The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

ReachMAN: a personal robot to train *reach*ing and *man*ipulation

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***Abstract*— Robotic devices able to train both reaching and manipulation are often large and complex and thus not suitable for decentralized use at home or in local rehabilitation centers. This paper describes a compact device with only three degrees of freedom (DOF) to train reaching and manipulation critical to activities of daily living. The design considers only the DOF necessary to train tasks such as pick-and-place of objects, drinking, eating and knob manipulation, based on low-dimensional synergies used in these tasks. Specifications from measured biomechanical parameters yield safety and suitable performance. A prototype demonstrates some of the resulting functions and therapeutic possibilities offered by this design.**

I. INTRODUCTION

Stroke affects approximately 0.2% of the population in developed countries every year, resulting in paralysis or loss of muscle control, usually on one side of the body [1]. Some spontaneous recovery occurs in the weeks after the stroke, and physical therapy is provided to support and enhance the recovery process [2]. Physical therapy typically consists of labor-intensive exercises performed by or with a physiotherapist.

Unfortunately, physiotherapy is generally limited to a few hours per week due to the large number of patients and the heavy financial burden this represents on the health care system. Stroke patients are generally sent home once they are mobile, even if they have not recovered upper limb functions essential to activities of daily living (ADL). However, there is evidence that an increase in training will improve the motor outcome [3]. Other limitations of current rehabilitation strategies include the lack of repeatability and objective assessment [4], as well as limited speed, sensing and strength of the therapists neuromuscular system [5].

Dedicated robotic devices may address these problems. Robot-assisted therapy promises an increase in training beyond what is currently possible, as well as systematic, well-controlled and motivating exercises based on virtual reality [5], with continuous assessment. We envision systems that could be used at home or in decentralized rehabilitation centers, such that the patients could train whenever they desire, improve their score in their preferred therapeutic games, possibly compete against each other, and so improve their motor condition.

Robotic systems have been developed in recent years to train ADL. These systems generally involve a large number

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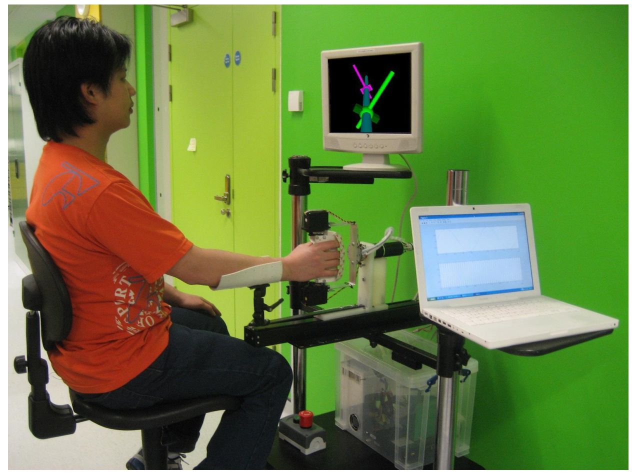

Fig. 1. Training with ReachMAN.

of degrees of freedom (DOF) to control movements in space. For example, ARMin II [6] has 6 DOF to enable positioning of the hand in 3D workspace and Gentle/S [7] has 9 DOF (6 active and 3 passive) to train both reaching and grasping in a reach-grasp-transfer-release sequence. As a consequence, these systems are often large and costly, and hardly conceived for decentralized use. In general, the more active DOFs used in a robot, the more expensive and less safe the system will be [8].

Is it possible to develop compact robotic devices with few DOF to train functional tasks involving reaching and manipulation? To perform arbitrary movements in 3D space, humans would need at least 6 DOF, more if hand and finger movements are considered. However, neuroscience studies have shown that humans generally use regular motion patterns involving fewer DOF or *synergies* [9] to simplify motion control.

Could we use these motion invariances to simplify the design of dedicated rehabilitation devices? For example, it is well known that, in reaching movements, the hand follows approximately a straight line path from the start to the target [10]. Therefore, ARM Guide [11] has only one active DOF, which considerably simplifies the design and makes the device safer and cheaper relative to systems with 6 DOF. However, ARM Guide can only train isolated reaching movements without wrist or hand movements critical to ADL.

In recent years, we have developed simple devices to train hand and finger function [12], [13]. These devices have been tested with chronic stroke patients, and clinical trials

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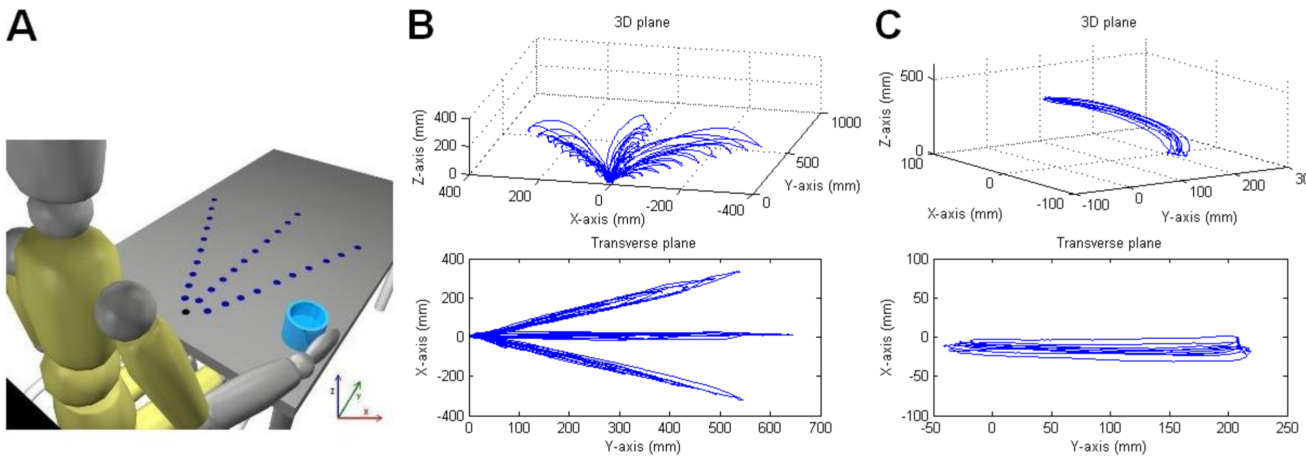

Fig. 2. Pick-and-place experiment with motion capture (A), paths adopted by a typical subject in this task (B) and in the drinking task (C).

using the Haptic Knob to train grasp and forearm rotation [14] showed a significant improvement in the Fugl-Meyer assessment scale accompanied by a decrease of spasticity.

Using a similar approach, we have developed Reach-MAN, a compact robotic device to train both *reach*ing and *man*ipulation (Fig. 1). Based on a study of these functions during object pick-and-place, eating and drinking, we could establish the minimal requirements to train these important ADL. This enabled us to come up with a simple design, based on an endpoint control approach and requiring only a few DOF. This paper describes the design, the resulting prototype and its performances, as well as the possibilities it offers to train reaching and manipulation in therapeutic virtual reality games.

II. Endpoint-based design motivated by natural motion synergies

The concept we propose to train reaching and manipulation is based on an endpoint approach. In contrast to exoskeleton-based approaches, joint movements are not constrained, which is important for training subacute patients. According to physiotherapists at the National Hospital Of Neurology and Neurosurgery (UK) , excessive and inadequate use of shoulder movement in these patients can lead to shoulder pain, which can jeopardize the recovery process.

In a recent study [15], we analyzed typical movements of five healthy subjects in three critical ADL: pick-and-place of objects, drinking and eating. The subjects were instructed to pick a glass at a starting location and place it on 30 predefined targets distributed along three different paths oriented at -30^o, 0^o and 30^o from the midsagittal plane. (Fig. 2, left panel). Glass trajectories and shoulder movements were recorded using a motion capture system (Vicon MX, UK) and analyzed in Matlab (MathWorks, US). Subjects were also asked to perform drinking and eating movements.

Analysis of the data (Fig. 2) showed that the path which the object is moved is predominantly confined to a vertical plane, and the deviation relative to this plane is only 5% of the traveled distance [15]. Based on these results, we assume that the object's path can be constrained to the sagittal plane.

As in these tasks the movement of the object is reduced to a few DOF due to natural synergies, we can design a mechanism controlling only these DOF. Specifically, we propose using a linear actuator constraining movement to the sagittal plane, which in fact supports the hand movement and prevents it from diverging from the straight path line. A module for pronosupination with an active grasping handle is fixed to the linear axis.

Moving both the linear and rotary mechanisms can create many desired trajectory or force field required to train functionally critical ADL tasks such as pick-and-place, drinking and eating. With this device, grasping, which is the prerequisite of manipulation, can be trained alone or in combination with arm and hand movement.

Placing the module with the rotary actuator normal to the linear axis enables 2 DOF motion in the sagittal plane, as is needed to train drinking (Fig. 3, left) or eating. By changing the orientation of the rotary actuator parallel to the linear axis (Fig. 3, right), one obtains a haptic knob. Knob manipulation (e.g. to manipulate knob to regulate the temperature of an oven or to select volume/frequency of a radio) is one the tasks chronic patients would like to recover most [12].

The combination of a linear axis, a rotation and grasp (3DOF) enables training of many common functions involved in manipulation. In particular, it enables training of complete functions (e.g. taking a key, placing it in a lock and opening the door) which are thought to be required for good recovery of ADL [16].

III. Specifications from human factors

Biomechanical factors were determined in order to select cost efficient components ensuring maximal safety and performance.

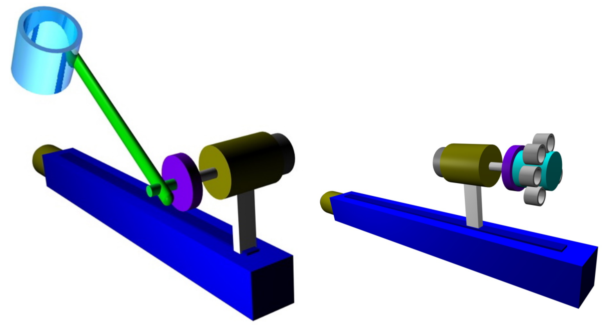

Fig. 3. ReachMAN robot design with different modules mounted on the linear axis to train drinking (left) and knob manipulation (right).

A. Reaching

The maximum distance the hand can reach depends on the arm length and is generally about 65 *cm* from shoulder to hand tip. The further the hand moves away from body, the more shoulder movement is involved. However, stroke survivors, in particular in the subacute phase, should avoid large shoulder movements, therefore we select the workspace for the arm extension without large shoulder movement and normally used in activities of daily living.

When eating, the arm extension is only about 20*cm* measured from chest to the working point. It is between 30 and 40*cm* for tasks such as opening of doors and drawers. Thus, we limited the travel of the movement to 40*cm* distance.

The maximum average push force for healthy subjects is 231*N* and the maximal average pull force 222*N* [17]. However, these values are too large for subacute patients and could jeopardize recovery. For safety reasons, the force range generated by the robot should correspond to the force range in usual tasks. For example, we have measured using a portable hanging scale that 20*N* is required to open a typical empty drawer and 40*N* for a heavier drawer. 35*N* is required to open a door and only 2.5*N* to pull a 700*g* bowl from one position to another position on a table. Considering this, we selected a maximal force of 100*N*.

TABLE I

MAXIMAL FOREARM SUPINATION AND PRONATION IN FUNCTION OF THE ELBOW FLEXION/EXTENSION ANGLE OF THE RIGHT FOREARM (ADOPTED FROM [18]).

	full extension	45^o flexion	90^o flexion	full flexion
supination	47.4^o	88.5^o	103.7^o	115.3^o
pronation	111.9^o	98.2^o	81.8^o	55.4^o

B. Forearm pronation/supination

The forearm rotation is important for manipulation and many ADL, e.g., eating, placement of the hand relative to a target object [18] and knob manipulation [12]. The range of forearm rotation at different elbow flexion angles were estimated in [18], which provided the values of Table I. The range of supination is greatest when elbow is fully flexed and pronation at its greatest when elbow is fully extended. We chose maximum values among all the possibilities so that the robot can provide adequate training independent of the angle of the elbow joint. The requirements for the robot are thus a range of 115.3^o for supination and 111.9^o for pronation.

The maximum torque is 13.73*Nm* for supination and 17.39*Nm* for pronation [17]. A smaller torque is required for rehabilitation of ADL. Tasks such as opening a bottle only require 0.7*Nm* [12] and turning a key 0.68*Nm* [17]. However, these values are too low when the robot is to guide or resist the patient's hand during rehabilitation. Lambercy et. al. developed a Haptic Knob that can generate up to 1.5*Nm* [12] which is adequate for rehabilitation purpose. Thus, we chose this torque value as requirement for the robot.

C. Grasping

The maximum average hand opening is about 0.18*m* [12], and we would like the patient to be able to close the hand as fully as possible. Therefore we determined the range of movement for the grasping as [0.05,0.18]*m*.

The maximal grasping force healthy subjects are able to produce amounts to more than 500*N* [17]. However, typical activities of daily living only require a force between 1-10*N*. 7.0*N* is required to manipulate a key and 10*N* is sufficient to assist hand grasping. Thus, we required the robot to be able to produce a grasping force up to about 10*N*.

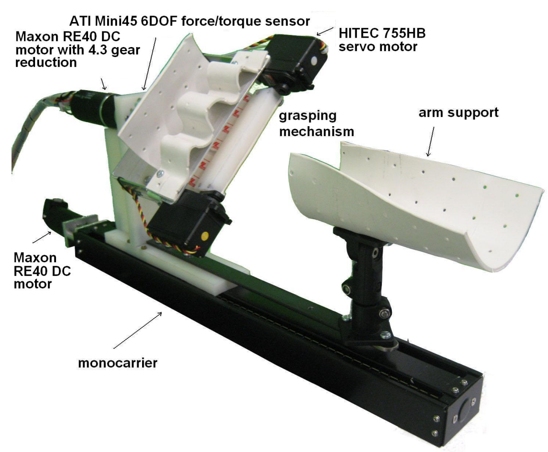

Fig. 4. 3 DOF ReachMan for reaching and manipulation training.

IV. IMPLEMENTATION

A. Hardware

The implementation of the ReachMAN concept shown in Fig. 4 has 3 DOF which are for linear reaching movement, supination/pronation and grasping. A monocarrier (NSK MCM05040H10K, Japan) actuated by a DC motor (Maxon RE40, Switzerland) is used to generate the linear movement. A rotary geared DC motor (Maxon RE40 with gear reduction of 4.3) is used for supination/pronation, which is attached to the output carriage of the monocarrier. This monocarrier is fixed to a stable platform and acts as the robot's base.

This platfrom is height adjustable to suit users with different height, standing or seating.

A grasping mechanism device attached to the rotary DC motor incorporates two servo motors (Hitec 755hb, South Korea) which are used for hand opening/closing exercises. These motors are modified to allow PWM voltage control and position readout. The two servo motors face each other and actuate the same fixture. The four fingers are placed on this moving fixture while the thumb is placed on a static fixture. Thus, the mechanism is capable of training opening and closing of the four fingers simultaneously.

Two digital encoder (Avago HEDL55 500cpr, US) are used to measure the linear position and rotary angle. Another digital encoder (Gurley R119 65536cpr, US) is used to measure the opening angle of the grasping mechanism. The current supplied to the servo motors is used to measure force generated against the fingers during hand opening and closing. A 6 DOF force/torque sensor (ATI Mini45, US) is attached between the grasping mechanism and the rotary actuator to measure interaction forces and torques during arm movements. An arm support attached to the moving monocarrier is added for the patient to rest the forearm. Two proximity magnetic flux sensors (NSK MC-SR05-00, Japan) are placed on each end of the linear guide for limit sensing. Another similar sensor is placed in between these two sensors to serve as initial starting position.

B. Control

The control is implemented on a LabView real-time target (RT Target) running at 1*kHz*. The RT Target reads forces, encoders and sensors from ReachMAN via a PCI-6259 (National Instrument,US) data acquisition card and sends motor commands. The host computer displays visual feedback at a rate of 30*Hz* and communicates with the RT Target via TCP/IP. Data is stored on the target at 1*kHz* and can be retrieved later for post-processing.

Admittance control is used for the linear axis where force is measured and the position of the end effector is computed by integrating

$$\ddot{x} = \frac{F - D\dot{x} - Kx}{m} \,. \tag{1}$$

Impedance control is used in the rotation and grasping where the angular displacement is measured and then the reaction torque is fed back to the user. Resistive or assistive torque is realized using

$$\tau = \dot{x}D \tag{2}$$

with positive or negative damping *D*, respectively.

C. Safety

The most important criterion for robots to physically interact with humans is safety. To ensure safe use of ReachMAN, we have implemented redundant safety through the following features:

- Mechanical limits at each joint to prevent excessive movement during reaching, supination/pronation or hand opening/closing;
- Sensors at both ends of the linear guide to ensure that the movement is within the stipulated range;
- Motor controllers are set to prevent exiting a safe range of output force and torque;
- Emergency buttons reachable by both the patient and the physiotherapist to stop the whole operation at any time;
- Software monitors to limit the force, torque and velocity and prevent unwarranted output that could harm users.

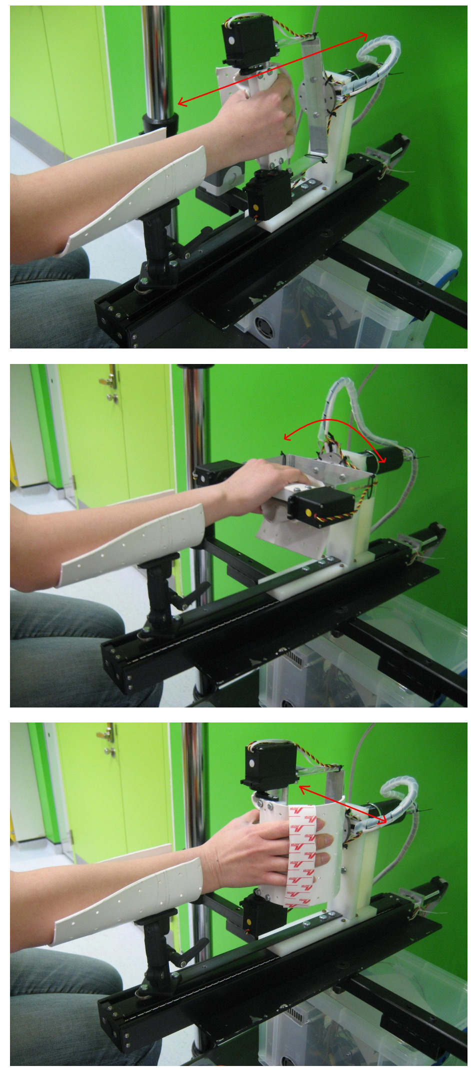

Fig. 5. Typical movements with ReachMAN. From top to bottom: reaching movement, forearm rotation and hand opening/closing.

V. Performances

The active workspace for exercises are [0-0.4]*m* for reaching, [-180^o,180^o] for pronosupination of forearm and [0.05-0.18]*m* for hand opening. The bandwidth of the system are 3.45*Hz* for reaching movement, 1.84*Hz* for pronosupination of forearm and 2.63*Hz* for hand opening and closing. These bandwidth are adequate as the exercises would be running less than 1*Hz*. The robot dimension without the platform is 0.70x0.30x0.35m^3 and can extend to the maximum of

1.0x0.30x0.35m^3. The weight of the robot is 8.20kg. Table II shows the characteristics of this system.

TABLE II
REACHMAN PROTOTYPE CHARACTERISTICS.

	push/pull	pronation/supination	grasping
active workspace	[0,0.4]m	[-180^o,180^o]	[0.05-0.18]m
max generated force	100N	1.5Nm	10.8N
force measuring range	±580N	±20Nm	±10.8N
static friction	15N	0.03Nm	2.0N
bandwidth	3.45Hz	1.84Hz	2.63Hz

dimension without platform (LxWxH)	1.0x0.30x0.35m
weight without platform	8.2kg

The complete setup is shown in Fig. 1. The user can either stand or sit while the arm rests on the arm support. The hand is placed on the grasping mechanism or strapped securely with Velcro if necessary, while the user looks at a monitor. The physiotherapist can observe the whole process from the host computer. Fig. 5 shows training of reaching, pronation/supination, grasping.

Motion control modes implemented include passive control as well as resistive/assistive control. One can, for example, implement "free" mode in which minimal interaction force is felt during motion. This mode is used for assessment, to identify the user's range of motion before and after rehabilitation sessions with the robot. In passive mode the robot guides the patient's hand, who should relax. This is used to reduce contraction of the arm muscles or to warm up before undergoing the actual exercises. Resistive and assistive forces are used during exercises. An assistive force will help a patient with a weak arm to complete the exercises and so motivate her or him, while resistive forces can be used to strengthen muscles.

Fig. 6 shows a healthy subject performing reaching movement from an initial position to 172mm away from the body, with three different control conditions of increasing loads. With the largest load, the subject had to use up to a maximum of 35N and found it hard to move the robot in this condition. Meanwhile, only 15N were required to move with the middle load (what we use as "baseline load"), and the interaction force was lower than 5N to move the robot with the smallest load and limited to the very first part of the movement.

ReachMAN can also be used to train complete tasks involving reaching, forearm rotation and grasp together in order to simulate functional tasks. For example, the user could perform grasping an object and then using simultaneous reaching and forearm rotation, such as when pouring a liquid into a glass (Fig. 7). Placing a key in a lock is another example of a scenario that can be trained with this interface.

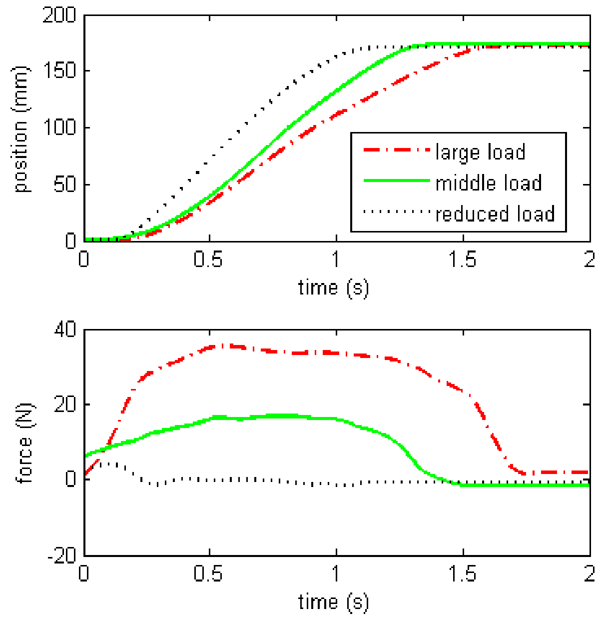

Fig. 6. Subject performing reaching under different loads. Note the possibility to reduce the interaction force to a minimum. Conversely, adding damping can help increase muscles strength.

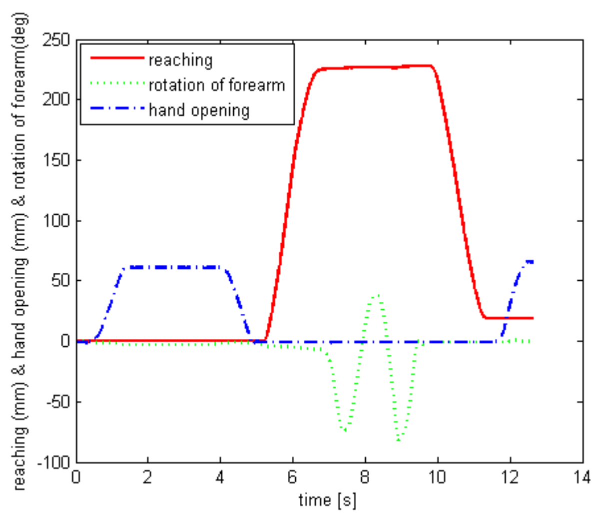

Fig. 7. Combined motion involving grasp, reaching and forearm rotation. The underlying task consisted in taking a bottle, bringing it above a glass, filling the glass and putting the bottle back to the initial position.

VI. DISCUSSION

Training with robotic devices using fewer DOF may constrain some of the movements, which may affect learning or rehabilitation processes. In the case of ReachMAN, the lateral motion constraint makes that the patient does not require to stabilize the hand during movement, and may lead to excessive relaxation [19]. Further, motion error provided by proprioception may be necessary for efficient learning [20].

We have performed a psychophysical study to examine this question and determine whether providing kinematic error is sufficient to promote a reliable feedforward internal model of a real task. In [21], we report the first results of an experiment in which subjects performed reaching movements with lateral constraint, while visual feedback of a virtual force field acting on these movements was provided on a display.

The results showed that learning the virtual force field enabled the subjects to compensate for the real force field when the lateral constraint was removed after learning was completed (in the virtual condition). This suggests that we could use signals from the 6 DOF force sensor incorporated in ReachMAN to provide visual feedback of virtual motion error in the missing DOFs. In this approach, the users would experiment virtual deviations from the ideal movement trajectory based on the interaction forces measured by the load cell.

VII. Conclusions

Using natural synergies observed in typical movements involved in main activities of daily living (ADL) such as reaching, manipulation, performing pick-and-place movements with objects, drinking and eating, may lead to simplified robotic devices for neurorehabilitation.

With this in mind, we first studied the motion characteristics during these ADL. The results enabled us to develop an interface to train reaching and object manipulation involved in these tasks with only 3 DOF. Consideration of biomechanical requirements lead to a human-centered design yielding safety and good performances adapted to the training of many tasks.

We believe that this device is suitable for basic training of stroke patients in the subacute phase, which could complement physiotherapy, and where largest possible recovery and impact are expected. This hypothesis will be evaluated in an upcoming clinical study on stroke patients in the acute phase at the National Hospital Neurology and Neurosurgery.

VIII. Acknowledgments

We thank Diane Playford and Karen Baker from the National Hospital Neurology and Neurosurgery (NHNN),UK for discussions about the physiological and rehabilitation aspects, and Olivier Lambercy for his comments on the manuscript.

C.F. Yeong's studies are sponsored by Universiti Teknologi Malaysia and A Melendez-Calderon's studies by CONACYT-Mexico.

References

[1] "What is a stroke," www.stroke.org.uk.

[2] "Understanding stroke," www.bbc.co.uk/health/conditions/stroke.

[3] G. Kwakkel, R. van Peppen, R. C. Wagenaar, S. Wood Dauphinee, C. Richards, A. Ashburn, K. Miller, N. Lincoln, C. Partridge and I. Wellwood," Effects of Augmented Exercise Therapy Time After Stroke A Meta-Analysis," Stroke, vol. 35, pp. 2529-2539, 2004.

[4] A. Frisoli, L. Borelli, A. Montagner, S. Marcheschi, C. Procopio, F. Salsedo, M. Bergamasco, M. C. Carboncini, M. Tolaini and B. Rossi," Arm rehabilitation with a robotic exoskeleton in virtual reality," Proc. 10th Int. Conf. on Rehabilitation Robotics, Noordwijk, The Netherlands, 2007, pp. 631-642.

[5] L.E. Kahn, P.S. Lum, W.Z. Rymer, and D.J. Reinkensmeyer," Robot-assisted movement training for the stroke-impaired arm: Does it matter what the robot does?," Journal of Rehabilitation Research and Development, vol. 43, pp. 619-630, 2006.

[6] T. Nef, M. Mihelj, G. Kiefer, C. Perndl, R. Muller and R. Riener," ARMin Exoskeleteon for arm therapy in stroke patients, Proc. 10th Int. Conf. on Rehabilitation Robotics," Noordwijk, The Netherlands, 2007, pp. 68-74.

[7] R.C.V. Loureiro and W.S. Harwin," Reach and grasp therapy: Design and control of a 9-DOF robotic neuro-rehabilitation system," Proc. 10th Int. Conf. on Rehabilitation Robotics, Noordwijk, The Netherlands, 2007, pp. 757-763.

[8] N. Hogan, H.I. Krebs, B. Rohrer, J.J. Palazzolo, L. Dipietro, S.E. Fasoli, J. Stein, R. Hughes, W.R. Frontera and D. Lynch," Motions or muscles? Some behavioral factors underlying robotic assistance of motor recovery," Journal of Rehabilitation Research and Development, vol. 43, pp. 605-618, 2006.

[9] N. Bernstein The co-ordination and regulation of movements, Pergamon, London, 1967.

[10] P. Morasso," Spatial Control of Arm Movements," Experimental Brain Research, vol. 42, pp. 223-227, 1981.

[11] L.E. Kahn, W.Z. Rymer, and D. J. Reinkensmeyer," Adaptive assistance for guided force training in chronic stroke," Proceedings of the 26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society., San Francisco, CA, USA, 2004, pp. 2722-2725.

[12] O. Lambercy, L. Dovat, R. Gassert, E. Burdet, C. L. Teo, and T. Milner," A Haptic Knob for Rehabilitation of Hand Function," IEEE Transactions on Neural System and Rehabilitation Engineering, vol. 15 no. 3, pp. 356-366, 2007.

[13] L. Dovat, O. Lambercy, R. Gassert, T. Maeder, T. Milnder, T.C. Leong and E. Burdet," HandCARE: A Cable-Actuated Rehabilitation System to Train Hand Function After Stroke," IEEE Transactions on Neural System and Rehabilitation Engineering, vol. 16, no 6, pp. 582-591, 2008.

[14] O. Lambercy, L. Dovat, H. Yun, S. K. Wee, C. Kuah, K. Chua, R. Gassert, T. Milner, T.C. Leong and E. Burdet," Rehabilitation of Grasping and Forearm Pronation/Supination with the Haptic Knob," IEEE International Conference on Rehabilitation Robotics (ICORR), Kyoto, Japan, 2009, pp. 22-27.

[15] C.F. Yeong, A. Melendez-Calderon and E. Burdet," Analysis of Pick-and-place, Eating and Drinking Movements for the Workspace Definition of Simple Robotic Devices," IEEE International Conference on Rehabilitation Robotics (ICORR), Kyoto, Japan, 2009, pp. 46-52.

[16] C.J. Winstein, A.M. Wing, and J. Whitall," Motor control and learning principles for rehabilitation of upper limb movements after brain injury," in Handbook of Neuropsychology, pp. 77-137, 2003.

[17] "Man-systems integration standards," http://msis.jsc.nasa.gov.

[18] H. Shaaban, C. Pereira, R. Williams and V.C. Lees," The Effect of Elbow Position of the Range of Supination and Pronation of the Forearm," Journal of Hand Surgery, European Volume, pp. 3-8, 2008.

[19] D.W. Franklin, E. Burdet, K.P. Tee, R. Osu, T.E. Milner, C.M. Chee and M. Kawato," CNS learns stable, accurate, and efficient movements using a simple algorithm," Journal of Neuroscience 28, vol. 44, pp. 11165-11173, 2008.

[20] R.A. Scheidt, D.J. Reinkensmeyer, M.A. Conditt, W.Z. Rymer and F.A. Mussa-Ivaldi," Perrsistence of motor adaptation during constrained, multi-joint, arm movements," Journal of Neurophysiology, vol. 84, pp 853-862, 2000.

[21] A. Melendez, L.Masia, M. Casadio and E. Burdet," Force field compensation can be learned without proprioceptive error," World Congress on Medical Physics and Biomedical Engineering 2009.