Direct Comparisons of Upper-Limb Motor Learning Performance Among Three Types of Haptic Guidance With Non-Assisted Condition in Spiral Drawing Task

Hisayoshi Muramatsu, *Member, IEEE*, Yoshihiro Itaguchi, Chiharu Yamada, Hiroshi Yoshizawa, and Seiichiro Katsura, *Member, IEEE*

***Abstract*—In robot-assisted rehabilitation, it is unclear which type of haptic guidance is effective for regaining motor function because of the lack of direct comparisons among multiple types of haptic guidance. The objective of this study was to investigate the effects of different types of haptic guidance on upper limb motor learning in a spiral drawing task. Healthy young participants performed two experiments in which they practiced the drawing movement using a robotic manipulandum with a virtual wall (Path guidance), running direction pushing and virtual wall (Path & Push guidance), restriction to the target movement (Target guidance), or without haptic guidance (Free guidance). Experiment 1 compared the learning effects of the four types of guidance. Experiment 2 investigated the effects of pre-learning with Path, Path & Push, or Target guidance on post-learning with Free guidance. In Experiment 1, Free guidance demonstrated the greatest learning effect, followed by Path guidance, which showed a significantly greater improvement in task performance than the other two types of guidance. In Experiment 2, the type of pre-learning did not influence post-learning with Free guidance. The results suggested that learning with Path guidance showed a slightly slower but comparable effect to Free guidance and was the most effective among the three types of haptic guidance. The superiority of Path guidance over other haptic guidance was interpreted within the framework of error-based learning, in which the intensity of sensory feedback and voluntary motor control play important roles.**

***Index Terms*—Motor learning, haptic guidance, upper limb, rehabilitation robotics.**

Manuscript received 24 December 2023; revised 11 April 2024 and 21 June 2024; accepted 3 July 2024. Date of publication 12 July 2024; date of current version 17 July 2024. This work was supported by JSPS KAKENHI under Grant JP21H04566 and Grant JP24H00321. *(Corresponding author: Hisayoshi Muramatsu.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethics Committee on Human Research of Waseda University.

Hisayoshi Muramatsu is with the Mechanical Engineering Program, Hiroshima University, Higashihiroshima 739-8527, Japan (e-mail: muramatsu@hiroshima-u.ac.jp).

Yoshihiro Itaguchi is with the Department of Psychology, Keio University, Minato-ku 108-8345, Japan (e-mail: itaguchi@keio.jp).

Chiharu Yamada is with the Advanced Research Center for Human Sciences, Waseda University, Tokorozawa 359-1192, Japan (e-mail: chiharu.i.yamada@gmail.com).

Hiroshi Yoshizawa is with the Department of Neurology, Tokyo Women's Medical University, Shinjuku-ku 162-8666, Japan (e-mail: yoshizawa.hiroshi@twmu.ac.jp).

Seiichiro Katsura is with the Department of System Design Engineering, Keio University, Yokohama 223-8522, Japan (e-mail: katsura@sd.keio.ac.jp).

Digital Object Identifier 10.1109/TNSRE.2024.3427319

I. Introduction

IN RECENT years, robot-assisted therapy has been widely introduced in clinical environments for upper limb rehabilitation [1], [2], [3], [4]. Previous studies found positive effects of robot-assisted therapy on upper limb rehabilitation in stroke patients over various intervention periods [5], [6], [7], [8]. Meta-analysis studies also found significant effects of robot-assisted therapies in rehabilitation, which were equal to or better than those of conventional methods [9], [10], [11]. In particular, the review [9] reported that robot-assisted therapies improved activities of daily living scores, arm function, and arm muscle strength in people after stroke without increasing the risk of participant dropout with rare adverse events. These findings indicate that robot-assisted therapy can be considered as an option for the rehabilitation of stroke patients with impaired motor function.

However, there is no consistent agreement on the type of robotic assistance, called haptic guidance [12], that is effective for robot-assisted motor learning [13], [14], [15], [16]. Different types of control, such as position and force control, vary movements and assistance intensity of robots, and most studies have used various types of haptic guidance [13], [14], [15], [17], [18]. Nevertheless, no study has directly compared three or more types of haptic guidance with non-assisted performance in a single upper-limb motor task using the same experimental design. In addition, no studies have investigated the interaction of the haptic guidance and non-assisted trainings. This makes it difficult to draw a definitive conclusion. Therefore, the present study compared the effects of three different types of haptic guidance with a non-assisted condition on movement improvement and examined the interaction effect of pre-learning with haptic guidance on post-learning without assistive guidance.

The impact of haptic guidance on human participants can be interpreted within the framework of feedback error learning, which is an important type of motor learning that is likely to be implemented in the central nervous system [19], [20], [21]. In feedback error learning, humans update an internal model, which is assumed to generate optimal motor commands for a desired movement [20], [22], using error information: the discrepancy between predicted and actual sensory inputs. Along with this framework, we assumed that variations in error information modulate the process of human motor learning. We hypothesized that the learning effect in a motor task would vary with the intensity of haptic guidance, which determines the quality of error information for human feedback error learning.

The present study compared the motor learning effects of three types of haptic guidance (Path, Path & Push, and Target guidance) with a non-assisted condition (Free guidance) in a spiral-drawing task (Fig. 1). In the Path and Path & Push guidance, the virtual walls prevented the participants from deviating their movements from the desired path using a virtual spring and damper [13]. In Path guidance, voluntary efforts were required to move forward within the walls, whereas in Path & Push guidance, participants were provided with assistive pushing force toward the goal so that a small amount of voluntary motor control was required. Target guidance completely governed the participants' movements [15], [23] and accomplished the task even without the participant's effort. These four types of guidance were set to vary in assistive intensity, which also adjusted the participants' voluntary effort and sensory feedback. We supposed that the intensity increases in the following order: Free, Path, Path & Push, and Target guidance, which can be categorized into the active, assistive, assistive, and passive modalities, respectively, according to the classification [24].

Two experiments were conducted. Experiment 1 examined the hypothesis that the learning effect would increase in the following order: Target, Path & Push, Path, and Free guidance. Experiment 2 was conducted to further consider the efficacy of robot-assisted rehabilitation supposing a situation closer to the real world, and we examined the effects of pre-learning with the haptic guidance on post-learning without assistive guidance. This experimental schedule was based on rehabilitation, in which robot-assisted rehabilitation would be performed before self-supported rehabilitation without robot assistance to decrease the burden on the patients.

II. Methods

A. Participants

A total of 89 and 64 right-handed students participated in Experiments 1 and 2, respectively, without any overlap. Seven participants who could not precisely follow the experimenter's instructions were excluded from the study, and the six participants whose scores in the evaluation phase exceeded three times the standard deviation were also excluded as outliers. The data of the other 80 (40 females, 21.1±2.5 years old) and 60 (30 females, 20.4±1.5 years old) students were analyzed. The participants in Experiment 1 were assigned to one of the four groups: Free, Path, Path & Push, and Target; the participants in Experiment 2 were assigned to one of the three groups: Path, Path & Push, and Target.

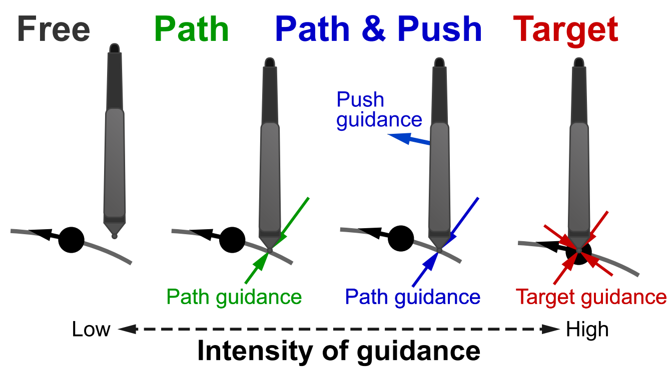

Fig. 1. Intensity of the four types of guidance.

B. Apparatus

A two-degree-of-freedom parallel robot composed of two direct-drive motors (SGMCS-02BDC41, Yaskawa Electric Corporation) was used to assist the participants' right upper-limb movements, and a 22-inch tablet monitor (DTK-2200, WACOM) was placed under the workspace (Fig. 2A). The direct-drive motors realized high backdrivability and enabled the participants to move the end effector easily with a small amount of force. A stylus was attached to the end effector of the robot, and robot-assisted drawing movements were performed using the stylus. The stylus was fixed vertically to the monitor. The angles θ of the motors were measured using encoders, and a participant's torque to each motor was estimated as $\hat{\tau}^{\text{hum}}$ using a reaction force observer [25], [26], [27]:

$$\mathcal{L}[\hat{\tau}^{\text{hum}}] = \frac{100}{s+100}(sM\mathcal{L}[\dot{\theta}] - \mathcal{L}[\tau]), \quad (1)$$

where $\mathcal{L}$, M and τ denote the Laplace transform, nominal moment of inertia, and motor torque, respectively. The angular velocity $\dot{\theta}$ was derived by pseudo-differentiation using a low-pass filter.

C. Spiral Drawing Task and Schedule

In both experiments, the participants performed a spiral-drawing task, and the procedure was identical except for the schedules. They sat on a chair, the stylus was held in a power grip, and the target movement was reproduced as accurately as possible in both the temporal and spatial aspects. A counterclockwise three-and-a-half-rotation logarithmic spiral trajectory was used (Fig. 2B), which is a difficult version of the clinical test for evaluating motor function [28]. The velocity profile of the target movement along the trajectory was calculated to satisfy the minimum angular jerk constraint with a movement time of 6 s. We instructed the participants to aim to complete the movement in exactly 6 s and prioritize temporal accuracy over spatial reproduction. This instruction

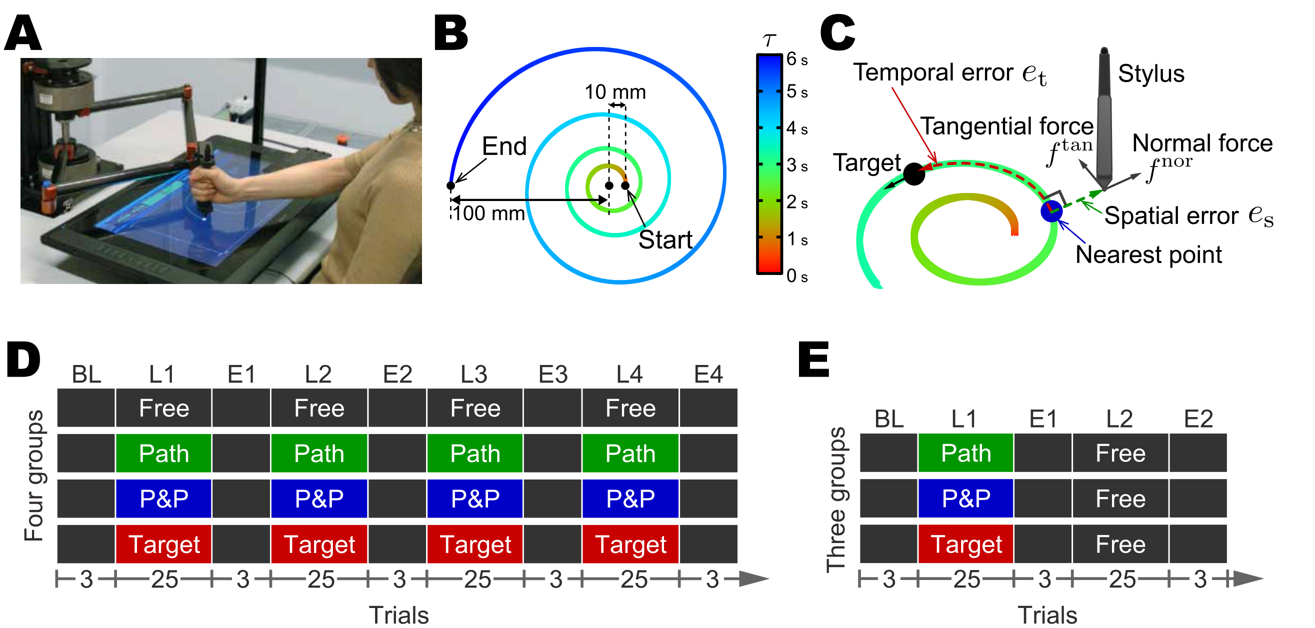

Fig. 2. Experiments of upper limb motor learning in a spiral drawing task using a two-degree-of-freedom parallel robot. (A) Experimental setup. Participants held the stylus attached to the end effector of the robot in a power grip to draw a spiral. (B) Logarithmic spiral trajectory satisfying a minimum angular-jerk constraint. (C) Variables related to the spiral and stylus for control and measures. (D) Schedule of Experiment 1. BL and E1-E4 indicate the baseline and evaluation phases without assistive force (Free guidance), and L1-L4 indicate learning phases with Free or haptic guidance. P&P indicates Path & Push guidance. (E) Schedule of Experiment 2.

was introduced because we focused on the evaluation of spatial performance under the influence of the speed-accuracy tradeoff [29], [30]. During the experiments, the experimenter observed that the participants followed our instructions and prioritized modifying their movement time over the accurate drawing.

After a countdown cue, the trial started with a moving marker of the target movement, which was presented for only 1 s to control both the start timing and direction of the initial movements. During each trial, the monitor displayed the start and goal points but did not display the target spiral trajectory. In the learning phase, before every five trials, the participants watched a moving marker on the monitor as a reminder of the target movement without moving their arms. After each trial, the participants received visual feedback on the trajectory drawn by them with the target spiral trajectory for 6 s. To prompt them to modify their movement time, a message about movement time (“slow,” “early,” or “good”) was given if $t_d > 6.5$ s, $t_d \leq 5.5$ s, or 5.5 s $< t_d \leq 6.5$ s, respectively. During the evaluation phase, the participants did not receive any information about their drawings or target movements.

Experiment 1 consisted of baseline (BL), four learning (L1–L4), and four evaluation (E1–E4) phases (Fig. 2D), whereas Experiment 2 consisted of baseline (BL), two learning (L1 and L2), and two evaluation (E1 and E2) phases (Fig. 2E). The baseline, learning, and evaluation phases contained 3, 25, and 3 trials, respectively. In Experiment 1, the participants took a ten-minute break between E2 and L3. Regardless of the assigned group, the participants performed the task without robotic assistance (with Free guidance) during the baseline and evaluation phase.

D. Four Types of Guidance

Four types of guidance were used in this study. Free guidance did not provide assistive force: $f^{\rm tan} = 0$ and $f^{\rm nor} = 0$, which are the tangential and normal forces applied to the stylus along the spiral, respectively (Fig. 2C).

Path guidance restricted the stylus on the spiral path using impedance control between the stylus and the nearest point on the spiral, which is formulated using the spatial error $e_{\rm s}$ as

$$f^{\rm tan} = 0 \tag{2a}$$
$$\bar{f}^{\rm nor} = -900{\rm dzn}(e_{\rm s}) - 300|{\rm sgn}({\rm dzn}(e_{\rm s}))|\dot{e}_{\rm s} \tag{2b}$$
$$\dot{f}^{\rm nor} = 200(\bar{f}^{\rm nor} - f^{\rm nor}), \tag{2c}$$

where the sign and deadzone functions are defined as

$${\rm sgn}(z) = \begin{cases} -1 & \text{if } z < 0 \\ 0 & \text{if } z = 0 \\ 1 & \text{if } z > 0 \end{cases} \tag{3a}$$
$${\rm dzn}(z) = \begin{cases} z + \varepsilon & \text{if } z < -\varepsilon \\ 0 & \text{if } |z| \leq \varepsilon \\ z - \varepsilon & \text{if } z > \varepsilon. \end{cases} \tag{3b}$$

Path guidance did not provide force in the tangential direction as (2a). While the spatial error exceeded the threshold $|e_{\rm s}| > \varepsilon = 0.05 \times 10^{-3}$ m, the impedance control in the normal direction (2b) became $\bar{f}^{\rm nor} = -900{\rm dzn}(e_{\rm s}) - 300\dot{e}_{\rm s}$. This realized the virtual spring (with a spring constant of 900 N/m) as $-900{\rm dzn}(e_{\rm s})$ and the virtual damper (with a viscosity of 300 Ns/m) as $-300\dot{e}_{\rm s}$. While the spatial error was within the range $|e_{\rm s}| \leq \varepsilon$, the deadzone function ${\rm dzn}(e_{\rm s})$ became zero, resulting in $\bar{f}^{\rm nor} = 0$. The deadzone function implemented haptic feedback as virtual walls located at $\pm\varepsilon$. A low-pass filter (2c) smoothed the force $\bar{f}^{\text{nor}}$ and yielded the normal force f^{nor}.

Path & Push guidance restricted the stylus in the same manner as Path guidance and applied force in the tangential direction

$$f^{\text{tan}} = f^{\text{spiral}}(\tau) \text{ s.t. } f^{\text{spiral}}(t) = M\ddot{x}^{\text{spiral}} \tag{4a}$$

$$\bar{f}^{\text{nor}} = -900\text{dzn}(e_{\text{s}}) - 300|\text{sgn}(\text{dzn}(e_{\text{s}}))|\dot{e}_{\text{s}} \tag{4b}$$

$$\dot{f}^{\text{nor}} = 200(\bar{f}^{\text{nor}} - f^{\text{nor}}), \tag{4c}$$

where τ denotes the time at which the target movement passes the nearest point (Fig. 2C). The relationship between τ and the target movement is depicted in Fig. 2B. These indicate that the tangential force $f^{\text{spiral}}(\tau)$ was determined by the spatial position of the nearest point, not by its temporal aspect. The spiral force f^{spiral} was calculated by multiplying the second-order derivative of the minimum angular jerk logarithmic spiral trajectory $\ddot{x}^{\text{spiral}}$ (acceleration of the target movement) with a virtual mass of $M = 2$ kg.

Target guidance restricted the stylus to the target marker with compensation for force applied by the participants. The controller is implemented in the joint space, and the torque τ of each motor was computed by

$$\tau = 270(\theta^{\text{cmd}} - \theta) + 90(\dot{\theta}^{\text{cmd}} - \dot{\theta}) - \hat{\tau}^{\text{hum}}, \tag{5}$$

where θ^{cmd} denotes the command angle given by the spiral trajectory and the inverse kinematics of the robot, and the term $-\hat{\tau}^{\text{hum}}$ compensates for a participant's torque using the estimated torque (1) as a disturbance observer [31], [32], [33]. For each guidance, the derivatives were computed by pseudo-differentiation using low-pass filters.

E. Performance Measures and Statistical Analysis

To quantify the improvement in the task, we defined a spatial error score J_{s}:

$$J_{\text{s}} = \frac{1}{t_{\text{f}}}\int_0^{t_{\text{f}}} |e_{\text{s}}(t)|dt, \tag{6}$$

and a temporal error score J_{t}:

$$J_{\text{t}} = \frac{1}{t_{\text{f}}}\int_0^{t_{\text{f}}} |e_{\text{t}}(t)|dt, \tag{7}$$

where $e_{\text{s}}(t)$ and $e_{\text{t}}(t)$ denote the spatial and temporal errors, respectively (Fig. 2C), and t_{f} is the shorter end time of either the participant's movement or the target movement. The spatial error is the distance between the stylus and the point nearest to the stylus on the spiral trajectory, and the temporal error is the distance on the spiral trajectory between the target marker and the position nearest to the stylus on the spiral trajectory. Using J_{s} and J_{t}, we defined the spatiotemporal error score J by integrating the normalized spatial and temporal error scores as follows:

$$J = \frac{1}{2}\left(\frac{J_{\text{s}}}{\bar{J}_{\text{sBL}}} + \frac{J_{\text{t}}}{\bar{J}_{\text{tBL}}}\right), \tag{8}$$

where $\bar{J}_{\text{sBL}}$ and $\bar{J}_{\text{tBL}}$ denote the means of the three-trial scores of the 20 participants assigned to the same group in BL

$$\bar{J}_{\text{sBL}} = \frac{1}{60}\sum_{i=1}^{20}\sum_{j=1}^{3} J_{\text{s}ij} \tag{9}$$

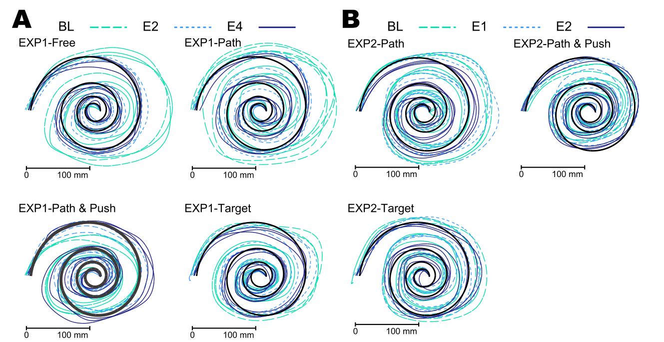

Fig. 3. Examples of the drawn spirals. Each phase has three lines from the three trials. (A) Spirals drawn by the four representative participants from the four groups at BL, E2, and E4 in Experiment 1. (B) Spirals drawn by the three representative participants from the three groups at BL, E1, and E2 in Experiment 2.

TABLE I
SIMPLE MAIN EFFECTS OF THE GUIDANCE AND SCHEDULE

Experiment 1		Experiment 2	
	p-value		p-value
Guidance at E1	$p < .001$	Guidance at E1	$p < .001$
Guidance at E2	$p < .001$	Guidance at E2	$p = 0.697$
Guidance at E3	$p < .001$		
Guidance at E4	$p < .001$		
Phases at Free	$p < .001$		
Phases at Path	$p < .001$	Phases at Path	$p < .001$
Phases at P&P	$p < .001$	Phases at P&P	$p < .001$
Phases at Target	$p < .001$	Phases at Target	$p < .001$

$$\bar{J}_{\text{tBL}} = \frac{1}{60}\sum_{i=1}^{20}\sum_{j=1}^{3} J_{\text{t}ij}. \tag{10}$$

The variables $J_{\text{s}ij}$ and $J_{\text{t}ij}$ denote the ith subject's spatial error score J_{s} and temporal error score J_{t} at jth trial in BL, respectively. A decrease in the scores indicates an improvement in drawing in terms of both speed and accuracy. Although the performance measure is spatiotemporal, the spatiotemporal error score reflects spatial aspect mainly because we instructed the participants to prioritize temporal accuracy over spatial accuracy.

To statistically compare the spatiotemporal error scores J of the four groups, we conducted a two-way analysis of variance (ANOVA) with a between-subject variable (type of guidance) and a within-subject variable (phases). Additionally, we conducted multiple comparisons using Shaffer's modified sequentially rejective Bonferroni procedure for post hoc analysis. All statistical hypothesis tests were performed at a significance level of 0.05.

F. Ethics Statement

The Ethics Committee on Human Research of Waseda University approved the study and consent procedures. All participants provided written informed consent in accordance with the Declaration of Helsinki.

III. RESULTS

A. Experiment 1

Representative examples of the drawn spirals are shown in Fig. 3A, and the spatiotemporal error scores during the evaluation phases are summarized in Figs. 4A and 4B. The

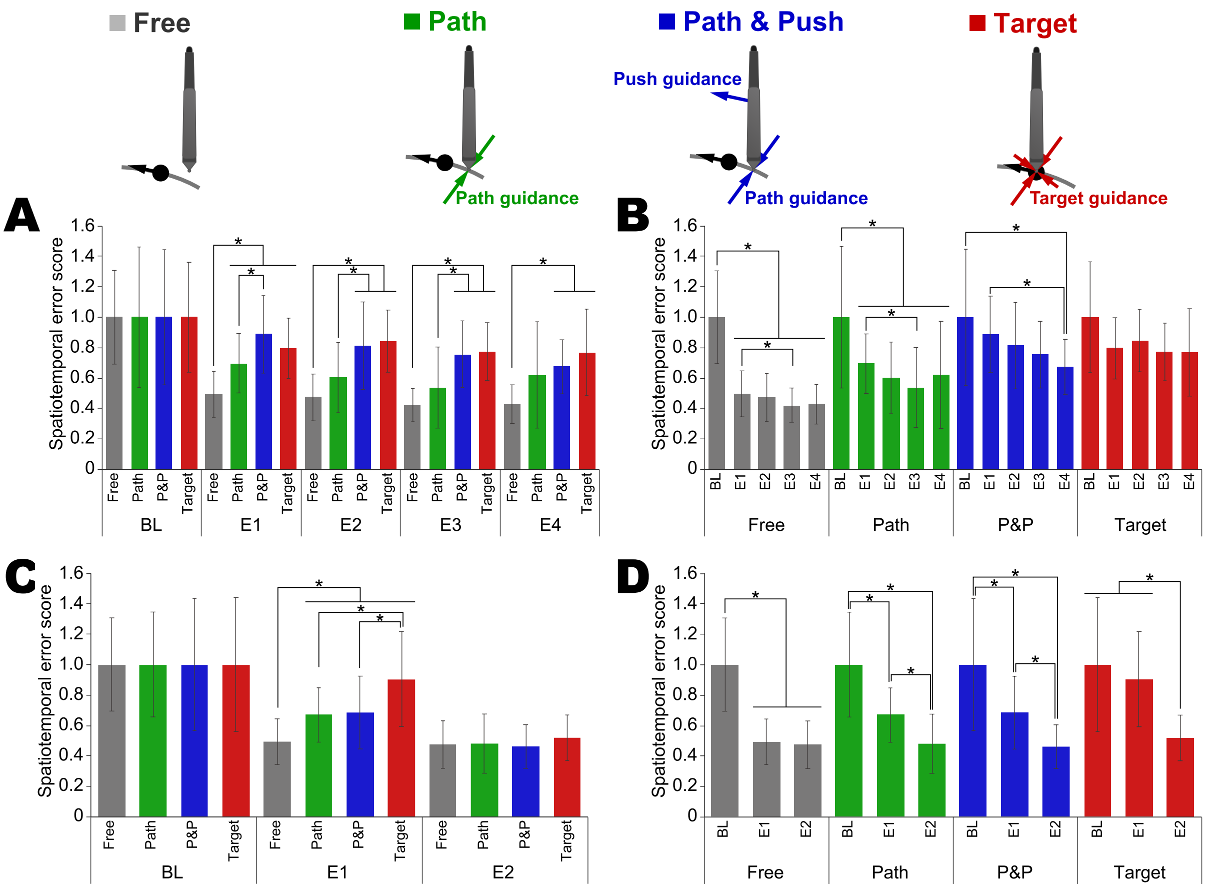

Fig. 4. Spatiotemporal error scores of the four types of guidance at the baseline and evaluation phases. The scores of the Free group in C and D are the same as those in A and B, respectively. (A) Comparison among the guidance for Experiment 1. (B) Comparison among the phases for Experiment 1. (C) Comparison among the guidance for Experiment 2. (D) Comparison among the phases for Experiment 2.

two-way ANOVA showed a statistically significant interaction between the schedule and the type of guidance ($F(12, 304) = 3.48$, $p < .001$). There were simple effects among groups ($F(3, 304) = 8.13$, $p < .001$) and through the phases ($F(4, 304) = 51.8$, $p < .001$). The results of the simple main effect analysis are summarized in Table I. In Experiment 1, the simple main effects of the type of guidance and the schedule were significant in all phases and groups. Multiple comparisons showed that the spatiotemporal error score of the Free group was significantly lower than those of the Path & Push and Target groups at all evaluation phases (E1–E4), and it was significantly lower than that of the Path group only at E1. Additionally, the scores of the Path group were significantly lower than those of the Path & Push group from E1 to E3. In the Free and Path groups, the spatiotemporal error score significantly decreased from BL, and the score at E3 was significantly lower than that at E1. In the Path & Push group, the score at E4 was significantly lower than those at BL and E1. No significant improvement was observed in the Target group.

B. Experiment 2

Representative examples of the drawn spirals are shown in Fig. 3B. The two-way ANOVA showed a significant interaction between the schedule and group ($F(6, 152) = 3.70$, $p < .01$). There was no simple effect among the groups ($F(3, 152) = 1.73$, $p = 0.167$), but there was a simple effect across the phases ($F(2, 152) = 118$, $p < .001$). The results of the three groups from Experiment 2 were compared with that of the Free group from Experiment 1. The results of the simple main effect analysis are summarized in Table I. The simple main effect of the guidance type was significant only at E1, and the effects of schedule were significant in all groups. Multiple comparisons showed that the spatiotemporal error score of the Free group was the lowest, and that of the Target group was the highest, at E1 (Fig. 4C). Additionally, the scores at E1 were lower than those at BL in all groups except for the Target group, while the scores at E2 were lower than those at BL in all groups.

IV. Discussion

Direct comparisons of different types of haptic guidance revealed that lower-intensity haptic guidance (Path guidance) led to greater learning effects in the spiral-drawing task, and the best learning was observed in the absence of any robotic assistance (Free guidance), according to Experiment 1 (Fig. 4A and 4B). First, the spatiotemporal error score in the Path group was smaller than that of the Path & Push group from E1 to E3 and that of the Target group at E2 and E3, while there were no significant differences among them at E4. Second, the errors in the Path & Push group significantly decreased as the practice proceeded, but not in the Target group. Third, errors in the Free group were consistently smaller than those in the other groups. These results support our hypothesis that the learning effect increases in the following order: Target, Path & Push, Path, and Free guidance, suggesting that the intensity of sensory feedback and voluntary motor control play an important role in robot-assisted motor learning. However, note that this order of learning effects may not be completely robust, as performance in the Path & Push group was not consistent at E1 between Experiments 1 and 2 (Fig. 4A and 4C).

In addition to the direct comparison of learning efficacy among the four types of guidance in Experiment 1, we examined the effect of pre-learning with haptic guidance on post-learning without haptic guidance in Experiment 2 (Fig. 4C and 4D). The results did not indicate significant differences among the groups, suggesting that self-supported learning after robot-assisted learning was neither facilitated nor hindered by pre-learning type. However, the overall learning speed was affected by the learning speed and effect of the pre-learning type. These findings are particularly important when considering the introduction of robot-assisted rehabilitation into clinical practice.

The superiority of the low-intensity guidance can be interpreted using error-based learning [19], [20], [21]. The error-based learning theory assumes that the differences between predicted and actual sensory outcomes are used to update motor commands for subsequent movements [19], [20], [21]. Based on this theory, it has been posited that the neural system for motor control recalibrates the mappings between sensory input and motor output according to sensory error feedback [20], [22]. We assumed that the four types of guidance involved different amounts of sensory feedback and voluntary effort. Because lower guidance intensity requires the participants' active motor output to complete the task, higher voluntary motor control would be necessary with Free and Path guidance, followed by Path & Push and Target guidance. Voluntary motor control allows participants to acquire sensory feedback error information [34], [35], while accurate movements without voluntariness, such as those achieved by Target guidance, do not provide much error information for learning. However, it is unclear whether visual or proprioceptive feedback strongly influences the learning performance.

Although it is not straightforward to compare our experiments with previous ones owing to their different controllers, tasks, and learning schedules, we briefly compare our results with them in the following paragraphs. Hereafter, we use our labeling of haptic guidance for those used in previous studies, although they are not exactly the same.

First, previous studies did not find a clear advantage of self-supported learning over robot-assisted learning; however, we observed a statistically significant improvement in Free guidance over the haptic guidance. Sigrist et al. [36] compared their haptic guidance condition, which was similar to our Path guidance, with their Free guidance condition in an oaring task. They showed that the Free group was significantly better than the Path group in velocity error but not in spatial error, in which learning outcome and speed were evaluated together. In our spiral-drawing task, we further observed a statistical difference in the spatiotemporal error score, putting a weight on the spatial performance, between the Free and Path groups. It was also found that a significant difference appeared only in the early phase as different learning speeds and disappeared in the later phases as similar learning outcomes in Experiment 1 (Fig. 4A). Marchal-Crespo et al. [14] also found a significant difference in the learning outcomes between Free and Path guidance, while their amount of training was less than that in our experiment. Their result may correspond to our transient result at E1, showing the significant difference; our results were consistent with them. Regarding Path & Push guidance, Bluteau et al. [15] did not find a significant difference between Push-only guidance (without virtual walls) and Free guidance, while the study did not observe a significant improvement in trajectory shape matching scores in either Free or Push-only group. In contrast, we found the superiority of Free guidance in terms of learning speed over Path guidance and of learning outcome over Path & Push and Target guidances significantly.

Second, consistent with the present experiment, previous studies have indicated the ineffectiveness of fully assisted control in motor learning, particularly in terms of spatial aspects. Consistent with our results, that the Target group showed the lowest learning effect among the four groups, Liu et al. [12] found that Target guidance, in addition to visual demonstration, did not improve the performance significantly compared to the visual demonstration only in a 3D drawing task. Moreover, in a rowing task, Rauter et al. [13] hypothesized the least and best effectiveness of Target guidance in the spatial and temporal aspects, respectively. Our results were consistent with their hypothesis because our spatiotemporal error score reflects the spatial accuracy more than the temporal accuracy, as we instructed the participants to prioritize temporal accuracy over spatial reproduction. This idea is possible because it has been reported that spatial and temporal accuracies develop separately in a drawing task [30] and should be addressed in future studies.

A. Implications for Stroke Rehabilitation

Experiment 2 examined the effect of pre-learning with haptic guidance on post-learning without robotic guidance, based on an ordinary clinical practice situation that aimed to regain self-supported movements. While lower-intensity guidance (Path and Path & Push guidance) was superior to highest-intensity guidance (Target guidance) at E1, no significant differences were found among them after experiencing post-learning with Free guidance at E2 (Fig. 4C). This result indicates that the self-supported learning after the robot-assisted learning was neither facilitated nor hindered by the type of haptic guidance used in the pre-learning. The similarity in the time course of the score decrease between the Free group in the first learning phase (L1) and the Target group in the second learning phase (L2) also supports this hypothesis

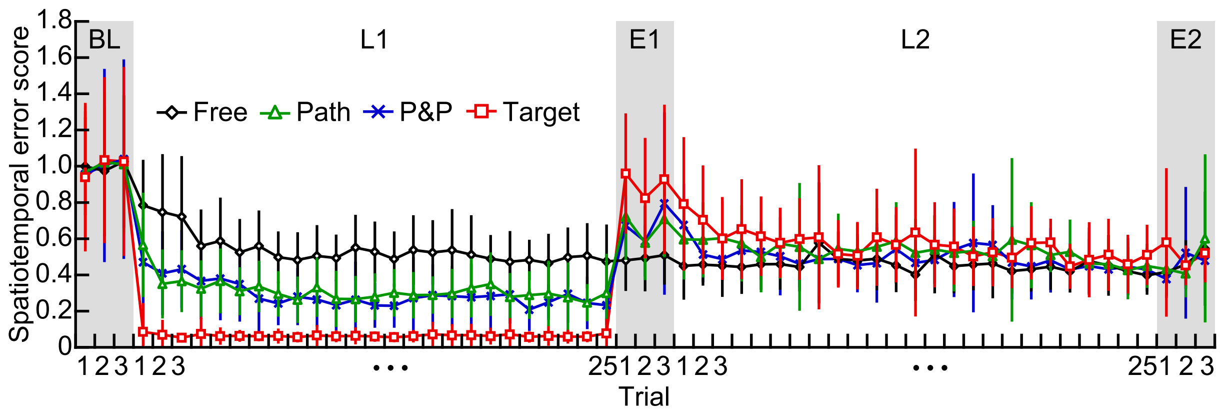

Fig. 5. Spatiotemporal error score of the four types of guidance at each trial in Experiment 2.

(see Appendix). This finding suggests that there are no qualitative (but quantitative) differences between self-supported and robot-assisted rehabilitation, which could support the introduction of robots into clinical practice before self-supported practice to mitigate the physical and mental burden on patients.

The findings from healthy participants cannot be directly applied to stroke rehabilitation. Given the above discussion, the important finding from our study is that robot-assisted guidance may provide participants with qualitatively similar but quantitatively less learning effect depending on available sensorimotor information. Unlike our findings from the two experiments that Free guidance was the best method for healthy young participants to learn the drawing movement, studies on chronic stroke patients reported that Path guidance was more beneficial than Free guidance [7] and that there was no statistically significant effect of Free guidance over Target guidance [5]. This may be because moving an affected limb itself is important for future recuperation even if it is not voluntary [37], [38]. Therefore, the appropriate selection of rehabilitation intensity according to the severity of the patient's motor dysfunction may contribute to the recovery of upper limb motor function equivalent to or better than self-supported learning. Nevertheless, to reconcile the discrepancies among these findings, further investigations focusing on stroke patients are necessary.

Appendix

Spatiotemporal Error Score at Each Trial in Experiment 2

The transitions in the spatiotemporal error scores for the four types of guidance at each trial in Experiment 2 are shown in Fig. 5. In the learning phases, the score of the Target group was the lowest because of its highest guidance intensity at L1, and those of the Path, Path & Push, and Target groups decreased at L2 because they underwent the post-learning with Free guidance in L2. Here, the scores of the Free group at BL and the Target group at E1 were similar, and the time course of the decrease in the Target group at L2 was similar to that of the Free group at L1. This similarity supports the effect of post-learning with Free guidance after pre-learning with haptic guidance, although the reduction in the scores of the haptic guidance groups was accomplished by the post-learning with the Free guidance, as the three scores after the post-learning at E2 were close to the score of the Free group at E1.

Acknowledgment

The authors would like to thank Takahiro Ebato for his assistance with the experiments.

References

[1] J. M. Veerbeek et al., "Effects of robot-assisted therapy for the upper limb after stroke: A systematic review and meta-analysis," *Neurorehabil. Neural Repair*, vol. 31, no. 2, pp. 107–121, 2017.

[2] H. I. Krebs et al., "Rehabilitation robotics: Performance-based progressive robot-assisted therapy," *Autonom. Robot.*, vol. 15, no. 1, pp. 7–20, Jul. 2003.

[3] G. Kwakkel, B. J. Kollen, and H. I. Krebs, "Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review," *Neurorehabilitation Neural Repair*, vol. 22, no. 2, pp. 111–121, Mar. 2008.

[4] E. Basalp, P. Wolf, and L. Marchal-Crespo, "Haptic training: Which types facilitate (re)learning of which motor task and for whom? Answers by a review," *IEEE Trans. Haptics*, vol. 14, no. 4, pp. 722–739, Oct. 2021.

[5] L. E. Kahn, M. L. Zygman, W. Z. Rymer, and D. J. Reinkensmeyer, "Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: A randomized controlled pilot study," *J. Neuroeng. Rehabil.*, vol. 3, no. 1, pp. 1–13, 2006.

[6] W.-W. Liao, C.-Y. Wu, Y.-W. Hsieh, K.-C. Lin, and W.-Y. Chang, "Effects of robot-assisted upper limb rehabilitation on daily function and real-world arm activity in patients with chronic stroke: A randomized controlled trial," *Clin. Rehabil.*, vol. 26, no. 2, pp. 111–120, Feb. 2012.

[7] Y.-W. Hsieh, C.-Y. Wu, W.-W. Liao, K.-C. Lin, K.-Y. Wu, and C.-Y. Lee, "Effects of treatment intensity in upper limb robot-assisted therapy for chronic stroke: A pilot randomized controlled trial," *Neurorehabilitation Neural Repair*, vol. 25, no. 6, pp. 503–511, Jul. 2011.

[8] C. Tamantini et al., "Tailoring upper-limb robot-aided orthopedic rehabilitation on patients' psychophysiological state," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 31, pp. 3297–3306, 2023.

[9] J. Mehrholz, M. Pohl, T. Platz, J. Kugler, and B. Elsner, "Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and arm muscle strength after stroke," *Cochrane Database Systematic Rev.*, no. 9, Sep. 2018, doi: 10.1002/14651858.CD006876.pub5.

[10] W.-T. Chien, Y.-Y. Chong, M.-K. Tse, C.-W. Chien, and H.-Y. Cheng, "Robot-assisted therapy for upper-limb rehabilitation in subacute stroke patients: A systematic review and meta-analysis," *Brain Behav.*, vol. 10, no. 8, p. e01742, 2020.

[11] J. Wu, H. Cheng, J. Zhang, S. Yang, and S. Cai, "Robot-assisted therapy for upper extremity motor impairment after stroke: A systematic review and meta-analysis," *Phys. Therapy*, vol. 101, no. 4, Apr. 2021, Art. no. pzab010.

[12] J. Liu, S. C. Cramer, and D. Reinkensmeyer, "Learning to perform a new movement with robotic assistance: Comparison of haptic guidance and visual demonstration," *J. NeuroEngineering Rehabil.*, vol. 3, no. 1, pp. 1–10, Dec. 2006.

[13] G. Rauter, R. Sigrist, R. Riener, and P. Wolf, "Learning of temporal and spatial movement aspects: A comparison of four types of haptic control and concurrent visual feedback," *IEEE Trans. Haptics*, vol. 8, no. 4, pp. 421–433, Oct. 2015.

[14] L. Marchal-Crespo, N. Rappo, and R. Riener, "The effectiveness of robotic training depends on motor task characteristics," *Exp. Brain Res.*, vol. 235, no. 12, pp. 3799–3816, Dec. 2017.

[15] J. Bluteau, S. Coquillart, Y. Payan, and E. Gentaz, "Haptic guidance improves the visuo-manual tracking of trajectories," *PLoS ONE*, vol. 3, no. 3, p. e1775, Mar. 2008.

[16] S. J. Kim et al., "Effect of dyadic haptic collaboration on ankle motor learning and task performance," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 31, pp. 416–425, 2023.

[17] R. Lokesh and R. Ranganathan, "Haptic assistance that restricts the use of redundant solutions is detrimental to motor learning," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 28, no. 6, pp. 1373–1380, Jun. 2020.

[18] J. L. Emken and D. J. Reinkensmeyer, "Robot-enhanced motor learning: Accelerating internal model formation during locomotion by transient dynamic amplification," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 13, no. 1, pp. 33–39, Mar. 2005.

[19] M. Kawato, "Feedback-error-learning neural network for supervised motor learning," in *Proc. Adv. Neural Comput.*, 1990, pp. 365–372.

[20] M. Kawato and H. Gomi, "A computational model of four regions of the cerebellum based on feedback-error learning," *Biol. Cybern.*, vol. 68, no. 2, pp. 95–103, Dec. 1992.

[21] H. Gomi and M. Kawato, "Neural network control for a closed-loop system using feedback-error-learning," *Neural Netw.*, vol. 6, no. 7, pp. 933–946, Jan. 1993.

[22] D. M. Wolpert, R. C. Miall, and M. Kawato, "Internal models in the cerebellum," *Trends Cogn. Sci.*, vol. 2, no. 9, pp. 338–347, Sep. 1998.

[23] L. Marchal-Crespo, M. Bannwart, R. Riener, and H. Vallery, "The effect of haptic guidance on learning a hybrid rhythmic-discrete motor task," *IEEE Trans. Haptics*, vol. 8, no. 2, pp. 222–234, Apr. 2015.

[24] A. Basteris, S. M. Nijenhuis, A. H. Stienen, J. H. Buurke, G. B. Prange, and F. Amirabdollahian, "Training modalities in robot-mediated upper limb rehabilitation in stroke: A framework for classification based on a systematic review," *J. NeuroEngineering Rehabil.*, vol. 11, no. 1, p. 111, 2014.

[25] T. Murakami, F. Yu, and K. Ohnishi, "Torque sensorless control in multidegree-of-freedom manipulator," *IEEE Trans. Ind. Electron.*, vol. 40, no. 2, pp. 259–265, Apr. 1993.

[26] S. Katsura, Y. Matsumoto, and K. Ohnishi, "Modeling of force sensing and validation of disturbance observer for force control," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 530–538, Feb. 2007.

[27] C. Mitsantisuk, K. Ohishi, and S. Katsura, "Estimation of action/reaction forces for the bilateral control using Kalman filter," *IEEE Trans. Ind. Electron.*, vol. 59, no. 11, pp. 4383–4393, Nov. 2012.

[28] D. Haubenberger et al., "Validation of digital spiral analysis as outcome parameter for clinical trials in essential tremor," *Movement Disorders*, vol. 26, no. 11, pp. 2073–2080, Sep. 2011.

[29] P. M. Fitts, "The information capacity of the human motor system in controlling the amplitude of movement," *J. Experim. Psychol.*, vol. 47, no. 6, pp. 381–391, 1954.

[30] Y. Itaguchi and K. Fukuzawa, "Influence of speed and accuracy constraints on motor learning for a trajectory-based movement," *J. Motor Behav.*, vol. 50, no. 6, pp. 653–663, Nov. 2018.

[31] E. Sariyildiz and K. Ohnishi, "Stability and robustness of disturbance-observer-based motion control systems," *IEEE Trans. Ind. Electron.*, vol. 62, no. 1, pp. 414–422, Jan. 2015.

[32] W.-H. Chen, J. Yang, L. Guo, and S. Li, "Disturbance-observer-based control and related methods—An overview," *IEEE Trans. Ind. Electron.*, vol. 63, no. 2, pp. 1083–1095, Feb. 2016.

[33] E. Sariyildiz, R. Oboe, and K. Ohnishi, "Disturbance observer-based robust control and its applications: 35th anniversary overview," *IEEE Trans. Ind. Electron.*, vol. 67, no. 3, pp. 2042–2053, Mar. 2020.

[34] M. Kawato, K. Furukawa, and R. Suzuki, "A hierarchical neural-network model for control and learning of voluntary movement," *Biol. Cybern.*, vol. 57, no. 3, pp. 169–185, Oct. 1987.

[35] J. Izawa and R. Shadmehr, "Learning from sensory and reward prediction errors during motor adaptation," *PLoS Comput. Biol.*, vol. 7, no. 3, Mar. 2011, Art. no. e1002012.

[36] R. Sigrist, G. Rauter, L. Marchal-Crespo, R. Riener, and P. Wolf, "Sonification and haptic feedback in addition to visual feedback enhances complex motor task learning," *Exp. Brain Res.*, vol. 233, no. 3, pp. 909–925, Mar. 2015.

[37] N. Kapadia, B. Moineau, and M. R. Popovic, "Functional electrical stimulation therapy for retraining reaching and grasping after spinal cord injury and stroke," *Frontiers Neurosci.*, vol. 14, Jul. 2020, Art. no. 529318.

[38] S. Blanton and S. L. Wolf, "An application of upper-extremity constraint-induced movement therapy in a patient with subacute stroke," *Phys. Therapy*, vol. 79, no. 9, pp. 847–853, Sep. 1999.