Upper limb and grasp rehabilitation and evaluation of stroke patients using HenRiE device

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Abstract—This paper presents a case study with a HenRiE (Haptic environment for reaching and grasping exercises) device with two hemiparetic subjects. The HenRiE device is intended for use in a robot-aided neurorehabilitation for training of reaching and grasping in haptic environments. The goal of the study is to develop a single system that retrains both hand grasping and releasing movements (which are essential to perform activities of daily living) and arm movements. The system combines a haptic interface and a grasping device, which is mounted on the end-effector of the haptic interface. The paper focuses on experimental training sessions with two hemiparetic subjects. Results show favourable effect both on arm and grasping.

I. INTRODUCTION

Current therapeutic interventions for patients with severe brain injury such as traumatic brain injury or stroke are based on neurofacilitatory techniques, muscle tonus controlling therapies, progressive strengthening, biofeedback or electrical stimulation [1]. Task-oriented therapies are important to improve the function of the affected arm [2]. It has been shown that forcing the affected limb to perform Activities of Daily Living (ADL) tasks yields functional gains allowing the stroke patient to increase the amount of use of the affected arm in the “real-world” environment [3]. Systematic review of Kwakkel et al. [4] also showed that longer training (“augmented exercise therapy”) has a favourable effect on activities of daily living, walking, and dexterity in stroke patients. A therapy should be enjoyable, challenging and motivating. The role of motivation is known to be important for the success of neurorehabilitation [5].

In recent years, several robotic approaches have been suggested in order to assist arm and gait therapy in patients with subacute and chronic stroke, traumatic brain injury, multiple sclerosis, and incomplete spinal cord injury [6]. Robot-aided neurorehabilitation is a sensory-motor rehabilitation technique based on the use of robot and mechatronic devices [7]. Aim is to aid and augment the traditional therapy intended for patients with motor disabilities to improve the patient’s motor performance, shorten the rehabilitation time, and provide objective measures for patient evaluation [8].

Computerized technology has the capability to create an environment where the intensity of practice and positive feedback can be consistently and systematically manipulated to create the most appropriate motor learning approach [9]. Adding VR capabilities to robotic training will yield a more appealing exercise environment.

The paper presents the HenRiE device, which combines haptic device for upper extremity training with a module for grasping and computer generated haptic and graphical virtual environments. The HenRiE device allows combined therapy for reaching and grasping movements. Joint therapy is reasonable because most of the activities of daily living require both arm movements and grasping [10].

The fundamental feedback loop involves detecting the patient’s activities within an immersive virtual environment so that the training effects are experienced as meaningful and purposeful rather than just experienced as mechanical training. The computed information is used to drive the robot in combination with immersive virtual reality systems including 3D graphics. Furthermore, feedback of the recorded information via multimodal display technologies (allowing the patient to manipulate virtual objects, observe the effects of movements and body activity) can not only immerse the patient into a virtual environment that is experienced as realistic but also motivate him or her to perform the training with maximum effort, endurance and fun. Such a multimodal interface allows the employment of a larger number of human motor and sensor channels, thus, maximizing the plastic changes in the patient’s central nervous system.

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II. METHODS

A. System description

The main system components are the HapticMaster robot with additional external axes for arm weight compensation and training of grasping and a 3D projection system. All devices are controlled by two independent computers, which are connected through TCP/IP. The measurement set-up for HapticMaster (see Fig. 1) includes various sensors and sensory systems for measuring forces and robot joint positions and velocities.

The HapticMaster robot is built with three active degrees of freedom in the translation-rotation-translation configuration. In addition to the three active degrees of freedom a passive gimbal is attached at the robot end-effector. In the center of the gimbal is attached a device for training of grasping, which is available in passive configuration. Each of above mentioned axis is equipped with position sensors. Each of the three active robot axes is equipped with an encoder for measuring joint angles and a tachometer for measuring joint velocities. Encoder signals are available to the user, while tachometer signals are only used in the hardware based velocity control loop and cannot be accessed from the control application. The controller is discussed in more details in [11]. Two gimbal passive axes are equipped with potentiometers, which signals are available to the user. A 3 axes force sensor is originally built in the HapticMaster robot. The sensor enables measurement of three forces acting at the robot end-effector. These measured forces are available to the user to be used in the robot control system. The HapticMaster robot is equipped with a standard controller. All external axes that include arm weight compensation and grasping device are controlled using a custom designed controller, which is interfaced to the HapticMaster controller via digital and analog connections. The HapticMaster control unit is the main controller for all moving subsystems. Signals from robot position and force sensors are directly connected to the robot three axes modules, which control each axis movements. External axes are interfaced to the robot controller through various input/output interface cards inserted in the HapticMaster control computer. MeasurementComputing Corporation interface boards are used to measure signals from auxiliary sensors and grasping device load cells.

Grasping device is built in a passive configuration. Fig. 2 shows the device with an attached support for thumb and fingers. Device uses adjustable spring system for generating different stiffnesses. Grasping device is equipped with two single axis (compression/extension) load cells. The load cells are positioned between the fingers and the respective finger attachments on the device itself. Each force cell is capable of measuring forces up to 100 N, which is enough for training applications envisioned for rehabilitation. The signals from the load cells are interfaced to the robot controller and are available to the user.

3D projection system consists of two InFocus projectors, a back projection screen and a multimedia computer. The system enables generation of visual 3D virtual environments.

B. Haptic path

An unconstrained human arm movement path of a healthy subject was used as a reference path for the arm movement in a haptic virtual environment. An arm movement path of a healthy subject conforms to several principles:

- the path is not perfectly straight with parts of it curved [12, 13]
- arm movement has bell-shaped tangential velocity profile [12, 13]
- accuracy of movement decreases with the speed of the movement [13],
- the speed is the lowest in the points with the highest curvature [14].

To accurately approximate the measured movement, the path was approximated with five b-spline waveforms for each component of the path in the Cartesian space. Fig. 3 shows the approximation for z-component of the path. Analysis of a set of 120 healthy subject arm movement paths has suggested the
segmentation of the movement in five sub-intervals: 0-15 %, 15-35 %, 35-65 %, 65-85 % and 85-100 % of the movement. The control point for the first waveform is the initial position and the control point for the last waveform is the final position. The middle three control points were calculated with a linear least squares method to fit the waveforms to the measured data. Hence, each approximated path was described with the initial x,y,z position, the final x,y,z position and nine control points (three for each component of the Cartesian space).

The approximated path was a central curve of a haptic path. The movement forth and back along the haptic path was unconstrained, while every deviation perpendicular to the path was constrained with force $F = K \cdot d$, where $d$ is a distance from the path. The corresponding points of the reference path were calculated using the de Boor algorithm [15]. This algorithm provides a fast and numerically stable way of finding a point on a B-spline curve.

C. Pick and Place task

In this task the subject must move the arm to the virtual object and grasp it. Then the subject must transport it to the designated location and releases it there. When the object is released, a new virtual object comes into the workspace and the subject must again reach it and transport it to the final location. If the subject does not apply a sufficiently large grasp force, the object falls down and has to be picked up again. The virtual objects in this task were apples, which fall of a tree. The subject has to carry them on a fruit stand where the apples are sold (see Fig. 4). Subject has to pick up the apple which has fallen from the tree (inset 1 of Fig. 4). When subject comes into contact with the apple (inset 2 of Fig. 4), he or she can grasp it. When a sufficient grasp force is applied, virtual fingers change colour to blue (inset 3 of Fig. 4) signalling to the subject that he or she can proceed with the movement. Subject then transports the apple to the fruit stand on the designated place (insets 4 and 5 of Fig. 4). When the apple is placed on the designated place (shown on insets as a purple platter), he or she can release the apple (inset 6 of Fig. 4). When the apple is released, a new apple falls down and the subject moves the arm to pick the new apple (insets 7 and 8 of Fig. 4). The experiments with healthy subjects performing the pick and place task have shown that the grasping patterns in HenRiE virtual environments are very similar to the grasping patterns in real situations [16].

D. Subjects

Two hemiparetic post-stroke subjects, a woman and a man, 5 and 7 years after stroke with chronic upper-extremity impairments were recruited. The woman was 40 years old and the man was 45 years old. Both subjects had impaired the right side of the body. The right arm was dominant arm before the stroke. Both participants were free of other neurological deficits.
E. Procedures

The full training lasted for 10 sessions for the subject 1 and 9 sessions for the subject 2. The pick and place task was performed four times in each session, and in each pick and place task the subject had to pick and place 20 apples. Between each course of the pick and place task subjects rested for one minute and between the first and the last two training courses the subjects rested for five minutes. A subject was seated comfortably in a chair in front of the haptic interface. If required so, a four point belt was used to limit the undesirable movements of the upper part of the trunk. An arm weight compensation system was used to support the arm of the subject. The arm was placed in two supporting cuffs, one for the upper arm and one for the forearm, of the arm weight compensation system. Next the wrist was placed in a splint to securely fixate the wrist in the gimbal device mounted on the end-effector of the haptic interface. Last but not the least the fingers were placed in finger attachments cuffs of the grasping device. The goal of these preliminary tests was to evaluate the HenRiE device, as well as the ergonomic suitability, comfort and performance of the HenRiE device.

III. RESULTS AND DISCUSSION

Fig. 5, 6, 7 and 8 show boxplots of deviations of the measured arm path from the reference arm paths. Fig. 5 shows boxplot for the subject 1 for the movement to the new apple and the Fig. 6 shows boxplot for the subject 1 for the movement with the grasped apple. The decrease of the deviation is present from the first session to the fourth session. Latter on the deviation remains constant. In both subjects a mean value and a variance of the deviation decrease, which confirms a positive effect of the haptic path on smoothness and accuracy of the arm movement path of the hemiparetic subjects. The haptic path is used to provide a robot-assisted movement training. This technique is also
known as a robotic guidance, which substitutes the manual
guidance of the patient’s limb performed by a therapist in a
conventional therapy. In the conventional therapy the manual
guidance is intended to demonstrate the correct movement
trajectory to promote re-learning of the correct movement
patterns, it may also enhance a somatosensory input involved in
a cortical plasticity, reduce spasticity by stretching and improve
properties of the soft tissue [17]. The robotic guidance has
previously shown to improve motor recovery of the arm
following acute and chronic stroke [17, 18].

Fig. 9 and 11 show a maximal grasp force applied
after the grasp of the virtual object. Red lines below
the boxplot are threshold grasp force required for grasping the virtual
object.

Figure 9. Figure shows boxplot of the maximal grasp force applied
after the grasp of the virtual object for subject 1. Black lines below
the boxplot are threshold grasp force required for grasping the virtual
object.

Figure 11. Figure shows boxplot of the maximal grasp force applied
after the grasp of the virtual object for subject 2. Black lines below
the boxplot are threshold grasp force required for grasping the virtual
object.

Fig. 10 and 12 show a minimal grasp force applied by the
subject after the release of the virtual object. Black lines above
the boxplot represent the release threshold. The subject had to
apply the grasp force smaller than the release threshold to
release the virtual object. During the course of the training
sessions the release threshold was decreased according to the
performance of the subject in the previous course of the pick and place task. In both subjects
values of the maximal grasp force for the first training session and the values of the maximal grasp force for the last training
session are significantly different (p<0.001). Both subjects
increased the maximal grasp force.

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Since both subjects who participated were hemiparetic post-
stroke patients the emphasis was on the ability to open the hand
and fingers and thus on the minimal grasp force applied after
the release of the virtual object. The ability to open the hand is
reduced due to a change in flexor/extensor coordination [19].
The flexor muscles are activated when the subject grasps the virtual object, and the extensor muscles are activated when the subject tries to release the virtual object. In the hemiparetic post-stroke subjects the ability to activate the extendors and to coordinate the simultaneousness activation of the flexors and the extensors is affected more than activation of the flexor muscles [19], although this cannot be generalized to all the hemiparetic subjects. Hence, the subjects often have difficulty releasing the grasped object [10]. The grasp release is thus essential to a functional use of the hand. An impaired ability to control the opening of the hand and fingers is a result of the improper and increased coactivation of the flexor muscles which appears during the activation of the extensor muscles. During the voluntary activation of the extensor muscles, involuntary activation of the flexor prevails over the decreased excitation of the extensor muscles [20]. A treatment which augments the ability to open the hand and fingers is important for regaining the functional ability to use the hand in activities of daily living [10]. Likewise both subjects have given more emphasis on the training of the opening of the fingers than on closing them. Many authors also emphasize the importance of the therapy of the extensor muscles. Fritz and colleagues [10] have shown that the wrist and finger extension has a predictive value for the functional use of the hand.

IV. CONCLUSION

This paper presents the experimental training session carried out with two hemiparetic subjects. The rehabilitation system was designed to positively influence the outcome of the rehabilitation period through more effective therapy especially by motivating the patient with the multimodal display and his active involvement in the therapy. The HEnRiE allows the training of reaching and grasping movements, such that beside the elbow and shoulder movement treatment, the therapy can be expanded to the grasp treatment and the therapies can be carried out jointly at the same time. The proposed automated rehabilitation system not only enables the enhanced rehabilitation but also provides an assessment of the progress of the rehabilitation in terms of specific and objective performance indices. The HEnRiE system was evaluated in the group of two post-stroke subjects during a one-month period of the training. Positive outcome of the training is reported for the strength of closing and opening of the hand and the accuracy of the arm movements.

REFERENCES


