Chapter Four

Robot-Assisted Rehabilitation of Hand Function After Stroke with the HapticKnob and the HandCARE

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4.1 INTRODUCTION

Robot-assisted rehabilitation is one of the most promising approaches to complement current clinical strategies for stroke rehabilitation. It could increase the intensity of therapy with affordable costs, and offer advantages such as (i) precisely controllable assistance/resistance during movements, (ii) good repeatability, (iii) objective and quantifiable measures of subject performance, and (iv) increased training motivation through the use of interactive feedback, such as virtual reality environments and stimulation of afferent pathways.

Over the last decades, upper limb robot-assisted rehabilitation after stroke has focused mainly on restoring arm function, yielding promising results that illustrate the potential of robots to complement traditional therapies and support stroke rehabilitation (Prange *et al.* (2006), Kwakkel *et al.* (2008)). However, arm function alone is not sufficient to perform most activities of daily living (ADL), such as eating/drinking, writing/typing and personal hygiene. In fact, hand function is fundamental to all these daily activities. These observations motivated us to develop robot-assisted rehabilitation strategies focusing on the distal parts of the upper extremity, i.e. the wrist, hand and fingers.

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A questionnaire given to a population of 27 stroke subjects illustrated that hand tasks such as handwriting, typing, and operating knobs and buttons are activities that stroke survivors find difficult and would like to recover most (Dovat *et al.* (2006)). This prompted us to develop robotic devices to train similar functional tasks. However, such hand activities are complex, require precise control and/or coordination of the forearm, wrist and fingers and involve a large number of joints. Further, hand activities also require contribution of the elbow and shoulder to support the weight and properly position the hand.

A possible approach is to decompose complex hand tasks into a combination of simple subtasks to be trained individually. For example, the task of operating a door knob can be decomposed into a series of subtasks (i) reaching for the knob, (ii) grasping the knob, (iii) turning the knob, and (iv) releasing the knob. These subtasks can be trained separately with dedicated interfaces and exercises (Fig. 4.1). Recent studies on rehabilitation of arm function in stroke patients did not yield better results in terms of motor improvement compared to complex tasks were trained directly (Krebs *et al.* (2008)); however, this presents the advantage of simplifying both the robot design and the implementation of exercises.

In order to optimize rehabilitation of hand function, patients should be able to train at home or in decentralized centers, in the context of their daily activities. Because this would limit transportation costs, be less disruptive to the patient and require only minimal (or remote) supervision from a therapist, it might allow the intensity and duration of therapy to be increased without increasing the costs. To facilitate their acceptance, rehabilitation robots should be designed with a human centered approach, focusing on stroke patients' needs and desires. They should

Figure 4.1 The *HandCARE* and the *HapticKnob*, two complementary robotic systems for rehabilitation of hand function.

also be compact, safe when used by the patient alone, "plug and play" on a personal computer, simple to use, adaptable to the user, and relatively inexpensive for patients or rehabilitation centers to buy or rent.

This chapter gives an overview of the challenges of robot-assisted rehabilitation of hand function after stroke. Two robotic devices we have designed for rehabilitation of hand function, the HapticKnob and the HandCARE, are then presented, and strategies for hand rehabilitation using such devices are discussed. Finally, the principal findings of clinical studies with the two systems are presented to illustrate the potential and future challenges of robot-assisted rehabilitation of hand function after stroke.

4.2 HAND FUNCTION AFTER STROKE

The hand is a fascinating neuromechanical system and a defining characteristic of humans. The ability to position the thumb in opposition to the other fingers in order to grasp objects is a unique characteristic of the human species, which is believed to have played a decisive role in our evolution. *Precision grip*, employed where fine motion and force are required, and *power grip*, employed to generate high force, provide the basis for almost all prehensile tasks used in ADL, such as eating, manipulating tools or enabling communication with each other, for example through gestures and writing. In addition to its motor function, the human hand acts as a sensory organ during tactile exploration of the environment, which is possible because of the high density of cutaneous sensory receptors in the fingertips. Tactile sensation is capable of replacing vision when this sense is impaired or unreliable. The hand is central to human psychology, as it is used in executive, perceptual and expressive activities (Valero-Cuevas (2009)).

Because of its direct control by the motor cortex, the hand is usually impaired after a stroke. Different dysfunctions such as muscle weakness, spasticity and compulsory co-activation of anatomical muscles at multiple joints contribute to impairment of finger and hand function after stroke (Fugl-Meyer *et al.* (1975)). Extension, abduction, and adduction of the fingers are particularly impaired, leaving the fingers in a flexed finger posture (Hunter and Crome (2002)).

In terms of function, damage to the sensorimotor system leads to specific impairments of the hand that include (i) limited ability to open the hand or position the thumb in opposition to the other fingers, which is the basis for all types of grasp (Kamper *et al.* (2006), Cruz *et al.* (2005), Dovat *et al.* (2007)), (ii) loss of finger independence, limiting the ability to move and generate force independently with individual fingers (Lang and Schieber (2004), Raghavan *et al.* (2006), Schieber *et al.* (2009)) and (iii) inability to control finger force and explore the environment, due to insufficient tactile sensation and impaired sensorimotor translation. These impairments result in difficulties in grasping and manipulating objects, leading to slow and uncoordinated movements.

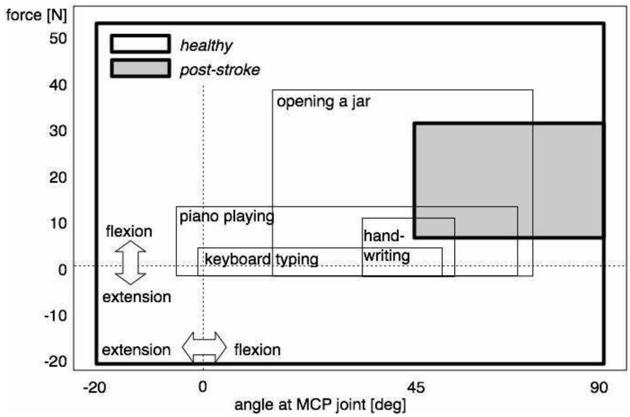

Figure 4.2 Finger range of motion (x-axis: angle at the Metacarpophalangeal (MCP) joint) and force (y- axis: force at the fingertips) required to complete typical ADL. The white square (thick outline) represents the performances of healthy subjects, in terms of maximal extension/flexion movement and force, while the black square represents the limited performances of poststroke subjects with mild impairments. Performances are based on actual data from the participants of the research study presented in this chapter (7 chronic stroke patients), while the range of motion and force required to complete the ADL are empirical. Post-stroke subjects are unable to completely perform the selected activities.

These impairments are often linked and severely limit stroke survivors' ability to perform ADL. Figure 4.2 summarizes data from stroke patients to illustrate how limited they are in performing typical activities requiring hand movements such as in typing, writing or opening a jar.

The principal challenge of hand rehabilitation after stroke is thus to restore grasping function and hand-wrist coordination, which are required to manipulate objects and essential for ADL. In addition, fine finger control should be addressed as it plays a crucial role in tactile exploration, manipulation of small objects and fine motor tasks such as handwriting. However, for the more severely impaired subjects, hand rehabilitation has to begin by training hand opening and working on overcoming flexor muscle synergies that prevent subjects from performing almost any type of activity with their hand.

4.3 ROBOT-ASSISTED REHABILITATION OF HAND FUNCTION

Robotic devices developed for arm and, more recently, for wrist rehabilitation, obtained promising results, suggesting that robot-assisted treatment may lead to increased gain relative to traditional therapy, which motivates the development of new devices dedicated to hand rehabilitation (Takahashi *et al.* (2008), Hesse *et al.* (2003), Lambercy *et al.* (2009)) (Fig. 4.3).

The HWARD (Takahashi *et al.* (2005)) and the GENTLE/G (Loureiro and Harwin (2007)) are examples of actuated exoskeletons designed to train grasping and releasing of objects, while the Gifu Haptic Interface (Kawasaki *et al.* (2007)) is

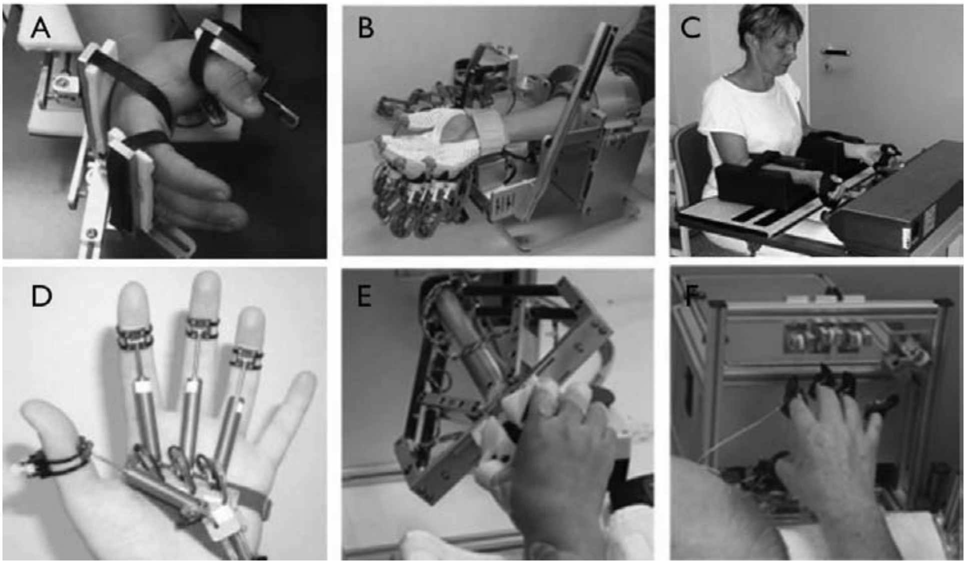

Figure 4.3 Hand rehabilitation robots. UC Irvine's HWARD (A) (Takahashi *et al*. (2005)), Gifu Haptic Interface (B) (Kawasaki *et al*. (2007)), BiManuTrack (C) (Hesse *et al*. (2003)), the Rutgers Master II (D) (Bouzit *et al*. (2002)), as well as our HapticKnob (E) (Lambercy *et al*. (2007)) and HandCARE (F) (Dovat *et al*. (2008)).

an exoskeleton designed to train movement of each finger individually. Exoskeleton devices usually are complex mechanical structures with multiple degrees-of-freedom (DOF), controlling several joints. Such systems have the advantage of precisely controlling subjects' movements and providing assistance in performing complex tasks, but it is difficult to adapt them to stroke patients with different hand sizes and impairments, and they suffer from inertia and friction due to the large number of joints.

On the other hand, end-effector robots such as the BiManuTrack (Hesse *et al.* (2003)), or the Rutgers Master II (Bouzit *et al.* (2002)) interact with the user only at the level of the hand or fingers. This may offer a more flexible solution with fewer mechanical constraints on how the movement is performed, corresponding better to manipulation of real objects in everyday life. Furthermore, end-effector devices are usually mechanically simpler, easier to use and more compact, which are important considerations for the deployment of robotic devices in rehabilitation centers or patients' homes. Following such an approach, we have developed and clinically evaluated the HapticKnob, and the HandCARE, two complementary end-effector based rehabilitation devices to train hand and finger function.

4.3.1 The HapticKnob

The HapticKnob is a 2 DOF robotic device for training grasping in coordination with pronation and supination of the forearm. A linear DOF enables opening and closing of the hand, and a rotational DOF provides pronation and supination around the long axis of the forearm. The HapticKnob uses two moving parallelograms similar to an umbrella, on which the user places the fingers (Fig. 4.3E). Fixtures of different size and shape can be attached to train various functionally relevant grips such as power grasp, precision grip or lateral pinch. The device can generate forces of up to 50 N in both opening and closing directions and torques of up to 1.5 Nm in pronation and supination.

Four force sensors are incorporated into the structure to measure grasping forces of up to 30 N applied by the subject. Various force effects can be implemented, e.g. to resist or assist movement as a function of the user's impairment in an assist-as-needed manner. This robot has dimensions of $60 \times 30 \times 25$ cm^3 and can easily be transported and set up in minimal time. Further information on the HapticKnob can be found in (Lambercy *et al.* (2007)).

4.3.2 The HandCARE

The HandCARE is a cable driven robotic device, where each fingertip is attached to a cable loop, connected to a single motor, allowing predominantly linear displacement corresponding to finger flexion/extension (Fig. 4.3(F)). The interface can thus assist the subject in hand opening and closing movements. Instead of using five actuators, a clutch system has been developed, which simplifies the control of the robotic device and reduces the cost. The clutch allows switching between three modes, (i) active, where the torque generated by the motor is transmitted to the finger, (ii) fixed, where no finger movement is possible and force control can be trained isometrically, and (iii) free, where the finger can be moved freely along the path of the cable. This clutch system makes training of different movements possible with only one actuator and one clutch per finger. It is thus possible to train grasping and precision grip as well as fractionation, i.e. independent movement or isometric force training of each finger, thereby increasing strength in individual muscles and coordination between fingers.

The active workspace consists of five linear paths of 8 cm length corresponding to a finger extension/flexion angle range of $0 - 70^\circ$ at the metacarpophalangeal (MCP) joint. The maximal continuous force that can be generated in flexion or extension is 15 N per finger (up to 75 N if only one finger is actuated), while inherent friction is less than 0.8 N in any position of the workspace. Forces applied at the fingertips during the exercises can be recorded by a sensing system measuring the tension in the cable attached to each finger. Further information on the HandCARE can be found in (Dovat *et al.* (2008)).

4.3.3 Rehabilitation Exercises and Strategies

Robotic devices offer a large number of new modalities for the treatment of stroke patients, but interactive, motivating and task oriented exercise programs are critical for subjects to use a rehabilitation robot to its full potential. We review here some concepts that should be considered for the design and implementation of exercises for hand rehabilitation.

Passive and active exercises are currently used in robot-assisted rehabilitation (Marchal-Crespo and Reinkensmeyer (2009)), with robots producing assistive or resistive forces, or more sophisticated assist-as-needed strategies, or event related assistance based on brain or muscle activity. Typically, at an early stage in stroke recovery, movements such as finger extension can only be performed passively, i.e., the robot has to move the fingers in order to compensate for the weakness in finger extensors observed in stroke subjects. In this phase, it is crucial that the robot monitors the interaction forces and gently moves the fingers.

However, passive movements driven by robotic interfaces may not be sufficient for hand rehabilitation; while passive movements contribute to reducing muscle tone and maintaining passive properties of joints and muscles (Hesse *et al.* (2003)), active movements initiated by the subject are required to promote correct patterns of muscle activation and improve strength (Hogan *et al.* (2006), Woldag *et al.* (2007)), which are crucial to dexterous manipulation.

Furthermore, active participation of the subject during training is fundamental to skill acquisition (Winstein *et al.* (2003)). Motor recovery after stroke is considered as a form of motor learning, where undamaged brain regions are recruited to generate motor commands to the same muscles that were used before the injury. It may, therefore, be advantageous to apply the motor learning principles observed in healthy subjects to improve stroke rehabilitation. Note that active participation can also be achieved during passive exercises by giving subjects proper instructions, but movements remain limited by the passive guidance and are thus far from real activities. In this sense, therapy should focus on intensive repetition of active movements where subjects interact with various force fields to help develop strategies that will be optimal for improving hand function in ADL (Krakauer (2006), Reinkensmeyer *et al.* (2004)).

However, intensive repetition of movements involving the impaired limb require considerable effort by the subject and may be painful and tiring. Additionally, after several repetitions, subjects may get bored, leading to decreased concentration and motivation to train, thus affecting the quality of the therapy.

Motivation is important to ensure that subjects are engaged and train at their full potential during therapy sessions, pushing the limits imposed by their impairment. A common way to keep subjects motivated during intense movement repetitions in the use of interactive feedback. Visual feedback is widely used in robot-assisted rehabilitation systems, and is probably the simplest way to interact with a user. Moreover, exercises with visual feedback or virtual environments may help improve the outcome of post-stroke rehabilitation, by augmenting subjects' awareness of their actual performance, and promoting visuomotor coordination (Henderson *et al.* (2007), Holden (2005)).

Robotic devices have the advantage of providing haptic feedback, i.e. specific force and/or torque patterns that can stimulate proprioceptive sensors in skin, joints and muscles to increase subjects' awareness and use of somatosensory information. Similarly, tactile feedback can be used to restore sensation in the impaired limb; typically small vibrator motors can be taped on the subject's hand or arm to stimulate the skin when a task is successfully performed.

Motivating rehabilitation exercises may be implemented as goal-oriented therapeutic games with a score indicative of the performance, and the possibility to choose between different levels of difficulty adapted to the impairment level. Indeed, therapeutic programs that build on a base of successively more demanding performance levels and that promote a sense of personal responsibility for accomplishment is believed to be more successful and motivating (Lewthwaite (1990), Johnson (2006)). It is debatable how sophisticated and complex these virtual reality environments need to be as stroke patients are typically older and do not have previous experience with video games, may suffer from cognitive deficits, and fatigue easily.

Exercises implemented on the HapticKnob and the HandCARE follow this concept, progressively requiring more accuracy or more force for successful completion. Simple and intuitive visual feedback is used, consisting of selected pictures that are visually scaled or rotated as a function of the motor task performed on the robot. Figure 4.4 illustrates the display presented to the subject during an exercise with the HapticKnob, where the objective is to perform pronation and supination movements with the forearm. The orientation and brightness of the picture are modulated as a function of the rotation angle of the robot, such that when the target is reached the picture is oriented normally. In addition to being intuitive, this approach offers subjects the possibility of training with personally selected pictures to further increase motivation and engagement in the therapy, i.e. photo of the family members or of places the patient would like to travel to (Lambercy *et al.* (2007b)).

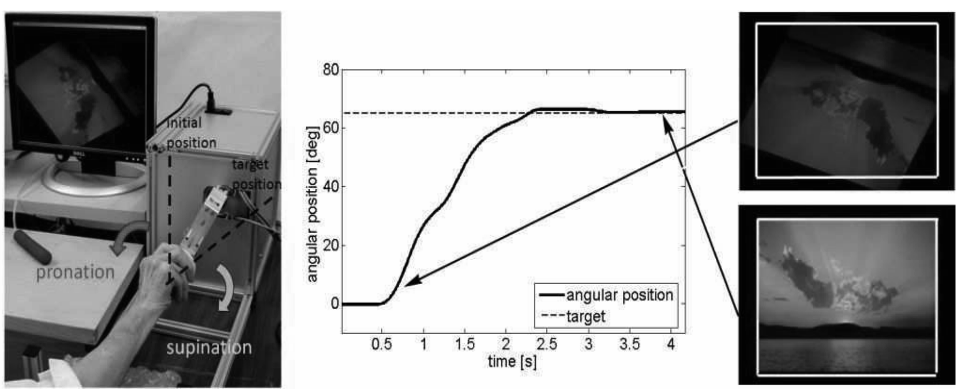

Figure 4.4 Angular position of the HapticKnob during an exercise training pronation/supination movements. Visual feedback is given by means of a picture whose orientation and brightness are modulated as a function of the angular position of the wrist.

4.4 PROMISES OF ROBOT-ASSISTED THERAPY OF HAND FUNCTION

This section presents some of the outcomes of clinical studies performed with the HapticKnob and the HandCARE, and discusses the potential of these robotic devices to restore hand function of chronic stroke survivors.

In a first pilot study, four chronic post-stroke subjects, more than 2 years after stroke (P1-P4, 54–83 years of age, 1 female) participated in an eight-week rehabilitation therapy, training a combination of exercises with the HapticKnob and the HandCARE. All subjects were right-handed and suffered from right hemiparesis. Participants were eligible for the study if they had a minimum manual muscle testing (MMT) level of 3 (i.e. able to move the arm against gravity, but not able to tolerate resistance), no more than level 2 spasticity in hand and arm muscles measured by the Modified Ashworth Scale (MAS, range [0-5], (Bohannon and Smith (1987))) and presented no other neurological disorder such as apraxia or tremor. They were able to move the right arm and hand, but had difficulties in performing many typical ADL.

Therapy sessions were given twice a week, and consisted of 20 minutes of training with the HandCARE followed by 20 minutes of training with the HapticKnob. Therapy was tailored to the subject's level of impairment, and consisted of exercises training sensorimotor function where subjects had to actively perform grasping movements and forearm pronation/supination with the HapticKnob. Exercises with the HandCARE focused on fine motor control by training finger coordination, and generation of independent finger force.

All stroke subjects improved their performance in the different exercises during the robot-assisted therapy, which was accompanied by improved hand motor function and force control.

4.4.1 Improvement in Motor Function

In an exercise to train forearm pronation/supination with the HapticKnob, patients were asked to reach a target forearm orientation by turning the knob against a resistive load, simulating the action of turning a door knob. The first movement was always supination, starting from the rest position of the forearm (full pronation). Once the target was reached, the image on the monitor was reoriented to require an identical returning movement in pronation for realignment. Figure 4.5 illustrates the evolution of a pronation movement from beginning to the end of therapy.

Stroke subjects found supination more difficult than pronation, which can be explained by abnormally high elbow flexor muscle activity increasing the difficulty of controlling fine movements in supination. However, significant improvements were found for the supination movement, which was the major goal of the exercise. In average, the time required to perform the "twisting" movement significantly decreased for both supination (-25%) and pronation (-13%) (Fig. 4.5(C)). However,

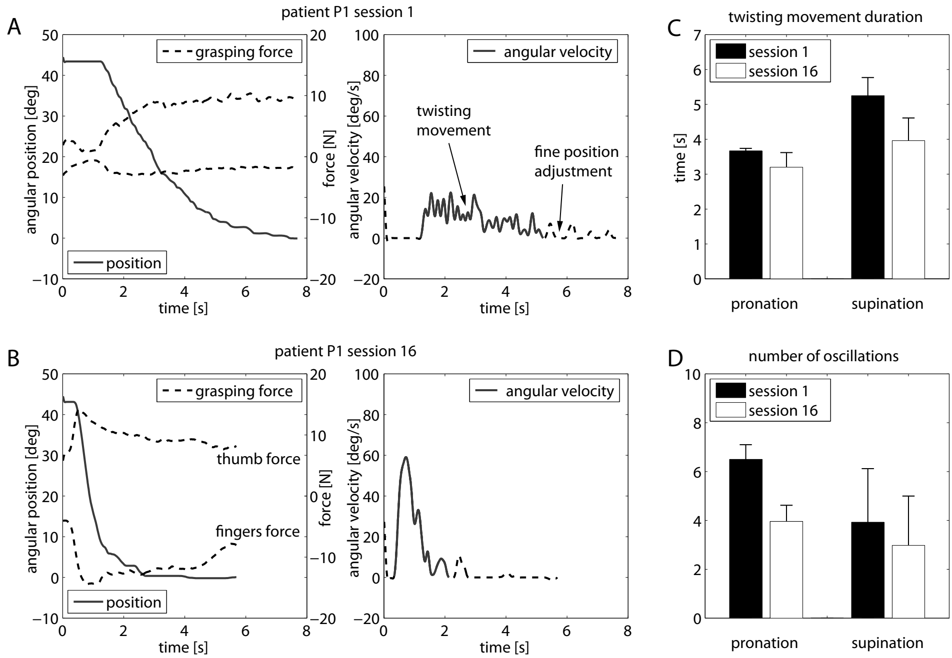

Figure 4.5 Angular position, grasping force and angular velocity during a representative pronation movement with the HapticKnob for stroke subject P1 (male, 63 years old and 2 years post-stroke) in the first (A) and last session of robot-assisted therapy (B). The duration of the twisting movement (C, mean over all patients) as well as the oscillations around the target (D, mean over all patients) decrease for both pronation and supination, while the coordination between forces applied by thumb and fingers increases.

even after training, the movement duration was longer than for healthy subjects of the same age group. In addition to the increase in speed, the number of oscillations to adjust the position around the target orientation decreased (−62% in supination and −24% in pronation, Fig. 4.5(D)). These results illustrate an important improvement in movement precision and control during tasks involving hand and forearm coordination.

Similar results were observed in finger movements trained with the HandCARE. In an exercise where subjects were asked to actively extend and then flex the fingers together, i.e. all fingers moving at the same time, we observed significant improvement in the coordination between the fingers (+31% during extension and +54% during flexion of the fingers). Control of finger motion also improved during the therapy, as we observed smoother movements (+6.2% and +1.4% in extension and flexion respectively).

4.4.2 *Improved Force Control*

Finger independence and finger force generation were trained with the HandCARE. Subjects were instructed to select different letters on a monitor in order

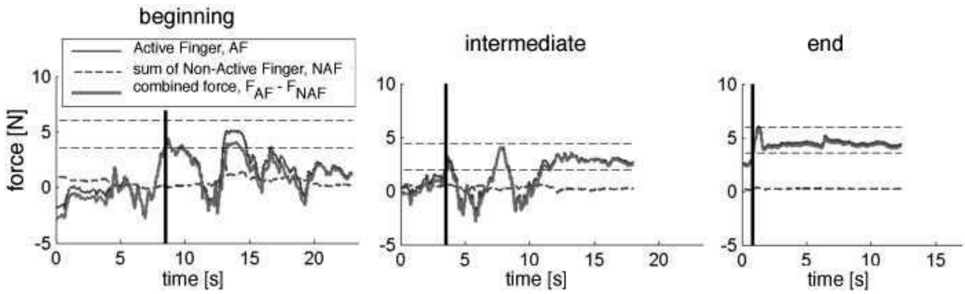

Figure 4.6 Comparison of fingertip force of stroke patient P3 (female, 83 years old and 6 years post-stroke) between the beginning (left), the middle (middle) and the end (right) of the training while the subject had to reach and maintain a target force (between dotted lines) with the index finger (AF in the figure). Forces of the AF and the NAF as well as the combined force are displayed.

to compose a specific word associated with a picture, e.g. the name of a city. While fingers were maintained in a fixed position by the HandCARE, letters were selected by isometrically applying a certain amount of force with a specific finger, i.e. Active Finger (AF), and by minimizing the force applied by the other fingers, i.e. Non- Active Fingers (NAF). The training was focused on the tripod thumb-index-middle as these fingers are most commonly used in ADL.

One stroke subject with limited finger impairment performed this exercise during the entire 8 weeks of therapy. With training, the number of successful trials (i.e. correctly selected letter) increased for these three fingers (+16% for the thumb, +28% for the index, and +29% for the middle finger). The time to perform a successful trial was also significantly reduced (−45%), which indicates that the subject felt more comfortable with the exercise and was able to better control forces generated by these fingers. This suggests that an intense isometric force training promotes recovery of finger function.

Figure 4.6 illustrates how the force applied by the NAF tends to decrease with training when the index finger produces force.

A similar exercise to train the regulation of power grasp force with the HapticKnob illustrated improvement in the ability to generate, quickly adjust and maintain precise grasping force.

4.4.3 Evolution in Muscle Activity Patterns

To determine whether post-stroke subjects were more limited in their ability to modify patterns of muscle activation than age-matched healthy subjects, we computed the principal components of the root-mean-squared (RMS) electromyography (EMG) of 8 muscles of the hand and forearm during the performance of the different exercises. We assumed that greater limitation would be evident as a higher percentage of the variance being accounted for by fewer principal components (PCs). We compared the number of PCs needed to account for at least

95% of the variance in the EMG. We found that in all cases only one or two PCs were needed and that this did not differ between post-stroke and healthy subjects. Therefore, we have no evidence that post-stroke subjects are any more limited in their ability to modify patterns of muscle activation than aged-matched healthy subjects. Because PC1 always accounted for more than 75% of the variance, we concluded that the individual exercises were generally performed using only one predominant pattern of muscle activation, both in the case of healthy and post-stroke subjects.

Although only one PC accounted for most of the variance, the profile of this PC (PC1) was quite different for exercises performed with the HandCARE compared to the HapticKnob (Fig. 4.7(A)) Given that the RMS-EMG was normalized with respect to maximal voluntary contraction prior to conducting the principal component analysis, the weighting coefficients of PC1 represent the relative activation of each muscle in the predominant activation pattern. In the example of Fig. 4.7(A), which represents muscle activity patterns prior to the robot-assisted rehabilitation, the PC1 profile shows that the forearm supinator, biceps (BI), and the finger abductor, first dorsal interosseus (1DI), are the primary muscles contributing to the pattern for the HapticKnob exercises training grasping and pronation/supination. For the HandCARE exercises training finger movement coordination, all of the finger muscles (1DI, FDS, EDC, ADM) contribute relatively equally and their contribution is greater than that of the wrist muscles (ECR and FCU). However, the biceps is the most active muscle, which represents abnormal activation. After the robot-assisted rehabilitation (Fig. 4.7(B)) the activity of the biceps activity in PC1 was the lowest of all the muscles, indicating that this aspect of the abnormal activation patterns had improved with the robot-assisted rehabilitation.

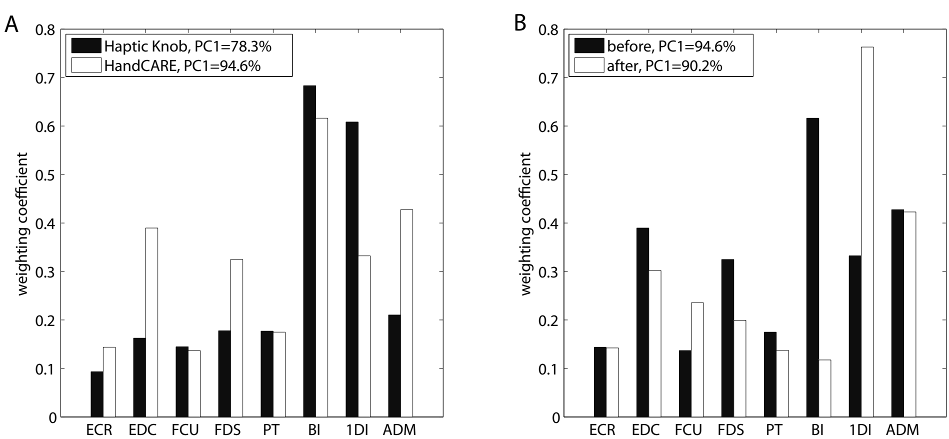

Figure 4.7 PC1 of a stroke patient (P1) pre-rehab muscle activity from PCAs for exercises with the HapticKnob and with the HandCARE (A). Comparison of PC1 of a stroke patient (P1) muscle activity during a grasping exercise with the HandCARE before and after robot-assisted therapy (B).

4.4.4 Improvement in Outcome Measures

Upper limb impairment was assessed before and after the therapy using the Chedoke-McMaster Impairment Inventory (CMMII) (Gowland *et al.* (1993)), where the impairment is scaled from stage 1 (severe impairment) to stage 7 (mild impairment). Robot-assisted training resulted in direct benefits in ADL for the four subjects, and in a reduction of their impairments. A mean improvement of +1.05 stages (+25%) was observed in the four patients who participated to the pilot study. Figure 4.8(A) presents the evolution of CMMII scores for the four stroke patients.

In addition, patients reported improvement in their daily activities at home; they felt more secure in grasping and manipulating objects, more skillful in fine motor tasks such as manipulating buttons or handwriting, and started to use their impaired hand more, which we believe is crucial for further improvement.

These preliminary results motivated a larger clinical study with the HapticKnob. Nine subjects (59.4 ± 12.3 years, 5 females) at the chronic post-stroke stage, 3 right and 6 left hemiparetic, participated in this study. Subjects participated in a one-hour session 3 times a week over a period of 6 weeks, resulting altogether in 18 sessions during which they trained with the HapticKnob. Evolution in arm and hand motor function was assessed using clinical tests including the Fugl-Meyer arm motor scale (FM, range [0-66], (Fugl-Meyer *et al.* (1975))). After 6 weeks of therapy with the HapticKnob, a mean increase of 4.3 points (+14%) was observed in the FM scores, with a maximum improvement of 11 points in one of the patients (Fig. 4.8(B)), which confirmed positive results obtained in the first study with the HandCARE and the HapticKnob (Lambercy *et al.* (2009)).

These results suggest that an intensive and repetitive training program improves motor function in chronic stroke subjects long after completion of con-

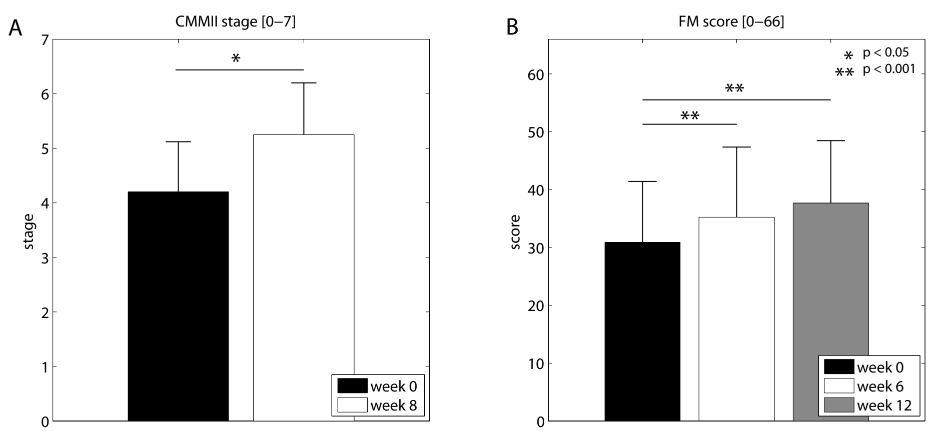

Figure 4.8 Evolution in clinical outcomes after robot-assisted rehabilitation of hand function, during the first clinical study with the HapticKnob and the HandCARE (A) and during the second study with the HapticKnob (B).

ventional therapy. These improvements correspond to a noticeable increase of hand and arm function of stroke survivors, and are in accordance with results obtained in other robot- assisted studies on upper limb rehabilitation of chronic stroke patients. Further, the observed improvements in arm and hand function were found to be maintained after the completion of the therapy, suggesting long term improvement in motor abilities.

4.5 CONCLUSIONS

This chapter offered an overview of the field of robot-assisted rehabilitation of hand function after stroke, by presenting the challenges of restoring fine hand movement and sensation, as well as describing two novel robotic devices developed to train hand and fingers, the HapticKnob and the HandCARE. These robots are based on an end-effector approach, i.e. interacting with the user only at the level of the hand or finger, which we believe provides more freedom and comfort for subjects to perform the required tasks, corresponds better to real interaction with objects during ADL, and also significantly decreases complexity and cost of robotic systems. Two clinical studies have been performed with chronic stroke survivors to determine the potential of our approach and these devices to restore hand sensorimotor function.

First, results of both studies show that robot-assisted rehabilitation with our robots was safe and well accepted by stroke survivors. All patients actively participated in the therapy and completed the study. They found the proposed exercises motivating and useful, eventually asking for more therapy time with the robots. This suggests that the stroke population is ready to accept robot-assisted rehabilitation as a new therapy standard in rehabilitation centers or at home.

Improvements in sensorimotor function of arm and hand were observed in all participants, which illustrates that an intensive and repetitive training program leads to improvement in motor function in chronic stroke subjects even long after completion of conventional therapy, suggesting long term improvement in the motor condition. Although most subjects reached a plateau, several subjects continued to significantly improve their arm and hand motor function after completion of the robot-assisted therapy. This may be due to an increased use of the impaired limb in daily activities at home, mediated by the motor improvements obtained during the therapy, and increased confidence in their motor abilities.

In most robot-assisted studies where only shoulder and elbow were trained, improvement in clinical assessments were mainly observed at the level of the upper arm, and only minimal change was observed in the components relative to the hand (Krebs *et al.* (2007); Volpe *et al.* (2008)). While upper arm training may lead to an increase in arm function, the benefits in subjects' ability to perform ADL may be limited without a similar increase in wrist and hand function. On the other hand, studies on robot- assisted training of hand and wrist function showed an increase in all arm segments (Krebs *et al.* (2007); Takahashi *et al.* (2008)).

Distal arm training involves activation of nerves and muscles in each segment of the upper limb, and consequently results in proximal as well as distal muscle activity. Furthermore, while training with end-effector based robots, subjects used their entire arm to perform the required tasks, thus involving elbow and shoulder, typically to stabilize the arm. Training distal segments of the upper limb may thus help improve arm function in a more homogeneous way and may lead to greater improvement in ADL.

Altogether, our results illustrate the feasibility of improving control of hand and finger motion as well as force control by training with dedicated robotic devices, which are compact, easy to use, and can thus be easily transported and installed. Although training of hand and fingers is limited to stroke subjects with some remaining motor function in these segments, restoring fine hand control, precision and power grip are crucial tasks that could have a significant impact on the quality of life of stroke survivors. In addition, the observed transfer from improvement of hand to arm function opens horizons for the development of new robotic devices focusing on hand and fingers. This could pave the way for a new generation of simple rehabilitation robots to be used as standard therapy and assessment tools in rehabilitation centers or directly in patients' homes.

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