Naviarm: Augmenting the Learning of Motor Skills using a Backpack-type Robotic Arm System

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ABSTRACT

We present a wearable haptic assistance robotic system for augmented motor learning called Naviarm. This system comprises two robotic arms that are mounted on a user's body and are used to transfer one person's motion to another offline. Naviarm pre-records the arm motion trajectories of an expert via the mounted robotic arms and then plays back these recorded trajectories to share the expert's body motion with a beginner. The Naviarm system is an ungrounded system and provides mobility for the user to conduct a variety of motions. In this paper, we focus on the temporal aspect of motor skill and use a mime performance as a case study learning task. We verified the system effectiveness for motor learning using the conducted experiments. The results suggest that the proposed system has benefits for learning sequential skills.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**; *Human computer interaction (HCI)*; • **Computer systems organization → Robotics**;

KEYWORDS

Augmented learning; Wearable Device; Motor Learning; Haptics; Robotics;

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1 INTRODUCTION

Our bodies are separate entities, and we rely on our sensory feedback to observe and learn from other people or instructors. In motor learning, beginners rely on indirect methods to learn the body motions or performances of another person and offline learning usually relies on prerecorded video and audio files. In other words, it is necessary to rely on information obtained via observations of a model or verbal instructions if the coaching cannot be obtained thoroughly. Beginners need to understand the obtained information and remember sequential motions, and then they need to remap the motion to their own bodies. This process is often non-intuitive and can yield incorrect motion trajectories for learners due to the lack of direct feedback on their body.

As a way to solve this problem, haptic feedback has been used to support other modalities. Multiple studies have aimed at assisting and accelerating the motor learning process by enhancing information feedback via haptic interfaces [23, 28]. In these approaches, tabletop mechanical devices often act as haptic displays. However, the use of such grounded approaches results in a motion range that is limited to the degree of freedom (DoFs) of the end effector of the device and by its fixed point in the environment.

In this paper, we propose Naviarm, a haptic assistance system for the augmented learning of motor skills that allows the user to record and play over a relatively wide motion range with the mobility. Naviarm is a backpack-type robotic arm device with seven DoFs per arm (Figure 1). In this system, the motion trajectories of an expert's arms relative to the expert's torso are recorded. The target user of this system is a beginner who aims to learn motor skills from the expert. The user can play back the prerecorded motion trajectories via the robotic arms as a learning support.

In this paper, we test this system using a case study for the motor learning of a mime performance. Mime artists require a high degree of muscle control to convey a convincing performance. The conducted user study verifies the degree of the learned motor skills for beginner users.

Our contributions are summarized as follows.

- We propose a wearable backpack-type haptic device with dual robotic arms.

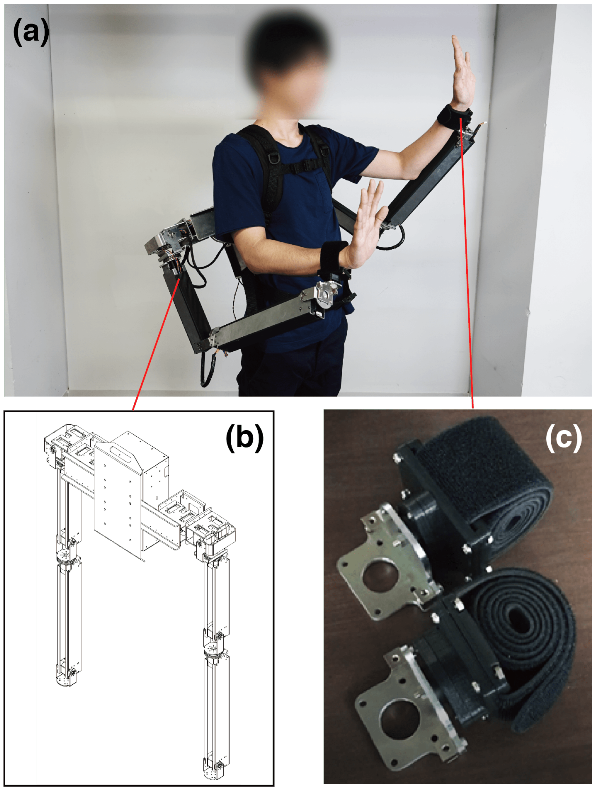

Figure 1: (a) A system overview of the wearable haptic guidance system called Naviarm. (b) The hardware design of the backpack-type robotic arms. (c) The wristband to provide haptic feedback from the robot to the wearer.

- We develop a haptic assistance system for augmented learning of motor skills including mobility and a wide range of motion.
- A case study verifies the benefits of the system for motor skill training using a mime performance.

2 RELATED WORK

Naviarm is derived from wearable haptic devices, haptic guidance for motor skill training, and systems for body performance training.

2.1 Wearable Haptic Devices

Many studies use grounded apparatuses for haptic guidance, such as commercially available haptic devices or manipulators. Therefore, the workspace available to a user is limited. One way to transfer haptic information to a user preserving spatial mobility is to use a wearable device. HapticGear and SPIDAR-W are backpack-type mechanical haptic feedback devices [14, 21]. Rotor thrust [12] and the gyro effect [33] have been utilized for hand-held-type haptic display devices. HapticSerpent [1] proposed a waist-worn robot to provide direct feedback on the user's body via a touch and pinch system.

Lopes et al. proposed a wearable approach for generating haptic feedback with electrical muscle stimulation (EMS) [19]. While these approaches can provide the feeling of touching an object in virtual space, they are not suitable for conveying continuous motion trajectories.

In an approach similar to our system, there have been studies conducted on robotic exoskeletons. However, many of these studies focus on power assistance and rehabilitation [3]. The work closest to that of Naviarm was proposed by Saraiji et al. [26] for remote guidance and collaboration by enforcing the posture of a surrogate via a remote user. However, there was no evaluation of their system with respect to the transfer and learning of motor skills.

Our goal is to use the developed backpack-type haptic system to assist in learning motor skills by actively simulating the user's body. The system evaluation presented in this paper verifies the effect of the proposed approach on learning motor skills.

2.2 Haptic Guidance for Motor Skill Training

Previous studies have not completely proved the advantages of a haptic guidance approach for learning motor skills. Several studies have reported that haptic guidance can improve motor skills [2, 4]; however, there are also results showing that haptic guidance does not have a significant effect on learning motor skills [8, 30, 32]. Further, Lee et al. demonstrated that haptic guidance was actually detrimental to learning motor skills and that haptic disturbances were more effective [17]. One likely reason for this is that the effect of haptic guidance depends on the type of learning task.

Conversely, in the case of the temporal aspects of a motor skill, e.g., timing, patterns, or sequences, several studies have shown that haptic guidance does provide benefits. Morris et al. reported that haptic guidance was effective for learning a sequence of forces [20]. Feygin et al. conducted an experiment to learn 3D hand trajectories. Their experiment showed that the temporal aspects of a task were effectively learned with haptic guidance, while the spatial aspects were not improved [6]. When playing musical instruments, timing and rhythm are both important and haptic benefits have been reported [7, 10]. In our proposed system, we conduct an experiment to verify the effectiveness of Naviarm on the temporal aspects of learning motor skills.

In addition, many approaches including those described above have concentrated on the range of motion in a hand or on a desktop range. Few verification studies have been done for systems that can handle relatively wide ranges of motion and motion accompanying whole body movement. We aim to construct a system that combines a wide range of upper arm workspace and mobility.

2.3 Training Assist System for Body Performances

Many approaches for providing external self-images have been proposed as methods to support the training of motor skills for activities such as dancing [31], jogging [29], and playing sports [13]. These approaches encourage users to improve their motor skills by allowing them to observe their own behavior. Lieberman et al. proposed an approach for the motor skill transfer of upper limb motions using a vibrotactile device [18]. They showed that the performance was improved via tactile feedback. Landin and Hebert developed the method for improvement of the skill of tennis players by enhancing mental ability[16]. Hiyama et al. proposed

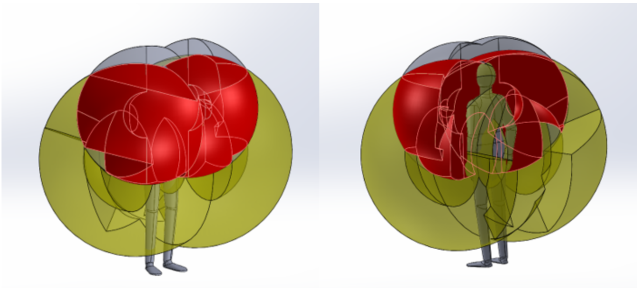

Figure 2: An overview of a common domain calculation for the range of motion of a human arm and the robot trajectory domain. The gray, yellow, and red regions indicate the ranges of motion in the human arm, Naviarm, and the common domain, respectively.

an expert-skill transferal system based on first-person audiovisual information and tactile feedback [15]. We aim to provide significant information for skills that are difficult to transmit using conventional approaches.

3 SYSTEM OVERVIEW

In this section, we present a wearable haptic guidance system for learning arm motor skills. Figure 1 shows an overview of the proposed device and system. The Naviarm system provides haptic feedback for the wrist position trajectory from experts to beginners using the medium of a wearable robotic arm. Our system for skill learning is composed of backpack robotic arms, haptic-feedback wristbands, and a record-and-replay system.

3.1 Backpack-type Robotic Arms

The hardware design of the backpack dual-arm robot is shown in Figure 1(b). The robot can be carried on the back and has a total weight of 5.75 kg. Each arm has six DoFs and a length of 787 mm. Each joint of the robotic arms is driven by servo-motors (Kondo B3M-SC-1070-A and B3M-SC-1170-A). The maximum torque of the shoulder joint is 15.2 N m, and the resolution is 0.088°. As shown in Figure 2, the proposed robotic arm sufficiently covers the range of motion of a human arm [22] and is longer than the average human arm [24]. Therefore, it does not limit the movement of the wearer's arm motion and maintains the DoFs necessary to learn a motor skill. For details on the design of the robotic arm, please refer to [25].

3.2 Haptic-Feedback Wristband

We designed a custom wristband that connects the end effector of the robotic arm to the wearer's wrist (Figure 1(c)). This wristband consists of 3D printed parts, bearings, and a cloth band. Its total weight is 91 g, and the cloth band can be applied regardless of body differences. The bearing gives a one-DoF passive joint to the wristband. The proposed number of DoFs was chosen because our feasibility study indicated that a seven-DoF robotic arm including an end effector is suitable for skill extraction from an expert and skill transmission to a beginner.

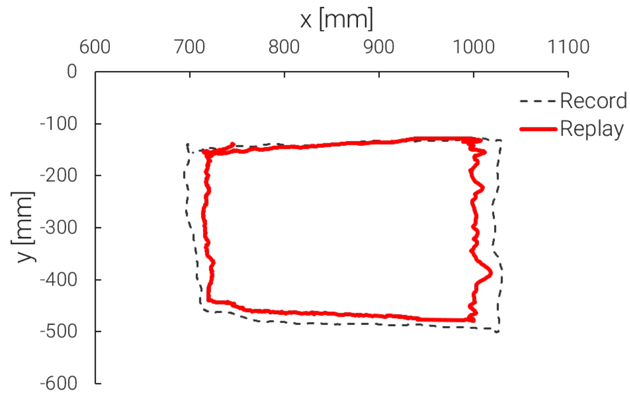

Figure 3: The position accuracy of proposed record-and-replay system without wearing.

3.3 Record-and-Replay System

The Naviarm system comprises a recording phase for the expert motion trajectory and a replay phase. First, in the recording phase, an expert carries the robot arms and a haptic-feedback wristband is attached to each of the expert's wrists. When the expert performs an arm motor skill movement, the joint angle data of each robot arm are sequentially recorded as the 3D trajectory of the wrist positions with respect to the wearer's torso. These angle data are translated into wrist position trajectories expressing the sequential motor skill of the expert. The sampling frequency of the system is set to 100 Hz. During the recording phase, the motors of the robotic arms are set to free rotation so that the system does not add extra force to the wearer and the expert can perform the motor skill performance in the same way as when the robotic arm is not worn.

In the replay phase, the robotic arm is set to active control, and therefore, all motors are activated. The arms move the beginner's wrists according to the sequential angle data of the recorded expert motor skill movement. In this phase, the recorded data are also queried at 100 Hz; therefore, the temporal resolution of the motion is 0.01 sec. At that time, a beginner can learn the sequential motion trajectory of the expert while a directed force is applied to the wrist via the wristband.

To measure the accuracy of the record-and-reply system, we used a HTC VIVE Tracker to make position measurements of the end effector. The position accuracy of the Naviarm record-and-replay system is shown in Figure 3. The maximum errors in the position trajectory between record and replay were 47.8 mm (x-axis) and 42.4 mm (y-axis). We assume that the main source of this error is due to the backlash in the gearing system of the motor. However, the replayed trajectories were similar to the recorded paths without sequential changes. Therefore, even though the proposed Naviarm system can be effective for teaching sequential motor skills, it is not suitable for motor skills that require high positional accuracy (such as painting).

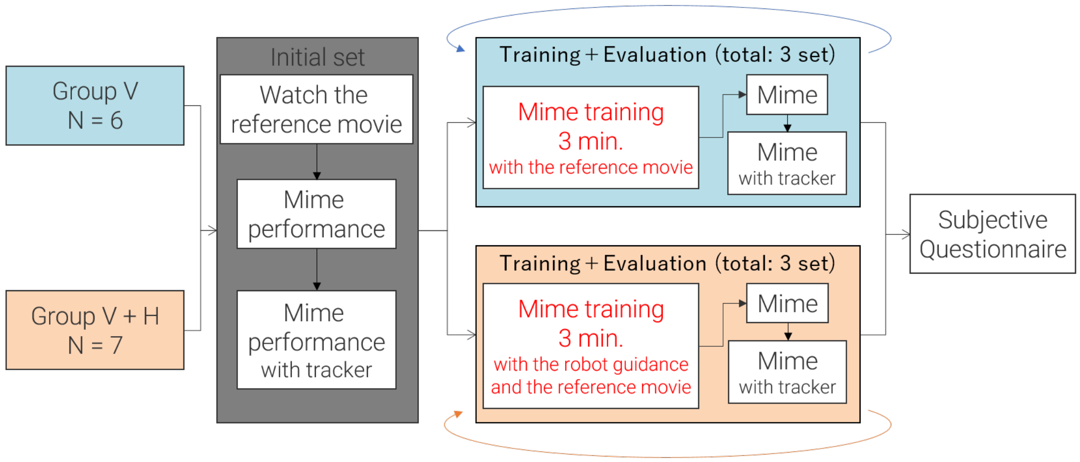

Figure 4: Experimental flow diagram. The difference between the two groups is the method used in the training phase.

3.4 Naviarm System

Here, we present the main characteristics of the developed backpack-type robotic arm system for learning motor skills. First, the proposed Naviarm system can directly teach the temporal aspects of a motor skill, e.g., timing, pattern, or sequence, via the dual-robotic arms. During the acquisition of a motor skill, it is challenging to learn sequential motor skills as a structure that smoothly connects individual motor skills [27]. However, the Naviarm record-and-replay system first assists in conveying an expert's motor skills without sequential changes. Therefore, the wearer is able to learn a sequential motor skill with motions involving both entire upper limbs via direct haptic feedback. Second, the backpack-type robotic arms are applicable to a wide range of upper limb motor skills while allowing for freedom of movement in the legs. Third, the proposed backpack-type robotic arms have higher mobility compared to grounded apparatuses. Mobility is essential for training a wide range of upper limb motor skills while involving the movement of a user's legs, for example, for activities such as dancing and sports. Therefore, the mobility of Naviarm is an important characteristic in terms of the variety of applicable motor skills. Next, Naviarm provides moderate agency of the upper limbs to the user. Because haptic feedback is only applied to the user's wrists, the user's other joints can move freely. Therefore, we assume that beginners can maintain a certain level of active learning. Finally, Naviarm can be used for learning motor skills both online and offline. As an example of online use, using Naviarm, one teacher would be able to teach sequential dance movements to numerous students in real time.

4 EXPERIMENTS

We verified the effectiveness of the Naviarm system for learning motor skills. In this study, we set the motion of a mime, in particular the motion used to express an invisible wall (Figure 5(c)), as the target learning task. This motor skill was selected for the following reasons. 1) Sequential motor skills for the arms are important for mime performances. 2) A mime requires the action to significantly move both their arms and trunk. 3) Such a movement is suitable for an evaluation because a mime moves relatively slowly. We compared learning using Naviarm to an existing motor skill learning method for learning a mime performance.

4.1 Setup and Protocol

We conducted a case study to compare the effect of the Naviarm system on learning a skill to a method based only on visual information. The experiment participants comprised 12 males and 1 female (ages: 22.9 ± 0.99, heights: 174 ± 4.66 cm), who had no previous experience in miming. We recruited a 23-year-old man who had 10 years of mime and dance experience to record a mime performance expressing an invisible wall as the expert motion trajectory. The recorded performance involves whole body movements including leg movements to use the mobility of Naviarm, and the recorded time was approximately 20 s. In addition, we recorded a video of the expert motion and used it as a reference during the training sessions. Then, the experiment participants were divided into two groups: group V (6 people) and group V + H (7 people). In group V, the participants were trained in the mime performance based only on the reference video. Meanwhile in group V + H, the participants were trained using the robot guidance and the reference video (visual and haptic cross modality).

The experimental procedure is described as follows (Figure 4).

(1) Each participant watched the reference video. Next, the participant performed the same operation with the HTC VIVE Tracker attached to his/her hands for motion measurement and evaluation (Figure 5(d)).
(2) Participants were instructed to practice the mime performance of the expert in the reference video for approximately 3 min. The video was projected onto a wall using a projector and looped for the duration of the training time. During training, both groups were instructed to focus on aligning the palm sides of both of their hands. Participants in the V + H group were trained using the Naviarm, worn as shown in Figure 5(a), while the V group were trained without the robot, as shown in Figure 5(b). The robotic arm motion was

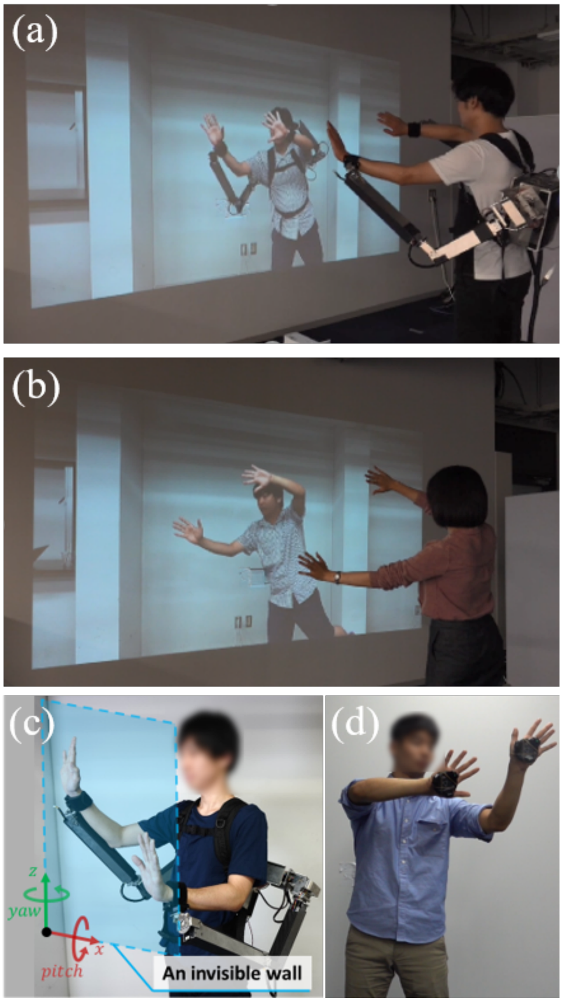

Figure 5: Overview of the experimental environment. (a) Participants in the V + H group practiced with Naviarm, which simultaneously replays the performance of the experts on the front video. (b) Participants in the V group practiced without Naviarm. (c) The overview of the mime's invisible wall (d) Measuring the palms of the hands for the mime motion using the HTC VIVE tracker fixed with rubber bands.

replayed in sync with the expert motion in the reference video.

(3) Similar to step 1, the participants' mime performance was recorded for evaluation using video playback and the tracker. In this step, group V + H participants performed without wearing the robot to evaluate the spatial memorization of the motion.
(4) Steps 2 and 3 were repeated three times (in three sets) for all participants to measure their temporal memorization.
(5) Finally, the participants filled in a questionnaire to provide a subjective qualitative evaluation of their experience.

4.2 Evaluation Criteria

We defined several evaluation criteria to evaluate the learning of the motor skills involved in the mime performance. Because miming is an artistic medium, a qualitative evaluation is important to indicate whether other people feel that an invisible wall exists. At the same time, from our interview of the mime expert, we found that one criterion to judge the miming skill level for an invisible wall is the alignment of the palm sides of both hands. In addition, a subjective evaluation focusing on not only the short-term skills being verified but also on long-term practice is a crucial index. Accordingly, the three evaluation criteria for the learning of the motor skill are shown below.

a) Experts qualitative evaluation score
The visual impression of the mime motion was qualitatively evaluated. Based on the interview with the expert and the grading criteria of rhythmic gymnastics [11], we set three scoring criteria comprising technique, composition, and expression points. *Technique points* evaluate the beauty of the mime's invisible wall. *Composition points* are evaluated based on the smoothness of the sequential connection of each motion. Finally, *composition points* involve the coincidence level of the expert's performance flow. Therefore, the composition points also refer to the level of the mime's sequential motor skills. The *expression points* evaluate the dynamics of the movement. In other words, we evaluated how much the wall could be expressed in relation to the spatial viewpoint. If participants express mobility in the reference video, high expression points are acquired.
Concerning the above three points, three experts with 10 years of mime or dance experience judged the participant's mime performances on a scale of 1–10. To eliminate any grading bias, we introduced a Z-score, which standardized the scores of each judge. If a raw score by a judge is x, then the Z-score is calculated as follows:

$$Z = \frac{1}{n}\sum_{k=1}^{n}\frac{x_k - \mu_k}{\sigma_k}, \tag{1}$$

where μ is the mean of the judges' scores, σ is the standard deviation, and n is the number of judges.

b) Quantitative evaluation based on the hand posture
To express an invisible wall in miming, it is important to align the palm sides of both hands as if the performer were touching the invisible wall. In other words, an evaluation is required for the level of coincidence between the pitch angle and the yaw angle for the palm sides of both hands. Therefore, we set the following evaluation index G based on the inclination of the hands in the pitch and yaw directions:

$$G = \frac{1}{T}\sum_{i=1}^{T}\sqrt{(p_i - p_0)^2 + (y_i - y_0)^2}, \tag{2}$$

where p is the pitch angle, y is the yaw angle, and p_0 and y_0 are the initial values for calibration. G is a scalar value. A smaller G value represents a smaller error from the coronal plane of the hand posture in the series of motions. The pose was measured by the tracker (Figure 5(d)).

Note that the Naviarm system is not able to assist in aligning the palm surface because wearers can move their wrist joints freely. As described in experimental procedure (2), both groups were verbally instructed to focus on aligning the palm sides of both of their hands. Therefore, by comparing this evaluation index, the influence of the verbal information provided for learning the skill can be examined for the two groups.

c) Subjective evaluation for the motor skill training
From the viewpoint of the long-term use of a training system, we conducted subjective questionnaires using the following eight statements at the end of the experiment. For each question, we asked participants to respond using a seven-point Likert scale from 1: "I do not think so at all" to 7: "I think so".

(1) I knew how to improve the mime skill while practicing.
(2) My performance improved with practice.
(3) I was able to concentrate on learning the mime skill.
(4) My motivation to learn the mime skill was high during practice.
(5) I wanted to use the device when practicing alone.
(6) I did not feel uncomfortable during practice.
(7) My level of fatigue was low during practice.
(8) Practicing the mime skill was enjoyable.

5 RESULTS AND DISCUSSIONS

The results of each evaluation criteria for each group (V and V + H) for the mime motor skill training are shown below.

5.1 Criteria A) Experts qualitative evaluation score

Figure 6 shows the results of the Z-score increase rate comparing before training and after training for each evaluation score. To exclude the bias with respect to the participants' fundamental skill levels, the increase rates of the scores are shown. Of the three scoring criteria, there was a significant difference ($p < 0.05$) in the increase rate of the composition points when comparing the V group and the V + H group. However, there was no significant difference in the technical and expression points between the V group and the V + H group.

The result for the composition points suggests that Naviarm may be useful for acquiring sequential motor skills. As described in Section 4.2(a), the composition points indicate the level of the sequential motor skills for an action, in this case, miming an invisible wall. Typically, it is difficult to communicate sequential motor skills verbally and a beginner needs to remember the sequence of the movements to reproduce the motor skill. However, a Naviarm wearer can directly access the sequential movements of an expert via the robotic arms' sequential trajectory information. Therefore, a novice does not need to remember the movement sequence. In this way, Naviarm appears to efficiently transfer sequential motor skills even for short-term training. Surprisingly, this occurred even though we did not tell participants to imitate the sequence of the

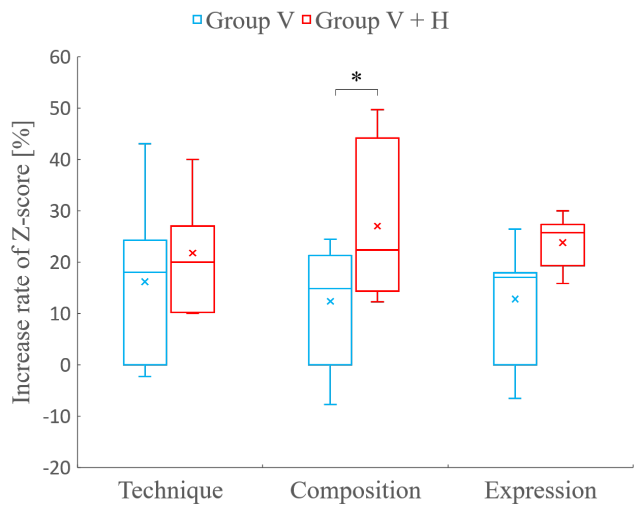

Figure 6: Results of the Z-score increase rate from before to after practice for each of the three evaluation scores. The Z-score was calculated using Eq. (1). The *p values were derived using the Bonferroni method (*$p < 0.05$).

expert's performance in this study. In other words, Naviarm made participants naturally learn the same sequence as that demonstrated by the expert. Therefore, it is possible that learning motor skills with Naviarm will be effective for learning sequential skills for activities such as dance choreography and assembly work procedures in factories.

5.2 Criteria B) Quantitative evaluation based on the hand posture

Figure 7 shows the result of the hand pose error (evaluation index G) measured by the tracker during the mime performances. In the V + H group, there was no significant difference between the practice repetitions, including the first and last sets. Conversely, in the V group, a significant difference was observed between the first and last sets ($p < 0.05$).

This result suggests that the V group efficiently acquired the skill of aligning their hands, which is a non-sequential fine motor skill. The robotic arm guidance appears to have made participants conscious of their arm trajectories via the haptic assistance; therefore, they could not concentrate on the skill of aligning the palms of their hands. That is, if haptic guidance is used, the assisted skill will be significantly recognized. Therefore, Naviarm is likely not suitable for non-sequential fine motor skill acquisition, which is not haptic guidance-based.

5.3 Criteria C) Subjective evaluation for the motor skill training

The result of the subjective questionnaire after the motor skill training sessions is shown in Figure 8. Overall, the standard deviation was large due to the influence of individual differences; however, a significant difference was found between the two groups regarding

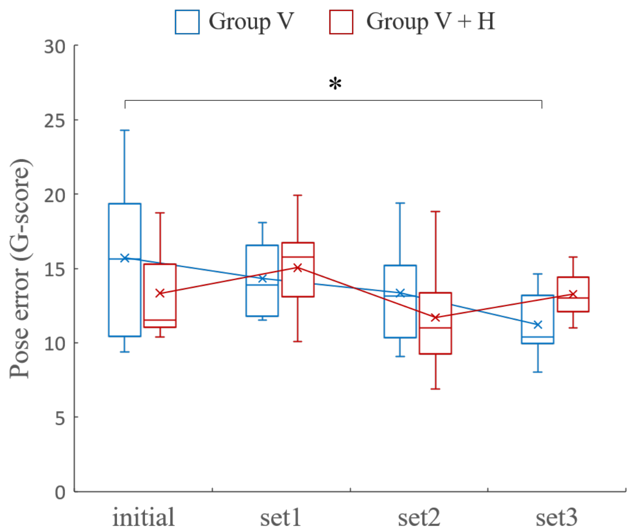

Figure 7: Results of the palm side poses of both hands in the training sets. The G-score was calculated using Eq. (2). The *p values were derived using the Bonferroni method (*p < 0.05).

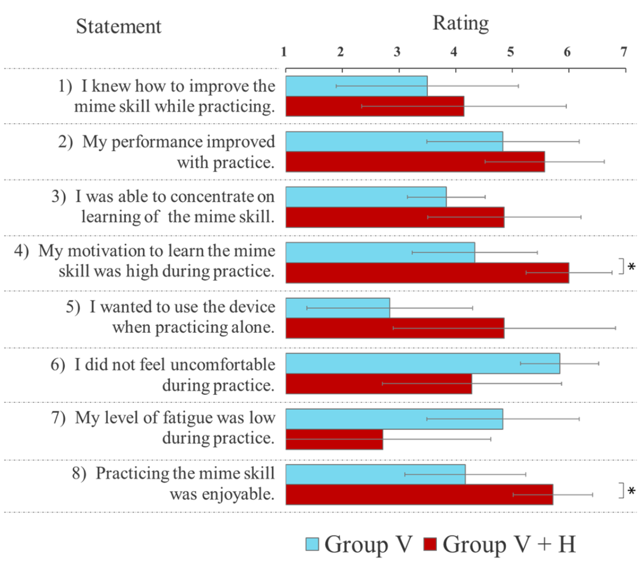

Figure 8: Subjective questionnaire results regarding the motor skill training sessions. The *p values were derived using the Bonferroni method (*p < 0.05).

motivation and enjoyment ($p < 0.05$). In particular, motivation received a high result of 6.00 ± 0.76 in the V + H group. Conversely, the level of fatigue was not significantly different between the two groups; however, the V + H group had a critically small result (2.71 ± 1.91).

The results suggest that Naviarm is effective for improving the participants' level of motivation. Despite being physically fatigued due to wearing the proposed backpack-type wearable robotic arms, the participants were motivated and enjoyed the mime training. We assume that this is because the participants were able to maintain an active learning state due to the mobility of Naviarm and the haptic feedback to their wrists. In addition to the novelty of the robot arm directing their bodies, motivation and enjoyment seems to be induced by the sense that an expert resides in the robot and teaches them "hand in hand". In other words, we suggest that skill learning assistance using Naviarm in long-term training may be effective to prevent from becoming tired of training and to maintain motivation for beginners.

5.4 Limitations and Future Work

The results obtained in this study only focused on skill acquisition for the motion used to mime an invisible wall and short-term training. Additional verification will be necessary to examine whether it is useful for learning other motor skills. In addition, Yang et al. [32] indicated that the effect of the feedback changes in long-term training. Therefore, it will be necessary to verify the effects of Naviarm for longer-term training sessions. In addition, further studies of control methods and systems are required to evaluate the effectiveness of this method for learning motor skills. The haptic feedback of the proposed system was continuous and constant; however, in a previous study, it was suggested that complicated haptic feedback including intermittent feedback [5] and impedance control [9] are effective. A promising avenue for future research is a record-and-replay system based on an absolute spatial coordinate system. In this study, the proposed system records the trajectory of the position of the arms relative to the torso. By introducing an absolute spatial position trajectory system, we will be able to provide new interactions according to the environment. Finally, the current system is not suitable for reproducing very quick physical actions that require instantaneous power. To respond to high-speed operations, it is necessary to review the hardware design and the control method.

6 CONCLUSIONS

In this paper, we proposed Naviarm, a novel haptic feedback system for augmenting the learning of motor skills. The system uses backpack-type robotic arms to transmit haptic information and can handle a larger range of motion compared to previous haptic guidance systems. In the developed system, the arm trajectories of a skilled expert are prerecorded with the robotic arms and then the recorded trajectories are used to allow beginners to learn the skill with haptic assistance. In this paper, we used a mime performance as the target motor skill to evaluate the proposed system. We conducted a user study to verify the benefits of the proposed system for learning motor skills, and the results suggest that Naviarm has benefits for learning sequential skills and helped increase users' motivation. In the current system, the haptic assistance is generated via the simple positional control of the servo-motors. In the future, we would like to change the control method and verify its effect on users. In addition, we will explore the possibility of applications such as remote work support or real-time hand-in-hand teaching.

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