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Use of a Pneumatic Glove for Hand Rehabilitation Following Stroke

Lauri Connelly, Mary Ellen Stoykov, Yicheng Jia, Maria L. Toro, Robert V. Kenyon, and Derek G. Kamper, *Member, IEEE*

Abstract—**Hand impairment is common following stroke and is often resistant to traditional therapy methods. Successful interventions have stressed the importance of repeated practice to facilitate rehabilitation. Thus, we have developed a servo-controlled glove to assist extension of individual digits to promote practice of grasp-and-release movements with the hand. This glove, the PneuGlove, permits free movement of the arm throughout its workspace. A novel immersive virtual reality environment was created for training movement in conjunction with the device. Seven stroke suvrvivors with chronic hand impairment participated in 18 training sessions with the PneuGlove over 6 weeks. Overall, subjects displayed a significant 6-point improvement in the upper extremity score on the Fugl-Meyer assessment and this increase was maintained at the evaluation held one month after conclusion of all training ($p < 0.01$). The majority of this gain came from an increase in the hand/wrist score (3.8-point increase, $p < 0.01$). Thus, the system shows promise for rehabilitative training of hand movements after stroke.**

I. INTRODUCTION

Stroke is a leading cause of disability, with approximately 780,000 Americans incurring a stroke each year. Thirty to sixty-six percent of all individuals who have had a stroke have arm impairments six months post-stroke [1]. In these stroke survivors, finger extension is the most common deficit. This impairment is especially difficult, because proper hand function is crucial to interaction with the environment and performance of the activities of daily living.

Rehabilitation interventions which incorporate intensive training of active repetitive movements appear to increase upper extremity function after stroke [2]. One such intervention which has been described at length in the literature is constraint induced movement therapy [3, 4]. However, the inclusion criteria for this therapy require both finger and wrist movement which the majority of stroke survivors do not have.

Mechatronic devices can assist movement in order to enable stroke survivors with more severe upper extremity impairment to undertake repetitive and intense practice. A number of devices have been developed which can actively facilitate extension of the digits [5-7]. Several of these devices have shown promise in rehabilitation trials [8, 9]

Unfortunately, few hand devices permit the freedom of arm motion to perform repetitive practice of reach-to-grasp movements, a task fundamental to functional use of the upper extremity. Often, if the device itself does not physically preclude displacement of the hand, the weight of the device greatly impedes arm movement in stroke survivors. Additionally, we have observed that the severity of impairment may vary from digit to digit within a given individual, in accordance with what has been reported with lacunar strokes [10]. The ability to match the necessary assistance to each digit individually would be beneficial.

Thus, we have developed a glove to provide independent assistance of extension for each digit while allowing reach-to-grasp movements. This pneumatic glove, the PneuGlove, can be used to train either within a virtual environment or with real objects. A pilot study using the device in training was performed with stroke survivors to examine the efficacy of the system in mitigating impairment following stroke.

II. DEVICE DESCRIPTION

A. PneuGlove

The PneuGlove utilizes air pressure to provide assistance of finger extension. It consists of a custom-fabricated air bladder on the palmar side of the glove and a lycra backing on the dorsal side. A zipper sewn into the lycra aids in donning and doffing the glove. The custom air bladder, fabricated from polyurethane, has a series of 5 independent channels, one for each digit. Air pressure within a channel creates an extension force which pushes the digit further into extension. Open-cell foam within each channel helps to reduce restriction of air flow within the channel during hand flexion. Each bladder channel is physically isolated with respect to the others so that assistance of each digit is achieved independently. Each channel is connected to an electropneumatic servo valve (QB02005, Proportion-Air, McCordsville, IN). The servo valve provides air pressure between 0 – 10 psi, linearly proportional to a command voltage. A software program written in Visual Basic controls the PneuGlove through a personal computer.

This manner of extension assistance mitigates potential problems with joint subluxation and hyperextension. When the air pressure is removed, the digit is free to flex (minimal impedance is offered by the deflated glove). Thus, it is possible to grab real objects with the PneuGlove.

Also, on the dorsal side of the glove, 10 polyester sleeve pockets are sewn at locations corresponding to the

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L. Connelly, M. Stoykov, Y. Jia, and D. Kamper are with the Rehabilitation Institute of Chicago, Chicago, IL.

M. Toro is with the Escuela de Ingenieria de Antioquia, Medellin, Colombia

R. Kenyon is with the University of Illinois at Chicago, Chicago, IL

D. G. Kamper is also with the Illinois Institute of Technology, Chicago, IL (e-mail: kamper@iit.edu).

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metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints of the fingers and the MCP and interphalangeal (IP) joints of the thumb to hold bend sensors measuring joint angle (see Fig. 1). The bend sensors (Flexpoint Sensors, Draper, UT) are part of the Shadow Monitor [11], which wirelessly transmits the joint angle data to the computer running the PneuGlove. In this manner, closed-loop control can be used to achieve a desired extension angle.

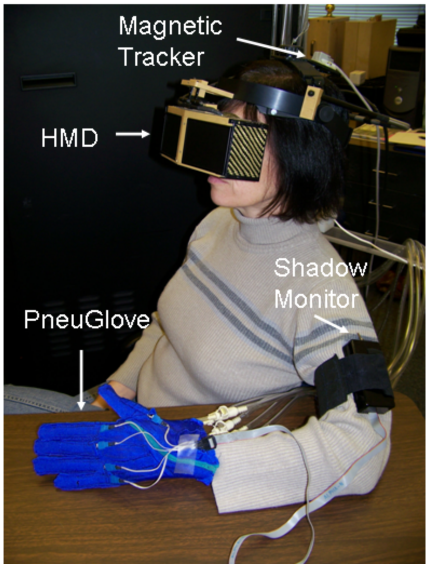

Fig. 1. Demonstration of utilitzation of the PneuGlove in a virtual environment. Subject views the virtual environment through the head mounted display (HMD). The magnetic tracker measures head position and orientation; the virtual scene is updated accordingly. The Shadow Monitor records joint angles for the digits both for updating the virtual hand and determining if assistance is needed.

B. Virtual Environment

The PneuGlove is well suited to be used in conjunction with a virtual reality (VR) environment, as it can provide haptic feedback in addition to assistance of finger extension. Our VR application (see [12]) uses the Wide5 Head Mounted Display (HMD) as the display device (Fakespace Labs, Inc., Mountain View, CA, Mechdyne). The virtual scene is created through the coordination of several software packages: Coin3D (Systems In Motion, Oslo, Norway) to implement the scene graphs and provide a comprehensive range of graphics and interactive objects; CAVELib™ software (VRCO, Virginia Beach, VA, Mechdyne) to control scene display; and the trackd® tool (VRCO, Virginia Beach, VA, Mechdyne) to collect head position and orientation data and provide them to the rendering thread transparently. Head posture is continuously monitored using a magnetic tracker (Flock of Birds, Ascension Tech, Burlington, VT) mounted to the HMD. The entire scene is updated at 20 Hz.

The virtual scene developed for the current project consists of a room with 4 walls, a floor, and a ceiling. Cues to depth are provided by stationary objects, such as pictures and a table in the room, and by texturing (see Fig. 2). A virtual hand with moveable joints is controlled by the user's own hand movements. We have created a set of virtual objects of different radii requiring different degrees of digit extension in order to grasp them. The user attempts to open her/his hand sufficiently within an allotted time to grasp the presented object.

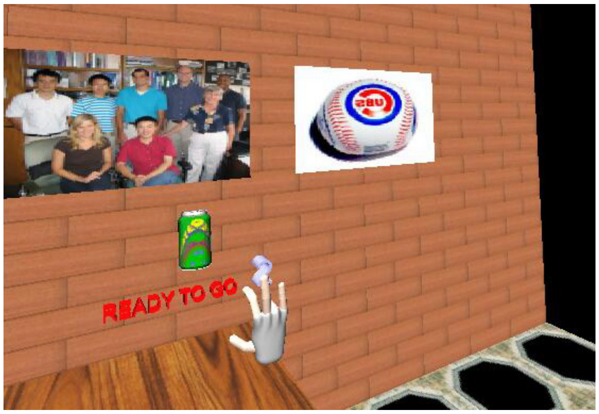

Fig. 2. Virtual environment. The environment consists of a room with walls and stationary objects to provide cues to depth. The virtual hand is controlled by the user, who attempts to open the hand sufficiently to grasp the objects displayed. A visible number displays the score to the user.

III. TRAINING PROTOCOL

Seven stroke survivors with chronic hemiplegia participated in the study. Subjects were recruited from the Rehabilitation Institute of Chicago Clinical Neuroscience Research Registry and from within the Rehabilitation Institute of Chicago. Eligible participants met the following criteria: (1) at least 18 years of age; (2) at least 6 months post-stroke; (3) at least 6 months post Botox injections in affected upper extremity; (4) Stage 4 or 5 on the Hand Stage of Recovery of the Chedoke-McMaster Stroke Assessment [13]; (5) sufficient cognitive status to follow complex commands, including auditory commands without sight of commander (6) full field of vision and hemispheric attention; and (7) the ability to tolerate 30 minutes of HMD wear. Each subject gave Informed consent in accordance with the procedure approved by the Institutional Review Board of Northwestern University.

Subject characteristics at enrollment are shown in Table 1. All subjects were naturally right hand dominant; 3 had primary impairment of the left hand and 4 had primary impairment of the right hand due to the stroke. Six of the 7 subjects were rated as Stage 4 of the Hand Stage of Recovery of the Chedoke-McMaster Stroke Assessment while one was rated as Stage 5.

All subjects participated in treatment sessions three times per week for six weeks (total of 18 sessions). As tactile feedback and functional task training may be important for rehabilitation, each training session consisted of approximately 30 minutes of training in the VR environment followed by 30 minutes of training in functional use of real objects.

In the VR environment, the subject attempted to open his/her hand sufficiently to grasp the virtual objects presented. For each session the therapist targeted one joint most in need of improvement in each digit (either the MCP or PIP/IP) and the sensor was placed over this joint. The required extension angles for each of these joints were computed for each virtual object based upon object dimensions, digit segment lengths, and a stereotypical grasping pattern [14]. The subject was asked to extend his or her fingers to grasp each object, maintain grasp of the object, and to release the object. If the subject was able to extend to the designated degree required to grasp the object, either with or without assistance, he or she was "awarded" the object and the virtual object moved to the subject's virtual hand. Visual and auditory feedback of success or failure were provided and a running score, visible to the subject in the virtual scene, was maintained. The therapist tailored the frequency of virtual object presentation to allow for adequate rest between trials to maximize the quality of movement. Conversely, virtual objects could be presented quickly if doing so created a challenge for the subject. A minimum of 60 and a maximum of 120 repetitions occurred during each session.

TABLE I

SUBJECT CHARACTERISTICS AT BASELINE

Quantity	Value
Age (years)[a]	57 (18)
Months post-stroke[a]	122 (42)
Baseline UE Fugl-Meyer score[a]	37 (8.8)
Right/ left hand impairment[b]	4/3
Chedoke Stage of Hand 4/5[b]	6/1

[a]Mean (standard deviation), [b]Out of 7.
UE = upper extremity.

In the VR environment, with known objects, the degree of assistance provided by the PneuGlove was determined by the error between the actual and required joint extension angles. Haptic feedback was provided during the hold phase to simulate object resistance to squeezing. The glove was slightly deflated prior to release of the object, in order to allow the subject time to actively extend their fingers before air assistance was provided.

Outside of the virtual environment, a task-oriented approach to training was employed in conjunction with real objects. Subjects were afforded the opportunity to choose between activities they felt best addressed real life performance problems, such as grasping and releasing dishware to set a table or opening a medication bottle and picking up pills to set up a daily pillbox. Additionally, subjects were encouraged and guided to analyze their own movement during activities, in an attempt to generalize to their home setting. Movement practice focused on grasp and release, pinch and release, digit individuation, and finger extension with wrist and elbow extension to facilitate function during reach-to-grasp.

The upper extremity portion of the Fugl-Meyer (FM) assessment of motor recovery after stroke [15] was administered at baseline prior to initiation of the training, at the conclusion of the 6 weeks of training, and at a follow-up session one month after the end of training. The total score and the portion related to the Wrist and Hand sections were analyzed using repeated measures ANOVA.

IV. RESULTS

All subjects tolerated the immersive VR training well. There were no reports of motion sickness or vertigo induced by the use of the VR system. All subjects completed the entire training program, including the follow-up evaluations.

The upper extremity FM score (maximum of 66) showed a significant gain across subjects. The score at the end of training, 43.1 (± 7.7), was significantly greater than the score at baseline, 37 (± 8.8), ($p < 0.01$). This improvement was maintained at one month after the end of training (43.3 ± 8.3) and remained significantly greater than the baseline value ($p < 0.01$). Thus the mean change was greater than 6 (Fig. 3).

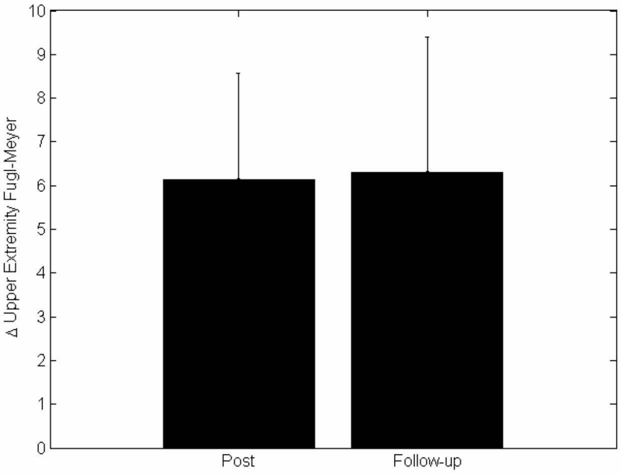

Fig. 3. Change in the upper extremity Fugl-Meyer score at the end of training ("Post") and at the one month follow-up ("Follow-up") with respect to baseline. Mean change across all 7 subjects. Error bar displays 95% confidence interval.

In particular, the hand section of the upper extremity FM showed improvement. It increased from 12 (± 4.4) at baseline to 15.9 (± 3.2) at the end of treatment, a significant difference ($p < 0.01$). This gain was again maintained at the one-month follow-up (15.7±3.9) and was significantly greater than at baseline ($p < 0.01$). Improvement was observed across all subjects (Fig. 4).

V. DISCUSSION

Despite the simplicity of the current VR environment, subjects were enthusiastic about using it. There were no reported incidents of motion sickness (subjects were monitored for 30 minutes after the end of exposure to the VR to ensure no latent reaction occurred). Providing a challenge in terms of a scored task and providing visual feedback of which digit or digits had failed to open sufficiently were two features which subjects found especially appealing. Improvement with the training protocol was evident across all subjects.

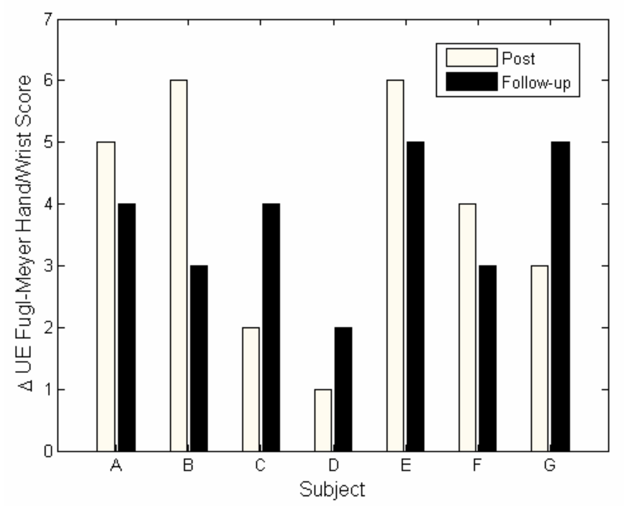

Fig. 4. Change in the Hand/Wrist portion of the upper extremity Fugl-Meyer score at the end of training (light gray bars) and at the one-month follow-up (black bars) with respect to baseline for each subject.

Significant increases in the upper extremity FM scores were observed. The change of 6 points, or almost 10% of the total scale, is considerable for rehabilitation and compares quite favorably to other interventions [16]. Importantly, there was also a significant improvement in the Hand/Wrist portion of the FM score. Thus, this targeted hand intervention did, indeed, have a beneficial effect on the hand. One month after completion of all training each subject exhibited an improvement of at least two points on the Hand/Wrist portion of the upper extremity FM score. Two of the subjects demonstrated a 5-point gain, which is equivalent to 20% of the maximum score of 24 for this portion of the FM assessment.

Preferential impairment of specific digits was indeed common in this population, so a device which can provide control of assistance/resistance to individual digits is seemingly beneficial. In future applications, we believe the PneuGlove could be especially useful for training individuation. While it can only provide opening force on the digit, this force can be used both for assistance of extension and resistance of flexion. Thus, the typical co-flexion of unintended digits can be resisted to permit flexion of only the intended digit. As the subject improves, resistance can be provided against the intended digit while all other digits are allowed to flex.

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