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HEnRiE – Haptic Environment for Reaching and Grasping Exercise

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Abstract— **Task-oriented repetitive movements can improve motor recovery in patients with neurological or orthopaedic lesions. HEnRiE is a robot based haptic environment for simultaneous training of reaching and grasping movements. It consists of a robot with three active and two passive degrees of freedom and a grasping device with one degree of freedom. A training scenario that includes a virtual physiotherapist is introduced. Presented are results of a preliminary study that requires reaching and grasping coordination.**

Index Terms— **Rehabilitation robotics, grasping, upper extremities, kinematics.**

I. INTRODUCTION

Several pathologies result in reduced upper limb functionality. Motor recovery is a dynamic process that usually starts with a total incapacity to move the affected limb followed by development of some imprecise movements. After some time these movements become more precise but sometimes stiffness and involuntary activity hamper the return to functionality.

Current therapeutic interventions for patients with severe brain injury such as stroke are based on neurofacilitatory techniques, muscle tonus controlling therapies, progressive strengthening, biofeedback or electrical stimulation [1], [2], [3]. Several studies have demonstrated the efficacy of different training therapies for arm paresis in stroke patients [3], [4] and that task-oriented therapies are important to improve the function of the affected arm [5].

There is evidence that machine delivered therapies can be effective in progressing the treatment [6]. Robotic devices are capable of reaction times far in advance of any human, which opens up the breadth of possible treatments, where robotic device responds to forces generated by the patient. For people with upper limb paralysis it is possible to consider therapies where intelligent assistance from a robot is able to provide varying degrees of compensatory movements for the affected limb. Evidence indicates that where patient is motivated and premeditates his movement, the recovery is more effective and intelligent machines allow a broad scope to investigate these conditions. Furthermore sensing that already exists within the robot can be used to provide a wealth of information about the underlying pathology.

While many of the necessary technologies are in place to produce robot based rehabilitation devices with the right characteristics for rehabilitation, there is a major need to integrate these and identify the optimum modalities of exercise from the point of view of motor training. Within traditional therapy there is considerable controversy surrounding the most appropriate method of therapy and there are still insufficient data to identify clearly the benefits of these different approaches.

A. Scientific Evidence for Automated Rehabilitation

One question that needs to be answered is whether a device for rehabilitation of upper arm functions should include the possibility to train proximal as well as distal functions. In [7] authors conclude that a repetitive training of complex movements is not beneficial compared with functional-based occupational and physiotherapy. Instead, a well-defined repetitive training of circumscribed functionally most important activities, particularly of the hand, is recommended. This would suggest that a complex device dedicated to training of proximal and distal arm functions would be less beneficial compared to two separate devices, one for proximal and the other for distal arm functions.

Evidence based physiotherapeutic concepts for improving arm and hand function in post stroke patients are analyzed in a review article [8]. Authors suggest that repetitive execution of complex movements is appropriate to support motor recovery in stroke patients and to accelerate its time course.

In a study reviewing different devices for robot based rehabilitation of upper and lower extremities authors address the problem related to the rehabilitation of proximal versus distal upper arm functions in robot-assisted upper limb rehabilitation [9]. They note that arguments in favor of a more distal approach may be the larger cortical representation of the forearm and hand, and the presumed competition of proximal and distal body segments for recovery. The competition of the proximal and distal functions for territory in sensorimotor cortex was confirmed also in [10]. Authors showed that even limited activity of the upper arm might prevent the hand from gaining motor control.

The lack of evidence is further supported by other studies. Insufficient evidence makes it impossible to draw definite conclusions about the effectiveness of exercise therapy on arm function in stroke patients [11]. The difference in results between studies with and without contrast in the amount of duration of exercise therapy between groups suggests that more exercise therapy may be beneficial. The messages resulting from the review are as follows: 1) trials comparing different types of exercise therapy for the arm function in stroke patients have shown no difference in effectiveness, 2) more intensive exercise therapy appears to be beneficial and 3) stroke patient should be encouraged to continue exercising the affected arm.

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Various robotic devices have been constructed that enable investigation of the above mentioned rehabilitation strategies. MIT Manus robot was upgraded with wrist functionality to allow training of complex movements [12], GENTLE/S robot system based on HapticMaster device (Moog FCS Inc.) was upgraded with device for training of reaching and grasping [13], ARMin robot was developed that allows training of complex activities of daily living (ADLs) [14].

In a number of critical reviews it has been found that it is highly important to start intensive rehabilitation in stroke patients as early as possible [15], [16]. It was also found that the therapeutic outcome with respect to neuromuscular function as well as a successful transition to daily live improves with increasing intensity of upper and lower limb training [17], [18], [19]. Further systematic reviews of Kwakkel et al. [20], [21] also showed that longer training (”augmented exercise therapy”) has a favorable effect on activities of daily living, walking, and dexterity in stroke patients.

Although, there is strong evidence that early and intensive exercise therapy enhances functional recovery in stroke and other neurological diseases, current rehabilitation treatment programmes are often shorter and less intensive than required for gaining an optimal therapeutic outcome. One reason for this deficit may be a lack of motivation and attention, which has been stated to be often the cause for the failure of conventional therapy. A therapy should be enjoyable, challenging and motivating. The role of motivation is known to be important in the success of neurorehabilitation [22], [23], [24]. However, a better understanding is still needed as to how entertainment, motivation and engagement can influence the intensity of the training and the therapeutic outcome.

Computerized technology has the capability to create an exercise environment where the intensity of practice and positive feedback can be consistently and systematically manipulated to create the most appropriate motor learning approach. Adding virtual reality (VR) capabilities to robotic training yields a more appealing exercise environment, when realistic scenarios with challenging tasks are offered to the patients. VR can engage and reward the patient, thus increasing the motivation. Adjusting the level of difficulty to the individual patient’s capabilities within a VR task is of crucial importance for cognitive and motor remediation.

Motor improvement during movement exercise is commonly achieved by applying tasks of increasing difficulty in combination with physical and/or verbal guidance of the patient’s movements or actions. Thus, integrating the means to modulate the level of difficulty within a VR task is of utmost importance. The possibility to change the VR setting relatively easily, to grade task difficulty and to adapt it to the individual patient capabilities, are important advantages of VR, as these features are essential for cognitive and motor remediation.

There are not many studies that investigated the effect of VR on the therapeutic outcome in comparison to conventional training. Although there are an increasing number of VR applications in motor rehabilitation, there are no studies that report the effects of different cues and VR scenarios on the feeling of presence and motivation of the patient.

In this paper a rehabilitation system is proposed that is based on the development of the GENTLE/S project [25]. A robotic device for rehabilitation of upper extremities, HEnRiE, was built based on the hypothesis that initial training of proximal arm segments hinders later rehabilitation of the distal ones. Therefore, the system enables simultaneous distal and proximal movement training. The rehabilitation is enhanced with a novel virtual environment that introduces a virtual physiotherapist to stimulate and guide the patient through the rehabilitation process.

II. METHODS

A. *HEnRiE Specification*

The rehabilitation system consists of the haptic interface device HapticMaster (Moog FCS Inc.), a grasping device, a gravity compensation mechanism, a wrist connection mechanism, a 3D visualization system and a Dolby surround sound display. The robot and grasping device are shown in Fig. 1.

The haptic interface allows adequately large reaching movements in three active degrees of freedom. These are coupled to a gimbal with two passive degrees of freedom to allow reorientation of the subjects’s hand (hand pronation/supination is constrained). The system is upgraded with a one degree of freedom finger training subsystem (isometric, passive isokinetic) in order to provide grasping, reaching and object carrying capabilities. This results is an upper limb rehabilitation system that allows training of complex ADLs in an adaptive virtual environment.

The patient sits in a chair with his/her arm supported by an elbow orthosis suspended from the overhead frame to eliminate the effects of gravity and minimize the problem of shoulder subluxation. The wrist is placed in a wrist-orthosis connected to the haptic interface. Fingers are placed in cuffs attached to the fingers training subsystem.

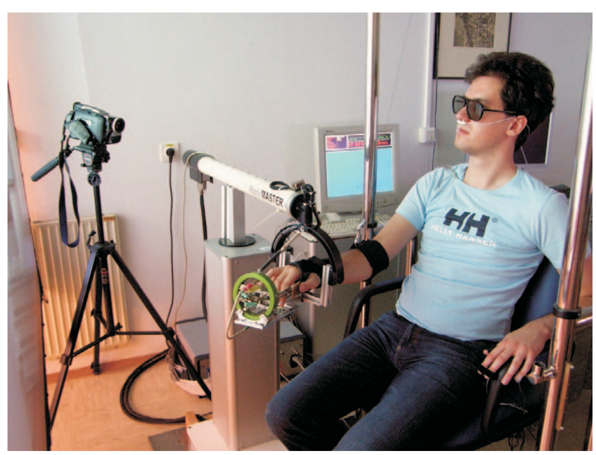

Fig. 1. Subject training with HEnRiE: a grasping device is attached to the HapticMaster end-effector, a 3D projection screen is positioned in front of the subject, a thin Kevlar wire connects the elbow cuff with the arm gravity compensation motor positioned above the subject.

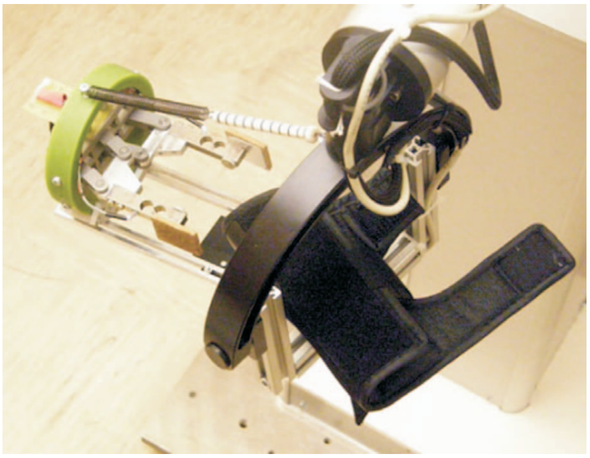

Fig. 2. Grasping device with finger plates easily replaceable with cuffs to restrain fingers. Parallelogram mechanism is visible on the right side of the green ring. Springs are attached on the opposite site of the ring. The parallelogram behaves as a lever system transmitting forces from springs to fingers.

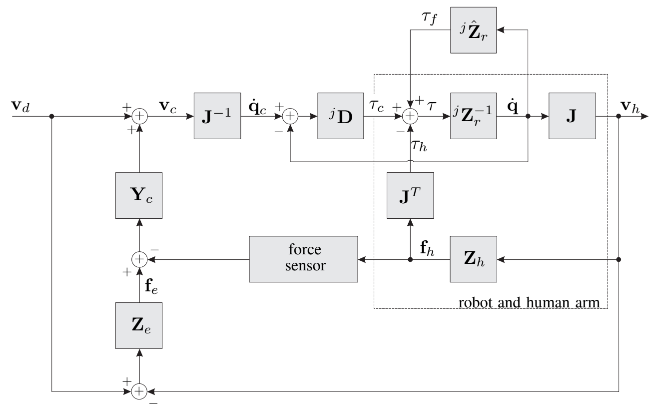

Fig. 3. Block diagram of the control system with robot dynamics expressed as a joint space impedance ${}^{j}\mathbf{Z}_r$. ${}^{j}\hat{\mathbf{Z}}_r$ denotes compensation of robot dynamics, $\mathbf{J}$ is the robot Jacobian matrix and ${}^{j}\mathbf{D}$ is the robot joint space controller. $\mathbf{Y}_c$ is the controller admittance. $\mathbf{Z}_h$ is the human arm endpoint impedance and $\mathbf{Z}_e$ is the impedance of the virtual environment.

B. Grasping Device

The device for training of grasping shown in Fig. 2 is built with one degree of freedom. The device is designed with two parallelogram mechanisms to allow parallel opening and closing of fingers attachments. Each finger attachment is equipped with a single axis tension/compression load cell (SMD, S230) for measurement of interaction forces between the fingers and the device. Force cells can measure forces up to 90N. The force signal amplifiers are integrated in the grasping device.

The patient's thumb finger is attached to the finger cuff on one side, while index and middle fingers are attached to the cuff on the other side. The device enables measurement of forces during finger flexion and extension. The grasping force is calculated as the difference between the forces measured by the two load cells.

For the first experiments the device was configured as a passive system with springs that determine the relation between the finger force and the closing of fingers. Springs were attached at the opposite side of the parallelograms in relation to fingers. A lever system is used to transmit the spring forces to the patient's fingers. Springs are easily replaceable to allow simulation of different object stiffnesses. However, in order to increase the flexibility of the device and make it programmable, the spring system is to be replaced with an electric motor. The parallelogram transmission was already designed in a way to easily allow motor actuation.

The total weight of the haptic grasping device is 0.5kg, which makes is suitable for the attachment to the robot end-effector. A handcuff is attached to the U-shaped module that allows fixation of the human arm to the robot.

C. HEnRiE Control System

Control system enables patient-cooperative control strategies. Fig. 3 shows the coupling between the high level task controller with the virtual environment, the low level joint space robot controller and the controlled plant consisting of the robot and the human arm. The human arm is coupled to the robot end-effector at the wrist position. The task level controller, which includes the physical model of the virtual environment is impedance based. The robot low level control is admittance based. Forces computed at the task level, $\mathbf{f}_e$, are compared to the actual interaction forces, $\mathbf{f}_h$, measured by the force sensor. The force difference is is fed to the controller admittance filters, $\mathbf{Y}_c$. The output of $\mathbf{Y}_c$ are desired world space velocities, which are then transformed into desired joint space velocities using the robot inverse Jacobian matrix $\mathbf{J}^{-1}$. These are then fed into the local proportional-integral (PI) controllers, ${}^{j}\mathbf{D}$ (note that PI feedback of velocity is equivalent to proportional-derivative feedback of position). The robot dynamics is compensated within the local controller with ${}^{j}\hat{\mathbf{Z}}_r\dot{\mathbf{q}}$.

Next, the impedance $\mathbf{Z}_{cl}$ felt by the user when coupled to the robot and operating in the virtual environment with the overall impedance $\mathbf{Z}_e = \mathbf{f}_e/\mathbf{v}_h$ will be estimated. From relations in Fig. 3 the following equation can be derived

$$\begin{aligned} \mathbf{v}_h &= \mathbf{J}{}^{j}\mathbf{Z}_r^{-1}(\tau_c - \mathbf{J}^T\mathbf{f}_h + {}^{j}\hat{\mathbf{Z}}_r\dot{\mathbf{q}}) \\ &= \mathbf{Z}_r^{-1}(\mathbf{J}^{-T}\tau_c - \mathbf{f}_h + \hat{\mathbf{Z}}_r\mathbf{v}_h)\,, \end{aligned} \tag{1}$$

where $\mathbf{J}$ is the robot Jacobian matrix, ${}^{j}\mathbf{Z}_r$ and $\mathbf{Z}_r$ denote robot impedance expressed in the joint space and in the Cartesian coordinates, respectively (*hat* over $\mathbf{Z}_r$ indicates the model used for the compensation of robot dynamics), and are related through

$$\mathbf{Z}_r = \mathbf{J}^{-T\,j}\mathbf{Z}_r\mathbf{J}^{-1}. \tag{2}$$

In order to estimate the closed loop impedance $\mathbf{Z}_{cl}$, which is defined by the ratio of the force exerted on the human arm, $\mathbf{f}_h$, and the velocity of the human arm $\mathbf{v}_h$, we suppose without loss of generality the desired task velocity to be zero, $\mathbf{v}_d = 0$. Torque τ_c can then be determined as

$$\begin{aligned} \tau_c|_{\mathbf{v}_d=\mathbf{0}} &= {}^{j}\mathbf{D}\left[\mathbf{J}^{-1}\left(\mathbf{Y}_c(-\mathbf{Z}_e\mathbf{v}_h - \mathbf{f}_h)\right) - \mathbf{J}^{-1}\mathbf{v}_h\right] \\ &= \mathbf{J}^T\mathbf{D}\left[-\left(\mathbf{Y}_c\mathbf{Z}_e + \mathbf{I}\right)\mathbf{v}_h - \mathbf{Y}_c\mathbf{f}_h\right]\,, \end{aligned} \tag{3}$$

where $\mathbf{I}$ is an identity matrix and

$$\mathbf{D} = \mathbf{J}^{-Tj}\mathbf{D}\mathbf{J}^{-1} \quad (4)$$

is a Cartesian space expression of robot joint space controller transfer functions.

With a simple algebraic manipulation of equations (1) and (3) it is possible to estimate the closed loop impedance $\mathbf{Z}_{cl}$ felt by the user as

$$\mathbf{Z}_{cl} = \frac{-\mathbf{f}_h}{\mathbf{v}_h} = (\mathbf{D}\mathbf{Y}_c + \mathbf{I})^{-1}\left(\mathbf{Z}_r - \hat{\mathbf{Z}}_r + \mathbf{D}(\mathbf{Y}_c\mathbf{Z}_e + \mathbf{I})\right). \quad (5)$$

By increasing the gains of the local PI controllers, ${}^{j}\mathbf{D} \rightarrow \infty$, the closed loop impedance simplifies to

$$\mathbf{Z}_{cl} \approx \mathbf{Z}_e + \mathbf{Y}_c^{-1}. \quad (6)$$

With high admittance of the robot controller $\mathbf{Y}_c$, the closed loop impedance $\mathbf{Z}_{cl}$ approaches the desired task impedance $\mathbf{Z}_e$.

D. Virtual Physiotherapist training scenario

A novel type of training scenario is being designed with the following requirements in order to address specific user needs: 1) improve motor functionalities of upper extremities after stroke and other pathologies; 2) movements are therapeutically meaningful (relevant for ADL); 3) behavior is trained through the reinforcement of successive approximations; 4) the system is adaptive to conform to motor/cognitive abilities of a particular patient and it supports adaptive training intensities; 5) the training scenario is engaging and motivating; 6) it stimulates emotional responses; 7) it is designed in a way to increase concentration and endurance; 8) in the long run the system should reduce the therapy time frame and costs.

The proposed training scenario is the implementation of a virtual physiotherapist. The patient sits in a chair with his hand attached to the HEnRiE end-effector. The weight of the arm is partially compensated using active gravity compensation system. The grasping device is attached to the robot end-effector and the patients is able to grasp the device with thumb on one side and index and middle fingers on the other side. A 3D projection screen is positioned approximately 1m away from the patient (across the robot from the patient). Sound speakers are positioned around the patient in order to provide audio surround.

Fig. 4. Virtual physiotherapist experimental setup - 3D projection screen (white) with a virtual physiotherapist projected in 3D, HapticMaster robot with haptic grasping device, patient doing exercise with the virtual physiotherapist.

A virtual physiotherapist (VPT) is presented in 3D mode on the screen in front of the subject. The VPT adequately selects and guides training exercises. Quality rendering is used to provide realistic look. Out-of-screen effect is such to enable the VPT's hand to virtually reach patient's hand attached to the robot end-effector. The patient gets an impression that the VPT is holding his arm /hand. The robot produces the haptic feedback simulating the forces produced by the VPT on the patient's arm/hand. A tactile feedback is added in order to simulate touching of the hands. The tactile feedback is important in cases where VPT generates only tiny forces on the patient (e.g. only indicating the direction of the movement with the touch of the hand).

When the patient is virtually coupled to the VPT, the training resembles real therapy. The VPT (robot) can passively move the patient's arm, it can only support the movements, it can provide active resistance, generate disturbances, constrain movements, guide movements, indicate directions; patient can virtually grasp the VPT's hand (tactile feedback) and then being moved by the VPT, he/she can grasp the VPT's hand or an object from her hand and feel its weight or grasp an object indicated by the VPT; playing "Braccio di ferro" or another force based game against VPT enables measurement of isometric forces. In all cases the trajectory, force direction and movement timing can be precisely controlled. The VPT haptic behavior is based on a set of control primitives: preprogrammed trajectories, impedance based virtual tunnels, force fields, and force pulses for disturbances. The virtual character responds not only in a haptic, but also visual (gesture and mimics, figure, dress) and acoustic way (commands, comments, encouraging statements). This allows the patient to encounter also social challenges: VPT can be motivating (smiling, supporting the movements, giving encouraging statements) or can respond in an ignorant way; other virtual characters can be there as well to encourage the patient.

The social component is removed from the scenario by implementing the same tasks using virtual tunnels and other non-social methods of indicating the subject what he/she needs to do. The haptic, tactile, and sound feedback remain equal to the feedback information provided by the VPT.

The expected performance values are expressed as biomechanical and physiological reactions (speed of movement, range of motion, force direction and magnitude, grasp and arm movement coordination precision of movement), cognitive behavior (coordination and accuracy, planning of movements), and psychological reactions (joy/relaxation when successfully accomplishing the task, annoyance when tasks are too difficult or challenging, enthusiasm when VPT gives praising and encouraging statements, stress/anger when the VPT is ignorant).

III. Case study - pick and place task

The HEnRiE robot as presented in this paper was evaluated in a case study. The goal of the study was to evaluate the robot controller and the grasping subsystem, as well as the visualization technology. The robot did not support subject's movements. It only generated movement constraints: collisions with other objects and simulation of weight of the object. The grasping subsystem was used as a passive impedance. The aperture between the thumb and index finger was inverse proportional to the force applied to the finger attachments.

The task was to grasp the virtual object and transport it to the new location. If the subject did not apply sufficiently large grasp force the object will fell down and had to be picked up again. The virtual objects in this task were apples, which fell of the tree and the subject had to carry them on a fruit stand where the apples are sold (see Fig. 5). Other tasks that were evaluated, but are not described in this manuscript include winded pipe, painting on the glass, and cube on the elastic cord. All tasks require both grasping and arm movements.

The case study was performed with one healthy subject. In total the subject performed 17 repetitions of the reaching and grasping task. There were no constraints imposed on the movement trajectory or timing.

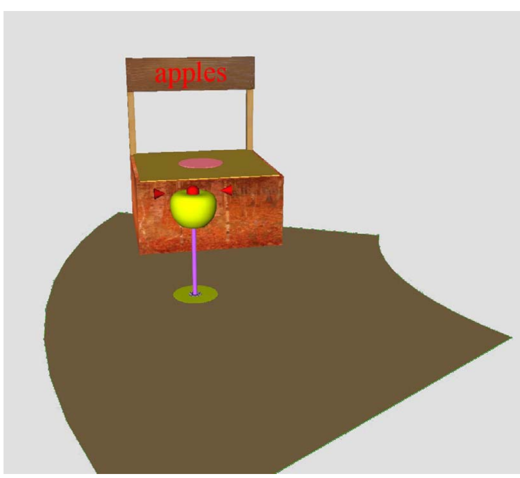

Fig. 5. Pick and place task. Transporting apple on the fruit stand. Red sphere represents end-point position and cones represent virtual fingers; mean value (black), standard deviation (grey).

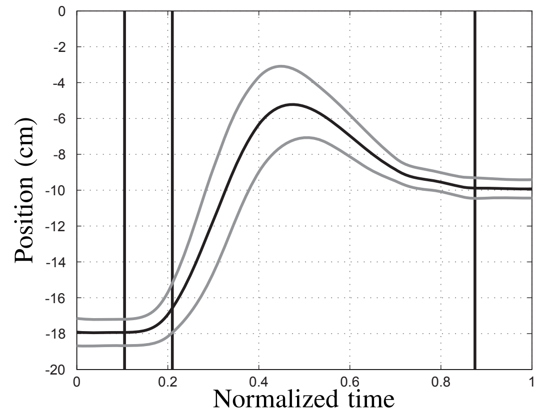

Fig. 6. Vertical position of the hand as a function of normalized time. Vertical lines denote time markers: first marker - end of preload phase and beginning of loading phase, second marker - beginning transport phase, third marker - beginning of release phase; mean value (black), standard deviation (grey).

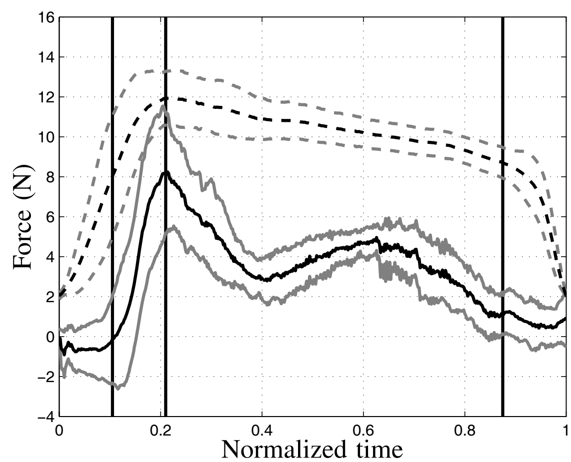

Fig. 7. Grasp (dashed line) and load forces (continuous line) as a function of normalized time.

IV. Results and Discussion

Fig. 6 shows the hand vertical position, while Fig. 7 shows grasp and load forces. The horizontal axis is shown in normalized time. Three time markers were chosen to divide transporting of the virtual object into phases:

1. Preload phase. In this phase the load force is negative. The subject gently presses the virtual object against the virtual ground and prepares for stable grasp.
2. 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 in [26]. 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.
3. 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. 7 as a second peak at about 0.65 of normalized

time. Flanagan et al. [27] report an increase in grasp force in parallel with load force. In Fig. 7. it can be seen that in our experiments the increase in grasp force is not present. In experiments performed in [27] the grasp and load forces were applied with fingers. In our experiments the grasp force is applied with fingers, while the load force is measured between the wrist and the endpoint of the haptic interface. Subject does not feel the load force on the fingers but on the wrist. Hence, the grasp force and the load force are decoupled. The HEnRiE device supports the subject's arm in the wrist, which is appropriate for upper extremity rehabilitation. Help provided by the haptic interface to the subject as well as its resistance to subject's movements are set according to subject's level of upper extremity impairment, while the grasp part of the task is set according to subject's level of grasp impairment. Transport phase ends at 0.9 of the normalized time when the subject puts down the virtual object on a new location.

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

V. SUMMARY AND CONCLUSIONS

The rehabilitation system was designed to positively influence the outcome of the rehabilitation period through more effective therapy especially by motivating the patient with a multimodal display and his active involvement in the therapy.

HEnRiE allows training of complex reaching and grasping movements, while the VPT scenario provides suitable platform for rehabilitation.

The proposed automated rehabilitation system not only enables enhanced rehabilitation but also provides assessment of the progress of rehabilitation in terms of specific and objective performance indices expressed as numeric values easy to understand to clinicians. Force/torque as well as position/velocity data are available for the analysis.

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