HARMiS – Hand and arm rehabilitation system

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ABSTRACT

This paper presents the HARMiS device (Hand and arm rehabilitation system), which is primarily intended for use in robot-aided neurorehabilitation and for training of reaching, grasping and transporting virtual objects in haptic environments. System combines haptic interface and module for grasping, which is mounted on the top of the haptic interface. This allows combined training of the upper extremity movements and grasping. High level of reality is achieved with use of the graphic and haptic visual environments, which is beneficial for the motivation of the patients.

1. INTRODUCTION

Robot-aided neurorehabilitation is a sensory-motor rehabilitation technique based on the use of robot and mechatronic devices (Loureiro et al, 2004; Mihelj et al, 2007). 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 parameters for patient evaluation (Harwin et al, 2006; Kahn et al, 2006). Measurements of forces and positions acquired during the tasks allow quantitative assessment of neuro-motor state of the patients and their progress. European project Gentle/s showed that subjects were motivated to exercise for longer periods of time when using an augmented virtual reality system composed of haptic and visual reality systems. Subjects could exercise "reach-and-grasp" type of movements but without the grasping component, which was identified as one of the shortcomings of the Gentle/s prototype. (Loureiro et al, 2004). With tasks implemented in virtual environments new quality is added if the tasks motivate and draw in the patient and also because apparatus allows to quantitatively evaluate the patient's state (Luciani et al, 2004; Kurillo et al, 2007).

Paper will present HARMiS device, which combines haptic device for upper extremity with a module for grasping and computer generated haptic and graphical virtual environments. The HARMiS device allows combined therapy for upper extremities and grasps rehabilitation. Joint therapy is reasonable because most of the activities of daily living require both arm movements and grasping (Fritz et al, 2005).

2. METHODS

2.1 Apparatus

HARMiS is based on a three-degree of freedom admittance controlled haptic interface HapticMaster (see Fig. 2). Completely new control algorithm for controlling the haptic interface arm was designed and implemented on RTLinux with 2.5 kHz sampling loop frequency. The adopted design paradigm allows implementation of a transparent custom-made robot controller. Custom-made robot controller allows building a custom made haptic virtual environments. Figure 1 shows the control algorithm, upper scheme shows the calculation of desired velocity v_{virt} and position p_{virt}, and lower scheme shows controller. End-point of the robot is represented with virtual mass point with mass m (in our case mass m was 3 kg). Forces that act on virtual mass point are measured force F_{meas} applied by the user and forces F_{VE} that act on the virtual mass point in virtual environment (force of the virtual wall, contact forces with virtual objects, etc). From sum of these forces the movement of the virtual mass point is calculated. From the velocity v_{virt} and position p_{virt} of the virtual mass point and actual position of the haptic interface p_{enc} reference velocity v_{ref} for the haptic interface

HapticMaster is calculated, which is input in the PD controller. PD controller is analog controller and is part of the hardware supplied by the FCS Control Systems. Input of the controller is also measured force v_{tah}, which is compared with reference velocity v_{ref}, and the output is generated current I_{reg} for the motors of the haptic interface.

The two-axis gimbal with a two-degree of freedom grasp module mechanism and a wrist support splint is attached on the end-point of the robot. The gimbal is used to carry the weight of the subject's arm and the grasp system and to allow unconstrained movements of the subject's arm. The force sensor on the end-point of the robot is used for measuring the interaction forces between the subject and the haptic virtual environment.

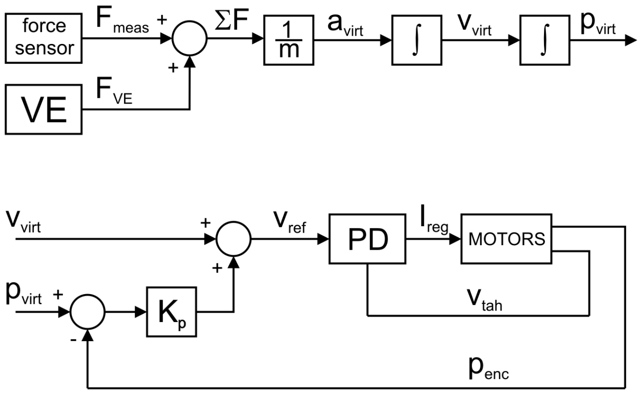

Figure 1. *Control scheme of the HARMiS device. Upper scheme presents the calculation of desired velocity v_{virt} and position p_{virt} from sum of measured force and forces of virtual environment. Lower scheme presents the control scheme of haptic interface HapticMaster.*

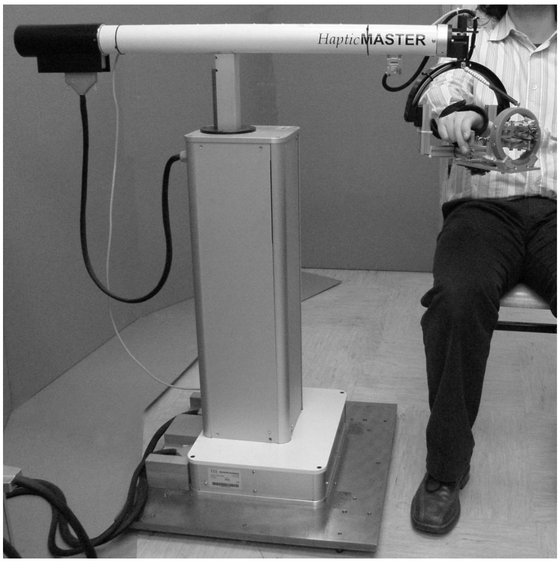

Figure 2. *HARMiS device. Figure shows haptic interface HapticMaster and the grasp module mounted on top of the robot arm. The user inserts the hand into the gimbal device which supports the arm.*

The grasp module (see Fig. 3) is a newly designed passive haptic system for grasping virtual objects in haptic virtual environment. It has two passive degrees of freedom each with a load cell for measuring grasp force, one for measuring the force applied by thumb and other for measuring the joint forces applied by index and middle finger. Passive haptic rendering was achieved by adding the elastic cord between the frame and the movable part of the grasp module. The grasp module can be quickly fully adapted to different sizes of hand, different levels of grasp force and for measuring on either left or right hand without a need to disassemble the grasp module.

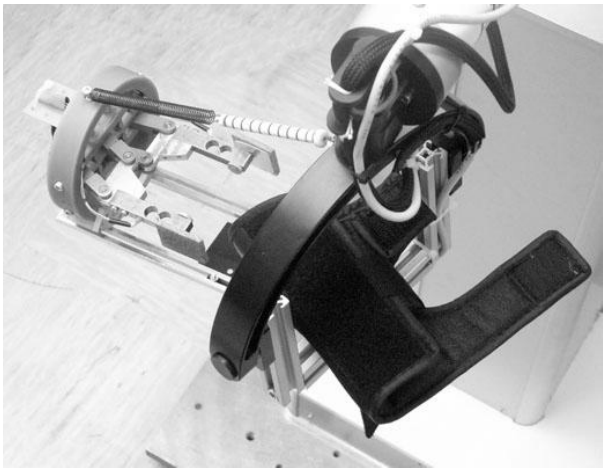

Figure 3. *Grasp module consists of gimbal device, a wrist support splint and two-degrees of freedom mechanism for measuring the grasp force and for passive haptic rendering.*

2.2 Pick and Place Task

In this task the subject must move arm to the virtual object and grasp it. Then the subject must transport it to the new location and releases it. When the object is released a new virtual object comes in to the workspace and the subject must again reach it and transport it to the new location. If the subject does not apply sufficiently large grasp force the object will fall down and will have to be picked up again. The virtual objects in this task were apples, which fall of the tree and the subject has to carry them on a fruit stand where the apples are sold (see Fig. 4).

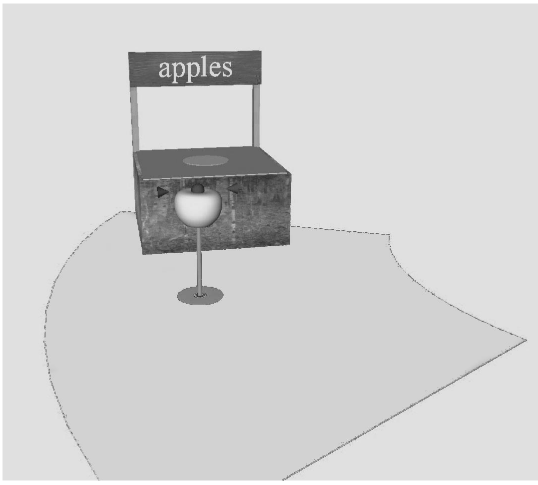

Figure 4. *Pick and place task in which the user is transporting apple on the fruit stand. Sphere represents the end-point position, while cones represent virtual fingers.*

2.3 Winded Tube

The aim of this task is to move through winded tube shown on the Fig. 5 and to navigate a virtual elastic ball through winded pipe, which covers major part of the subject's arm workspace. The radius of the pipe changes along the path of the tube. The position of the hand is represented with elastic ball. The radius of the elastic ball changes according to grasp force applied by the subject in similar manner as if the subject would be squeezing the actual rubber ball. At the start the radius of the ball is larger than the radius of the pipe and the user is required to apply sufficient grasp force to squeeze the ball to the radius which is smaller than the radius of the pipe. As the pipe gets wider or narrower over the course of the path through the pipe the subject has to "squeeze" the ball to appropriate radius if it wants to get to the end of the pipe. Whenever the subject does not apply sufficiently large force the walls of the pipe stop him because the radius of the ball becomes larger than the radius of the pipe. When this happens the user is required to increase the grasp force.

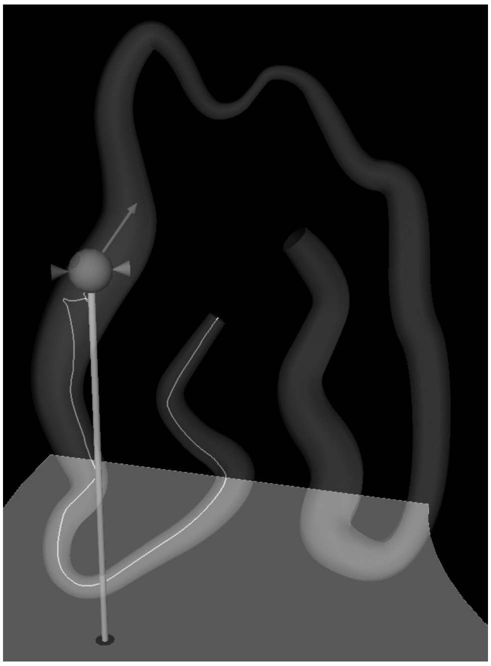

Figure 5. *Task winded tube. When the user applies the grasp force the radius of the ball will change according to grasp force applied.*

2.4 Subjects

Five healthy male, right-handed subjects (25–29 years old) participated in the present study. The participants had no history of neuromuscular or musculoskeletal disorders related to the upper extremities.

3. RESULTS AND DISCUSSION

3.1 Pick and Place Task

Figures 6, 7 and 8 show the grasp force, position and load force for 17 trials of transporting the virtual object. Figure 6 shows the grasp force. Figure 7 shows the position of the wrist. The grounds are on the height -0.18 m and the stand is the height -0.10 m. Figure 8 shows the load force. The load force is the force that acts on the wrist and is applied by the user's arm. The x-axis is shown in normalized time. Three time markers were chosen to divide transporting of the virtual object into phases:

- Preload phase. Forssberg et al (1991) has described basic mechanisms of coordination between grasp and load force in preload and load force in children and adult subjects. In preload phase we have observed small negative load force, which the Forssberg et al (1991) has observed in children but not in adult subjects. The subject gently presses the virtual object against the virtual ground and prepares for stable grasp. One could speculate that adult subjects in virtual environments employ mechanisms which are typical for early years of development of grasp to load force coordination in children. However, it is more likely that due to less rich sensory information available in virtual environments, the user compensates it with pressing the object to the ground to assure stable grasp.
- Loading phase. Both grasp force and load force increase to their maximum at about 0.20 of normalized time. In our experiments we can observe same lift synergies in grasp and load forces as in the case of lifting real objects as described by the Forssberg et al (1991). This shows that adult subjects, when lifting the object in virtual task, employ same anticipatory control of the force output during the loading phase as in real situation.
- Transporting phase in which the subject lifts the virtual object and transports it to a new location. The grasp force is slowly decreasing, but does not fall below the grasp force required to hold the virtual object. When object is lifted and held stationary, subject has to compensate only for the weight of the object and load force is constant. However, when object is moved inertial loads arise and result in increased load force. This increase can be seen in Fig. 8 as a second peak at about 0.65 of normalized time. When transporting actual objects held with fingers grasp force increases in parallel with load force (Flanagan et al, 1993; Nowak, 2004). In Fig. 6 it can be seen that in our experiments the increase in grasp force is not present. In experiments performed by Flanagan and Wing (1993) and recently

Nowak (2004) the grasp force was force in normal direction and load force was force in tangential direction, fingers thus applied both forces. In our experiments the grasp force is force in normal direction and applied by fingers, while load force is force measured between the wrist and the end-point of the haptic interface. Hence, subject does not feel the perturbations with the fingers but on the wrist. Hence, the grasp force and the load force are decoupled. This was necessary for a successful use of HARMiS device as a rehabilitation device for upper extremity and grasp rehabilitation. The HARMiS device supports the subject's arm in the wrist, which is appropriate for upper extremity rehabilitation. The help provided by the haptic interface to the subject or a resistance will be set accordingly to subject's level of upper extremity impairment, while the grasp part of the task will be set accordingly to subject's level of grasp impairment. The HARMiS device is thus designed intentionally for use in rehabilitation with special emphasis on joint rehabilitation of upper extremity and grasp, and it can be adapted to special requirements of the patient's level of impairment. Transport phase ends at 0.9 of the normalized time when the subject puts down the virtual object on a new location.

- Release phase is the last phase in which the subject releases the virtual object.

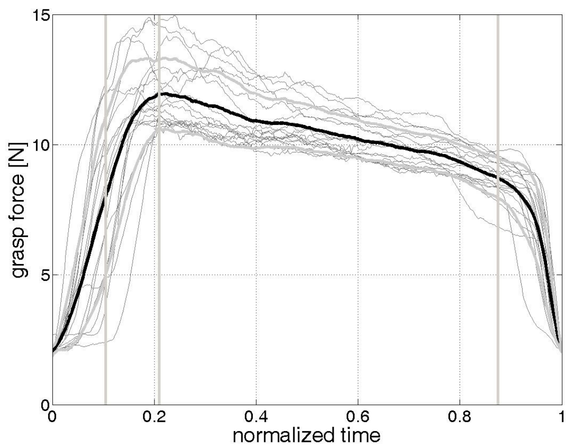

Figure 6. *Grasp force as a function of normalized time in task pick and place. Vertical lines denote time markers: first marker – end of preload phase and beginning of loading phase, second marker - beginning transport phase, third marker – beginning of release phase*

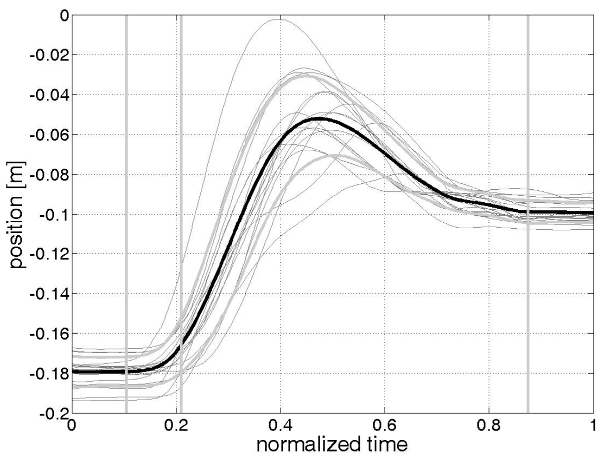

Figure 7. *Z-axis position of the wrist as a function of normalized time in task pick and place.*

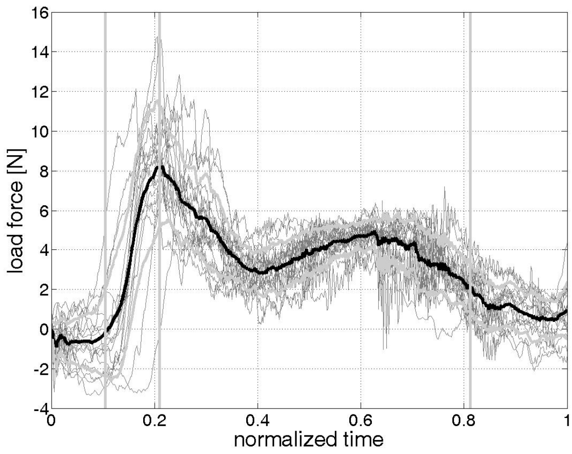

Figure 8. *Load force as a function of normalized time in task pick and place.*

3.2 Winded Tube

Figure 9 shows the trajectory through the winded tube (bold line) and the dimension of the ball (two thin black lines). The two most outer black thin lines represent the walls of the tube. Trajectory through the tube is colored in three different shades of grey to represent different ways the subject moved through the pipe. Black bold line represents the parts of the trajectory where the radius of the ball is larger than the radius of the pipe. The subject gets "stuck" in the pipe and has to increase the grasp force to continue through the pipe. Figure 10 shows the grasp force in the task winded tube. Grey field represents the minimum necessary grasp force required to get through the pipe. Grasp force is represented with bold black line when the grasp force applied by the subject is bellow the required grasp force and with dark grey line when the subject applies sufficiently large grasp force. Whenever the grasp force becomes lower than required grasp force the user increases the grasp force in order to again move freely along the pipe. Dark grey bold line in Fig. 9 represents the part of the trajectory when the radius of the ball is smaller than the radius of the pipe and the ball is in the contact with the wall of the pipe. Light gray bold line in Fig. 9 represents the part of the trajectory when the ball is smaller than the pipe and the ball is not in the contact with the wall. From the Fig. 9 it can be seen that the user slides along the pipe when moving through the pipe.

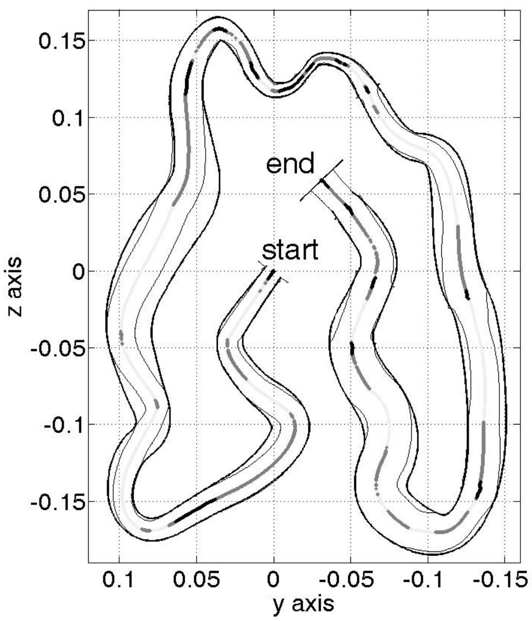

Figure 9. *Central bold line represents the trajectory of the ball. Light gray – the ball is not in the contact with the wall of the tube; dark grey – the ball is in contact with the wall of the tube; black – the radius of the ball is larger than the radius of the tube.*

This task also requires user to move the arm and use the hand to grasp. But it differs from the pick and place task, because the user has to change the grasp force during the task in accordance with the radius of the tube. In the pick and place task the user has to apply sufficiently large force for the stable grasp in the virtual environment. It is only required to reach the threshold grasp force which corresponds to the grasp force for stable grasp in virtual environment. This force is chosen before the task begins and it remains constant through the pick and place task. On the other side, in winded tube task the radius of the tube defines the minimum grasp force at a certain part of the trajectory through the tube. Hence, the winded tube task can be placed among tracking tasks (Wetherell, 1996; Jones, 2000), since the user is required to apply grasp force larger than the minimum grasp force which is the reference. However, the winded tube tasks introduces new modality since the user is not just tracking the visual reference, which is in case of winded tube the radius of the tube, but it also can feel the haptic stimulus. The user can apply larger grasp force than required, while if the grasp force is lower than minimal grasp force the user will feel that the ball got stuck in the tube and will have to apply much larger force with the arm to continue. Hence, the user will be compelled to increase the grasp force.

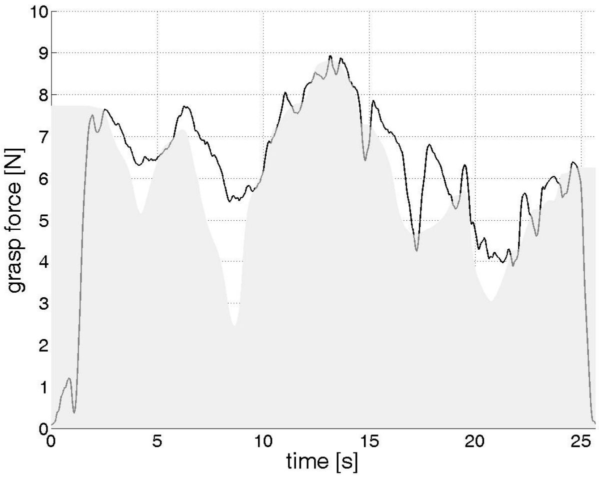

Figure 10. *Grasp force applied by the user in winded tube task. Grey field represents the minimal grasp force.*

4. CONCLUSIONS

System HARMiS described in this paper allows the therapy to be expanded to grasp treatment. The possibility to grasp objects in virtual environment introduces new level of tasks, which resemble even more to the activities of daily living. Hence, beside the elbow and shoulder movement treatment, the therapy can be expanded to grasp treatment and therapies can be carried out jointly at the same time. Subjects have also reported that the ability to grasp the objects in virtual environment gives them the feeling of more natural interaction with the virtual objects. Subjects have also reported that they feel more motivated to finish the task successfully. However, the system has several drawbacks. Grasp module is passive and can only render passive haptics. To improve the grasp module an active mechanism would be required. The preliminary experiments on healthy subjects showed that the two-degrees of current mechanisms could be coupled and one active degree would suffice.

The future work will also include patients with movement disabilities.

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