 2018.

SHO SAKAINO received the B.E. degree in system design engineering and the M.E. and Ph.D. degrees in integrated design engineering from Keio University, Yokohama, Japan, in 2006, 2008, and 2011, respectively. He was an Assistant Professor with Saitama University, from 2011 to 2019. Since 2017, he has been a Researcher with Japan Science and Technology Agency (JST), Precursory Research for Embryonic Science and Technology (PRESTO), Tsukuba, Japan. Since 2019, he has been an Associate Professor with the Department of Intelligent Interaction Technologies, Graduate School of Systems and Information Engineering, University of Tsukuba, Tsukuba. His research interests include mechatronics, motion control, robotics, and haptics. He received the IEEJ Industry Application Society Distinguished Transaction Paper Award, in 2011.

TOSHIAKI TSUJI received the B.E. degree in system design engineering and the M.E. and Ph.D. degrees in integrated design engineering from Keio University, Yokohama, Japan, in 2001, 2003, and 2006, respectively. He was a Research Associate with the Department of Mechanical Engineering, Tokyo University of Science, from 2006 to 2007. He is currently an Associate Professor with the Department of Electrical and Electronic Systems, Saitama University, Saitama, Japan. His research interests include motion control, haptics and rehabilitation robots. Dr. Tsuji received the FANUC FA and Robot Foundation Original Paper Award, in 2007 and 2008, respectively.