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Haptically facilitated bimanual training combined with augmented visual feedback in moderate to severe hemiplegia

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Abstract— This study describes the design and feasibility testing of a hand rehabilitation system that provides haptic assistance for hand opening in moderate to severe hemiplegia while subjects attempt to perform bilateral hand movements. A cable-actuated exoskeleton robot assists the subjects in performing impaired finger movements but is controlled by movement of the unimpaired hand. In an attempt to combine the neurophysiological stimuli of bilateral movement and action observation during training, visual feedback of the impaired hand is replaced by feedback of the unimpaired hand, either by using a sagittaly oriented mirror or a virtual reality setup with a pair of virtual hands presented on a flat screen controlled with movement of the unimpaired hand, providing a visual image of their paretic hand moving normally. Joint angles for both hands are measured using data gloves. The system is programmed to maintain a symmetrical relationship between the two hands as they respond to commands to open and close simultaneously. Three persons with moderate to severe hemiplegia secondary to stroke trained with the system for eight, 30 to 60 minute sessions without adverse events. Each demonstrated positive motor adaptations to training. The system was well tolerated by persons with moderate to severe upper extremity hemiplegia. Further testing of its effects on motor ability with a broader range of clinical presentations is indicated.

I. Introduction

RESTORING function in individuals who have severe paralysis of the upper extremity secondary to stroke is challenging. Most of the interventions with research supporting their efficacy for this group involve subjects with active movement of the fingers. Our lab has developed a system of virtually simulated hand activities utilizing haptic robotic facilitation to rehabilitate persons with mild to moderate UE hemiplegia [1, 2]. This system has proven successful in persons with limited active movement of their hands but the technology cannot accommodate persons unable to initiate finger movement. This paper describes a system providing assist as needed robotic facilitation, with several approaches to recruiting undamaged neural networks in order to rehabilitate hand function in people without active finger movement.

The use of a mirror image has been explored as a means of rehabilitation for individuals suffering from upper extremity hemiparesis [3], developed from studies identifying increased activation of motor areas of the brain during the observation of actions without any physical movement [4]. In addition an initial fMRI study of action observation of a virtual representation of impaired hand movement, controlled by the unimpaired hand of persons with stroke demonstrated increases in ipsi-lesional motor cortex activation [5]. Further, studies of action observation show a positive effect on recovery of motor function after stroke, when observation is combined with execution of the observed movements [6, 7] .

Bimanual training activities have been utilized to increase the recruitment of undamaged motor pathways in persons with hemiparesis as well. It has been suggested that symmetrical movements of the upper extremities may activate neural networks in both hemispheres that control inter-limb coordination, resulting in improved functional therapeutic outcomes [8]. A study utilizing a robot to facilitate bilateral symmetrical movements of the wrist demonstrated larger improvements in motor function than controls performing a unilateral intervention [9].

This study will describe the design and feasibility testing of a system that combines the observation of hand movements of the unimpaired hand of persons with stroke using two different visual presentations, while they attempt to perform similar movement of their impaired fingers. A robot will assist the subjects to perform impaired finger movements that correspond to unimpaired finger movement in an attempt to combine the stimuli of action observation and bilateral movement.

II. Methods

A. Hardware

Metacarpal phalangeal and proximal interphalangeal joint angles for both hands are measured using CyberGloves™ (Immersion, USA) at a rate of 100 Hz. The VirtualHand© calibration software is used to calibrate the CyberGloves prior to use which interacts with the CyberGlove Interface Unit (CGIU) which contains amplification and digitization

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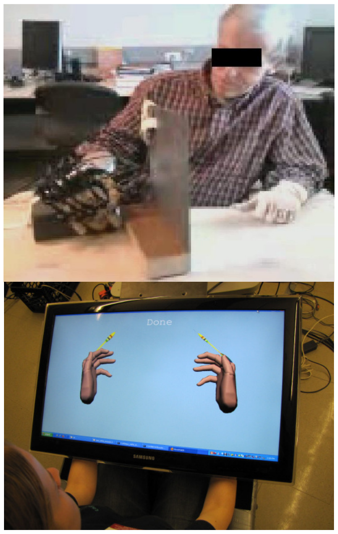

Fig. 1: Experimental set-up. Top: Mirror set-up. CyberGrasp on right hand is controlled by data glove on left hand. Subject watches mirror image of his left hand to simulate observation of his right hand moving normally. Bottom: Virtual Reality set-up. Both virtual hands are controlled by movement of the unimpaired hand, showing the subject an image of their impaired hand moving normally.

circuitry for the CyberGlove. The CyberGloves act as an interface between the subject and the control software described below. Hand extension during training is assisted using the CyberGrasp™ (Immersion, USA), a lightweight exoskeleton that fits over the top of the CyberGlove device, by providing an extension force to individual fingers via a system of cables that traverse the back of the hand and are affixed at the tip of each finger. The assistive force can be applied in the direction of digit extension only, up to a maximum force of twelve Newtons. Electromyography (EMG) was collected using Delsys Bagnoli™ EMG system at rate of 1000Hz. The receiving electrode was placed on the medial side of the forearm, at the muscle belly of the flexor digitorum superficialis.

During training the CyberGrasp was used in order to assist the affected hand to move in sync with the unaffected hand, during bilateral movement training. It was proposed that the effect of the mirror image on brain reorganization might be increased if the subject received simultaneous proprioceptive feedback that their affected hand was moving in the same way as the visualized image.

Two visual presentations were utilized during this study. When using the first, a mirror set-up, both arms were supported on a platform, and a sagittally oriented mirror was placed in the subject's midline. The actual impaired hand was blocked from the subject's view by the mirror which was positioned in a way that the subject could clearly see the mirror image of their unaffected hand superimposed on the location of their affected hand. (Figure 1).When using the virtual hand presentation, the CyberGlove on the unimpaired hand is interfaced with a virtual reality (VR) environment developed with Virtools 4.0 software package (Dassault Systems) and a VRPack plug-in that communicated with an open source Virtual Reality Peripheral Network VRPN interface [10]. The VR environment shows left and right virtual hand models positioned in 1st person view, in semi-pronated positions (Figure 1). The VR hands are actuated in real-time by data streamed from the CyberGlove.

B. Software

Software from the CyberGrasp and the CyberGlove were merged using C++, and a graphic user interface (GUI) was created. EMG is synchronized with the other devices using MATLAB programming. An algorithm allowed the extension force provided by the CyberGrasp to depend on the position of the subjects' hands. The algorithm controlled force generated by the CyberGrasp based on two variables:

$$Fdiff = \frac{glove\ diff}{90} + \frac{maximum\ assistive\ force}{2} \tag{1}$$

where glove diff equals the difference between the average unimpaired finger flexion angle and the corresponding average impaired finger flexion angle. And Max assistive force is the largest assistive force necessary to fully extend finger during calibration.

$$Falpha = \frac{UFA}{90} + \frac{maximum\ assistive\ force}{2} \tag{2}$$

where UFA is unimpaired finger actual angle that equals the average unimpaired finger flexion and max assistive force is the largest assistive force necessary to fully extend finger during calibration. These two variables are combined to determine the assistive force provided by the CyberGrasp (Fassist).

$$Fassist = Fdiff + Falpha \tag{3}$$

This results in increasing levels of assistive force when the difference between each average finger flexion angle gets larger and decreases as the difference gets smaller (Figure 2).

C. Subjects

Three male subjects (mean age = 63 years) with chronic strokes (Mean time since CVA = 67 months) were selected based on appropriate movement patterns for the experiment. Subjects had moderate to severe right UE hemiplegia (Chedoke McMaster Hand Impairment Stage = 3 or 4), Mean Finger Flexion Ashworth Stage = 2 or 3) and could not close their hand from an open position, without active digit extension were included in the study. Exclusion criteria included right visual neglect, and receptive language and cognitive issues. Severe finger flexor spasticity that would limit the ability of the CyberGrasp to extend fingers also resulted in exclusion.

D. Training Protocol

Subjects performed 4, thirty to sixty minute training sessions per week for 2 weeks. During the experiment, subjects viewed only the unimpaired hand and its mirror image, superimposed on the impaired hand's position. Actual view of the impaired hand was occluded by the mirror or VR monitor. Subjects engaged in cycles of three to five seconds of simultaneous bilateral finger extension

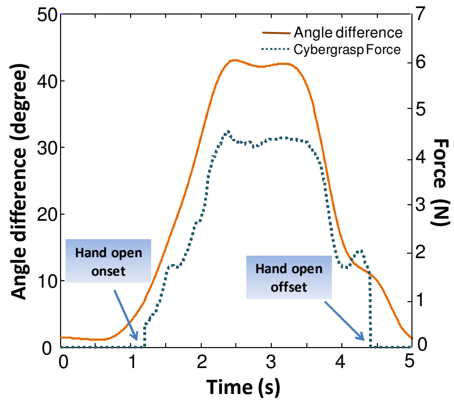

Fig. 2. Graphic demonstration of the relationship between position difference between average flexion angle of the unimpaired and impaired index finger as measured by data gloves (solid gold line) and the assistive force exerted on the impaired index finger by the CyberGrasp (dashed blue line).

initiated in response to the auditory command "Open" interleaved with three to five seconds of simultaneous bilateral finger flexion, cued by the auditory command "Close". Each session began and ended with 3 minutes of active movement, during which no assistance was provided to the impaired hand by the CyberGrasp. After 3 minutes of unassisted movement, impaired digit extension was assisted by the CyberGrasp using the algorithm designed to minimize the difference between average impaired and unimpaired finger flexion angles as described above (Figure 3).

E. Outcome measurement

Active range of motion data was collected during the unassisted movement preceding training as measured by the CyberGlove as well as EMG data collected during passive movement of the hand by the CyberGrasp. Active range of motion was determined by identifying the largest joint excursion form close to open in response to these cues. Before and after training, a licensed Occupational Therapist administered the Modified Ashworth scale to the finger flexors [11]. Motor control was graded using the Chedoke McMaster Hand Impairment Inventory [12] and motor function was measured using the Jebsen Test of Hand Function [13].

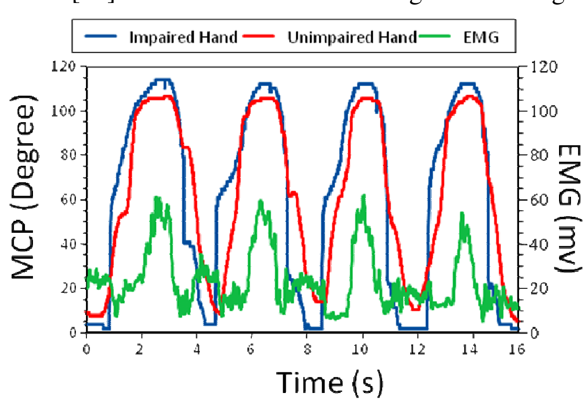

Fig. 3. Four consecutive repetitions collected performed by Subject One during training on Day Two. Red line is unimpaired index finger MCP angle. Blue line is impaired index finger MCP angle. Note the symmetrical position changes. Green line is the EMG signal collected at the muscle belly of the impaired hand FDS. Note the strong EMG signal during active flexion (MCP angle increasing) and the reflexive activation during passive elongation (MCP angle decreasing) of the impaired hand for each repetition.

III. RESULTS

All three subjects completed 100% of their scheduled training visits. Adverse effects were limited to transient hand muscle fatigue and soreness that did not limit their activities of daily living. No performance differences were apparent with the use of the two visual presentations (mirror or virtual). Subjects averaged 30 to 60 minutes of activity per session over the course of the study. None of the subjects described discomfort during training.

Each of the subjects demonstrated changes in motor function subsequent to the intervention but a consistent pattern of adaptation was not demonstrated. Subject One demonstrated a decreased stretch reflex in response to having his fingers passively extended by the CyberGrasp during training. Figure 4 demonstrates averages in EMG response to active finger flexion and passive finger extension. Twenty cycles on training day two show a spike in EMG output during active finger flexion and another spike during passive lengthening. During movements of similar amplitude on training day six, EMG output is similar during active flexion but flexor muscle EMG response is absent during passive lengthening, suggesting that training may have reduced the abnormal response to muscle lengthening. Subject one did not demonstrate consistent changes in active unassisted movement during training but demonstrated the ability to open his hand sufficiently to grasp transport and release sixteen ounce cans during his post training examination, which he was unable to do during

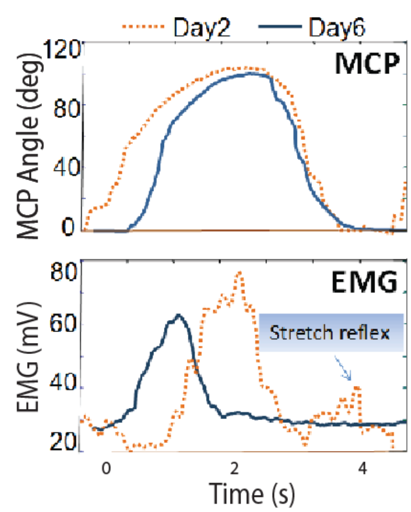

Fig. 4. Finger position and EMG responses collected during training of Subject One. Top panel: MCP of impaired hand index finger during single opening and closing of the hand (average of 20 trials). Finger starts in full extension, closes actively, and finally is extended passively by the CyberGrasp. Bottom panel: Mean EMG response to the movement in top panel. Day 2 response (gold line) shows a strong activation during active flexion movement and a secondary burst in response to passive lengthening. On Day 6 (blue line) there is no reflex activation in response to passive lengthening.

pretesting.

Subject Two did not demonstrate increases in active movement during training but was able to extend his wrist more than twenty degrees following training which he was not capable of at pre-testing. Subject three demonstrated inconsistent performance during the active portions of training and did not seem to attend to his hemiparetic limb consistently. Interestingly, Subject three was able to stack four checkers during post-testing which he was unable to do at pretesting.

IV. Discussion

The three feasibility study subjects all tolerated 8 sessions of activity without adverse effects and the system performed as designed over approximately 20 hours of interaction with impaired subjects. Previous descriptions of action observation have not described significant reductions in resistance to passive movement as measured by the Modified Ashworth Scale. This lack of improvement in Modified Ashworth scores was demonstrated by our subjects as well, but subject one demonstrated EMG responses consistent with reduced resistance to passive movement. Ashworth grades inconsistent with EMG responses in persons with stroke are described elsewhere in the literature[14].

Improvements in active movement during training were not demonstrated by our subjects. This may be related to the sensory conditions provided during training or the cues provided to subjects, which did not emphasize large excursions. Interestingly, all three subjects demonstrated active motor function at post-testing that they were not capable of at pre-testing. Two of the subjects demonstrated the ability to perform active functional movements at post-test that they were unable to perform prior to training. Wolf et al describe this pattern of change as clinically significant[15].

The use of virtually presented mirror image movements in this study did not have an apparent effect on motor performance. Further study to confirm this initial finding is indicated.

This study is unique in its attempts to provide bimanual training limited to distal musculature. The modified master slave relationship between the two hands was maintained by the robot throughout the training period. This symmetrical, active assisted movement did not result in increases in unassisted movement. The incorporation of an algorithm to systematically decrease slacking or a more task oriented training activity as opposed to action observation may be necessary for persons with stroke to benefit from this type of training [2, 16].

V. Conclusion

The system described in this study performed as designed and was well tolerated by persons with moderate to severe UE hemiplegia. Further testing of its effects on active motor ability with larger sample and a broader range of clinical presentations is indicated.

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