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Development and Feasibility Study of a Sensory-enhanced Robot-aided Motor Training in Stroke Rehabilitation

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Abstract: Functional impairment of the upper limb is a major challenge faced by many stroke survivors. The present study aimed at developing a novel sensory-enhanced robot-aided motor training program and testing its feasibility in stroke rehabilitation. A specially designed robot handle was developed as an attachment to the Inmotion2 robotic system. This handle provided sensory stimulation through pins connected to small servo motors inside the handle. Vibration of the pins was activated during motor training once pressure on the handle reached a certain threshold indicating an active motion of the study subject. Nine chronic stroke survivors were randomly assigned to either a sensory-enhanced robot-aided motor training group (SERMT) or robot-aided motor training only group (RMT). All participants underwent a 6-week motor training program, performing target reaching movements with the specialized handle with or without vibration stimulation during training. Motor Status (MS) scores were measured for functional outcome prior to and after training. The results showed significant improvement in the total MS scores after training in both experimental groups. However, MS sub-scores for the shoulder/elbow and the wrist/hand increased significantly only in the SERMT group ($p<0.05$). Future studies are required to confirm these preliminary findings.

Introduction

Stroke may result in severe impairments of the affected upper extremity [1]. The impairments limit the ability to regain functional independence in the activities of daily living. Although a number of rehabilitation techniques for stroke survivors have been introduced over the years [2-4]. These techniques have their pros and cons [2-8]. More effective rehabilitation strategies and approaches are strongly desired both by the patients and their caregivers.

Robot-aided therapy has been developed and studied in recent years in stroke rehabilitation [9-12]. The studies have demonstrated that robot-aided therapy can be equivalent in quality to the therapy provided by a therapist. The advantages of robot-aided therapy include accuracy and consistency in movement training; capacity to be customized according to individual requirements; and reduction in the therapist's time and effort.

Stroke survivors often suffer from impaired sensation [1, 13]. Past studies in both animals and humans have demonstrated a strong correlation between the recovery of sensorimotor function and reorganization of the central nervous system [14]. Sensory impairments have been shown to be predictors of motor recovery in stroke subjects [15, 16]. Sensory feedback during motor training serves as an important triggering signal for brain reorganization. Robot-aided motor training incorporates sensory feedback from visual displays and cutaneous receptors. However, it may be difficult for stroke survivors to perceive tactile sensory input and changes of pressure on their hands during arm movement because of their diminished cutaneous sensation.

The purpose of the present study was to develop a robot handle that provided sensory enhancement during motor training and to examine the feasibility of the sensory enhanced motor training program using a training robot for chronic stroke survivors.

Methods

Development of sensory enhanced robot handle

Hardware: To improve the effectiveness of robot-aided motor training, enhanced cutaneous sensory inputs during motor training were implemented through controlled vibration at specific contact regions between a robot handle and the subject's hand. The training robot used in this study was the InMotion2 robot (Interactive Motion Technologies, Inc, MA)[17], which (Figures 1a) is capable of "shaping" motor skills [17]. The robot interacts with a patient to guide the patient's limb through a series of desired exercises [18]. It has been tested at Burke Rehabilitation Hospital in White Plains, NY [19]. In this project, we developed a new robot handle to replace the original handle (Figure 1b).

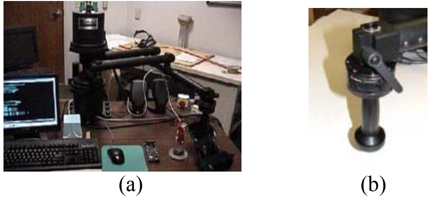
(a) (b)

Figure 1. (a) InMotion 2 training robot sitting on a desk; (b) the original robot handle.

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The special robot handle was designed to generate cutaneous sensory inputs for the middle and index fingers, the thumb, or the palm of the subject, depending on the direction of the active force applied on the handle by the subject. An indentation of at least 2mm on the fingers and the palm was required [20]. Studies have shown that vibration stimuli around 30 Hz can be easily sensed by human skin [21]. The robot-aided motor training program should be able to adjust the amplitude and the frequency in real time if the patient was not able to feel the vibration. In choosing the appropriate servomotor for the designed handle, a major limiting factor was the size of the servomotor which had to fit inside a cylindrical handle with a small diameter and still have the appropriate angular velocity and torque. The MX-50HP/BB (Maxx Products International, Lake Zurich, IL) was chosen and used, as utilized by Dr. Robert Howe and his research team in developing a tactile shape display [22]. This was a high performance servomotor (Figure 2a) that combined low weight, small size, high speed and appropriate torque with low cost. Each servomotor was slightly larger than a quarter, rotated 60 degrees in 80 milliseconds, and produced 0.18 Newton-meter of torque.


(a) (b)

Figure 2. (a) A servo motor; and (b) four small servo motors mounted on cuboids inside a plastic handle.

To produce a displacement of 2mm, an arm that is 10mm in length had to rotate about 6 degrees. The peak speed of the servomotor was given as 80ms per 60 degrees. It should take approximately 8ms for the motor to produce an angular displacement of 6 degrees. However it was found that both the 10% to 90% rise time and the 90% to 10% fall time was 41ms for a 2mm displacement. Therefore, for an amplitude of 2mm it was possible to produce frequencies around 20Hz which was smaller than the desired frequency but acceptable in this study. In order to transfer deformation to the skin, a 1mm diameter steel wire was used to fabricate mechanical pins with a viscoelastic tip protruding from the external cylindrical enclosure.

Four servo motors were mounted and glued to a high density plastic cuboids that had grooves cut into it to fit the servos in. This single plastic piece held the servos in place. The arrangement was then enclosed in a high density plastic tube (Figure 2b). Four holes were drilled into the tube to enable the steel pins to protrude out just enough to produce the necessary cutaneous sensory inputs to the middle and index fingers, the thumb, or the palm of the subject. The subject, while holding the handle, was stimulated in the direction of the push or the pull force to enhance their tactile sensory feedback during hand movement training.

Software: The servomotors interfaced with three wires, one for the positive of the power supply, one for the ground/negative, and one for the control signal. The servomotors were powered by an external 4.5V power supply. Each servomotor could be moved to any position by using pulse width modulation. The control pulse was a positive going pulse with ‘On’ time of 0.7ms to 2.3ms followed by ‘Off’ time of 12ms to 20ms. Thus the time period of one whole pulse was about 14ms. During the ‘On’ time the pulse was high (3V to 5V) and during the ‘Off’ time the pulse was low (0V). For this particular servomotor, sending a 0.7ms ‘On’ time pulse set the servo to one end position and sending a 2.3ms pulse set it to the other end position. Sending 1.5ms pulses set the servo motor to the center position. The total angular displacement of the arm of this servomotor was about 185 degrees.

The sensory-enhanced handle required independent control of each servomotor vibration. Although controlling the servomotor was relatively simple and commercial servo control chips were easily available, they were either limited by the number of servomotors that could be controlled at a time or the speed at which the control could be switched between the servos. A custom control was desired for this application. The specific platform selected for this purpose was the XSA-50 manufactured by XESS Corp. This was a development platform available off-the-shelf that contained a Xilinx© Spartan-II Field-Programmable Gate Array (FPGA), flash memory and a 100MHz on-board programmable clock. Using a FPGA with 50,000 gates made the design extremely scalable and flexible. The FPGA was programmed using Very High Speed Integrated Circuit Hardware Description Language (VHDL). The digital design consisted of two main components – a decoder implemented as a Finite State Machine (FSM) and a programmable pulse generator. The decoder was used for selecting the specific servomotor and the pulse generator produced the required control signal to be sent to the servomotor. The XSA-50 platform was connected to a PC computer through the parallel port, of the same computer that was used to control the InMotion2 robot. Six out of the eight data pins of the parallel port were used to send signals from the computer to the XSA-50 platform. Since four bits were used to select a servomotor, the software component of the sensory-enhanced handle could be scaled up to control 16 servomotors without any major modification. The current design of FPGA-based controller provides 4 bit resolution for the amplitude. The programmable pulse generator was an improvised version of a down counter. The on-board clock was set at a frequency of 50MHz. This frequency was divided by 1024 within the VHDL program giving a new clock frequency of 48.83 kHz. This was used as the clock input for the pulse generator. The 'Off' time of the pulse was a constant and was set at 13ms (a safe value for the 'Off' time should be close to and above 12ms). If this time was too small, then the servomotor arm would not have enough time to rotate to the opposite side of the initial motion. Since the required motion was vibratory, the arm of the servomotor was set at its midpoint and from there an angular displacement of ±6 degrees was applied. This angular displacement was converted in terms of time period as ±0.14ms from the midpoint. The servomotor could be rotated to its midpoint by applying a pulse with an 'On' time of about 1.5ms. This time period was equal to 73 pulses at the clock frequency of 48.83k Hz. Similarly 0.14ms was approximately equal to 7 clock pulses. A down counter was implemented, initially at 73. If the counter started from 73-7=66, then the servomotor arm would move in one direction. In the subsequent cycle when the counter started from 73+7=80, then the servomotor arm would move in the opposite direction. The amplitude could be increased by increasing the number to be added or subtracted from 73. But due to the slew rate, increasing the amplitude would result in the reduction of the frequency of vibration.

During the robot-aided training, different servomotors were activated. The computer that controls the InMotion2 robot was a natural choice to control the servomotors. The robot controller ran on the Linux operating system using C programming language and the user interface as created using Tcl/TK. The servo control software was also written in C programming language. To start and to stop any servomotor a series of five signals were sent to the parallel port. As far as the software was concerned it was a simple output call to the parallel port. Each parallel port output call only took about 1μsec.

Feasibility study

Study Subjects: Nine chronic stroke subjects (3 men and 6 women) who were recruited from the local community participated in the feasibility study of the sensory enhanced motor training program using the developed handle. The subjects were on average 57.3 ± 13.9 years old, ranging from 36 to 78 years age. All subjects except one had a single stroke episode and were on average 94.9±116.1 months since the onset of stroke. Four subjects had right-side hemiparesis and the remaining five had left-side hemiparesis. The exclusion criteria included: a stroke onset of less than 3 months; unable to follow a three step command; progressive or severe neurological disease, heart conditions, unstable hypertension; fractures and/or implants in the upper limb of less than 6 months duration; apraxia (Florida apraxia score < 27); pain at the time of screening; neglect, poorly controlled diabetes, amputation, blind, and living more than 60 miles from University of Kansas Medical Center. For cognitive screening purposes, the subjects underwent the Folstein Mini mental status exam; the Florida Apraxia screen; and the Geriatric depression scale. The study protocol and informed consent was reviewed and approved by the human subjects committee of the University of Kansas Medical Center.

Study Design: Each subject made 20 visits to the laboratory of which 18 visits were made for the sensory enhanced motor training program (three times a week for 6 weeks). On the first and the 20th visits, the subjects went through a battery of tests to assess their sensorimotor status and also were tested for motor performance with the robot. The subjects were randomly assigned to two experimental groups. One group received sensory-enhanced robot-aided motor training (SERMT group), while the other group received the same robot-aided motor training without sensory enhancement (RMT group). This study used a single blind design. The researchers who conducted subject clinical evaluation and quantitative testing were blinded to the subject's treatment group.

Training Procedure: For subjects in the SERMT group, vibro-tactile stimulation provided by servo motors was applied to the hand during training if the subject's active force was applied to the robot handle. For subjects in the RMT group, no vibro-tactile stimulation was provided during training. During a training session, the subject sat on a chair and was strapped onto the chair to prevent the trunk motion while performing reaching movements. The subject held the robot handle comfortably with his/her affected hand and when necessary elastic bands were used to secure the hand position. A computer monitor was placed in front of the subject at a distance of approximately 1 meter. The subjects made reaching movements from the center of the screen (start position) to a diagonal target followed by making reaching movements to targets on each corner of a square in either a clockwise or counterclockwise manner. The training sessions lasted 40 minutes.

Testing Procedure: Motor performance of the subject's upper limb was evaluated using the Motor Status (MS) Score [23] prior to and after training. The MS score is an expanded Fugl-Meyer assessment to thoroughly assess the upper limb motor function by adding the number of isolated muscle groups. The MS score consists of functional scores of the shoulder/elbow (MS-SE; maximum=42) and the wrist/hand (MS-WH; maximum=40) The MS-SE score is capable of detecting a significant advantage of robot therapy for shoulder and elbow movements [23].

Data analysis: The independent t-test was conducted to identify the effects of training on motor performance of the paretic upper limb using SPSS software (SPSS Inc.). The total MS, MS-SE, and MS-WH scores were analyzed in the two experimental groups.

Results

A significant increase of the total MS score was revealed in the SERMT group (from 40.4±19.36 to 48.04±20.23; $p<0.01$) as well as in the RMT group (21.95±13.35 to 30.65±17.13; $p<0.05$). Both MS-SE and MS-WH scores in the SRMT group were significantly improved from 24.4±9.17 to 28.04±8.41 ($p<0.05$) and from 12.75 ±10.5 to 17±13.74 ($p<0.05$), respectively. However, neither MS-SE ($p=0.06$) nor MS-WH scores ($p=0.08$) was significantly changed after training in the RMT group.

Discussion

In the present study, the robot-aided motor training significantly improved the total MS scores of the paretic arm in both groups of stroke survivors. This is in agreement with findings reported in previous studies [9, 12, 24, 25]. Significant improvements of MS-SE and MS-WH scores were, however, shown in the SERMT group, but not in the RMT group. Stroke survivors often present with impaired sensation [1, 13] which significantly influences their motor recovery [14-16]. It has been suggested that sensory training may help accelerate motor functional recovery after stroke [26]. The enhanced sensory input for subjects in the SERMT group might have facilitated the reorganization of the central nervous system and thereby promoted motor recovery in the hemiparetic upper limb [27]. This hypothesis, however, needs to be further explored in future studies. A major limitation of our study is the small sample size. Another limitation is the use of pins to provide vibro-tactile stimulation, which could cause pain and discomfort feelings to the subjects' hands. In the future study, we will revise the design of the sensory-enhancement device and conduct a similar study with greater sample size to confirm our preliminary findings.

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