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Neurocognitive Robot-Assisted Therapy of Hand Function

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Abstract—Neurocognitive therapy, according to the Perfetti method, proposes exercises that challenge motor, sensory as well as cognitive functions of neurologically impaired patients. At the level of the hand, neurocognitive exercises typically involve haptic exploration and interaction with objects of various shapes and mechanical properties. Haptic devices are thus an ideal support to provide neurocognitive exercises under well-controlled and reproducible conditions, and to objectively assess patient performance. Here we present three neurocognitive robot-assisted exercises which were implemented on the ReHapticKnob, a high-fidelity two-degrees-of-freedom hand rehabilitation robot. The exercises were evaluated for feasibility and acceptance in a pilot study on five patients suffering from different neurological disorders. Results showed that all patients were able to take part in the neurocognitive robot-assisted therapy, and that the proposed therapy was well accepted by patients, as assessed through subjective questionnaires. Force/torque and position measurements provided insights on the motor strategy employed by the patients during the exploration of virtual object properties, and served as objective assessment of task performance. The fusion of the neurocognitive therapy concept with robot-assisted rehabilitation enriches therapeutic approaches through the focus on haptics, and could provide novel insights on sensorimotor impairment and recovery.

Index Terms—rehabilitation, Perfetti method, grasping, haptic perception, kinesthesia, proprioception, sensorimotor control, attention, perceptual learning

1 Introduction

INTERACTION with the environment during activities of daily living strongly relies on the unique dexterity and manipulation skills of the hand — highly cognitive tasks involving both motor commands and rich sensory feedback [1], [2]. Fast gross movements to approach or move objects are largely guided by visual cues, whereas stable grasping and fine manipulation of objects, such as holding a cup or buttoning a shirt, involve fine motor control strongly relying on touch and proprioception [3]. In daily activities, visual and haptic sensory information is unconsciously integrated to optimize the overall task performance [4].

Following a neurological injury such as stroke, sensorimotor function is often strongly impaired, limiting the quality of life and independence. About two thirds of stroke survivors suffer from partial paralysis at the level of the arm and hand. The prevalence of sensory deficits is less documented and varies from 10% to 90% [5]–[7], but there is strong evidence that sensory deficits negatively influence motor performance and recovery [8]. This is especially important for hand function, where motor and sensory deficits are tightly coupled. Nevertheless, conventional rehabilitation programs focus strongly on training gross motor function, while fine motor control and sensory aspects receive much less attention [9], [10].

The *neurocognitive therapy approach* proposed by Perfetti [11] was designed to include both motor and sensory aspects, as well as the cognitive processes linking them, in rehabilitation exercises. It requires that the patient solves a cognitive problem through the use of his/her body, focusing attention on both the generated movements and the perception of the interaction with the environment (space, time, pressure, weight, etc.). More specifically, the patient relies on haptic perception induced by active or passive movements of body segments, e.g. the arm, hand or individual fingers. Exercises typically involve interaction with objects of different shapes and mechanical properties. Patients are asked to explore and identify objects, as well as to discriminate object properties such as length, shape or compliance with closed eyes to focus on haptic perception (Figure 1). This approach therefore integrates all components of the sensorimotor loop into the training. One recent study has evaluated neurocognitive therapy in stroke patients, showing promising results even for severely impaired patients with very limited motor function [12].

The repetitive nature and demand for varying mechanical object properties make haptic interfaces uniquely suited supports for the implementation of neurocognitive exercises. Motor exercises and sensory stimuli can be rendered in a well-controlled

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and reproducible manner while being incorporated into cognitive tasks. The precise and objective data measured by the robot can be used to assess the patient's performance and adapt the task difficulty accordingly (e.g., variation of mechanical properties of a rendered object). Nevertheless, actively training haptic perception and the cognitive processes required for the interpretation of haptic cues has so far received little attention in robot-assisted rehabilitation. The bulk of research has focused on providing varying amounts of assistance, all the way to passive movements, typically in visually guided gross motor tasks [13]. Patients may thus use this visual information to compensate for impaired haptic perception, and are not required to train their haptic sense. Robot-assisted therapy has so far failed to demonstrate superiority over conventional therapy in terms of motor recovery, as illustrated by meta-analyses comparing robot-assisted and dose-matched conventional therapy for the upper extremity [14], [15]. Therefore, it is worth exploring novel avenues in robot-assisted rehabilitation, taking advantage of the unique inherent features of robotic/haptic interfaces [16].

This paper presents the design and implementation of neurocognitive exercises on a robotic platform for hand rehabilitation. The ReHapticKnob is a two-degrees-of-freedom (DOF) high-fidelity haptic interface [16], [17] to train hand opening/closing (e.g. grasping) and forearm rotation (pronation/supination of the wrist). We propose three exercises based on the neurocognitive therapy approach, taking advantage of both DOF of the ReHapticKnob as well as of the integrated sensing and advanced interaction control.

Five patients with different neurological disorders received repeated therapy sessions in an attempt to evaluate the feasibility and acceptance of the neurocognitive robot-assisted therapy approach. Preliminary data of each exercise are presented to further illustrate how patients achieved the neurocognitive tasks relying on perceived haptic cues, demonstrate the high-fidelity haptic interaction with the ReHapticKnob, as well as how patients' sensorimotor performance can be monitored and assessed throughout the exercises.

2 Materials and Methods

2.1 Apparatus

The ReHapticKnob is a two DOF haptic device developed for the rehabilitation of hand function after stroke [17] (Figure 2). A translational DOF allows the training of hand opening and closing, i.e. the grasping function, while the second, rotational DOF, allows for the training of forearm rotation (pronation/supination). Grasping aperture and wrist rotation are measured with two encoders located on the motor shafts in joint space, as well as, for safety, with one rotational and two linear potentiometers directly in task space. The interaction force between device and user is measured with two 6DOF force/torque transducers placed directly behind the two finger supports and used both for the low-level interaction control and for assessment purposes (Figure 2 E). Fingers can be fixed to the finger supports with Velcro® straps such that force along the translational DOF and torque on the rotational DOF can be transferred to the hand and to the wrist, respectively. Two motor-gear combinations actuate the two DOF and two brakes attached to the motor shafts allow locking the two DOF independently, such that they can be decoupled or used for isometric training.

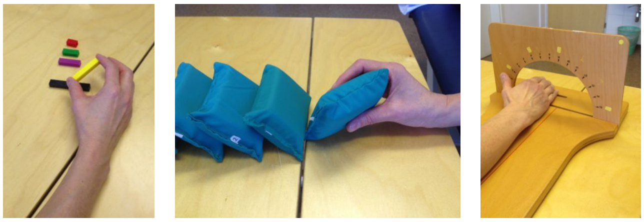

Fig. 1. Representative neurocognitive therapy exercises: grip aperture identification (left), compliance identification (center) and active reproduction of a forearm rotation which was passively induced by a physiotherapist (right). All exercises are cognitive tasks which are executed with closed eyes to focus patients' attention on haptic sensory cues.

Two power amplifiers control the two motors in current mode and receive their set values from an outer control loop running on a real-time system with 1 kHz sampling frequency (LabVIEW real-time target on a desktop PC, National Instruments). The controller used for the ReHapticKnob (illustrated in Figure 2 F and presented in [16]) is selected according to the task to be trained and is either a basic position controller with a proportional and a derivative gain, or an impedance controller with force feedback [18], [19], following the control law:

$$\begin{aligned} F_{ee}(x,\dot{x},F_m) &= F_d + K_f\cdot(F_d - F_m) \\ &= K\cdot(x-x_0) + B\cdot\dot{x} + \\ &\quad K_f\cdot(K\cdot(x-x_0)+B\cdot\dot{x}-F_m) \end{aligned} \tag{1}$$

where all the parameters are described in task space, F_{ee} corresponds to the force rendered at the end-effector, F_d to the desired force, x to the position and $\dot{x}$ to the velocity of the end-effector, K and B to the stiffness and damping constants of the impedance controller, F_m to the measured interaction force at the end-effector along the movement direction and K_f to the force feedback gain.

Thanks to the force feedback the inherent dynamics of the device can be partially compensated and a large range of desired impedances can be rendered at the output. The renderable range of output impedances of the haptic device (Z-width, [20]) ranges from an

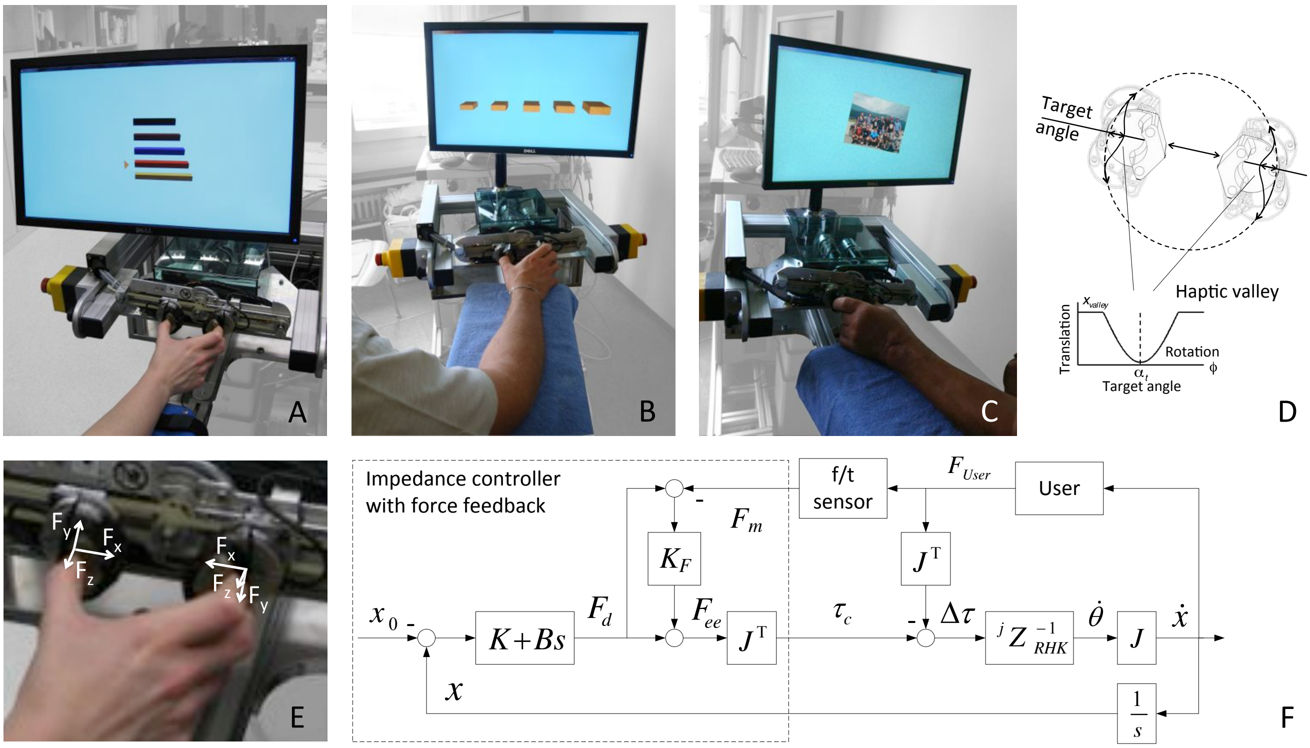

Fig. 2. The ReHapticKnob and three implemented neurocognitive exercises. A: Length identification exercise: the hand of the patient is passively moved by the robot to one of five predetermined hand apertures (represented by bars of different length and color), which has to be identified through haptic perception. B: Compliance identification exercise: the sponge with the corresponding compliance has to be identified out of five sponges with different compliance based on haptic perception from active grasping/squeezing movements by the patients. C: Haptically cued forearm rotation exercise: A picture has to be rotated to a target angle α_t which is indicated *haptically* rather than visually. A haptic valley is rendered when rotating over the target angle. D: The haptic valley is perceived along the translational DOF of the ReHapticKnob and implemented within a narrow band around the target angle. E: force measurement frames of the two force/torque sensors. F: Control diagram of the implemented impedance controller with force feedback: the transformation from joint to task space is described by the Jacobian matrix J (derivation in [17]). The impedance of the ReHapticKnob in joint space is noted as ${}^jZ_{RHK}$.

almost transparent display (zero desired impedance), ideal for the assessment of the patient's functional level, to compliant objects and rigid contact with virtual objects (e.g. virtual wall with stiffness K = 50′000 N/m) [16]. Force measurements are low-pass filtered with a first order Butterworth filter (35 Hz cut-off frequency) and the velocities are calculated with a first order adaptive windowing estimator which has been shown to optimally increase the range of renderable impedances [21]. The same controllers, but with different control parameter settings, are used for the two DOF. The pronosupination torque applied by the user on the rotational DOF is estimated from the two force/torque transducer measurements by solving the hard-finger contact problem as described in [22].

2.2 Neurocognitive robot-assisted exercises

Neurocognitive exercises are designed as tasks to be solved with kinesthetic and/or tactile feedback during passive or active movement. Three exercises, inspired from conventional neurocognitive tasks used during therapy sessions (Figure 1), were selected for their suitability to robot-assisted therapy, and were implemented on the ReHapticKnob.

The three neurocognitive exercises have a similar structure. Each of them presents the patient with a cognitive task consisting of an initial sensorimotor exploration (familiarization) phase followed by an identification (therapy) phase. All exercises involve a functionally relevant physical interaction with the environment that requires cognitive attention and reasoning as well as fine motor skills. The exploration phase of the first two exercises consists in the presentation of five different sensorimotor stimulus levels rendered one after the other, which the patient has to explore in order to develop a sensory memory of each of them. The patient can explore each stimulus level several times, and decides when to switch from one level to the next. In the identification phase, one out of the five previously explored stimuli is randomly selected, rendered by the ReHapticKnob, and has to be identified by the patient. The stimuli are numbered from 1 to 5 and the patient has to verbally report the identified number to the operator who enters the answer into a graphical user interface. In the third exercise, the exploration phase allows the patient to familiarize with a forearm rotation task, in which a target angle, presented through visual and haptic cues, has to be reached. During the identification phase, the visual cues are removed and only the haptic cues are provided. For all exercises, performance is evaluated through the number of successful trials, i.e. the number of correct identifications or successfully completed forearm rotations.

The computer screen is placed over the patient's hand to block direct visual information on the hand position in order to force patients to rely on their haptic perception. The computer screen is further used during exercises to provide visual instructions, feedback related to the task and immediate information about the performance in the current trial. The visual feedback is implemented in OpenGL, with elements of the open source CHAI 3D haptics interface library [23].

For patients with limited or no remaining hand and arm motor function, a physiotherapist can provide the necessary support to move the patient's hand or forearm. The physiotherapist is asked not to assist in the identification or target recognition, respectively. While this affects the motor abilities of the patient (which is intended, as the patient would otherwise not be able to carry out the exercise), it does not affect the patients ability to solve the task (i.e. the patients must rely on their haptic perception to solve the task).

2.2.1 Length identification

The goal of the length identification exercise is to train passive object exploration and identification relying on kinesthetic and/or tactile feedback from the hand. Series of trials are repeated where the hand of the patient is passively moved by the robot from an initial grip aperture of 12 cm to one of five randomly selected grip apertures (7-11 cm in steps of 1 cm) which patients have to identify. These movements are implemented with the position controller, i.e. the movements are guided by the robot and the patient remains passive. This exercise is thus expected to be achievable even by patients with severe motor impairment, as long as their fingers can be safely and comfortably fixed to the robot and that some level of haptic perception is retained. Each grip aperture is represented on the computer by a bar of different length and color (Figure 2 A). Immediate visual feedback about the correctness of the patient's answer is displayed for two seconds by means of a green check mark appearing next to the rendered bar in case of a correct answer, and all bars except the presented stimulus disappear in case of a wrong identification. While the visual feedback is displayed the robot opens the hand to the initial grip aperture, such that the next trial can be initiated.

2.2.2 Compliance identification

The goal of the compliance identification exercise is to train active exploration and identification of objects with different viscoelastic properties. Series of trials are repeated where the patient is asked to actively grasp and identify one out of five virtual sponges rendered by the ReHapticKnob. The rendering is performed with the impedance controller with force feedback. Five different spring-damper parameter combinations result in smooth and soft (sponge like) grasping interactions. The K-B parameter combinations for this exercises were chosen so that stiffness and damping increments from one to the next sponge are always the same: ΔK = 300 N/m and ΔB = 20 Ns/m (Table 1). K and B values are selected such that a healthy subject would easily be able to discriminate between sponges: the smallest stiffness Weber fraction $\mathrm{Wf}_K = \Delta \mathrm{K}/\mathrm{K} = 300/1100 = 27\%$ is larger than the smallest detectable stiffness difference reported in literature ([24], Weber fraction of 22%). Furthermore, the smallest damping increment with a Weber fraction of $\mathrm{Wf}_B = 20/70 = 29\%$ is selected larger than the smallest detectable damping difference reported in literature ([25], Weber fraction of 13.6%). Prior to the start of the exercise the patient's hand is opened to a comfortable initial grip aperture $x_i \in$ [9 cm, 12 cm], which is set as the reference position of the spring: $x_0 = x_i$. Based on the patient's strategy, either force, displacement, work (i.e. force times displacement) or compliance cues can be used to discriminate between the mechanical properties of the different objects [24].

Each sponge is represented via a virtual avatar of different size on the computer screen which is animated using a deforming mesh and a sponge-like texture to enhance the perception of the squeezing interaction through the integration of visual and haptic cues (Figure 2 B). During identification, all avatars are animated simultaneously to force patients to rely on haptic perception only. Immediate visual feedback about the correctness of the patient's answer is then displayed for two seconds on the computer screen; if the answer is correct, the color of the selected sponge is changed to green, while if the answer is wrong, the correct sponge, i.e. the one which is currently rendered by the robot, changes its color to red to indicate a failed trial. Before the next trial, the hand is passively opened to x_i, i.e. to the equilibrium position of the spring.

2.2.3 Haptically cued forearm rotation

The goal of this exercise is to train active forearm rotation movement in coordination with grasping. Patients have to grasp and actively rotate the ReHaptic-

TABLE 1
Stiffness and damping parameters of the five sponges of the compliance identification exercise.

Sponge Nr	1	2	3	4	5
Stiffness K [N/m]	200	500	800	1100	1400
Damping B [Ns/m]	10	30	50	70	90

Knob to a randomly selected target angle α_t, selected within the patient's reachable pronosupination range and displayed haptically, to force patients to rely on kinesthetic and/or tactile feedback from the hand. To facilitate the movement and make the rotational DOF transparent, impedance control with torque feedback with a desired output impedance of zero (K = 0, B = 0) is used. As a result, only small torques ($<$ 0.1 Nm) are required to accelerate and rotate the end-effector of the robot. Visual feedback of the current robot angle ϕ is provided on the computer screen via a rotating picture to attract the patients attention to the screen. Visual target information is provided during the exploration phase via a frame indicating the target angle with which the picture must be aligned. Haptic target information is provided via a haptic valley along the translational DOF, which is rendered around the target angle (Figure 2 C and D). The haptic valley is implemented with the position controller of the translational DOF such that the desired translational position profile ($x_{valley} = f(\phi)$) follows a cosine function with a maximal amplitude of 1 mm at α_t within the range $[\alpha_t - 2°, \alpha_t + 2°]$:

$$x_{valley}(\phi) = (-1\ mm) \cdot cos(\pi/2 \cdot (\phi - \alpha_t)/2°) \qquad (2)$$

where $(\phi - \alpha_t) \in [-2°, 2°]$.

A trial is successfully completed if the rotation angle ϕ is kept within the error band of $\pm 2°$ around the target angle α_t for at least 2 seconds, i.e. the end-effector ϕ is maintained within the haptic valley. Once a trial is successfully completed, the screen background turns green for two seconds to indicate success, and α_t for the next trial is selected. No time limit is given for a specific trial, such that overall exercise performance is indicated by the estimated number of trials which would be completed within 15 minutes based on the measured number of repetitions in one minute.

2.3 Clinical pilot study

In order to evaluate the feasibility of using the aforementioned neurocognitive exercises on a heterogeneous group of patients with different levels of neurological impairment, a non-systematic pilot study was conducted. Five patients (P1-P5, Table 2) were recruited from the Clinica Hildebrand Centro di Riabilitazione Brissago, Switzerland; P1, P2 and P5 were inpatients receiving full-time rehabilitation programs at the Clinica Hildebrand, while P3 and P4 were outpatients visiting the clinic for part-time treatments (2 and 3 days per week, respectively). Inclusion criteria were: age between 18-90 years, mild to severe upper limb sensorimotor impairment due to a neurological disorder and ability to understand instructions. Exclusion criteria were: strong cognitive limitations, upper limb pain, and severe aphasia. Patients volunteered for the study and gave written informed consent prior to enrollment. The study was carried out in accordance with the ethical standards of the Declaration of Helsinki.

Depending on patients' schedules, between three and six 45 min sessions were performed with the robot over a duration of two weeks. A physiotherapist was present during all exercise sessions with the robot and decided on the number of trials and the exercise selection according to the abilities of the individual patient. All patients tried each exercise at least once with their impaired hand in order to evaluate feasibility of each of the proposed exercises.

To investigate the acceptance of the proposed neurocognitive robot-assisted therapy, a subjective questionnaire was given to the patients at the end of the pilot study, composed of the five following questions:

- Q1 Were the exercises with the robot motivating?
- Q2 What was comfortable when executing exercises with the robot?
- Q3 What was uncomfortable when executing exercises with the robot?
- Q4 Which differences did you perceive between the exercises conducted with the robot compared to those conducted with a physiotherapist?
- Q5 Would you recommend the additional neurocognitive robot-assisted therapy to fellow patients?

A therapist from the Clinica Hildebrand, blinded to the study, guided the patients through the questionnaire and collected the answers.

3 Results

In the following, results from the pilot study with 5 patients (P1-P5) training with the three neurocognitive exercises on the ReHapticKnob are presented. An analysis of feasibility and acceptance of the neurocognitive robot-assisted exercises is first described. This is followed by examples of representative data of each exercise illustrating how patients interacted with the robot and which performance measures can be extracted from each exercise.

3.1 Feasibility

All patients were able to comfortably place their hand on the robot and train with all the three exercises, despite their different neurological disorders and varying levels of impairment. All patients were able to

TABLE 2
Patients' demographics

Patient	Age [years]	Gender	Handed -ness	Time post lesion [months]	FMA[1]	FMA[1] subscore (hand function)	Neurological disorder
P1	50	M	right	3	6/ 66	0/ 14	ischemic stroke in the left superior temporal gyrus
P2	34	M	right	7	49/66	11/14	hemorrhagic stroke in the left frontotemporal lobe and capsule
P3	42	F	right	11	43/66	9/ 14	ischemic stroke in nucleo-capsular region
P4	46	M	right	22	39/66	13/14	inflammatory encephalitis affecting different brain regions (frontal-insula, left pyramidal tract, left frontal-temporal lobe)
P5	62	M	right	2	60/66	13/14	cervical-spinal trauma with multiple right frontal-basal contusive lesions

[1] Fugl-Meyer Assessment (FMA) [26]. FMA scores for the upper extremity (maximum score =66) and hand (maximum score =14) subsections are reported (lower scores indicate greater impairment).

perform the length identification exercise, based on robot-guided passive movements, on their own. Patient P3 who had relatively small hands was presented with the four lower stimuli only and, accordingly, the initial hand position was also adjusted (x_i = 11 cm). In contrast, both the compliance identification and the forearm rotation exercise required some remaining hand motor function. Patients P2, P4 and P5 were able to perform these two exercises on their own, while patients P1 and P3 required support from a physiotherapist. Table 3 summarizes the number of exercise sessions and trials performed, as well as the average number of trials per minute (number of identification trials divided by total time for exploration and identification phases) as well as the average exercise performance for all five patients.

Aside from patient P4, who suffered from cognitive deficits and had some difficulties in understanding the tasks, all patients achieved at least 50% in their task performance. Over all patients, an average performance of 68.4% and 61.4% for the length and compliance identification exercises, respectively, was found. The performance in the forearm rotation exercise was measured by the number of conducted trials within 15 minutes and resulted in an average of 51.3 trials/15 min over all patients.

While for the length identification and the forearm rotation exercise 3.0 and 3.4 trials/min, respectively, were conducted on average, only 1.26 trials/min were achieved for the compliance identification exercise. This can be explained by the additional time required for active exploration of the mechanical properties of the sponge before patients could provide an answer.

3.2 Acceptance

Patients' feedback was generally very positive and is summarized in Table 4. Patients well accepted the neurocognitive robot-assisted exercises as a part of their rehabilitation program. Almost all patients were motivated by all the exercises and would recommend the therapy to fellow patients. Patient P1 reported difficulties in placing his hand on the robot and asked for a larger finger support while patient P4 indicated that the exercises became repetitive after a while. Furthermore, patients P1 and P3 stated that the compliance discrimination exercise was more difficult with the robot than the conventional one executed with real sponges.

3.3 Length identification exercise

Data collected by the robot during three consecutive representative trials of patient P1 are presented in Figure 3. In these trials the grip apertures 10 cm,

TABLE 3
Patients' performance evaluation

Patients	Length identification				Compliance indentification				Forearm rotation			
	S	T	$\frac{T}{min}$	P	S	T	$\frac{T}{min}$	P	S	T	$\frac{T}{min}$	P
P1	5	68	4.5	58%	6	72	1.1	50%	6	88	3.0	45
P2	1	19	3.2	74%	5	53	1.4	75%	6	200	4.0	60
P3	4	82	2.5	83%	4	41	1.3	54%	2	41	4.1	61.5
P4	2	23	1.4	42%	3	13	0.4	49%	2	16	2.0	30
P5	1	13	3.25	85%	5	55	2.1	79%	5	88	4.0	60
Average	-	-	3.0	68%	-	-	1.26	61%	-	-	3.4	51

S: number of sessions performed, T: number of trials performed, $\frac{T}{min}$: number of trials per minute, P: performance metric: percentage of correct identification answers (length and compliance identification), extrapolated number of trials conducted in a 15 minute session (forearm rotation).

TABLE 4
Patients' subjective feedback

Patient	**Q1** Were the exercises with the robot motivating?	**Q2** What was comfortable when executing exercises with the robot?	**Q3** What was uncomfortable when executing exercises with the robot?	**Q4** Which differences did you perceive between the exercises conducted with the robot compared to those conducted with a physiotherapist?	**Q5** Would you recommend the additional neurocognitive robot-assisted therapy to fellow patients?
P1	some more than others	Exercise 2	Finger supports	Ex. 2 was more difficult	Yes
P2	Yes	All exercises	Nothing	None	Yes
P3	Yes	Exercise 3	Nothing	Ex. 2 was more difficult	Yes
P4	Yes	All exercises	Repetitive exercises	None	Yes
P5	Yes	Exercise 2	Nothing	None	Yes

7 cm and 9 cm were rendered with the ReHapticKnob. Hand closing and opening movements with the position controller were executed with minimal overshoot (0.02 mm), a steady state error of maximally 0.02 mm and without instabilities from the human-robot interaction. When the hand, and especially the fingers, were moved to the initial position (x_i = 12 cm) forces of almost 5 N were exerted in grasping direction (Force_x) caused by stretching of the hand and increased muscle tone in patients. Forces along the grasping direction reduced as soon as the hand was closed to one of the five stimulus apertures. Force profiles in lifting and especially in push/pull directions were used to monitor undesired forces in transverse directions and indicated negligible interaction forces ($<$ 2.5 N) during hand closing and maintenance of grip aperture. These forces resulted from the bending motion of the fingers as the hand was closed during the stimulus presentation. These measurements allow to monitor undesired forces for assessment and safety purposes.

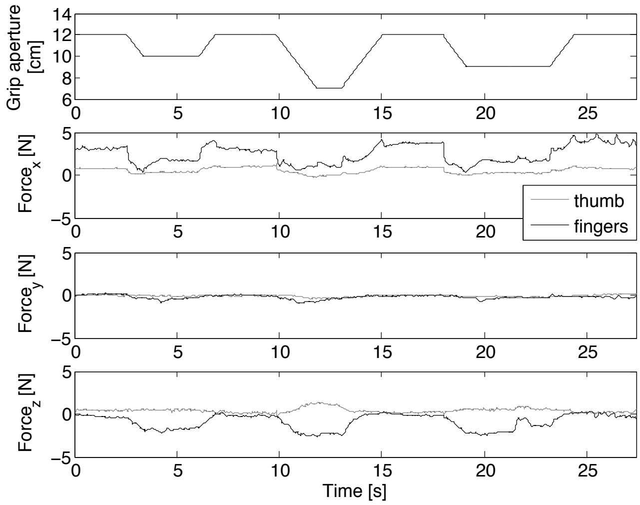

Fig. 3. Three representative trials of the length identification exercise of patient P1 in session 3. Movement started at the initial hand opening (12 cm) and ended at randomly selected grip apertures (10 cm, 7 cm and 9 cm). After the patient gave his stimulus identification answer the hand was opened again to the initial position. Forces applied with thumb and fingers were recorded during the robot-guided movements in grasping (Force_x), lifting (Force_y), and push/pull (Force_z) directions.

3.4 Compliance identification exercise

During this exercise, patients typically explored the rendered virtual sponges by applying a specific temporal force profile to the end-effector of the robot, as illustrated in Figure 4 for a block of 20 trials conducted by patient P2. The 20 temporal force profiles were similar over trials and could be approximated by a sinusoidal function with an amplitude of A = 1 N and a frequency of $\omega = 2\pi \cdot 0.67$ Hz:

$$F_{ee}(t) = A \cdot (sin(\omega \cdot t - \frac{\pi}{2}) + 1) \tag{3}$$

Because of the different stiffness and damping parameters of the five sponges, this resulted in distinguishable spatial force profiles (force as a function of position as described by Tan et al. [24] and indicated in Figure 4). Hence, patients were able to use position, work and/or compliance cues to discriminate between sponges and solve the identification task.

The softest sponge offered only little resistance to movement, such that patient P2 immediately reduced the amplitude of the temporal input force (after about 250 ms). Hence, for the simulation of the haptic interaction with the softest sponge, a smaller force amplitude of A = 0.5 N was used to model the temporal force profile.

The strategy of exploring object properties with similar temporal force profiles, e.g. sinusoidal ones as shown for patient P2, was also observed in patients P1 and P5. For patients P3 and P4 no clear strategy could be identified, with the shape and amplitude of the temporal force profiles varying from trial to trial.

In the case of an ideal impedance controller ($F_{ee} = F_d$) the user would perceive only the force resulting from the virtual spring-damper combination. To demonstrate that the force feedback worked prop-

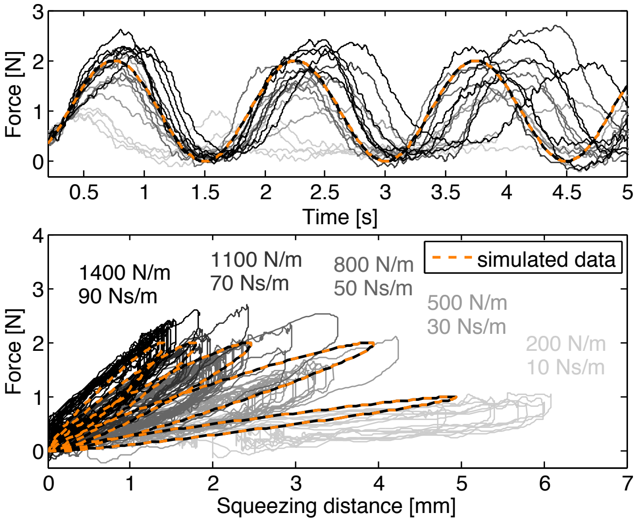

Fig. 4. Representative trials of the compliance identification exercise conducted in therapy session 5 of patient P2. The five different grey levels indicate the five different sponges. The top plot shows that patient P2 always applied a similar sinusoidal temporal force profile to explore the displayed virtual object. An emulated sinusoidal force profile used for the verification of the haptic interaction is plotted in orange (dashed line). The lower panel shows the resulting and clearly distinguishable spatial force profiles which vary proportionally with the virtual object compliance. The simulated spatial force profiles (dashed orange ellipses) are plotted as a comparison on top of the measured spatial force profiles (in grey).

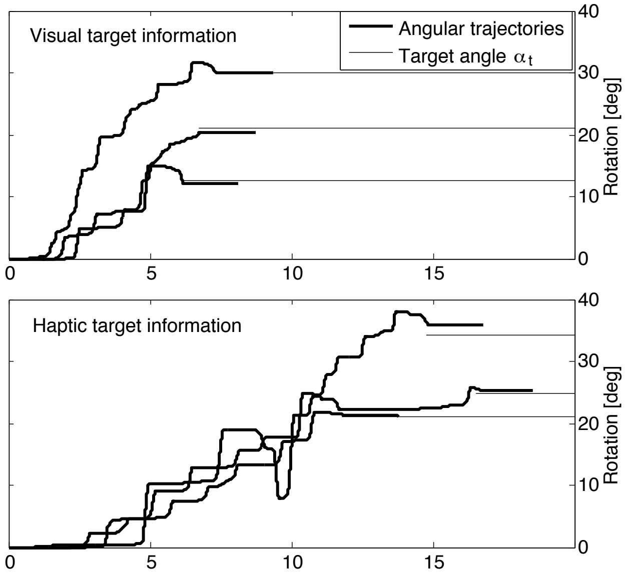

Fig. 5. Haptically cued forearm rotation exercise: comparison of three representative trials of P2 in session 4 conducted during task familiarization in which visual feedback was provided via the computer screen (top) to three trials in which the target angle α_t was indicated only haptically, i.e. without visual feedback (bottom).

erly and therefore the spring-damper combinations were rendered as desired, the measured spatial force profiles were compared to the theoretically resulting spatial force profiles when simulating the haptic interaction following the sinusoidal temporal force input according to Eq. 3. The resulting spatial force profiles are plotted in Figure 4 as a comparison to the measured profiles. Only small differences (< 0.4 N) were observed between the simulated profiles and measurements, indicating the high fidelity haptic rendering of the ReHapticKnob enabled by the force feedback.

3.5 Haptically cued forearm rotation exercise

This exercise required patients to concentrate on haptic perception in order to detect the haptic valley rendered by the ReHapticKnob, corresponding to the target angle α_t to be reached. Representative movement trajectories are presented in Figure 5 for patient P2, who rotated the ReHapticKnob with a small rotational speed of about $2.5°/s$ while searching for the haptic target cue. In contrast, familiarization trials with visual feedback involved fast rotations up to the respective target angles. A one-sided Wilcoxon signed-rank test was conducted to compare the median of the task execution times with and without visual feedback for all patients. Significantly shorter ($p = 0.0312$) execution times (median $\pm$ median absolute deviation) were observed with visual feedback (8.7 s $\pm$ 1.0 s) compared to without visual feedback (12.9 s $\pm$ 0.9 s).

4 Discussion

This paper proposed and evaluated three robot-assisted rehabilitation exercises, implemented on the ReHapticKnob, following the approach of neurocognitive therapy. The goal of these exercises is to train the complete sensorimotor loop, with a special focus on haptic perception. Solving cognitive tasks with the body encourages patients' active mental and physical participation, resulting in a highly motivating therapy. This approach goes beyond existing movement therapies focusing primarily on visually-guided movement repetitions [13], and is uniquely suited for the implementation on haptic interfaces. A haptic device such as the ReHapticKnob can provide motor and sensory stimuli in a well-controlled and reproducible manner. Furthermore, it offers the ability to display virtual objects with a wide range of viscoelastic properties, which can be precisely rendered and automatically presented to patients without any apparent changes to the setup, increasing exercise variety and range of difficulty.

Feasibility and acceptance of the three proposed neurocognitive robot-assisted exercises were investigated on a heterogeneous group of five patients, suffering from different types of neurological impairments and varying upper limb impairment levels, who received therapy session with the ReHapticKnob as an integrative part of their rehabilitation program. All patients could understand the exercises, actively participate in the robot-assisted therapy sessions and achieve good exercise performance (i.e. they were able to "actively" achieve the goal of the task), even if their motor abilities were strongly limited and they relied on assistance from the robot or physiotherapist. Three out of five patients were able to conduct all the exercises on their own, while the remaining two patients, who suffered from more severe hand impairment, required support from the physiotherapist to perform the two exercises requiring active motor participation (i.e. compliance identification and haptically cued forearm rotation). On the other hand, all patients were able to perform the length identification task without relying on the assistance of a physiotherapist, even if they could not actively move the hand. This task is thus ideal for severely impaired patients, engaging them more than conventional passive therapy by requiring active participation through the cognitively demanding task of identifying the object based on the haptic perception of its length. Accordingly, this ability to participate and solve parts of the task independently could positively impact patients' motivation. Results of a subjective questionnaire suggested that patients well accepted the neurocognitive exercises with the ReHapticKnob and indeed found them motivating. All participants would recommend this type of therapy to their fellow patients. One patient even suggested that the robot could be used without supervision from a physiotherapist. Indeed, use of such a system for self-training in the evening or during spare time in the clinic, or even at home, could complement conventional therapy with similar exercises to increase the overall duration and intensity of therapy in patients with sufficient sensorimotor and cognitive function.

The automatic transition between different stimuli (e.g. viscoelastic properties or length of an object) could also help increase therapy intensity. The results of this pilot study suggest that patients on average performed between 1.26 and 3.4 repetitions of an exercise per minute. This would represent an increased intensity compared to 1.21 repetitions per minute reported in [27] or 0.92 repetitions per minute as calculated from [28] (average number of upper limb movement repetitions divided by the average session length) for conventional upper limb physiotherapy and occupational therapy exercises.

Haptic devices used for rehabilitation therapy offer the additional advantage of collecting objective force and position data to quantify performance and assess patient-robot interaction [29]. The data collected during repeated interactions with the ReHapticKnob within the context of the three proposed exercises could provide new insights on sensorimotor control of grasping in neurologically impaired patients, and especially on the control strategies used during exploration of viscoelastic objects when motor or sensory function are impaired [30]. In the compliance identification exercise, it was observed that mildly impaired patients (P2 and P5) applied a well-defined temporal force profile to interact with the robot and to discriminate objects based on different perceived spatial force profiles. These results are in accordance with other studies on healthy subjects [24]. More severely impaired patients could likely not control grasp force well enough and had to rely on a different strategy to discriminate between object properties, or to rely on therapist assistance, leading to less successful performance. Robotic assessments could also be used to select and adapt exercise parameters. By adapting parameters such as the distances between two grip apertures or the stiffness and damping increments (ΔK and ΔB) between two sponges to the individual patient, the appropriate training level could be selected and adapted online. These quantities could be determined directly from robotic assessments following psychophysical methods [31], or even online during the therapy itself and based on the exercise performance.

The proposed neurocognitive robot-assisted therapy provides new perspectives on merging concepts from haptics, such as psychophysics and perceptual learning, with those of robot-assisted neurorehabilitation. The present study is limited by the small number of participants, short intervention duration and non-systematic design. Further work and a more systematic clinical study are thus needed to determine and exploit the potential of neurocognitive robot-assisted therapy in promoting recovery of sensorimotor function, especially at the level of the hand.

5 Conclusion

We proposed a novel concept for robot-assisted rehabilitation of hand function using a neurocognitive approach, where motor, sensory and cognitive processes involved in hand movements are trained together. Three neurocognitive exercises implemented on the ReHapticKnob were successfully tested with five patients suffering from different neurological disorders and impairment levels. Feasibility and acceptance of the proposed exercises were high, and initial data collected with the robot during this preliminary study underlined the potential of this approach to integrate haptics for intensive sensorimotor therapy of hand function.

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References

[1] L. Jones and S. Lederman, *Human hand function*. Oxford University Press, USA, 2006.

[2] M. Wiesendanger and D. Serrien, "Neurological problems affecting hand dexterity," *Brain Research Reviews*, vol. 36, pp. 161 – 168, 2001.

[3] R. S. Johansson, G. Westling, A. Bäckström, and J. R. Flanagan, "Eye-hand coordination in object manipulation," *J Neurosci*, vol. 21, no. 17, pp. 6917–6932, Sep 2001.

[4] M. O. Ernst and M. S. Banks, "Humans integrate visual and haptic information in a statistically optimal fashion," *Nature*, vol. 415, no. 6870, pp. 429–433, 2002.

[5] A. Kusoffsky, I. Wadell, and B. Nilsson, "The relationship between sensory impairment and motor recovery in patients with hemiplegia." *Scandinavian journal of rehabilitation medicine*, vol. 14, no. 1, p. 27, 1982.

[6] J. S. Kim and S. Choi-Kwon, "Discriminative sensory dysfunction after unilateral stroke," *Stroke*, vol. 27, no. 4, pp. 677–682, Apr 1996.

[7] L. M. Carey and T. A. Matyas, "Frequency of discriminative sensory loss in the hand after stroke in a rehabilitation setting," *J Rehabil Med*, vol. 43, no. 3, pp. 257–63, Feb 2011.

[8] E. Abela, J. Missimer, R. Wiest, A. Federspiel, C. Hess, M. Sturzenegger, and B. Weder, "Lesions to primary sensory and posterior parietal cortices impair recovery from hand paresis after stroke," *PLoS One*, vol. 7, no. 2, p. e31275, 2012.

[9] H. I. Krebs, B. T. Volpe, D. Williams, J. Celestino, S. K. Charles, D. Lynch, and N. Hogan, "Robot-aided neurorehabilitation: a robot for wrist rehabilitation," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, vol. 15, no. 3, pp. 327–335, 2007.

[10] M. Yekutiel and E. Guttman, "A controlled trial of the retraining of the sensory function of the hand in stroke patients." *Journal of Neurology, Neurosurgery & Psychiatry*, vol. 56, no. 3, pp. 241–244, 1993.

[11] C. Perfetti, *Der hemiplegische Patient. Kognitiv - therapeutische Übungen*. München: Pflaum, 1997.

[12] R. Chanubol, P. Wongphaet, N. Chavanich, C. Werner, S. Hesse, A. Bardeleben, and J. Merholz, "A randomized controlled trial of cognitive sensory motor training therapy on the recovery of arm function in acute stroke patients," *Clinical Rehabilitation*, vol. 26, no. 12, pp. 1096–1104, 2012.

[13] L. Marchal-Crespo and D. J. Reinkensmeyer, "Review of control strategies for robotic movement training after neurologic injury," *Journal of neuroengineering and rehabilitation*, vol. 6, no. 1, p. 20, 2009.

[14] G. Kwakkel, B. Kollen, and H. Krebs, "Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review," *Neurorehabilitation and Neural Repair*, vol. 22, no. 2, p. 111, 2008.

[15] A. Lo, P. Guarino, L. Richards, J. Haselkorn, G. Wittenberg, D. Federman, R. Ringer, T. Wagner, H. Krebs, B. Volpe, C. Bever, D. Bravata, P. Duncan, B. Corn, A. Maffucci, S. Nadeau, S. Conroy, J. Powell, G. Huang, and P. Peduzzi, "Robot-assisted therapy for long-term upper-limb impairment after stroke," *New England Journal of Medicine*, vol. 362, no. 19, pp. 1772–1783, 2010.

[16] J.-C. Metzger, O. Lambercy, and R. Gassert, "High-fidelity rendering of virtual objects with the rehapticknob – novel avenues in robot-assisted rehabilitation of hand function," *Proc. IEEE Haptics Symposium*, 2012.

[17] J.-C. Metzger, O. Lambercy, D. Chapuis, and R. Gassert, "Design and characterization of the rehapticknob, a robot for assessment and therapy of hand function," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2011, pp. 3074–3080.

[18] N. Hogan and S. Buerger, "Impedance and interaction control," *Robotics and Automation Handbook*, pp. 19–1, 2005.

[19] C. Carignan and K. Cleary, "Closed-loop force control for haptic simulation of virtual environments," *Haptics-e*, vol. 1, no. 2, pp. 1–14, 2000.

[20] J. Colgate and J. Brown, "Factors affecting the z-width of a haptic display," in *Proc. IEEE International Conference on Robotics and Automation*, 1994, pp. 3205–3210.

[21] F. Janabi-Sharifi, V. Hayward, and C. Chen, "Discrete-time adaptive windowing for velocity estimation," *IEEE Transactions on Control Systems Technology*, vol. 8, no. 6, pp. 1003–1009, 2000.

[22] B. Panchaphongsaphak, R. Burgkart, and R. Riener, "Three-dimensional touch interface for medical education," *IEEE Transactions on Information Technology in Biomedicine*, vol. 11, no. 3, pp. 251–263, 2007.

[23] Chai 3d, open source haptics interface library. [Online]. Available: http://www.chai3d.org

[24] H. Tan, N. Durlach, G. Beauregard, and M. Srinivasan, "Manual discrimination of compliance using active pinch grasp: The roles of force and work cues," *Perception & psychophysics*, vol. 57, no. 4, pp. 495–510, 1995.

[25] G. L. Beauregard, "Sensorimotor interactions in the haptic perception of virtual objects," DTIC Document, Tech. Rep., 1997.

[26] A. Fugl-Meyer, L. Jääskö, I. Leyman, S. Olsson, S. Steglind *et al.*, "The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance." *Scandinavian journal of rehabilitation medicine*, vol. 7, no. 1, p. 13, 1975.

[27] T. J. Kimberley, S. Samargia, L. G. Moore, J. K. Shakya, and C. E. Lang, "Comparison of amounts and types of practice during rehabilitation for traumatic brain injury and stroke," *J Rehabil Res Dev*, vol. 47, no. 9, pp. 851–62, 2010.

[28] C. E. Lang, J. R. MacDonald, D. S. Reisman, L. Boyd, T. Jacobson Kimberley, S. M. Schindler-Ivens, T. G. Hornby, S. A. Ross, and P. L. Scheets, "Observation of amounts of movement practice provided during stroke rehabilitation," *Archives of physical medicine and rehabilitation*, vol. 90, no. 10, pp. 1692–1698, 2009.

[29] O. Lambercy, L. Luenenburger, R. Gassert, and M. Bolliger, *Neurorehabilitation Technology*. Springer Verlag Berlin, 2012, ch. Robots for Measurement and Clinical Assessment.

[30] C. L. Van Doren, "Differential effects of load stiffness on matching pinch force, finger span, and effort," *Experimental brain research*, vol. 120, no. 4, pp. 487–495, 1998.

[31] O. Lambercy, Y. Kim, and R. Gassert, "Robot-assisted assessment of vibration perception and localization on the hand," *Disabil Rehabil Assist Technol*, vol. 8, no. 2, pp. 129–135, Mar 2013.

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