A Haptic Knob for Rehabilitation of Hand Function

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***Abstract*—This paper describes a novel two-degree-of-freedom robotic interface to train opening/closing of the hand and knob manipulation. The mechanical design, based on two parallelogram structures holding an exchangeable button, offers the possibility to adapt the interface to various hand sizes and finger orientations, as well as to right-handed or left-handed subjects. The interaction with the subject is measured by means of position encoders and four force sensors located close to the output measuring grasping and insertion forces. Various knobs can be mounted on the interface, including a cone mechanism to train a complete opening movement from a strongly contracted and closed hand to a large opened position. We describe the design based on measured biomechanics, the redundant safety mechanisms as well as the actuation and control architecture. Preliminary experiments show the performance of this interface and some of the possibilities it offers for the rehabilitation of hand function.**

***Index Terms*—Hand function, haptic knob, human-oriented mechatronic design, robotic rehabilitation.**

I. INTRODUCTION

THE STRONG impairment of motor function in stroke survivors affects daily activities such as eating, manipulating objects, or writing. Therefore, physical rehabilitation is performed in hospital centers using intense arm/hand training, electrostimulation, and/or drug treatment. The results obtained with these therapies suggest that it is possible to partially restore hand function in stroke patients and thus improve their quality of life. In particular, studies have shown that intense practice of repetitive movements can help improve the strength and functional use of the affected arm or hand [1]–[3].

Robot-assisted rehabilitation is a recent approach to stroke therapy which promises to redefine current clinical strategies [4]. Robotic devices can accurately and systematically control the applied force and progressively adapt assistance/resistance to the patients abilities. Game-like virtual reality exercises may motivate patients to train at home without clinical supervision, and so improve rehabilitation and decrease costs. While classical rehabilitation is limited by subjective observation of therapists and patients, robotic devices can precisely quantify the progress achieved by stroke patients. Further, treatments may be designed to adapt to patient's state [5], [6].

We recently performed a study to evaluate the needs of chronic stroke patients with mildly impaired hand function. The results showed that the functions they most desire to recover are knob manipulation (e.g., turn doorknobs, operate ovens, or washing machines), handwriting, card playing and similar fine manipulation, actions that may require bimanual manipulation (e.g., buttoning a shirt), and driving.

To limit the complexity of learning, we will promote gradual training from simple to more complex tasks [7]. The robotic tools thus have to be able to offer several exercises of gradually increasing complexity. We will first focus on enabling the patient to open the hand again. Then more complex movements will be trained as a combination of simple ones, i.e., turning a knob, which is a combination of grasping and rotation of the hand, requiring coordination of fingers and wrist. The final goal is to help poststroke patients acquire skills necessary for fine object manipulation and handwriting [7], [8].

Pioneering work in robotic assisted rehabilitation of hand function was performed with the Rutgers Master II [9], a dedicated robotic glove with pneumatic actuators fixed to the palm to actuate each finger. Experiments with stroke patients showed an increase in range-of-motion (ROM) of fingers and force amplitude after training [10]. A pneumatic glove was also developed at Northwestern University [11], [12], which was used to train grasping and releasing of objects. A hand extension module has been built for the arm rehabilitation device MIT-MANUS [13], with a handle to assist hand opening. However, the fingers ROM allowed by these interfaces is limited, and it is not possible to train hand opening from a closed hand.

A different kind of pneumatic device was presented in [14] to exercise wrist flexion/extension as well as grasping and releasing of real objects placed in the palm of the hand, using a structure that is fixed around the hand. Another device, designed as an exoskeleton which allows movement of individual joints, has been developed to train the opposition between the thumb and index finger for pinching [15]. This setup is based on a master–slave system; the motion of the healthy hand is recorded with a data glove, and the robot produces an equivalent motion for the affected hand. Both of these devices are conceived to train one specific function.

A semi-exoskeleton rehabilitation robot, the ARMin, has been developed for full arm rehabilitation, including a hand module to train forearm pronation/supination and wrist flexion/extension. [16], [17]. The BiManuTrack is a commercialized device that can train the latter two movements [18], [19]. The system is composed of two handles actuated with a master–slave system based on the motion of the healthy limb. These two devices allow forearm and wrist movement but cannot train grasping and fine finger motion.

Manuscript received October 2, 2006; revised February 27, 2007; accepted April 24, 2007. This work was supported by the National University of Singapore.

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Digital Object Identifier 10.1109/TNSRE.2007.903913

This review of current technology suggests that the challenges of regaining fine motor control of the hands and fingers have yet to be addressed by suitable interfaces. Current interfaces have too limited a range of motion or do not offer sufficient flexibility for training the different tasks required for the rehabilitation of hand function. For example, pronation/supination of the forearm combined with finger control coordination required during fine manipulation and knob interactions, one of the functions stroke patients desire to recover most, has not been addressed by current rehabilitation robot designs. Furthermore, differently affected patients may adopt different grasping strategies to manipulate objects (which may also differ from the usual strategy used by healthy subjects). The interface should be sufficiently adaptable to allow patients to use different types of grasp.

We have developed interfaces addressing these needs to train recovery of specific hand functions [7]. This paper describes a two degree-of-freedom (DOF) device, the *Haptic Knob*, to train opening and closing movement of the hand as well as the interaction with knobs (Fig. 1). The approach we chose for the development of this interface is as follows. We first examined the different tasks for which this interface is to be used, and analyzed the corresponding biomechanics and ergonomics (Section II). The design, including material choice, mechanical structure, control and safety architectures were determined by these factors (Section III). Finally, simple experiments with healthy and poststroke subjects were carried out to evaluate the performance of the realized prototype (Section IV).

II. Hand Biomechanics Requirements

A. Selected Tasks

The design of a rehabilitation tool must take into account the biomechanics of the hand, as well as the impairments resulting from stroke, in order to allow natural and comfortable movements. The goal of our Haptic Knob is to train fine hand manipulation for stroke survivors in the chronic phase i.e., more than six months after stroke. The physiological functions at this stage are more stable than during the acute phase and subjects are more likely to have at least partial motor function of the arm and shoulder as a result of spontaneous recovery or due to other interventions. The design is thus oriented towards subjects capable of minimal movement with the hand.

Hemiparesis or muscle weakness and spasticity are typical consequences of stroke i.e., flexor muscles of the affected limb remain in a strongly contracted state preventing movements [20]. Due to extensor muscle weakness, the hand is locked in a closed position and stroke patients are not able to control hand motion. Thus, the first function the robotic interface should train is opening of the hand.

Next, the reverse operation i.e., closing of the hand and applying suitable force to grasp objects should be trained. In addition, the manipulation of objects frequently involves wrist pronation/supination and application of isometric wrist torque together with grip force. Training this coordinated action has not been addressed with previous interfaces.

Typically, at an early stage during recovery, finger extension can only be performed passively, i.e., the robot moves the fingers. Passive movements are believed to improve joint, muscle

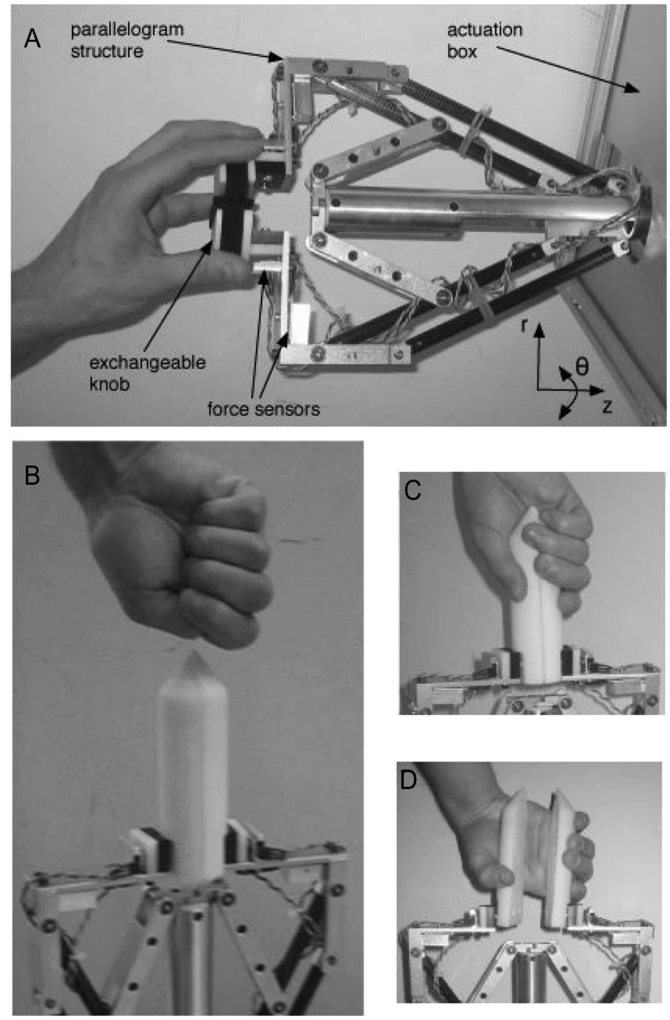

Fig. 1. 2-DOF Haptic Knob for hand rehabilitation. A: Parallelogram structure is equipped with four force sensors located close to the output, allowing measurement of grip and insertion force. Dimensions of the interface are $60 \times 30 \times 25\ \mathrm{cm}^3$. Different fixtures can be used to interact with the subject, depending on the level of impairment. A cone mechanism mounted on the haptic knob can be used to train a complete opening movement, from a strongly contracted and closed hand (B) to a widely opened position (D).

and tendon mobility, while at the same time reducing muscle tone [18]. However, passive movements driven by robotic interfaces may not be sufficient to offer good rehabilitation; while passive movements help to prevent changes in passive properties of joints and muscle, active movements initiated by the patient are required to improve the strength and coordination between muscles, and promote correct patterns of muscle activation and coordination [6]. Other exercises to train force generation, such as interaction with loads to reduce muscle weakness [5], are also necessary. Active movements against resistive forces might be the best way to improve motor function of the hand after stroke.

B. Design Constraints

Simple experiments with eight healthy subjects and three poststroke subjects were performed to measure parameters of the hand such as the maximum grasping force, wrist torque and maximum hand aperture, and to describe how humans interact with various objects during prehension (Fig. 2). The results

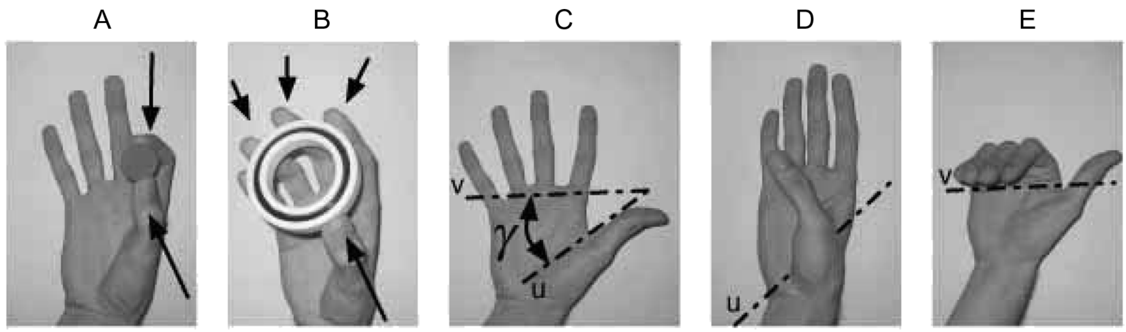

Fig. 2. Main functions and movements of the fingers. A: *Pinch* is the closure of the thumb against one or two other fingers. It is the hand function that stroke patients most desire to recover. B: The *Grasp* generally involves the thumb and at least two fingers. C: Dashed-lines u and v represent the axes of rotation of the thumb (D) and of the four other fingers (E), respectively. The angle γ between these axes and movement of the thumb varies with each person.

of these investigations are summarized in Table II, and in the following points.

- Functional rehabilitation of the hand aims at exercising fine manipulations that do not require high force levels. Typical activities of daily living (ADL), such as opening or closing a jar require torques of 0.7 Nm or less, while pinching and manipulating small objects typically require forces smaller than 20 N (Table I) [21], [22].
- The size and shape of the hands vary from one person to another. The robotic interface design should allow easy adaptation to any type of hand, i.e., the attachments supporting the fingers have to be adapted to the subject to train suitable opening movements.
- The thumb and the opposing four fingers do not move along the same axis during grasping. The angle γ between the rotation axes of the thumb and the other fingers [Fig. 2(c)] varies from -45° for the left hand, to $+45^\circ$ for the right hand, and is different for each person. Furthermore, the orientation of these axes depends on the task. For example, they are oriented in different directions during *grasping* (i.e., enclosing an object with all fingers) and *pinching*, i.e., prehension only with the thumb and the index finger.
- In general, the thumb moves at the same speed as the other fingers. However, for some people, the thumb moves slower, leading to an asymmetrical movement.
- During grasping (with the whole hand), all the fingertips move in approximately the same plane. This is in contrast to the movement of only one finger where the fingertip follows a circle around the metacarpophalangeal (MCP) joint.
- Subjects use a different number of fingers to grasp an object depending on the size of the hand and of the object [23]. However, an analysis of the position of the fingers around a cylindrical object during grasping demonstrated that (independent of the number of fingers involved), the thumb could always be separated from the other fingers such that the thumb and fingers formed a jaw. Therefore, the design does not need to consider all fingers individually.

III. Interface Design

Several designs for a 2-DOF haptic knob addressing these points were analyzed in [24]. The selected mechanical structure consists of two moving parallelograms (Fig. 1) similar to an umbrella, such that linear displacement of the linear belt drive supporting the structure in the z-direction is transformed into perpendicular motion in the r-direction. This enables a linear opening of the hand without undesired movement of the output in the z-direction.

TABLE I
Typical Activities of Daily Living

torque to open a jar	0.7 Nm
pinch force to hold a fork [21]	11.0 N
pinch force to manipulate a key [21]	7.0 N
grip force to lift a $200g$ weight [22]	3.8 N

This system can generate forces in both opening and closing directions. One actuator is used to control the translation of the linear belt drive and another one rotates the system. The inertia of the complex parallel structure is larger than with other possible designs presented in [24]. However, this is not a critical factor as the targeted movements involve only a slow wrist rotation, i.e., low angular acceleration, and the large opening amplitude makes this mechanism attractive for our purpose.

The angle γ corresponding to the mean orientation of the thumb [Fig. 2(c)] is adaptable to each patient: the knob has been designed to allow rotation of one of the two finger supports, as shown in Fig. 3(a). It is also possible to vary the velocity of one finger support. The velocity depends on the distance between the two parallelograms and the velocity of one finger support can be adjusted by shifting the carriage, as illustrated in Fig. 3(b) and (c).

Fixtures of various shapes can be attached to the interface in order to train different hand functions. In particular, buttons of different diameters with special finger supports to fix the hand between the two parallelograms can be used to train interaction with objects (Fig. 1).

Materials were chosen based on their mechanical properties, weight, and comfort for the user. The cylinders for the rotation and translation are made from aluminum, the parallelograms are of carbon fiber to reduce the inertia, and the fixtures are of polyoxymethylene (POM), offering the patient a comfortable grip. The external dimensions of the interface are $60 \times 30 \times 25\ \mathrm{cm}^3$ for a total mass of 12 kg (including actuators, power supply, and electronics).

TABLE II
QUANTIFICATION OF HAND PROPERTIES

	healthy subjects.	stroke subjects.
maximum hand aperture (between thumb and middle finger)	180.0 mm	180.0 mm
maximum rotation of wrist	180.0 deg	180.0 deg
mean orientation of the thumb (γ on Fig. 2C)	30.0 deg	30.0 deg
maximal grasping force (male subject)	450.0 N	240.0 N
maximal grasping force (female subject)	300.0 N	120.0 N
maximum wrist torque (pronation/supination)	20.0 Nm	N.A.

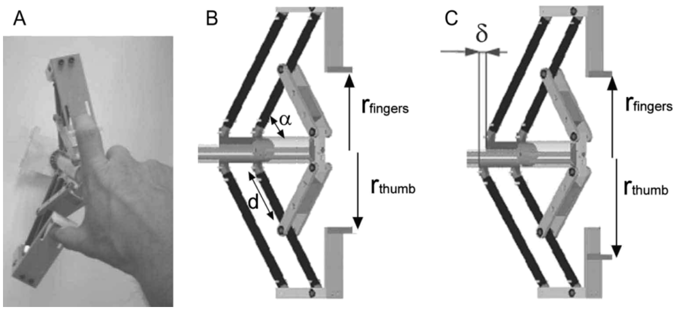

Fig. 3. A: Adjustable orientation of one parallelogram within a range of $\pm 45°$ allows the orientation of the finger supports to be adapted to any hand. B: With two symmetric parallelograms, the displacements of the thumb (r_{thumb}) and the fingers (r_{fingers}), as well as the velocity of the two endpoints are similar. C: By shifting the carriage (δ), the displacement of the thumb support (r_{thumb}) is different from the displacement of the finger support (r_{fingers}). The maximal opening is 15 cm.

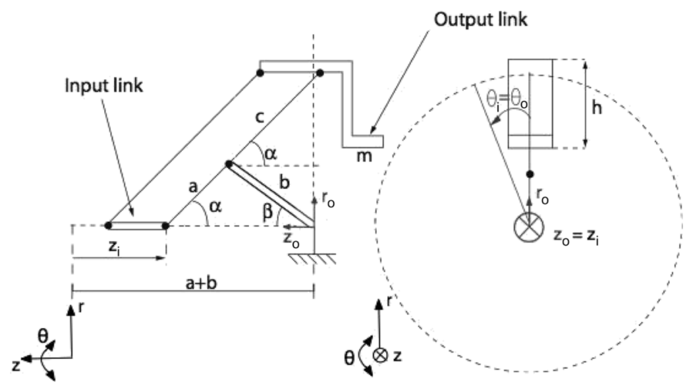

Fig. 4. Diagram of one parallelogram arm. α is the opening angle of the parallelogram, a; b, and c are the lengths of the parallelogram components. In our case $a = b = c = d$, where no parasitic movement in the z-direction is observed, m is the endpoint of the system and h is the distance between the endpoint and the top of the interface.

A. Kinematic Analysis

The *input* parameters of the system are the displacement of the linear actuator z_{in} and the rotation angle θ_{in} of the second actuator (Fig. 4). The *output* parameters are the aperture of the knob r_{out} and the knob angle θ_{out}. The differential direct kinematics are given by

$$\underbrace{\begin{bmatrix} \dot{r}_{\text{out}} \\ \dot{\theta}_{\text{out}} \end{bmatrix}}_{\text{output}} = \underbrace{\begin{bmatrix} \frac{2d - z_{\text{in}}}{\sqrt{z_{\text{in}}(4d - z_{\text{in}})}} & 0 \\ 0 & \frac{1}{2} \end{bmatrix}}_{\text{Jacobian}} \underbrace{\begin{bmatrix} \dot{z}_{\text{in}} \\ \dot{\theta}_{\text{in}} \end{bmatrix}}_{\text{input}} \tag{1}$$

where d is the length of one parallelogram rod, as shown in Fig. 3. The Jacobian is a diagonal matrix, as the outputs r_{out} and θ_{out} are independent of each other. Singularities occur if the determinant of the Jacobian equals zero or infinity. In our case, there are three singularities, when the opening angle of the parallelogram $\alpha = 0°, 90°, 180°$ [24]. As α is between 15° and 75° in our design, these singularities are outside of the reachable workspace.

B. Actuation

A brushed dc motor M_1 (Maxon RE40, 150 W; encoder 2000 counts/rev.; gear GP42C, ratio 15:1; control card EPOS 24/5), actuates the linear displacement to open and close the Haptic Knob. The rotation of the motor axis is converted into a translational movement by a commercial linear belt drive module (Minimodule MLM-9, Schneeberger AG, Roggwil, Switzerland, 11 mm/rev) with a moving carriage fixed to a belt. The belt is driven by a pulley fixed on the motor shaft.

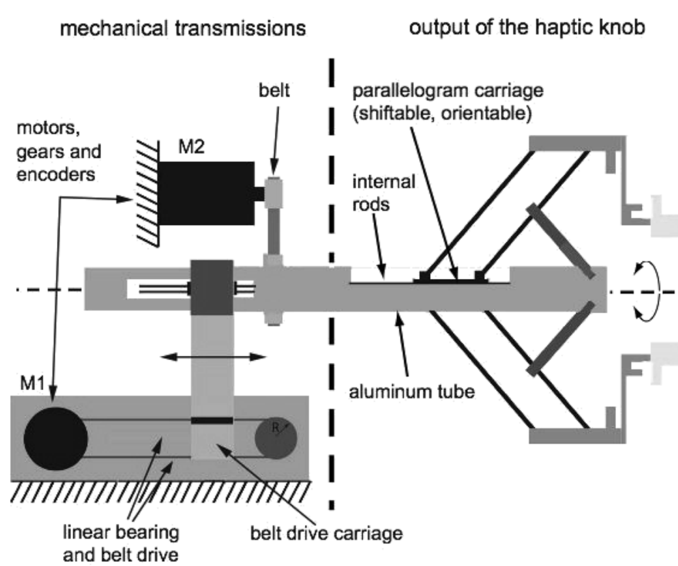

Fig. 5. Details of the mechanical transmissions for the 2-DOF. Linear bearing is used for the linear DOF and a belt for the rotational DOF.

The linear movement of the carriage is transmitted to two internal rods to which the two parallelogram structures are fixed. (Fig. 5). These rods slide inside the central aluminum tube.

A similar motor M_2, but with a reduction ratio of 4.3:1, actuates the rotation of the knob. A belt transmits the rotation of the motor axis to the axis of the interface, with a reduction ratio of 2:1.

The position of the output of the Haptic Knob is measured with the motor encoders. The relations linking the motor outputs

q_1 and q_2, and the output of the interface, r_{out} and θ_{out} are given by

$$r_{\text{out}} = \sqrt{\frac{2\pi R}{r_1}q_1\left(4d - \frac{2\pi R}{r_1}q_1\right)} - h$$
$$\theta_{\text{out}} = \frac{q_2}{r_2 r_3} \qquad (2)$$

where r_1 is the reduction ratio of motor M_1, R the radius of the pulley fixed on the shaft of motor M_1, r_2 the reduction ratio of motor M_2, r_3 the reduction factor selected for the belt transmission, and h the distance between the top of the parallelogram and the position of the finger fixation (Fig. 5).

The inverse kinematics [derived from (2)] are

$$q_1 = \frac{r_1}{2\pi R}\left(2d - \sqrt{4d^2 - (r_{\text{out}} + h)^2}\right)$$
$$q_2 = r_2 r_3 \theta_{\text{out}}. \qquad (3)$$

C. Force Measurement

Four force sensors [Millinewton 2N, LPM-EPFL [25], Fig. 6(a)] are used to measure the grasping force F_g and perpendicular force F_p applied by the user during movement. In our configuration, the sensors can measure grasping and perpendicular forces of up to 30 N with a resolution of 0.2 N. The sensing principle is based on the deformation of a cantilever beam on which resistors made from piezoresistive pastes are printed. Any mechanical deformation of the paste induces a variation of the resistivity which is converted into a variation of voltage. The linearity error of these sensors is smaller than 1%FS (full scale). The electronics integrated on the base of the sensor amplifies the signal and output a voltage which is a linear function of the force.

One force sensor is fixed to each fixation support of the Haptic Knob [front force sensors, Fig. 6(b)]. The force is measured in an indirect way: the sensor is preloaded with a screw touching the sensor cantilever to adjust initial offset for bidirectional measurements. The grasping force applied by the user deforms the finger fixation support, which induces a displacement of the cantilever. The two other sensors (rear force sensors) are placed under the aluminum brackets on which the finger supports are mounted [Fig. 6(b)]. They measure the flexion of the fixation support during interaction with the Haptic Knob, and can also determine the force perpendicular to the opening direction, along the axis of rotation (z-direction). Fig. 6(c) presents the calibration curves of the force sensors, which demonstrate their linearity.

D. Control Program

Control and visual feedback are implemented in LabView 8.2 (National Instruments), in a multirate timed-loop structure with a high priority control loop at 100 Hz and a low priority visual feedback loop at 20 Hz. This control frequency is sufficient because only slow movements are performed with the Haptic Knob. Fig. 7 presents the architecture of the control program. Data from the EPOS controllers of the two motors (positions, velocities and current) are transferred to the main program over a RS232 protocol. Data from force sensors are sampled at a frequency of 100 Hz, through a data acquisition card (PCI-6221, National Instruments).

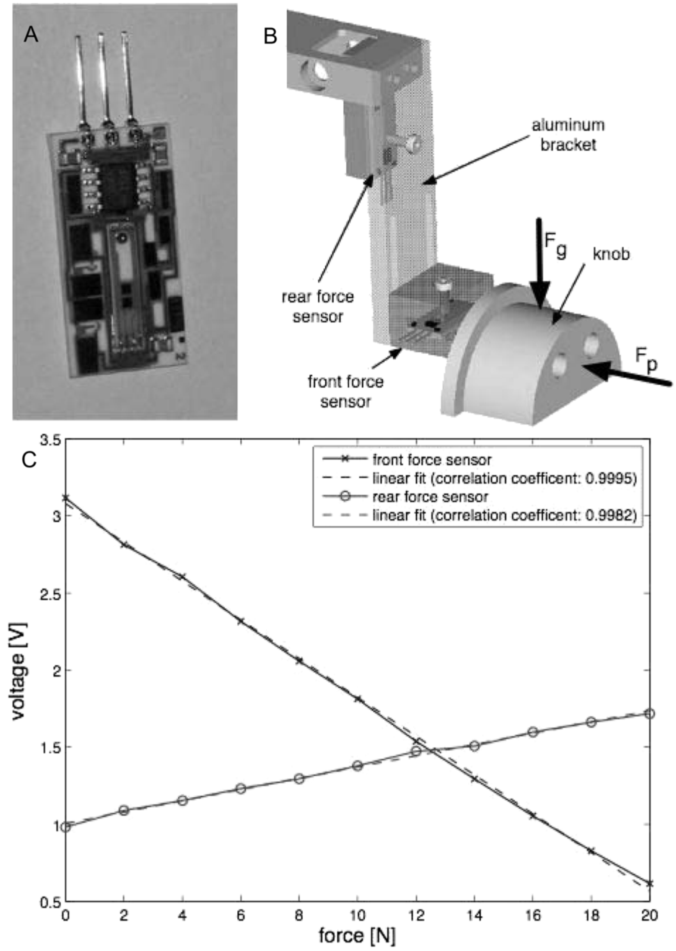

Fig. 6. A: Milinewton force sensor (LPM-EPFL). B: Position of the force sensors on one parallelogram structure of the haptic interface. C: Calibration curves for the front and rear force sensors.

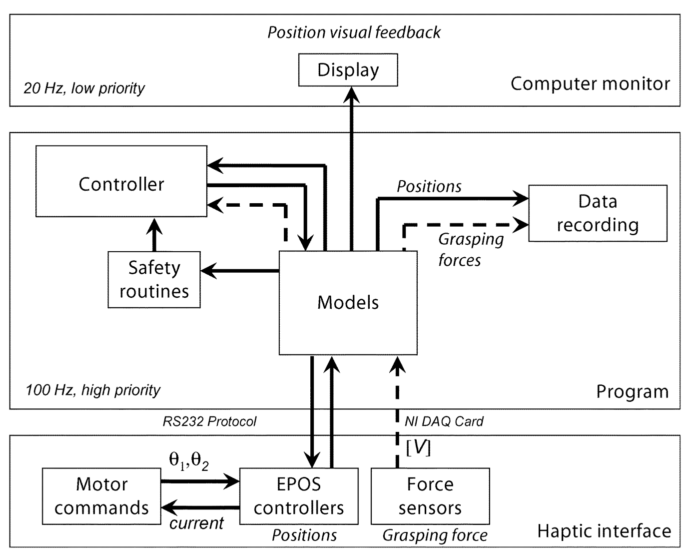

Fig. 7. Haptic knob interface control diagram.

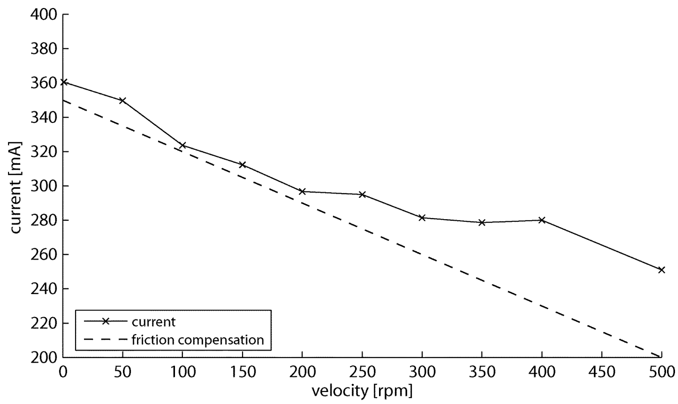

Fig. 8. Identification of friction in the linear DOF and feedforward command implemented to compensate the friction (dashed line).

Impedance control is used for the 2-DOF, with friction compensation for the opening/closing mechanism. Linear friction was compensated with a linear function, as shown in Fig. 8. The sign of this feedforward compensation is in the direction of the movement performed by the subject, which is inferred from the force applied by the hand to the interface. In this way, different force effects can be created to resist or assist the subject's movements.

E. Redundant Safety

Interacting with human subjects requires a high level of safety. To prevent any harm or damage, both software and hardware emergency systems have been implemented as in [26]. Redundant safety is realized through the following.

- Mechanical travel limitations for the 2-DOF of the interface to prevent excessive opening or rotation.
- Software safety routines that monitor motor output to prevent excessive velocities, accelerations or forces that could harm the subject.
- Electronic end-of-travel switches that stop the translational module before reaching the mechanical travel limits.
- A main power interruptor, that can be actuated by the human subject during the experiments, by means of a pneumatic emergency bellows, as well as by the experimenter by means of a standard emergency pushbutton switch.
- Low-level security surveillance routines embedded in the motor controllers. This allows the experimenter to set speed, acceleration, and force limitations in advance. If the high-level control generates commands that exceed these limits, the motor controllers will automatically stop the motors and alert the experimenter, independent of any malfunction of the high level control.
- The position of the subject in front of the device prevents interference of the fingers with the parallelogram structure. In addition, knobs have a protection barrier to restrain the fingers from touching the force sensors.

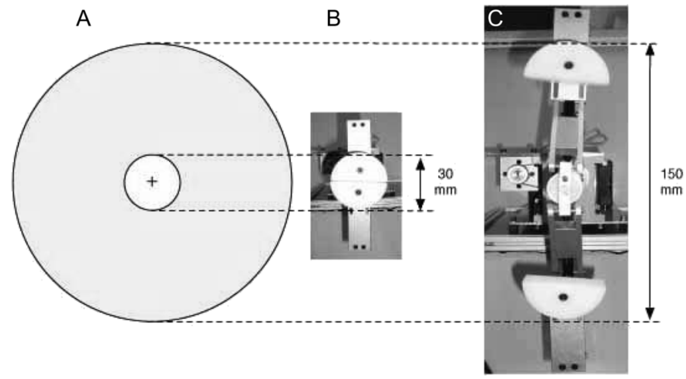

Fig. 9. Interface workspace. The active workspace of the Haptic Knob is defined by two circles in the same plane (A). View of the interface when it is (B) fully closed (30 mm) and (C) fully opened (150 mm).

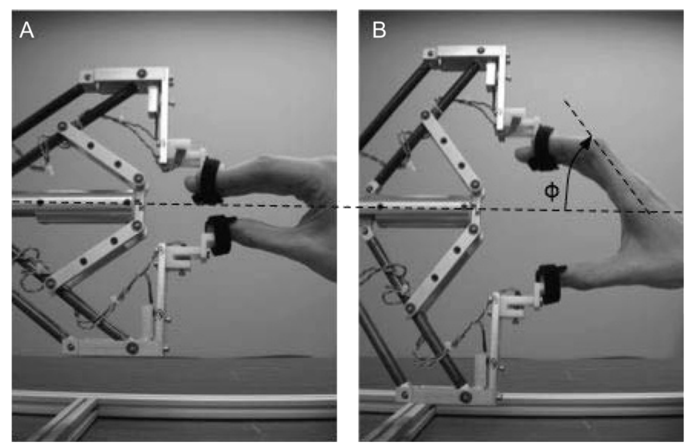

Fig. 10. Fingers can be fixed inside the parallelogram structures to train grasping of real objects. Workspace of the hand starts from a closed position where the fingers are touching the thumb (A), to a 60 ° MCP ϕ (B).

IV. EXPERIMENTS AND PERFORMANCE

A. Specifications

The active workspace of the Haptic Knob is a ring with outside and inside diameters determined, respectively, by the maximal and minimal opening of the device (Fig. 9). These parameters can be modified using special fixtures which can be mounted on the interface. With no fixture, maximal opening of the Haptic Knob is 150 mm while the minimal opening is 30 mm. The fingers can also be attached to the inside of the parallelogram structure, and thus reduce the minimal radius Fig. 10. The range of motion in rotation is $\pm 180\,^{\circ}$.

Friction affects the sensitivity and dynamics of the interface and the quality of the interaction with the user. The static friction torque for the rotation of the Haptic Knob is less than 0.02 Nm. The static friction for the opening/closing amounts to 9 N due to the linear module and the carriages. Friction on this axis was estimated by measuring the mean current required to open or close the device at a constant velocity (Fig. 8).

Fig. 11 illustrates the effect of the friction compensation during a closing movement with the Haptic Knob. With compensation the interaction force decreases dramatically to less than 1 N. Fig. 11 also shows the effects of two constant resistive

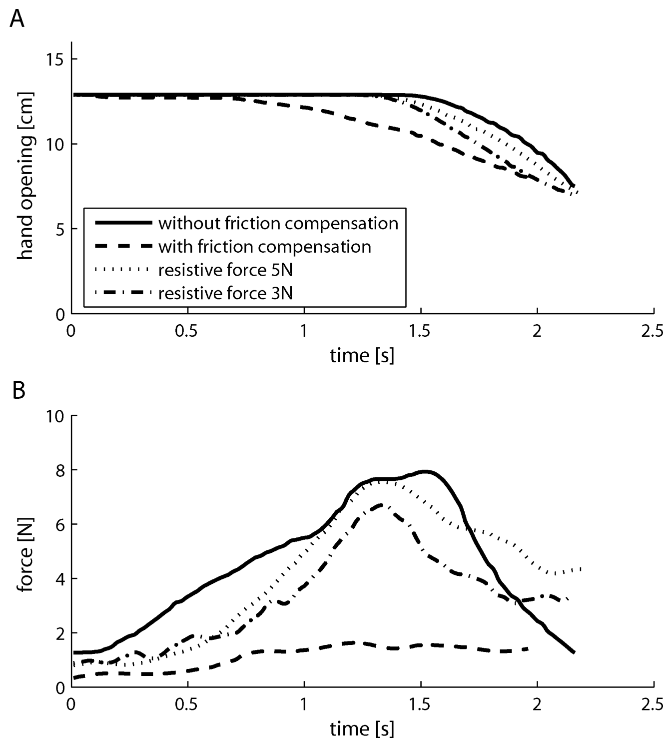

Fig. 11. A: Closing movement of the Haptic Knob without and with the friction compensation and with the addition of constant resistive forces of 3 and 5 N. B: Corresponding grasping forces during the four trials.

TABLE III
HAPTIC KNOB SPECIFICATIONS

maximum opening of the interface	150.0	mm
minimal opening of the interface	30.0	mm
maximum rotation of the interface	± 180.0	deg
maximum rotation of the moving parallelogram	± 45.0	deg
maximum generated opening/closing force	50.0	N
maximum generated torque	1.5	Nm
friction force for the linear DOF	9.0	N
friction torque for the rotation DOF	0.02	Nm
inertia (closed position)	$4.83 \cdot 10^{-4}$	Kgm^2
inertia (open position)	$19.3 \cdot 10^{-4}$	Kgm^2
workspace of one finger (MCP flex./ext. ϕ)	60.0	deg

forces on the grasping force applied by the subject during closing movements.

The maximal constant opening or closing force that can be generated by the haptic interface is 50 N, while the maximal constant torque is limited to 1.5 Nm. Table III summarizes the specifications of the Haptic Knob.

B. Opening of the Hand

Stroke patients have different levels of impairment and the interface can offer exercises adapted to each patient. The output of the interface can be changed to offer knobs of different diameters or shapes. The fingers can also be fixed inside the parallelogram structures to train grasping of real objects that can be placed in the palm of the user, and allow complete closing [Fig. 10(a) and (b)].

Fig. 1 shows a cone mechanism mounted on the haptic interface to help stroke patients with a high level of spasticity open

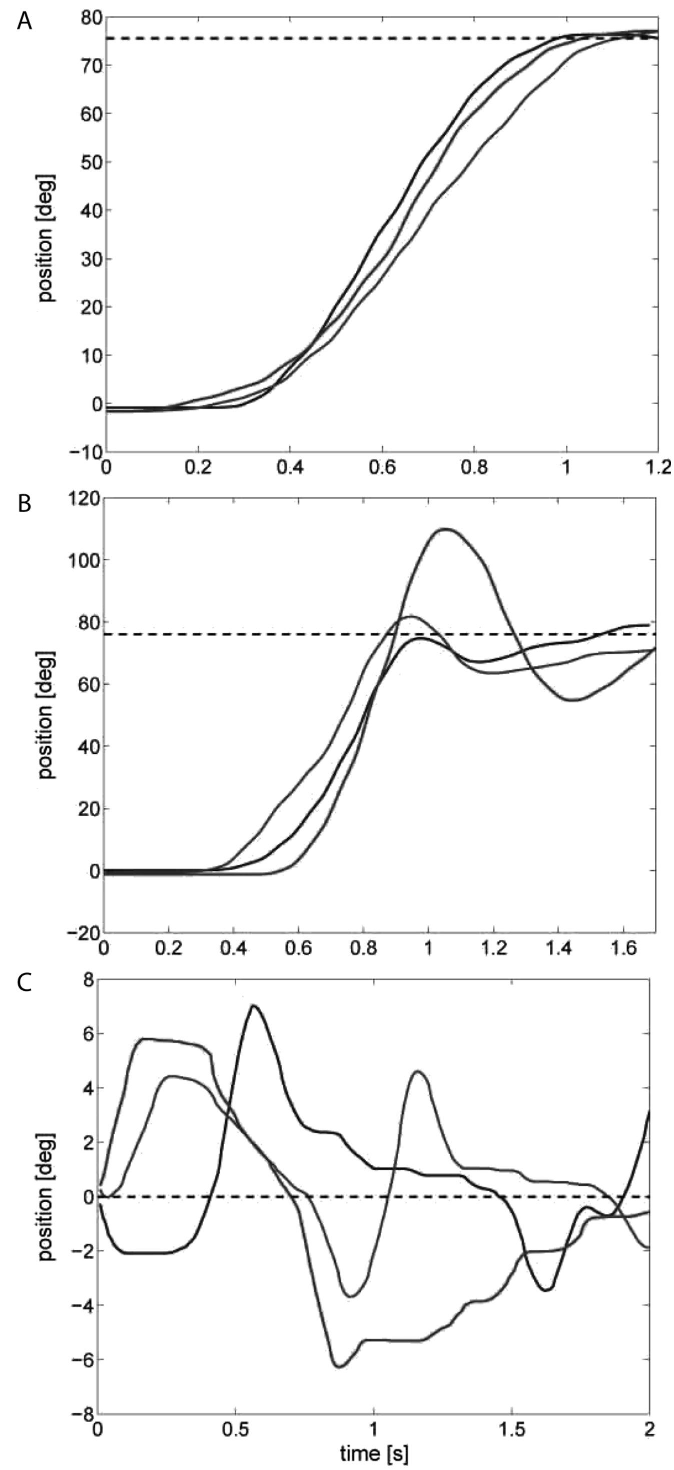

Fig. 12. Rotation movements of a healthy subject interacting with the haptic interface. Dashed lines represent the target position. Movements with a velocity dependent resisting torque (A) and with a velocity dependent assisting torque (B). C: Position-dependent torque which creates an instability around a target position.

and close the hand. The cone mechanism allows the subject to sweep the hand along the form to gently open it, then the Haptic Knob can provide assistance to attempt the opening movement. The device can thus assist complete hand opening, beginning from a strongly contracted and closed hand. The four force sensors can measure the force along the cone during the insertion

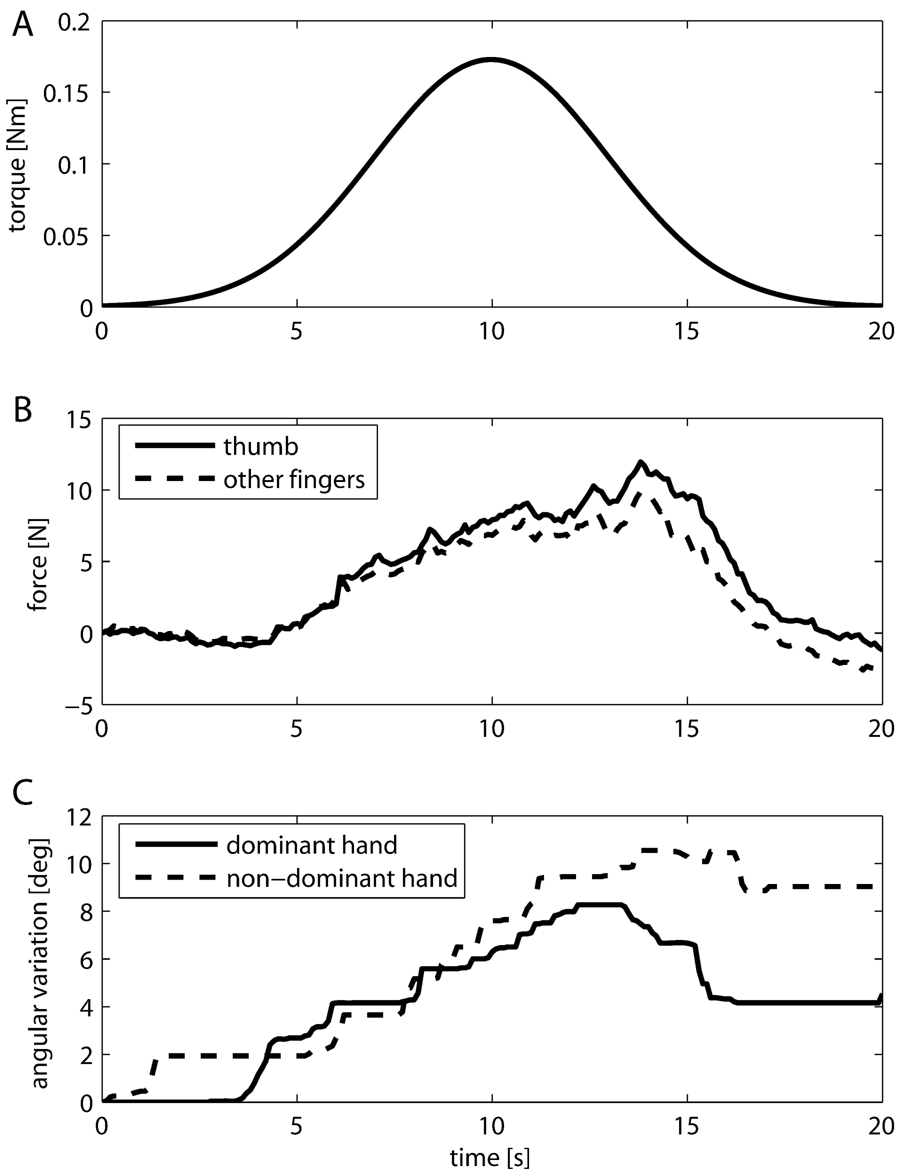

Fig. 13. Force applied by a healthy subject in order to prevent a torque produced by the interface (A) from moving the knob. B: Grasping force applied by the fingers to maintain the knob at the target position (thumb: solid line, other fingers: dashed line). C: Variation of angular position (dominant hand: solid line, nondominant hand: dashed line).

as well as the force during the opening movement, which may provide a novel method of assessment for hand rehabilitation.

Because stroke patients may move parts of the body other than the hand and finger to compensate for impairments, the arm and elbow of the subject are placed on an adjustable support fixed to the device, which prevents the subject from rotating the trunk or other parts of the body while performing the exercises.

C. Interface Forces and Torques

The dynamic performance of the interface is adequate to generate force and torque as functions of position and velocity. Fig. 12(a) and (b) shows the effect of a velocity dependent torque

$$\tau = D\dot{\theta}_{\text{in}} \tag{4}$$

implemented on the rotational DOF of the Haptic Knob. Positive damping $(D > 0)$ produces a resistive torque and can be used to strengthen the muscles. Conversely negative damping can assist the rotational movement and help subjects with weak muscles to extend their range of movement.

Fig. 12(c) shows the effect of destabilization produced by a position dependent torque

$$\tau = K\theta_{\text{in}}. \tag{5}$$

Negative stiffness $(K < 0)$, as in this figure, can be used to amplify movement error. Positive stiffness can guide movement along a desired path or drive the hand so as to teach and modify movement. Impulse perturbations can also be generated to study

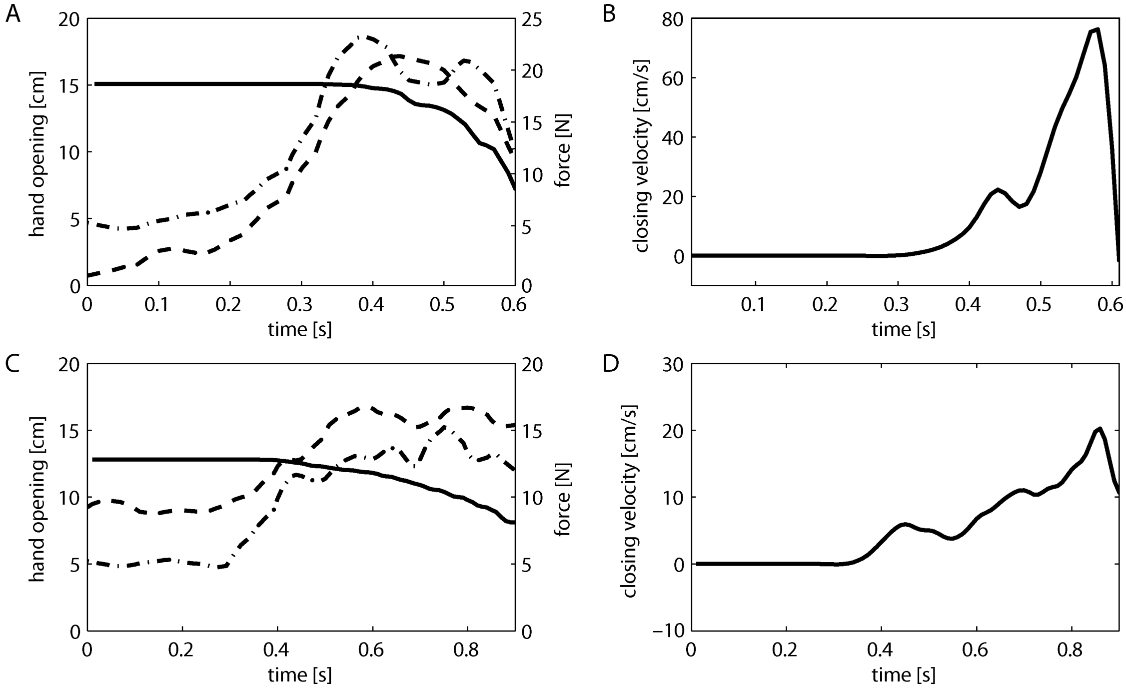

Fig. 14. Closing the hand in a healthy (A), (B) and in a stroke patient (C), (D). A, C: hand aperture, the distance between the two parts of the Haptic Knob, during a closing movement of the hand. Target position represented 7 cm opening of the hand. Dashed line represents the grasping force applied by the thumb, measured in the lower parallelogram. Dotted line represents the grasping force applied by the other fingers used to hold the knob, measured in the upper parallelogram. B, D: closing velocity.

reflexes or estimate impedance. Similar effects are possible on the linear DOF of the Haptic Knob.

D. Coordination of Hand Rotation and Opening

The interface is capable of quantifying coordination of hand opening and rotation. To illustrate this, we describe a basic experiment which was performed in order to test the position and force measurement systems, and study the effect of grasping parameters such as the number of fingers used (i.e., two, three, or four fingers) and the hand used for the experiment (i.e., dominant or nondominant). The subject was instructed to grasp a knob of 7 cm diameter mounted on the haptic interface and maintain it in the initial position while a variable torque (maximum torque applied 0.2 Nm) was applied for 20 s [Fig. 13(a)].

The subject was able to see his hand and the knob during the experiment, while the level of torque applied by the device was displayed on the monitor. The grasping force contribution from the subject was recorded, as well as the variation of angular position. The wrist was not constrained and the subject could choose the position of the fingers around the knob such that he could move naturally. The results show the following.

- The hand used for the experiments is a significant parameter influencing the angular variation ($p < 0.05$): as expected, the angular variation is greater with the nondominant hand [Fig. 13(c)].
- The forces applied to the knob are higher when fewer fingers grip the knob to provide the necessary stability. The maximal grasping force that was applied by the subject during the experiments was 18 N.
- The force magnitudes recorded by the force sensors in the two arms of the Haptic Knob, corresponding to the force applied by the thumb on one side and by the fingers on the other side, are similar [Fig. 13(b)]. The subject adapts the force applied by the fingers opposing the thumb, so that the resulting force is equal to that applied by the thumb, but in the opposite direction.
- The grasping forces of the thumb and the opposing fingers increase with the torque applied by the motor ($p < 0.03$), i.e., the subject coordinates his grip force with the load force [22].

E. Preliminary Experiments With Stroke Patients

The Haptic Knob has been tested by three chronic stroke patients (54–91 y with right hemiplegia, all right-handed). The selected subjects were representative of the population for which the Haptic Knob has been designed, i.e., poststroke subjects in the chronic phase, capable of minimal movement of the arm and hand. The three patients had similar hand function impairment preventing them from using their right hand for typical ADL such as key pinch, combing, and handwriting. The goal of these preliminary tests was to evaluate the interface and its control. Prior to participating, the subjects gave written informed consent.

Closing movements of the hand and pronation/supination of the forearm (target reaching movements) were performed at different force levels, using a knob with a diameter of 5 cm. The amplitude of movement was adapted to the ROM of each subject. The mean amplitude of movement of the subjects corresponded to a rotation of the MCP joint angle ϕ of $45^\circ \pm 5^\circ$, the maximal opening for healthy subject being 60°. The maximal resistive forces applied by the Haptic Knob were between

0 and 10 N. With this level of force the exercises are comfortable and it was possible for each patient to perform the tasks. In our current study, resistive forces will be set at 10% of the maximal grasping force of the subject (Table II). The subjects did not report any discomfort associated with using the robotic device and in fact found the exercises to be comfortable.

The principal observation was that, due to limited finger adduction, the angles between the fingers of stroke patients were smaller than for the healthy subjects, especially for the angle between the thumb and the other fingers. Due to joint stiffness, muscle tightness/contracture, synergy or spasticity, the stroke patients were all unable to place the thumb in opposition to the four other fingers. On the robot, the thumb has to be centered on the knob in a way to measure grasping forces collinear to the opening movement, and to prevent any deformation of the structure. To solve this problem and offer a more comfortable grip, the orientation of the parallelogram structures of the Haptic Knob can be rotated. Typically, angles of 25° were used to adapt to the subject's hand, and place the thumb in the centre of the finger support.

Representative trials of the opening and closing exercise are presented in Fig. 14. The goal of the exercise was to close the hand to a target value of 7 cm, starting from a fully opened hand position. A comparison between healthy and stroke subjects illustrates that the movement was slower for stroke patients, and the grasping forces applied to the two parts of the Haptic Knob were smaller.

V. Conclusion

This paper presented a novel 2-DOF robotic interface to assist stroke survivors in recovering motor function of the hand. The selected design, consisting of two parallelogram structures, was developed to train basic hand functions, such as opening and closing of the hand and coordination between grasping and wrist rotation, which are necessary for most activities performed with the hand. The interface is adjustable to suit the user's hand, and it can be used to train a large range of movements.

The performance tests and preliminary experiments with healthy and stroke subjects illustrate the possibilities offered by the Haptic Knob for hand rehabilitation. Typical features of manual dexterity such as regulation of force in the thumb and opposing fingers or the coordination of grip with load force in manipulating objects can be measured by the sensors with which the interface is equipped. They can be used to infer the physiological states of stroke patients and examine the neuromechanical control of the hand.

Future research with the Haptic Knob will be directed toward the development of training protocols for rehabilitation of hand functions after stroke, that provide augmented somatosensory (proprioceptive and tactile) information. Increasing subjects' awareness and use of somatosensory information is vital for improvement in motor function. We plan to use the Haptic Knob to improve regulation of hand aperture, grip force and hand orientation.

The Haptic Knob offers a choice of protocols, which can be selected for effectiveness with different patients. For example, to train subjects to regulate grip force, the Haptic Knob could be programmed to generate a constant opening force which the subject would be asked to match by maintaining a specified (target) hand aperture. Alternatively, the Haptic Knob could be programmed to remain stationary if subjects maintained a target grip force and to rotate in one direction if the grip force was greater than the target force or in the opposite direction if the grip force was lower than the target force.

Both of these tests could be conducted with a pinch type grip (fingers closing towards the thumb) or a power grip (using the cylindrical attachment, illustrated in Fig. 1). These two training protocols illustrate the use of different types of proprioceptive feedback to train the same function. We will also examine the feasibility of augmenting tactile feedback. This could be done by applying high frequency dither to the force or torque control signals so as to produce small amplitude vibration of the structure, which the subject would sense at the fingertips.

One of the complications of stroke is spasticity, particularly in finger flexor and wrist flexor muscles. One goal of our research will be to determine whether abnormal patterns of muscle activation following stroke are due to spasticity, disordered high level control or both. We are able to record electromyographic activity from the small muscles of the hand and the larger forearm muscles. By applying perturbations, which stretch these muscles, we can determine whether subjects have lower than normal thresholds or exaggerated reflex responses, indicative of spasticity.

Acknowledgment

The authors would like to thank Y. Ruffieux, D. Chapuis, T. Maeder, G. Corradini, and H. Bleuler from EPFL, B. Salman and V. Johnson from SFU, as well as therapists and stroke patients at the Society for the Physically Disabled in Singapore and at stroke recovery clubs in Vancouver, who have all contributed to the design of the device described in this paper.

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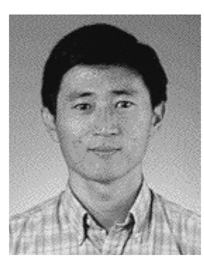

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