Title
A Robotic Device for Hand Motor Therapy After Stroke

ISBN
9780780390034

Authors
Takahashi, CD
Der-Yeghiaian, L
Le, VH
et al.

Publication Date
2005

DOI
10.1109/icorr.2005.1501041

Proceedings of the 2005 IEEE
9th International Conference on Rehabilitation Robotics
June 28 - July 1, 2005, Chicago, IL, USA

A Robotic Device for Hand Motor Therapy After Stroke

C.D. Takahashi, L. Der-Yeghiaian, V.H. Le, S.C. Cramer

Abstract— **This paper describes the design of a robotic device – the Hand-Wrist Assisting Robotic Device, or HWARD ("Howard") – that can assist functional grasping and releasing movements of the stroke-impaired hand. The 3 degrees-of-freedom device is pneumatically-actuated and backdriveable. The design of HWARD was guided by neurobiological principles of motor learning, such as sensorimotor integration, movement repetition, environmental complexity, and attention. Specifically, HWARD can assist repetitive grasping and releasing movements while allowing the subject to feel real objects during therapy. The use of real objects having rich sensory and functional characteristics can stimulate sensorimotor cortex activation while enhancing subject motivation and attention – features hypothesized to reduce impairment and disability. A pilot study will test the safety and efficacy of HWARD, with endpoints that include established motor function scales as well as brain mapping with functional MRI (fMRI).**

I. Introduction

STROKE is a pervasive and debilitating disease that afflicts approximately 5 million people and is the leading cause of adult disability in the United States [1]. Many survivors cannot lead productive independent lives due to an inability to use their hands and arms for activities of daily living (ADL's) such as feeding and grooming.

Research has shown that intense active repetitive movement practice can enhance the strength and functional use of the affected arm and hand [2-8]. Treatment approaches for the fingers, hand, or wrist include conventional physical and occupational therapy, use of supports and splinting (reviewed in [9]), electrical stimulation [10-13], and robotics [14].

Robot-assisted therapy has been shown to improve arm motor function after stroke [15-21]. Robots – with their unique ability to accurately quantify limb movement and apply consistent un-fatiguing movement assistance – hold great promise for enhancing traditional post-stroke therapy. Robots have the potential to relieve the labor intensiveness of the therapy or enhance the recovery process through the use of novel force assistance patterns [22].

At present, however, the mechanisms of recovery with retraining are not well understood, and it is still unclear what specific aspects of therapy are the most essential in promoting recovery of motor function after stroke. Cortical reorganization, or plasticity, is known to play a major role in the restoration of motor function after stroke [6, 8, 23, 24]. Similar processes are involved in motor skill acquisition in healthy subjects [25, 26]. These similarities suggest that successful approaches to post-stroke therapy may involve factors that enhance motor learning.

Two neurobiological principles that enhance motor learning are environmental complexity and attention. Environmental complexity – or enriched environments - has been found to alter brain function and structure in normal [27, 28] and neurologically impaired [29, 30] animals. Similarly, the quality of post-stroke experience influences the functional outcome in humans [31, 32]. Indeed, the approach of modern occupational therapy is to exercise the patient in a functional, sensory rich context to improve coordinated movements. The use of real objects in a natural context (e.g., grasping the receiver of a working phone) or the performance of purposeful exercises may enhance the motor performance of individuals with hemiparesis [33-35]. A few studies have used robotics or other motion tracking technology along with a virtual reality interface to further explore the utility of sensory rich functional environments to create motivating therapeutic exercises [36-38].

These neurobiological principles have been applied in prior robotic studies of patients with stroke [16, 19]. However, these studies have focused primarily on shoulder and proximal arm movements, rather than on hand and distal arm movements. The goal of the current study is to develop a robotic device that retrains hand grasping and releasing movements (which are essential to performing activities of daily living), coupled with wrist movements, while simultaneously using natural objects during therapy.

II. Design of Robotic Device

We therefore developed HWARD – the Hand Wrist Assisting Robotic Device (or "Howard"), whose general design was guided by neurobiological principles of motor learning. Specifically, HWARD can assist grasping and releasing movements while simultaneously allowing the

Manuscript received February 14, 2005. This work was supported in part by the National Institutes of Health (NIH) Institutional Training Grant T32 AR047752.

C.D. Takahashi is a post-doctoral fellow in the Department of Physiology and Biophysics, College of Medicine, University of California, Irvine; Irvine, CA 92697-1385 USA. (phone: 949-824-6032; fax: 949-824-3360; e-mail: ctakahas@uci.edu).

L. Der-Yeghiaian is an occupational therapist II at the University of California, Irvine Medical Center, Orange, CA 92868-4280 USA (e-mail: lderyech@uci.edu).

V.H. Le is a software engineer in the U.C. Irvine General Clinical Research Center; Irvine, CA 92697-1385 (e-mail: vhle@uci.edu).

S.C. Cramer is a neurologist in the Departments of Neurology and Anatomy & Neurobiology, College of Medicine, University of California, Irvine; Irvine, CA 92697-1385 USA (e-mail: scramer@uci.edu).

subject to feel real objects during therapy. This feature is achieved by keeping the palmar surface of the hand unobstructed so that objects may be placed into the hand. Also, the open surface area of the palm and fingers is maximized so that the subject retains tactile sensation of the grasped object (Fig. 1).

HWARD provides assistance in a pattern that combines wrist extension with hand grasping (known as a "power grip"), and wrist flexion with hand release. This combination of joint movement serves to increase grasping force. In addition, wrist extension practice activates the motor system from the level of the primary cortex and corticospinal tract. Wrist extension, unlike simple grasping, is a cortically-based motor behavior.

During therapy, subjects will grasp and release a variety of real objects (with varying size, shape, surface texture, temperature, and functional valence) based on visual and auditory cues, and they will attend their movements based on purposeful instructions (e.g., squeeze the toothpaste out of the tube). During this period, HWARD will assist both grasping and releasing movements. We believe that rich sensory and functional settings will enhance the effects of robotic therapy by increasing subject attention and motivation.

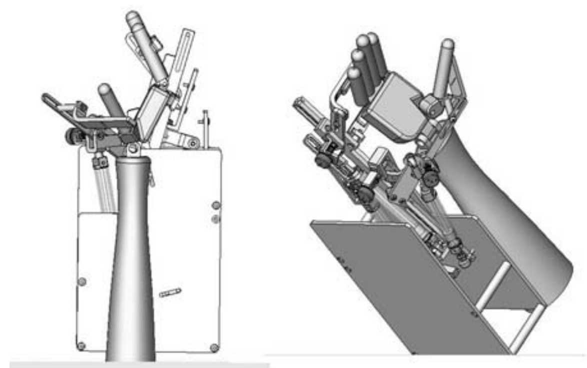

Fig. 1. HWARD is a 3-DOF pneumatically-actuated robotic device that assists the stroke-impaired hand in grasping and releasing movements.

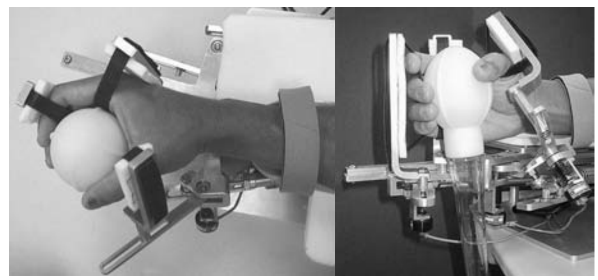

Fig. 2. HWARD allows the subject to grasp, feel, and release real objects of varying sizes and shapes.

A. Mechanical design and kinematics

HWARD is a 3-degrees-of-freedom (3-DOF) mechanism that allows the rotational movement of the fingers, thumb, and wrist. HWARD allows the movement of the 4 fingers as a single unit about the metacarpophalangeal (MCP) joint with a range of movement (ROM) of approximately 25 to 90 degrees flexion. HWARD allows thumb movement out of the plane of the palm and fingers with an approximate ROM of 90% full extension to 75% of full flexion. Finally, HWARD allows wrist flexion-extension movement with a ROM of approximately 20 degrees extension to 15 degrees flexion. Robot joint movement is achieved using a lever design. Each air cylinder and limb interface is mounted on opposite ends of a lever, with a revolute joint in between.

The right hand is positioned in the device so that both the MCP joint and the wrist center of rotation are aligned with the robot's finger and wrist joint axes, respectively. The device contacts the subject along the dorsal side of the fingers, hand, and thumb. This design feature leaves the region of the open hand unobstructed, permitting the placement of real objects into the hand (Fig. 2). The subject is secured to the device through the use of narrow padded Velcro straps. The strap width is minimized so that the palmar surfaces of the hand are accessible for tactile sensation of the object. With the hand secured in the robot mechanism, the subject's forearm rests inside of a padded splint that is mounted to the surface of a platform. The splint is designed to stabilize and anchor the forearm.

HWARD can be adjusted to accommodate a variety of hand sizes. First of all, the distance between the finger and wrist joint axes can be adjusted between 7.6 and 12.7 cm, so the robot can accommodate hand sizes with that range of distance between the wrist center of rotation and the MCP. The finger interface has a range of adjustment between 2.5 and 7.6 cm away from the robot finger joint. The thumb interface has a range of adjustment between 4.6 and 10.6 cm from the robot thumb joint.

B. Backdriveability

The device was specifically designed to be backdriveable so that subjects can move the mechanism while it is in a passive state. Backdriveable robots will not encumber the subject's natural movement even while applying assistive forces. In addition, they can be used as tools for assessing kinematic measures of movement performance such as active range of motion.

Backdriveability is achieved by minimizing friction in the mechanism. Each of the revolute joints is assembled using paired radial ball bearings. The air cylinder friction (1 to 2% of load with no side loading) is low due to the use of graphite pistons riding through glass-lined cylinders (Airpel). Finally, sensors are low friction conductive plastic rotary potentiometers (Midori America Corp.) which use ball bearings. Backdriveability is also enhanced by designing the levers of each joint so that mechanical advantage is given to the subject's limb rather than to the air cylinder.

C. Robot actuation and control

HWARD is pneumatically actuated by 3 double-acting air cylinders with bore diameters of 1.59 cm. Each cylinder can produce up to 122.8N (at source pressure of 689kPa) of force, but air pressure is regulated so that the air cylinders produce roughly 4-15N, the estimated levels necessary to assist movements. Pneumatics is strong, clean, and has the potential – with some modifications to the existing design – to be used in the MRI environment.

Pressurized air is routed to the air cylinders through 3-port pneumatic solenoid valves, one positioned on each side of each air cylinder. In the de-energized position, the valves vent the air cylinder to ambient pressure, putting the device into passive mode. This attribute serves as a safety feature for the device. Inline flow control valves allow for manual adjustment of the rate of application of force. Precision regulators control source air pressure levels entering the pneumatic system, so they serve as a reliable safety measure for limiting the maximum force that the robot can apply to the subject's limb.

Rotary potentiometers measure the finger, wrist, and thumb joint angles. Microstructure pressure sensors (Honeywell) are mounted on both sides of each air cylinder to measure the pressure levels. The applied forces by the robot can be computed from data from these sensors.

The device is interfaced to the computer through a PCI bus data acquisition board (National Instruments) having digital input and output, analog input, and analog output functions.

HWARD has multiple safety mechanisms. Adjustable hard stops prevent overextension of the subject's joints. Air pressure is regulated to maintain safe force levels. An emergency stop button can render HWARD passive by de-energizing the solenoid valves. The control software also provides a safety shutdown feature.

D. *Software interface*

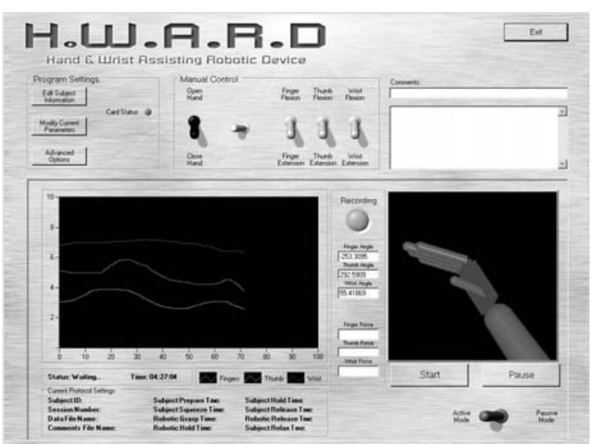

Fig. 3. Software interface and control panel for HWARD gives the experimenter control of the robot. The interface also provides a simple way of running standardized protocols and emergency shutdowns.

HWARD is controlled through a customized software interface (Fig. 3) that was written in Visual Basic using the Measurement Studio development environment (National Instruments), running on a Windows XP computer. The program allows the experimenter to control the robotic functions, execute standardized training protocols, perform emergency safety shutdowns, and collect data (joint angles and air cylinder pressures). The program also controls an LCD monitor (placed near the hand) that visually instructs the subject through a sequence of motor tasks (e.g., grasp object, hold object, release object, relax, etc.).

III. Proposed Pilot Study

We plan to conduct a pilot study to test the safety and effectiveness of HWARD. Subjects with chronic stroke will undergo two pre-tests that measure hand motor function ability (using established motor function tests) as well as fMRI. Subjects will then receive assistive robotic therapy, during which they will practice grasping, feeling, and releasing a variety of real objects of varying sensory characteristics (size, shape, texture, valence, etc.). During therapy, subjects will view both their hand and the grasped object. A key aspect of the study will be to enhance subject attention by giving instructions that add purpose to the task (e.g., squeeze the toothpaste from the tube). Following therapy, subjects will undergo a post-treatment assessment of hand motor function ability as well as a repeat fMRI. They will also return for a follow-up assessment about 1 month after completing treatment in order to assess retention of therapy-related motor gains.

IV. Conclusion

This paper has described the rationale and design for a pneumatically-actuated robot, called HWARD, for providing assistive hand motor therapy after stroke. HWARD uses low friction air cylinder actuators to provide mechanical assistance during the grasping and releasing of real objects. The rationale for this design is to incorporate functional and purposeful tasks during assistive therapy that may enhance recovery through established theories of motor learning. Future work will be to complete fabrication of the device and begin a pilot study to assess its safety and effectiveness.

References

[1] G. Gresham, P. Duncan, W. Stason, H. Adams, A. Adelman, D. Alexander, D. Bishop, L. Diller, N. Donaldson, C. Granger, A. Holland, M. Kelly-Hayes, F. McDowell, L. Myers, M. Phipps, E. Roth, H. Siebens, G. Tarvin, and C. Trombly, *Post-Stroke Rehabilitation.* Rockville, MD: U.S. Department of Health and Human Services. Public Health Service, Agency for Health Care Policy and Research, 1995.

[2] C. Butefisch, H. Hummelsheim, P. Denzler, and K. H. Mauritz, "Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand," *J Neurol Sci*, vol. 130, pp. 59-68., 1995.

[3] J. R. Carey, T. J. Kimberley, S. M. Lewis, E. J. Auerbach, L. Dorsey, P. Rundquist, and K. Ugurbil, "Analysis of fMRI and finger tracking training in subjects with chronic stroke," *Brain*, vol. 125, pp. 773-88., 2002.

[4] E. Taub, N. E. Miller, T. A. Novack, E. W. Cook, 3rd, W. C. Fleming, C. S. Nepomuceno, J. S. Connell, and J. E. Crago, "Technique to improve chronic motor deficit after stroke," *Arch Phys Med Rehabil*, vol. 74, pp. 347-54., 1993.

[5] B. Kopp, A. Kunkel, W. Muhlnickel, K. Villringer, E. Taub, and H. Flor, "Plasticity in the motor system related to therapy-induced improvement of movement after stroke," *Neuroreport*, vol. 10, pp. 807-10., 1999.

[6] C. E. Levy, D. S. Nichols, P. M. Schmalbrock, P. Keller, and D. W. Chakeres, "Functional MRI evidence of cortical reorganization in upper-limb stroke hemiplegia treated with constraint-induced movement therapy," *Am J Phys Med Rehabil*, vol. 80, pp. 4-12., 2001.

[7] J. Liepert, I. Uhde, S. Graf, O. Leidner, and C. Weiller, "Motor cortex plasticity during forced-use therapy in stroke patients: a preliminary study," *J Neurol*, vol. 248, pp. 315-21., 2001.

[8] H. Johansen-Berg, H. Dawes, C. Guy, S. M. Smith, D. T. Wade, and P. M. Matthews, "Correlation between motor improvements and altered fMRI activity after rehabilitative therapy," *Brain*, vol. 125, pp. 2731-42., 2002.

[9] Y. Aoyagi and A. Tsubahara, "Therapeutic orthosis and electrical stimulation for upper extremity hemiplegia after stroke: a review of effectiveness based on evidence," *Top Stroke Rehabil*, vol. 11, pp. 9-15, 2004.

[10] J. Chae, F. Bethoux, T. Bohine, L. Dobos, T. Davis, and A. Friedl, "Neuromuscular stimulation for upper extremity motor and functional recovery in acute hemiplegia," *Stroke*, vol. 29, pp. 975-9., 1998.

[11] M. B. Popovic, D. B. Popovic, T. Sinkjaer, A. Stefanovic, and L. Schwirtlich, "Clinical evaluation of Functional Electrical Therapy in acute hemiplegic subjects," *J Rehabil Res Dev*, vol. 40, pp. 443-53, 2003.

[12] J. Cauraugh, K. Light, S. Kim, M. Thigpen, and A. Behrman, "Chronic motor dysfunction after stroke: recovering wrist and finger extension by electromyography-triggered neuromuscular stimulation," *Stroke*, vol. 31, pp. 1360-4., 2000.

[13] H. P. Weingarden, G. Zeilig, R. Heruti, Y. Shemesh, A. Ohry, A. Dar, D. Katz, R. Nathan, and A. Smith, "Hybrid functional electrical stimulation orthosis system for the upper limb: effects on spasticity in chronic stable hemiplegia," *Am J Phys Med Rehabil*, vol. 77, pp. 276-81, 1998.

[14] S. Hesse, G. Schulte-Tigges, M. Konrad, A. Bardeleben, and C. Werner, "Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects," *Arch Phys Med Rehabil*, vol. 84, pp. 915-20., 2003.

[15] M. L. Aisen, H. I. Krebs, N. Hogan, F. McDowell, and B. T. Volpe, "The effect of robot-assisted therapy and rehabilitative training on motor recovery following stroke," *Arch Neurol*, vol. 54, pp. 443-6., 1997.

[16] S. E. Fasoli, H. I. Krebs, J. Stein, W. R. Frontera, N. Hogan, S. H. Jang, Y. H. Kim, S. H. Cho, J. H. Lee, J. W. Park, and Y. H. Kwon, "Effects of robotic therapy on motor impairment and recovery in chronic stroke," *Arch Phys Med Rehabil*, vol. 84, pp. 477-82., 2003.

[17] M. Ferraro, J. J. Palazzolo, J. Krol, H. I. Krebs, N. Hogan, and B. T. Volpe, "Robot-aided sensorimotor arm training improves outcome in patients with chronic stroke," *Neurology*, vol. 61, pp. 1604-7., 2003.

[18] L. E. Kahn, M. L. Zygman, W. Z. Rymer, and D. J. Reinkensmeyer, "Effect of robot-assisted and unassisted exercise on functional reaching in chronic hemiparesis," presented at Proceedings of the 23rd Annual EMBS International Converence, Istanbul, Turkey, 2001.

[19] H. I. Krebs, B. T. Volpe, M. Ferraro, S. Fasoli, J. Palazzolo, B. Rohrer, L. Edelstein, and N. Hogan, "Robot-aided neurorehabilitation: from evidence-based to science-based rehabilitation," *Top Stroke Rehabil*, vol. 8, pp. 54-70., 2002.

[20] P. S. Lum, C. G. Burgar, P. C. Shor, M. Majmundar, and M. Van der Loos, "Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke," *Arch Phys Med Rehabil*, vol. 83, pp. 952-9., 2002.

[21] B. T. Volpe, H. I. Krebs, N. Hogan, L. Edelsteinn, C. M. Diels, and M. L. Aisen, "Robot training enhanced motor outcome in patients with stroke maintained over 3 years," *Neurology*, vol. 53, pp. 1874-6., 1999.

[22] J. L. Patton and F. A. Mussa-Ivaldi, "Robot-assisted adaptive training: custom force fields for teaching movement patterns," *IEEE Trans Biomed Eng*, vol. 51, pp. 636-46., 2004.

[23] J. Liepert, H. Bauder, H. R. Wolfgang, W. H. Miltner, E. Taub, and C. Weiller, "Treatment-induced cortical reorganization after stroke in humans," *Stroke*, vol. 31, pp. 1210-6., 2000.

[24] S. C. Cramer, "Changes in motor system function and recovery after stroke," *Restor Neurol Neurosci*, vol. 22, pp. 231-8, 2004.

[25] A. Karni, G. Meyer, P. Jezzard, M. M. Adams, R. Turner, and L. G. Ungerleider, "Functional MRI evidence for adult motor cortex plasticity during motor skill learning," *Nature*, vol. 377, pp. 155-8., 1995.

[26] A. Karni, G. Meyer, C. Rey-Hipolito, P. Jezzard, M. M. Adams, R. Turner, and L. G. Ungerleider, "The acquisition of skilled motor performance: fast and slow experience-driven changes in primary motor cortex," *Proc Natl Acad Sci U S A*, vol. 95, pp. 861-8., 1998.

[27] G. Kempermann, H. G. Kuhn, and F. H. Gage, "More hippocampal neurons in adult mice living in an enriched environment," *Nature*, vol. 386, pp. 493-5, 1997.

[28] H. van Praag, G. Kempermann, and F. H. Gage, "Neural consequences of environmental enrichment," *Nat Rev Neurosci*, vol. 1, pp. 191-8, 2000.

[29] B. Kolb and R. Gibb, "Environmental enrichment and cortical injury: behavioral and anatomical consequences of frontal cortex lesions," *Cereb Cortex*, vol. 1, pp. 189-98, 1991.

[30] B. E. Will, M. R. Rosenzweig, E. L. Bennett, M. Hebert, and H. Morimoto, "Relatively brief environmental enrichment aids recovery of learning capacity and alters brain measures after postweaning brain lesions in rats," *J Comp Physiol Psychol*, vol. 91, pp. 33-50, 1977.

[31] P. Langhorne, B. O. Williams, W. Gilchrist, and K. Howie, "Do stroke units save lives?," *Lancet*, vol. 342, pp. 395-8, 1993.

[32] K. J. Ottenbacher and S. Jannell, "The results of clinical trials in stroke rehabilitation research," *Arch Neurol*, vol. 50, pp. 37-44, 1993.

[33] C. Wu, C. A. Trombly, K. Lin, and L. Tickle-Degnen, "Effects of object affordances on reaching performance in persons with and without cerebrovascular accident," *Am J Occup Ther*, vol. 52, pp. 447-56, 1998.

[34] C. Wu, C. A. Trombly, K. Lin, and L. Tickle-Degnen, "A kinematic study of contextual effects on reaching performance in persons with and without stroke: influences of object availability," *Arch Phys Med Rehabil*, vol. 81, pp. 95-101, 2000.

[35] C. L. Hsieh, D. L. Nelson, D. A. Smith, and C. Q. Peterson, "A comparison of performance in added-purpose occupations and rote exercise for dynamic standing balance in persons with hemiplegia," *Am J Occup Ther*, vol. 50, pp. 10-6, 1996.

[36] M. K. Holden, A. Dettwiler, T. Dyar, G. Niemann, and E. Bizzi, "Retraining movement in patients with acquired brain injury using a virtual environment," *Stud Health Technol Inform*, vol. 81, pp. 192-8, 2001.

[37] D. Jack, R. Boian, A. S. Merians, M. Tremaine, G. C. Burdea, S. V. Adamovich, M. Recce, and H. Poizner, "Virtual reality-enhanced stroke rehabilitation," *IEEE Trans Neural Syst Rehabil Eng*, vol. 9, pp. 308-18., 2001.

[38] J. Ku, R. Mraz, N. Baker, K. K. Zakzanis, J. H. Lee, I. Y. Kim, S. I. Kim, and S. J. Graham, "A data glove with tactile feedback for FMRI of virtual reality experiments," *Cyberpsychol Behav*, vol. 6, pp. 497-508., 2003.