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Gaze-controlled Robot-assisted Painting in Virtual Reality for Upper-limb Rehabilitation

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Abstract— **Stroke is the leading cause of adult disability. Robot-assisted rehabilitation systems show great promise for motor recovery after a stroke. In this work, we present a gaze-controlled robotic system for upper limb rehabilitation. Subjects perform a painting task in virtual reality. We designed a novel and challenging painting task to encourage motivation and engagement, as these are critical factors in treatment efficacy. Because the robotic system can be programmed to provide varying amounts of assistance or resistance to the subject, it can be applied to a wide range of patients at different phases of recovery. We describe here the system configured in two modes: resistive control and hierarchical control. The former is designed for later stages of recovery, where the patient's impaired limb has recovered some function. It can be configured to provide varying degrees of resistance by adjusting the properties of an admittance controller. The latter targets patients in more acute phases, where the impaired limb is less responsive. It provides a combination of assistive and corrective control. We pilot tested our system on 10 able-bodied subjects. Our results show that the system can provide varying degrees of resistive control, and that the integration of high level control modulated by gaze can improve engagement. These results suggest that the system may provide a more engaging environment for a wide range of rehabilitative therapies than currently available.**

I. INTRODUCTION

Stroke is the leading cause of adult disability worldwide [1]. The loss of brain cells in the affected area leads to paralysis or numbness of the face, arm and/or leg, often on one side of the body. More than 75% of survivors have impairment of the upper limbs, and 50% of victims suffer from a chronic reduction in arm function [2]. To help stroke patients recover motor function, conventional interventions such as occupational therapy have been developed [3], which often requires a professional therapist to perform intensive exercises on the patient in the clinic [4]. Limitations of this approach are the limited availability of trained therapists and the financial resources required.

The high demand for physical therapy has stimulated strong recent interest in developing robot-mediated therapy, which enables high-intensity, repetitive, task-specific and interactive training, as well as the sensorimotor function assessment [2]. In this paper, we describe a system based upon a 2-D planar robot, which does not require additional gravity compensation, is easy to learn and is safe for use by patients with reduced motor ability. Other examples of this type of system include the MIT-MANUS, a 2-DOF robot designed for upper-limb rehabilitation, which allows subjects to execute reaching movements in the horizontal plane. During the movement, the device can assist or resist the subject by monitoring arm position and applying appropriate forces [5]. Its success as a clinical device for treatment has been reported in a randomized control study of 76 acute patients and trials of chronic stroke [6]. Mirror Image Motion Enabler (MIME) robots [7] were developed for unrestricted unilateral or bilateral shoulder and elbow movement. It has been shown that recovery can be improved through additional therapy aided by robot technology.

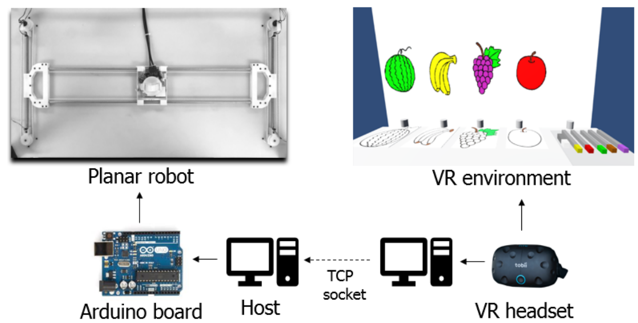

Fig. 1. System architecture

However, several gaps still remain to be filled. First, task complexity is generally low, which might not be sufficiently motivating during a repetitive training process. Most previous rehabilitation systems have used simple discrete tasks, such as reaching, grasping and transporting [8]. While some work has looked at implementing more complex tasks, such as drawing circles, stars or squares while navigating through a 2D screen [9] or in Virtual Reality (VR) cooking where patients were instructed to pick up a meatball and drop it into a pan [8], these are still somewhat constrained. For example, the cooking system was limited to 2D VR and provided only pre-defined trajectories. Second, most systems have used non-immersive VR [10], [11], such as a 2D screen. A major distinction between non-immersive and immersive VR is that the former involves exocentric navigation where the subject is outside of the environment, while the latter involves egocentric navigation where the subject is surrounded by it. Fully immersive VR increases

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the sense of presence, which also contributes more to neuroplasiticity since it requires allocation of more brain and sensory resources for cognitive/motor control during task performance [12]. Third, few systems with the flexibility to satisfy the needs of patients with varying degrees of impairment have been designed. The amount of assistance should be reduced during recovery. Rehabilitation robots programmed to drive the impaired limbs to a certain position following a fixed trajectory [5] are useful in initial stages of recovery, but it may cause a 'slacking' problem and violate the "assist-as-needed" principle [2].

In this work, we present a multi-modality rehabilitation system that combines a planar robot, an immersive VR system and eye tracking technology. To enhance motivation and engagement, we designed a novel and challenging painting task with high level control modulated by eye gaze. Additionally, the system combines multiple control strategies, enabling customization of the training program. A demo video of our system in is available at `https://youtu.be/bX9dPZpzdIk`.

II. System description

Fig. 1 shows the system architecture. The system includes two main parts: a planar robotic rehabilitation system and an immersive VR system with integrated eye tracking. The two systems communicate in real time through a TCP socket. The host sends commands to an Arduino controller, which controls the robot.

A. Planar robot

We used a cabled differential robotic manipulandum in our experiment, which uses an H-shaped drive. The system is driven by two motors, M_l and M_r. The motor torques are transmitted through the cable. The subject's wrist is attached to the center platform using a velcro strap. When the two motors rotate in the same direction, the center platform moves left and right. When the two motors rotate in the opposite direction, the center platform moves up and down.

B. VR Environment

We developed the interactive VR-based painting game using the Unity 3D graphics engine. As Fig. 1 shows, there are four colored objects on the wall and four blank objects on the table. On the right side of the table, there are five pens of different colors. The subject is asked to paint the blank objects on the table following the colored templates on the wall. The subject must pick up a pen to color an object, and return it back to its original place afterwards. The task is completed when all four objects are colored. The VR workspace encompasses the patients' reaching space.

To enhance the interactive experience, several visual and haptic feedbacks are added:

- A pen is highlighted when touched, indicating it can be grasped.
- The controller vibrates when the pen touches the canvas.
- A cylinder placed beyond each object on the table is highlighted if the object is being gazed at.

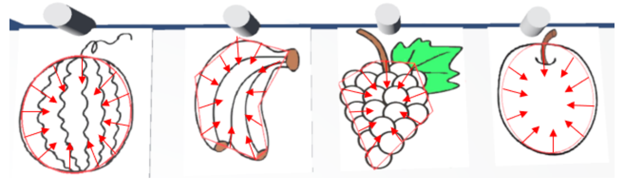


Fig. 2. Constraint boundary of the painting. The red line shows the boundary. The red arrows show the direction of the constraint force applied at different locations.

C. System control strategy

To fit various needs of the patients at different injury levels, the system can operate in one of two control modes. The hierarchical control mode is designed for the patients in the early recovery stage when the impaired limb is less responsive. The resistive control mode is designed for the patients in the late stage when their impaired limbs have recovered some function. The resistance level can be adjusted easily by configuring the system with different parameters.

In the resistive control mode, the subject's motion is unassisted and unconstrained. The subject can move to any point in the workspace along any trajectory, but must exert force to overcome resistance from the planar robot.

When in the resistive control mode, the task becomes more challenging since the subject must perform the task against the resistive force provided by the robot. It resembles a muscle strengthening exercise. To control the resistance, we adjusted the parameters of an admittance controller. The planar robot system can be modeled as a virtual mass-damper with dynamics given by:

$$m\ddot{x}(t) + d\dot{x}(t) = f(t), \tag{1}$$

where $x(t)$ is the displacement of the robot at time t, $\ddot{x}(t)$ is the acceleration, and $\dot{x}(t)$ is the velocity at time t. m is the mass and d is the damping ratio. $f(t)$ is the force exerted by the subject. In discrete time, the dynamics of the system can be described by

$$v(t) = \alpha_{\mathrm{f}} f(t) + \alpha_{\mathrm{v}} v(t-1), \tag{2}$$

where α_{f} is the force parameter, α_{v} is the viscosity parameter, $v(t)$ is the velocity at time t and $v(t-1)$ is the velocity at time $t-1$. The resistance can be adjusted by changing α_{f} or α_{v}.

The hierarchical control mode provides both assistance and constraints, for patients who have trouble controlling their hands. This mode combines three control strategies. An assistive mode is adopted during a long-distance travel. Once a target has been selected by gaze, the robot exerts assistive forces to guide the subject's hand to the target along a predefined path. During painting, an admittance mode is adopted to allow more freedom while the subject is coloring within the boundary. A corrective mode is adopted when the hand moves outside the boundary. This is similar to the "virtual tunnel" idea of [8], where the force constrains the hand to a virtual tunnel around the desired trajectory.

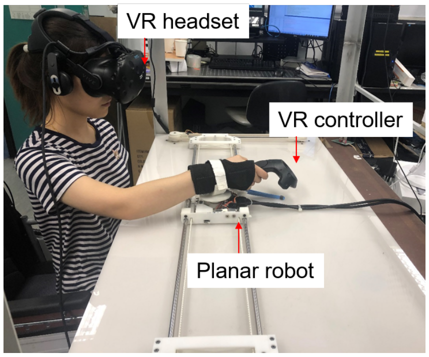


Fig. 3. Experimental setup

The subject selects a target to reach (e.g. an object or pen) by gazing at it for a dwell time of 500 ms. The planar robot then moves the subject's hand to the selected target along a predefined trajectory. Once the pen is inside an object, The system then switches to the admittance control mode so that the subject can actively move within the object boundary. The planar robot applies corrective forces when the pen crosses the boundary to keep it within the boundary, as shown in Fig. 2. The controller acts like a (damped) spring and the controller force increases proportionally as the subject moves away from the boundary.

III. Experiment

Fig. 3 shows the experimental setup. The subject is painting in the VR environment with the assistance of the planar robot. The VR system is a HTC Vive headset with an integrated Tobii Pro eye tracker. We recruited 10 able-bodied subjects. Before the experiment, the experimenter explained the experiment procedure to the subjects. The experimental protocol was approved by the Human Research Ethics Committee of the Hong Kong University of Science and Technology (Protocol HREC#533).

Two sets of experiments were conducted. First, we tested the two control modes: resistive and hierarchical. The parameters of the admittance controller used over the entire workspace in the resistive control mode and inside the object in the hierarchical control mode were the same. The force parameter α_{f} was 300, and the viscosity parameter α_{v} was 0.3, corresponding to a moderate level of resistance. Each subject performed two trials in randomized order. Subjects' motivation was measured by means of a modified Intrinsic Motivation Inventory (IMI) questionnare, which is a multidimensional measurement method designed to assess participants' subjective experience. Higher scores indicate greater intrinsic motivation [13]. For the current study, the IMI subscales “Interest”, “Competency”, “Effort”, “Value”, and “Pressure” were used. The questionnaire consists of ten items rated on a 7-point Likert (two items per subscale), plus one item for the overall evaluation.

Second, we tested the adjustment of the resistance level (low/moderate/high) in the resistive control mode. We set the force parameters empirically to $\alpha_{\mathrm{f}} = 500, 300, 100$ (from low-resistance to high-resistance), while keeping the viscosity parameter constant, $\alpha_{\mathrm{v}} = 0.3$. We randomized the order of the three trials.

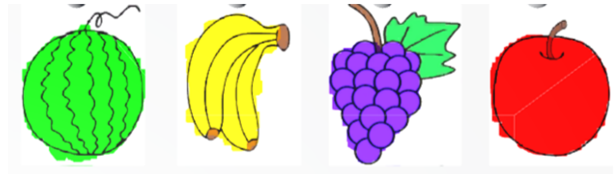


Fig. 4. Example of one painting result.

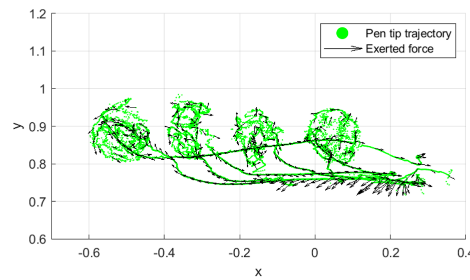


Fig. 5. Pen tip trajectory in resistive control mode.

IV. Results

Fig. 4 shows an example painting result. Two kinematic metrics: force magnitude and velocity, were measured.

A. Configuring the system in different modes

Fig. 5 and Fig. 6 show examples of pen tip trajectories labelled with force vectors applied by the subject in the resistive and hierarchical modes, respectively. In the resistive control mode, subjects must exert force to move, since there is no assistive force provided by the robot. In the hierarchical control mode, fully assitive force is provided to guide the arm to move to the objects. The movement direction is independent of the force applied by the subject. During painting, the corrective mode will be triggered when the pen moves outside the boundary due to the hand trembling.

The average magnitude of the applied force is significantly smaller in the hierarchical control mode as expected (hierarchical control mode: 3.18 ± 0.18 N, resistive control mode: 3.75 ± 0.17 N). In the hierarchical control mode, the subject's arm can remain passive as is moved to the target.

Fig. 8 shows an example of the gaze and pen tip trajectories along the x and y axes. As annotated in the figure, there are different phases in the task: the painting phase, the pen switching phase, and the moving to new object phase. The gaze and pen tip trajectories match up very well.

Fig. 7 compares the IMI scores of the two control modes. The mean score on the interest/enjoyment scale was 5.2 (SEM=0.37) for the resistance mode and 5.6 (SEM=0.30) for the hierarchical mode on a 7-point scale (two-tailed paired t-test, $p<0.05$). The high interest/enjoyment score and the low variability indicated that the subjects felt motivated while performing the VR task in both of the control modes. The motivation is comparatively higher for the hierarchical

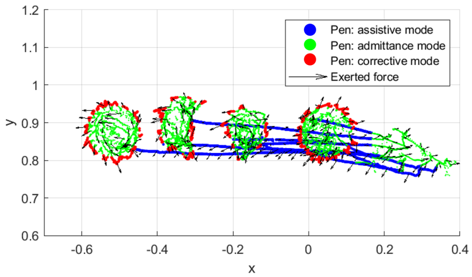


Fig. 6. Pen tip trajectory in hierarchical control mode.

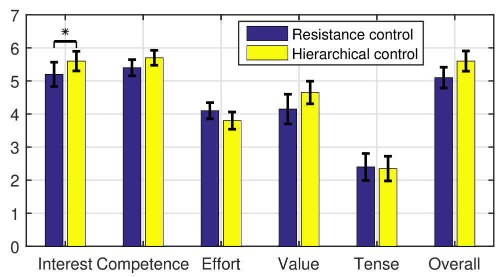


Fig. 7. IMI score of the two control modes. * denotes p<0.05 and ** denotes p<0.01. Data are shown as means ± SEM.

control mode. The competence and value subscales are considered positive predictors of intrinsic motivation. The mean score on the competence subscale was 5.4 (SEM=0.24) for the resistance mode and 5.7 (SEM=0.23) for the hierarchical mode. The value subscale resulted in a mild score: 4.2 (SEM=0.45) for the resistance mode and 4.7 (SEM=0.34) for the hierarchical mode. No significant difference was found. Collectively, this suggests these subjects had high intrinsic motivation for this type of training, especially in the hierarchical mode. The score on the effort subscale was a little lower for the hierarchical mode (4.1 ± 0.25) than for the resistance mode (3.8 ± 0.26), which indicated that subjects put less effort in performing the task in the hierarchical mode. This is not surprising because assistance was provided by the system in the hierarchical mode. The pressure/tension subscale obtained a low score with low variability (hierarchical mode: 2.4 ± 0.37, resistance mode: 3.8 ± 0.26). This means that most subjects did not experience much tension during the VR training. Furthermore, subjects gave a higher overall score to the hierarchical mode (resistance mode: 5.1 ± 0.31, hierarchical mode: 5.6 ± 0.31). Many of them expressed their interest in the gaze selection function used in the hierarchical mode. Example comments from subjects include: "The system is very useful with the automatic driver and it makes me feel good to control the system without exerting any force.", "With the assistance of gaze control. I could reach quickly.", "It would require me to put more effort without the gaze selection.

B. Adjusting the resistance level

We can increase the difficulty level by increasing the resistance level. We average the force and velocity over the painting session for each subject. Fig. 9 compares the average force and velocity across all subjects. At higher resistance, subjects must exert more force, and generally move at a lower velocity. There is a significant difference between the different resistance levels. The right table shows the minimum and maximum values of the force and velocity at three different resistance levels. These ranges can help us to identify preliminary baseline values for future studies involving the progressive resistance training with impaired subjects.

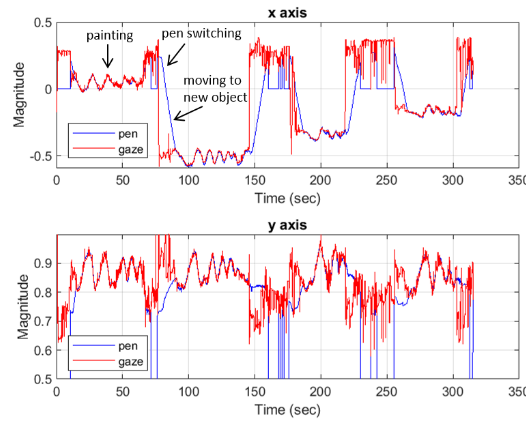
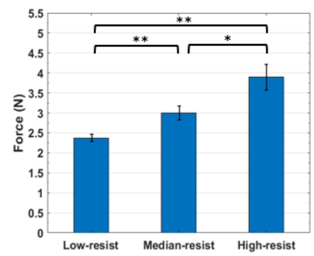


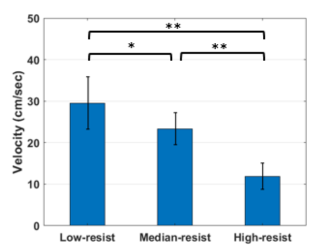
Fig. 8. Gaze and pen trajectory.



Range of the average force

	Min (N)	Max (N)
Low-resist	1.98	2.72
Median-resist	1.79	3.59
High-resist	2.83	5.31

(a)



Range of the average velocity

	Min (cm/sec)	Max (cm/sec)
Low-resist	21.17	37.37
Median-resist	14.12	27.94
High-resist	8.72	16.31

(b)

Fig. 9. Comparison of (a) force and (b) velocity at different resistance levels. * denotes p<0.05 and ** denotes p<0.01.

V. Discussion

In this work, we developed a gaze-controlled robotic system for upper limb rehabilitation as subjects perform a painting task in an immersive virtual reality system. Compared with the existing works, our proposed system has several advantages.

First, subjects engage in a novel painting task in a fully immersive virtual environment. We expect this to be more motivating than screen-based simple tasks in previous studies, such as point-to-point reaching or drawing circles. Skinner and Nagel proposed that painting is a wonderful way for the stroke patients to practice any motor skills that were lost, especially for those who have lost their ability to speak, either completely or partially [14]. The also note that it is also a medium to help them convey their emotions and personality. Additionally, we enhanced subjects' sense of control, which is vital to recovery after a neural injury [15], by adding the visual and haptic feedback and the gaze selection function.

Second, the system contains multiple control strategies, which can target patient populations at different injury levels. Moderate amounts of assistance are provided in the hierarchical mode. Since movement targets can be inferred from the gaze, limbs can be moved passively yet intentionally when self-generated movement is not possible. This can provide novel somatosensory stimulation, which helps induce brain plasticity [16]. We speculate that the volitional control enabled by the gaze control interface will increase subject engagement compared to when the arm is moved passively to a number of pre-defined targets without choice. Indeed, some subjects commented that the gaze selection function made them more engaged in the experiment.

When the impaired limb has recovered to the point that self-motion is possible, resistance mode can be adopted, which requires higher effort from the impaired limb. Our experimental results on healthy subjects demonstrate the ability of our system to adjust the resistance level, which alters task difficulty. Progressive resistance training in chronic stroke patients has been found to be an effective training method to improve and maintain muscle strength over the long-term [17].

There are several potential directions for further development of our system. A performance evaluation system can be developed such that subjects can get the feedback of the therapy. More interesting and demanding tasks could be implemented. Finally, the system should be evaluated on patients, to validate its effectiveness for rehabilitation.

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