Haptic Assistance in Virtual Environments for Motor Rehabilitation

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Abstract. This paper presents the MIMICS MMS rehabilitation system with a virtual rehabilitation task that includes several modes of haptic assistance. We observed the influence of these different modes of assistance on task performance and work performed toward the target during the pick-and-place movement. Twenty-three hemiparetic subjects and a control group of twenty-three subjects participated in the study. The haptic assistance resulted in improved task performance and lower work performed during pick-and-place movement.

Keywords: haptic interface, haptic assistance, rehabilitation robotics.

1 Introduction

Robotics is advancing into different areas of human lives [1]. One of these is the area of rehabilitation where robot-enhanced physical therapy improves recovery after stroke [2]. In rehabilitation robotics, haptic interfaces combined with virtual reality largely improve the patient's motivation [3]. Several robotic training systems for upper extremities have been developed. For instance, MIT-MANUS [4] with SCARA configuration interactively treats stroke survivors. The MIME [5] system uses a Puma 560 robot manipulator and is capable of four modes of haptic assistance. The robot system for upper limb rehabilitation developed by Deneve et al. [6] uses impedance control to avoid a large movement deviation from the desired trajectory. The Gentle/G [7] system based on the HapticMaster robot includes reach and grasp tasks, correcting movements that stray too far from the correct pathway. These systems use virtual reality and apply different modes of haptic assistance to the patients. The HapticMaster has also been used in other areas, such as haptic modeling of digital shapes [8]. This paper presents the MIMICS MMS (Multi Modal System) rehabilitation system with the HapticMaster haptic robot and a virtual rehabilitation task as well as the results of exercising in hemiparetic subjects and control group. Our goal was to determine how different modes of haptic assistance influence the task performance of the training in stroke subjects. Catching efficiency, pick-and-place movement efficiency and work performed during pick-and-place movement were observed.

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2 Methods

2.1 Haptic System Specification

The HapticMaster (Moog FCS Inc.) is an admittance-controlled haptic interface with one rotational and two translational degrees of freedom. It presents a suitable device for upper extremities in rehabilitation tasks. A grasping mechanism is attached to a gimbal, which allows reorientation of a wrist connection mechanism and therefore the subject's hand. The mechanism is upgraded with a one degree of freedom finger opening and closing subsystem in order to provide grasping and object carrying capabilities. Support of the lower and upper arm is provided by an active gravity compensation mechanism. The graphic environment is presented to the subject on a back-projection screen via two LCD projectors and uses OGRE 3D library for graphic rendering. The projectors have polarizing filters that enable a subject with polarizing glasses to perceive a virtual environment in 3D.

2.2 HapticMaster Blocks in Simulink

The HapticMaster runs on the xPC Target^{TM}(The MathWorks, Inc.) host-target environment that enables the connection of models to physical systems and their execution in real time. The task executes at 2500 Hz. A new library was developed to link together the robot and the Simulink environment. The library includes input and output drivers, control blocks, robot kinematics and dynamics, haptic objects and collision detection blocks. The inputs to the haptic model are the measured forces on the top of the robot and the positions of the three robot joints. The outputs to the robot are the velocities of the joints. The control blocks subsystem includes an admittance model, a PD controller, a direct and an inverse kinematic of the robot and a Jacobian matrix. These blocks provide the bases for development of a haptic virtual environment.

2.3 Haptic Objects and Collision Detection

The haptic environment in Simulink consists of haptic objects and collision detection among them. The basic haptic objects are the sphere, the box, the cone and the wall. For each of the objects we can set parameters: dimensions, mass, initial position and velocity, initial orientation and rotation, stiffness, damping, gravitation, environment translation damping and environment rotation damping. All the combinations of the collisions among objects are available in collision detection blocks. Collision detection blocks involve algorithms from Open Dynamics Engine (ODE) library [9]. The top of the haptic interface is modeled as a point and presents a haptic interaction point (HIP) in the virtual environment. When a collision is detected, a virtual force that effects on the user and the virtual object is computed. With these basic objects, we can develop different haptic scenes in combination with visual environment scenes.

2.4 Virtual Rehabilitation Task

The rehabilitation task is a catch-and-place exercise. A table is positioned in a room with several objects around the scene (Fig. 1). A small sphere and two small cones

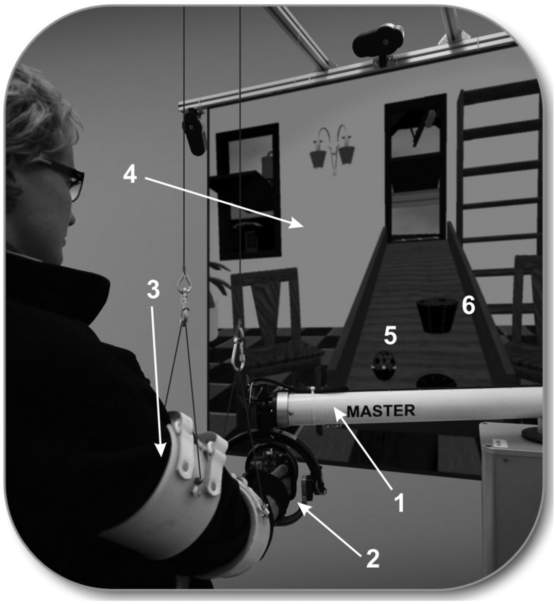

Fig. 1. A subject performing the virtual rehabilitation task. The subject performs the task using the robot (1) and grasping device (2) while his/her arm is supported by cuffs (3). The screen (4) shows a sloped table, a ball (5) and a basket (6).

on the left and right sides of the sphere represent the current position of the robot in the virtual environment. The distance between the cones is proportional to the grasping force. A ball rolls from the opposite side of the sloped table. The subject needs to catch the ball and place it in a basket which appears when the ball is grasped. After the ball is successfully placed in the basket, a new ball rolls down. The task is a combination of catching, grasping, pick-and-place movement and releasing.

The task includes different options for haptic assistance. These include:

1. **Catching assistance.** The catching assistance helps the subject catch the ball. It is an impedance controller that moves the subject's arm in a frontal plane.
2. **Grasping assistance.** The grasping assistance causes the ball to stick to the virtual end-effector. When the subject reaches the place point, the ball is dropped.
3. **Tunnel assistance.** The haptic trajectory tunnel enables movement from the catch point to the place point along a desired trajectory in a virtual haptic environment. An impedance controller prevents the subject from deviating from the desired trajectory. The bisector of the tunnel is generated using B-splines and control points [10]. The control points are approximated by using B-splines from trajectories measured in healthy subjects' movements. The guidance assistance provides a trajectory guidance force in the advancement of the haptic trajectory tunnel.

In the experiment, catching efficiency and pick-and-place efficiency were observed to find how different modes of haptic assistance influence on the outcome of the exercise.

Twenty-three hemiparetic subjects (age 51.0 ± 13.3 years, age range 23-69 years, 16 males, 7 females) and a control group (twenty-three subjects, age 50.5 ± 12.6 years, age range 24-68 years, 16 males, 7 females) participated in the study. As a result of the stroke, 13 hemiparetic subjects suffered from hemiparesis of the left side of the body and 10 suffered from hemiparesis of the right side of the body. All were right-handed before the stroke. The subjects in control group had no major physical or cognitive defects. All were right-handed. The participants had 6 minutes training in virtual rehabilitation task with different haptic assistances. These assistances were activated if subject was unable to perform a particular component of the task. Therefore, 7 patients had catching and tunnel assistance and 16 patients had no assistance. The control group also performed the task without any assistance. Several haptic parameters were measured during training including positions, forces on the top of the robot, catching efficiency and pick-and-place movement efficiency. The listed parameters were analyzed using the t-test to determine significant differences between patients using the assistance and the patients without the assistance as well as between the patients and the control group.

3 Results

We observed catching efficiency, pick-and-place movement efficiency and performed work toward target of stroke group with and without assistance as well as in control subjects (Table 1). The control group caught more balls than the stroke group without the catching assistance during the virtual rehabilitation task ($p < 0.001$). Catching efficiency in stroke group was greater when the catching assistance was applied ($p < 0.001$). Fig. 2a shows the pick-and-place efficiency for stroke and control group, both without the tunnel assistance. The control group performed more successful pick-and-place movements than the stroke nTA group during the virtual rehabilitation task ($p = 0.006$). The stroke TA group pick-and-place efficiency was greater than the efficiency of the stroke nTA group ($p < 0.001$) and the control group ($p < 0.001$). Fig. 2b shows the work performed to move toward the place point. The stroke nTA group performed more work toward target than the stroke TA group ($p < 0.001$). There is not a statistically significant difference of performed work in stroke nTA group and control group ($p = 0.362$).

Table 1. The results of observed catching efficiency (CE), pick-and-place efficiency (PE) and work performed toward the target (WTT). The stroke patients are divided into the groups with catching assistance (CA), without catching assistance (nCA), with tunnel assistance (TA) and without tunnel assistance (nTA).

	Stroke nCA	Stroke CA	Control nCA
CE [%]	63 ± 17	86 ± 14	86 ± 13

	Stroke nTA	Stroke TA	Control nTA
PE [%]	79 ± 14	98 ± 6	91 ± 9
WTT [J]	1.39 ± 0.65	0.12 ± 0.38	1.23 ± 0.91

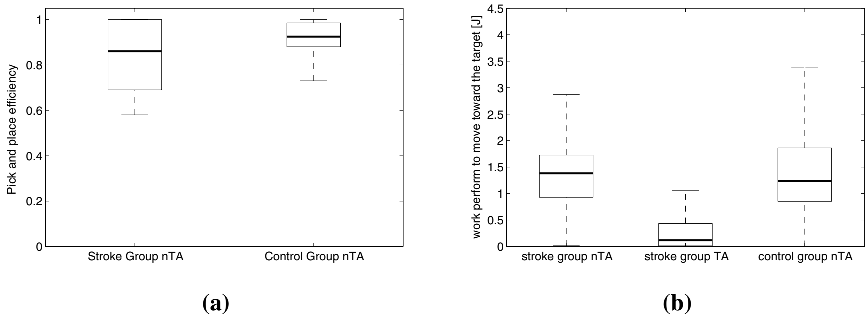

Fig. 2. (a) Pick-and-place efficiency of the stroke group and control group without the tunnel assistance (nTA). (b) Work performed to move toward the target during pick-and-place movement of the stroke group without the tunnel assistance (nTA), stroke group with the tunnel assistance (TA) and control group without the tunnel assistance (nTA).

4 Discussion

The results in patients showed that the catching efficiency of stroke group was greater when the catching assistance was applied. The results are even higher than in control group. The similar holds for the tunnel assistance (Fig. 2a). Therefore as expected the assistances can raise the performance of the exercise. On the other hand, the work toward the target performed during pick-and-place movement in patients was smaller when the assistance was present. There is not a statistical significant difference between the stroke group without the tunnel assistance and the control group. We believe that the subjects benefits the most from the exercising when besides the task efficiency also the performed work is high. In the future, the adaptive haptic support system might substitute the tunnel assistance in the rehabilitation task. We assume that the subjects will be allowed to select the most comfortable movement trajectory and will therefore increase the performed work and maximize the outcome of the exercise.

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