Hand Rehabilitation Following Stroke: A Pilot Study of Assisted Finger Extension Training in a Virtual Environment

Heidi C. Fischer, Kathy Stubblefield, Tiffany Kline, Xun Luo, Robert V. Kenyon, and Derek G. Kamper

Background and Purpose: The purpose of this pilot study was to investigate the impact of assisted motor training in a virtual environment on hand function in stroke survivors. **Participants:** Fifteen volunteer stroke survivors (32–88 years old) with chronic upper extremity hemiparesis (1–38 years post incident) took part. **Method:** Participants had 6 weeks of training in reach-to-grasp of virtual and actual objects. They were randomized to one of three groups: assistance of digit extension provided by a novel cable orthosis, assistance provided by a novel pneumatic orthosis, or no assistance provided. Hand performance was evaluated at baseline, immediately following training, and 1 month after completion of training. Clinical assessments included the Wolf Motor Function Test (WMFT), Box and Blocks Test (BB), Upper Extremity Fugl-Meyer Test (FM), and Rancho Los Amigos Functional Test of the Hemiparetic Upper Extremity (RLA). Biomechanical assessments included grip strength, extension range of motion and velocity, spasticity, and isometric strength. **Results:** Participants demonstrated a significant decrease in time to perform functional tasks for the WMFT ($p = .02$), an increase in the number of blocks successfully grasped and released during the BB ($p = .09$), and an increase for the FM score ($p = .08$). There were no statistically significant changes in time to complete tasks on the RLA or any of the biomechanical measures. Assistance of extension did not have a significant effect. **Discussion and Conclusion:** After the training period, participants in all 3 groups demonstrated a decrease in time to perform some of the functional tasks. Although the overall gains were slight, the general acceptance of the novel rehabilitation tools by a population with substantial impairment suggests that a larger randomized controlled trial, potentially in a subacute population, may be warranted.

Key words: *hand, finger extension orthosis, stroke, virtual reality*

Approximately 60% of stroke survivors experience upper extremity dysfunction limiting participation in functional activities.[1] Chronic deficits are especially prevalent in the hand. In fact, finger extension is the motor function most likely to be impaired.[2] This distal limb impairment is especially problematic, because proper hand function is crucial to manual exploration and manipulation of the environment. Indeed, loss of hand function is a major source of impairment in neuromuscular disorders, frequently preventing effective occupational performance and independent participation in daily life.

Several intervention approaches have been used in an effort to treat impairment and enhance functional recovery following stroke. Evidence indicates treatment techniques incorporating repetitive use of the affected limb, massed practice, task-oriented re-education, and constraint-induced movement therapy are the most effective strategies to date to improve motor recovery of the upper extremity.[3,4] Their use is further supported by observations from animal models of stroke in which practice seems to be the primary factor leading to synaptogenesis and brain plasticity.[5–7] Functional magnetic resonance imaging and transcranial magnetic stimulation studies in humans provide evidence for functional adaptation of the motor cortex following injury.[8–12] Imaging

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performed after constraint-induced training protocols has shown evidence of cortical plasticity as well.[13,14] Furthermore, many studies have demonstrated that neuroplasticity can occur even in the chronic stages of stroke.[14–18]

Rehabilitation is more effective when individuals are allowed opportunities for massed practice in a task-oriented context.[4] Robotics emerged in an effort to provide opportunities for this massed practice, which may be difficult for therapists to provide due to time and staffing limitations. For example, in lower extremity rehabilitation, body-weight–supported treadmill training has been found to be effective for individuals with decreased sensorimotor control.[19,20] However, this type of treadmill training is labor intensive, requiring assistance from up to three therapists for walking. Robotic machines have been introduced to assist with this task and to, ideally, make this treatment more readily available to clients.[21] Similarly, for the upper extremity, robots have been created to assist with therapeutic training of the arm and shoulder.[22–25] Robotic devices have also been investigated as tools in upper extremity rehabilitation for chronic stroke survivors[20,24,26,27] in an effort to allow rehabilitation professionals to focus on functional independence and increased motor recovery for their clients. Research studies indicate that devices which incorporate intensive training of active repetitive movements increase upper extremity function following stroke.[20,28–30] However, few devices have been designed specifically for hand rehabilitation,[31,32] especially for stroke survivors with moderate to severe impairments.

Robots and mechatronics also provide a convenient interface with virtual reality environments. These virtual environments have been recently applied to rehabilitation paradigms for stroke survivors.[31,33–38] The use of virtual reality in rehabilitation affords the opportunity for individuals to practice movements in several different environments, allows rapid transition between tasks, and provides unlimited options for object size, type, and location. Researchers have previously integrated a hand actuator with a virtual reality system for the purposes of rehabilitation after stroke, but the hand actuator was intended for individuals with relatively mild impairment and could not be used with real objects.[33,34,36–38]

In previous studies, we have found that individuals with moderate to severe chronic hemiplegia subsequent to stroke have directionally dependent weakness, such that finger extension is impaired to a greater extent than finger flexion.[39] Thus, we have developed two devices to assist finger extension when needed: a portable, cable orthosis (CO) with which the user could provide self-assistance, and a pneumatic orthosis (PO) that could provide automatic assistance. These devices were integrated with a virtual reality system. The purpose of this study was to explore whether repetitive practice with finger extension assistance could improve hand function in stroke survivors with moderate to severe upper extremity hemiparesis.

Method

Participants

A total of 15 adult participants (at least 1 year post stroke) with an average baseline Fugl-Meyer[40] score of 24 (see **Table 1**) volunteered to take part in this study. Participants had chronic upper extremity hemiparesis due to a stroke (7 ± 9 years post injury) and were classified as stage 2–3 on the Hand Subscale of the Chedoke McMaster Stroke Assessment, meaning that participants had some active finger flexion but no or less than half range of finger extension.[41] Participants had no severe cognitive limitations, had not received botulinum toxin in the previous 6 months, and were not concurrently participating in any other upper extremity treatment programs. The Institutional Review Board of Northwestern University (Chicago, IL) approved the protocol prior to use, and participants signed informed consent to enroll in this study after meeting inclusion criteria.

Intervention

Participants were randomly assigned to one of three groups: cable orthosis (CO), pneumatic orthosis (PO), or control. Participants in the CO and PO groups used devices to assist hand open-

Table 1. Characteristics of stroke survivors (*n* = 15)

Group & subject	Age (years)	Gender	Time post-stroke (years)	Impaired side	Handedness	UE Fugl-Meyer score
Control						
1	42	M	4	R	L	23
2	60	M	9	R	L	20
3	58	M	3	L	R	34
4	68	F	38	L	R	27
5	50	F	2	L	R	22
Cable orthosis						
1	64	M	12	L	R	NA
2	57	F	2	R	R	14
3	32	M	2	R	R	37
4	56	F	9	L	R	47
5	56	F	7	L	R	14
Pneumatic orthosis						
1	75	M	5	R	R	29
2	76	M	9	R	R	27
3	88	M	1.25	L	R	8
4	50	M	3	L	R	13
5	69	F	4	R	R	16
Mean ± *SD*	60 ± 14		7 ± 9			24 ± 11

Note: UE = upper extremity; M = male; F = female; L = left; R = right; NA = not available.

ing. The CO and PO were designed with the basic goals of assisting gross (simultaneous) extension of all of the digits while minimizing weight and maximizing the workspace of arm postures in which they could be used. The CO uses basic prosthetics technology. Five cables (SpiderWire, Spirit Lake, IA) traverse the back side of the hand. Each cable is attached to the tip of a digit on a glove and runs through cable guides attached to a glove (see **Figure 2**). The five cables are conjoined at the wrist to form a single cable that travels through a standard arm cuff to a figure-of-eight shoulder harness through metal cable housing (**Figures 1** and **2**). Either combined biscapular abduction and glenohumeral flexion of the shoulders or elbow extension pulls on the single cable, thereby causing the five digits to extend simultaneously. Our measurements showed that the cable displacement necessary to move from full flexion to full extension was quite similar across the digits (within a couple of millimeters), so a single actuator was feasible. This type of body-powered control has generally proven easy to use and is the most common control employed by adult prosthetic users.[42]

In this manner, the user is able to directly control the amount of assistance provided. Feedback about cable force is generated and is continuously available through interactions with the harness. Additionally, external feedback was provided by directly measuring cable tension with an in-line force sensor (Sensotec, Columbus, OH) spliced into the cable between the cuff and harness (see **Figure 1**). This information can either be displayed graphically on a computer monitor or be provided as an audial cue.

An externally powered system was also developed. The PO consists of a glove containing a single chamber air bladder (Vinyl Technologies, Inc., Monrovia, CA) with five channels mirroring the shape of the hand (**Figure 3**). This bladder is sewn onto the palmar side of a nylon/lycra glove, which has a zipper on the back side to ease donning of the glove. Inflation of the air bladder forces straightening of the bladder channels, thereby assisting in

Figure 1. Back view of cable orthosis showing figure-of-eight harness (1), in-line load cell (2), and cable (3).

Figure 2. Side view of cable orthosis showing upper arm cuff (1), forearm cuff (2), cable housing (3), and cable guides for fingers (4).

extension of the digits. Open cell foam was inserted into each of the channels to prevent kinking of the channels, which could impede inflation.

Pressure is provided as needed to assist finger extension under feedback control. An electro-pneumatic servo valve (Pressure Control Valve, QB02005; Proportion-Air, McCordsville, IN) regulated pressure between 0 and 41 kPa under control of custom software, written in Visual Basic, running on a personal computer. The servo loop

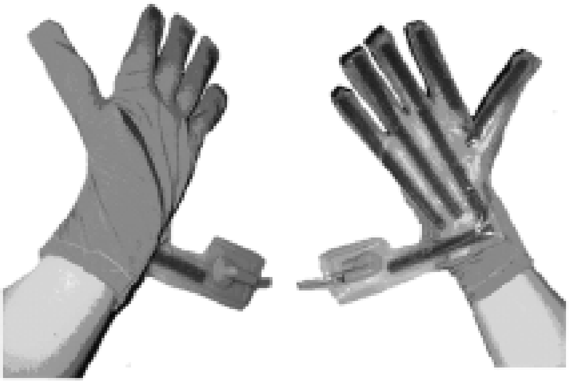

Figure 3. Pneumatic hand orthosis. Left: dorsal view. Right: palmar view.

regulated joint angle, continuously monitored with electro-goniometers (F35; Biometrics, Ladysmith, VA).

Two electro-gonimeters were used; one was placed over a proximal interphalangeal (PIP) joint and one was placed over a metacarpophalangeal (MCP) joint. As all digits were to move in synchrony, the PIP and MCP measurements were assumed to be representative of all of the joints. The therapist chose the PIP and MCP joints of the digits either with poorest extension or of greatest interest.

The training paradigm consisted of 6 weeks of therapy, with 1-hour sessions held three times per week for a total of 18 training sessions. Each session was comprised of a total of 30 functional grasp-and-release tasks involving a mixture of virtual objects and actual objects.[15] The virtual objects permitted manipulation without the weight or stability constraints that might hamper interaction with real objects, while the actual objects provided sensory input. The participant viewed the virtual objects through a PC Glasstron® head-mounted display (PLM-S700; SONY Electronics, Inc). The Glasstron display permits augmented reality, meaning that it allows the participant to see his/her own hand along with the virtual object. The virtual environment consisted of a room with a table and other fixed objects to provide visual cues to depth and a functional context. Within the virtual scene, mobile objects were presented for practice of grasp and release. The virtual environment was generated using CAVE Library (VRCO, Inc., Virginia Beach, VA). Head position was monitored using a magnetic sensor (Flock of Birds; Ascension Technology, Burlington, VT) such that the virtual scene could be continuously updated.

Objects of various size and shape were randomly presented in both the virtual and actual environments, and participants attempted to reach to the object and then grasp, move, and release it. In the virtual environment, successful acquisition of the object was judged based on hand location and posture. A magnetic tracker (Ascension Technology) worn on the wrist provided hand position and orientation within the virtual room. Either the electro-goniometers or visual inspection by the therapist conducting the training determined whether the hand was sufficiently open to grasp the object. When the hand was in the proper location with appropriate digit extension, the virtual object became attached to the hand. The virtual object subsequently moved with the participant's hand until the participant attempted to release the object and the therapist issued a release signal to the computer.

The CO group received assistance in hand opening from the orthosis. They were instructed to provide their own assistance in order to sufficiently open the hand to grasp the object but to try to minimize the amount of assistance. Audial feedback of cable tension was provided to the subject, and tension values were recorded on a PC for future reference.

The PO group received assistance in accordance with the known size of the object. The joint angles needed to accommodate the given object dimensions were computed assuming that the desired motion of the fingertips followed stereotypical trajectories similar to those observed in neurologically intact individuals.[43] For the actual objects, once grasp posture was achieved, the air pressure was released to permit grasping of the object. Without air pressure, the PO does not impede motion of the joints.

The control group performed the grasp-and-release of the virtual and actual objects but without any assistance of hand opening. Participants in each group received audio feedback (applause) according to the level of activity in extensor digitorum communis, as recorded from a surface electrode using electromyography (Delsys Inc., Boston, MA).

Evaluation

Evaluations occurred prior to, following, and 1 month after the 6-week training program. Outcome measures included range of motion, strength, and observation of functional task performance through standard clinical measures. An occupational therapist assessed each participant's ability to actively move the upper extremity into different positions with the Upper Extremity portion of the Fugl-Meyer Motor Assessment (FM)[40] and the Chedoke-McMaster Hand Scale.[41] The Chedoke McMaster Stroke Assessment consists of a seven-stage rating scale corresponding to seven stages of motor recovery, which follow a stereotypical course according to Brunnstrom's theory.[44] The FM scale is a test of motor performance consisting of 32 items based on the authors' observations of a definable motor recovery following hemiplegia. The clinician also evaluated total time to perform tasks with the affected upper extremity using the Wolf Motor Function Test (WMFT)[45] and Rancho Los Amigos Functional Test of the Hemiparetic Upper Extremity (RLA).[46] The WMFT consists of a series of tasks (e.g., lift your elbow on top of a box, slide your hand to a point on a table, grasp and stack checkers) with joint-based criteria for successful completion of each task. The RLA focuses more on completion of everyday tasks involving the impaired limb (e.g., zipping a jacket, placing a pillow in a pillowcase) with task-based criteria for completion. The ability of the participant to grasp-and-release objects was assessed with the Box and Blocks (BB) Test.[47] Grip strength was measured using a dynamometer (JAMAR Hydraulic Hand Dynamometer, 5030J1; Sammons Preston, Bolingbrook, IL).

Mechanical measurements such as spasticity, isometric strength and velocity, and range of motion (ROM) were measured using a hand manipulator system.[48] A fiberglass cast was placed around the wrist and secured to a table with clamps to fix forearm pronation/supination, wrist flexion/extension, and wrist ulnar/radial deviation in neutral. The hand was positioned above the servomotor of the system such that rotation of the motor shaft produced equivalent rotation of the four MCP joints. Torque, angular position, and angular velocity of the MCP joints were recorded during the trials.

The servomotor was programmed to produce a number of conditions for testing. Spasticity was assessed using constant-velocity rotation of the MCP joints. The corresponding joint torque was recorded to permit quantification of the level of spasticity. The servomotor moved the MCP joints from flexion into extension at either 10°/s, a speed sufficiently slow to preclude generation of a stretch reflex, or 300°/s, a speed sufficiently fast to elicit a stretch reflex in participants with spasticity.[49] Five trials were recorded at each speed. Peak isometric torque generation was then tested at two MCP angles, 0° and 30°, of MCP flexion. The servomotor maintained the desired angle as the participant attempted to produce both maximal MCP flexion and extension torque. Active range of MCP motion and peak velocities were recorded during trials in which the participant was instructed to open the hand as fast and as far as possible, from an initially flexed posture, while the manipulator maintained a no-load state.

Analysis

For the mechanical measures, the torque, angle, and velocity data were low-pass filtered at 150 Hz prior to sampling at 500 Hz. All of the data were digitally low-pass filtered at 10 Hz using a 30th-order finite impulse response filter. Spasticity was quantified by examining the magnitude of the velocity-dependent torque. The nominally passive torque from the slower 10°/s rotation was subtracted from the torque recorded at the faster 300°/s rotation to obtain the velocity-dependent torque. Average velocity-dependent torque during the stretch and subsequent 2-second hold phase was computed. For the isometric trials, peak voluntary torque was determined for each trial. For the movement trials, peak MCP extension and velocity and displacement were found for each trial.

For the clinical assessments, the time to complete each task was averaged across all of the tasks to obtain a single value for both the WMFT and RLA. A total upper extremity score was computed for the FM, and the number of blocks successfully

Table 2. Group values for pre, post, and follow-up outcome measures

Evaluation measures	Session	Control Mean (±*SD*)	CO Mean (±*SD*)	PO Mean (±*SD*)
WMFT time (seconds)	Pre	86.1(±32.2)	76.4 (±37)	92 (±36.4)
	Post	79.9 (±38.8)	74.7 (±37.5)	79.1 (±34.2)
	F/U	73.9 (±31.9)	75.8 (±34.7)	76.1 (±37.2)
BB number of blocks	Pre	0 (±0.4)	3 (±5.3)	4 (±7.1)
	Post	2 (±3.6)	5 (±7.1)	3 (±6.6)
	F/U	3 (±1.9)	4 (±9.4)	4 (±8.3)
FM total score	Pre	25 (±5)	28 (±17)	19 (±9)
	Post	28 (±7)	32 (±11)	18 (±10)
	F/U	28 (±5)	29 (±15)	20 (±11)
RLA time (seconds)	Pre	44.9 (±12)	51.5 (±18.3)	65.7 (±15.5)
	Post	33.1 (±13.8)	40.5 (±19.1)	58.9 (±37.7)
	F/U	39.8 (±16.2)	38.9 (±19.6)	63.7 (±46.8)
Normalized grip strength	Pre	0.22 (±0.05)	0.18 (±0.08)	0.21 (±0.1)
	Post	0.27 (±0.13)	0.20 (±0.09)	0.20 (±0.1)
	F/U	0.26 (±0.05)	0.19 (±0.09)	0.25 (±0.1)
Spasticity (N-m)	Pre	0.7 (±0.5)	0.9 (±0.5)	1.2 (±0.8)
	Post	0.6 (±0.5)	1.2 (±0.7)	1.3 (±1.0)
	F/U	0.6 (±0.7)	0.7 (±0.5)	1.7 (±1.3)
Isometric flexion (N-m)	Pre	1.7 (±1.3)	2.5 (±1.8)	2.5 (±1.6)
	Post	2.0 (±1.3)	2.4 (±1.4)	2.8 (±1.5)
	F/U	1.6 (±1.3)	2.2 (±1.5)	2.9 (±1.5)
Isometric extension (N-m)	Pre	0.2 (±0.4)	0.2 (±0.3)	0.3 (±0.6)
	Post	0.2 (±0.3)	0.1 (±0.2)	0.3 (±0.6)
	F/U	0.2 (±0.3)	0.2 (±0.3)	0.3 (±0.6)
Peak extension velocity (degree/second)	Pre	20.5 (±19.1)	11.1 (±11.8)	33.5 (± 45.2)
	Post	17.7 (±22.4)	19.6 (±28.0)	28.3 (±43.2)
	F/U	15.4 (±11.4)	15.1 (±20.4)	35.1 (±35.2)
Extension ROM (degrees)	Pre	5.6 (±7.5)	2.0 (±2.4)	10.9 (±15.5)
	Post	5.3 (±6.9)	4.8 (±9.0)	9.8 (±14.9)
	F/U	5.8 (±6.8)	2.8 (±3.3)	12.1 (±11.6)

Note: *SD* = standard deviation; F/U = follow-up; WMFT = Wolf Motor Function Test; BB = Box and Blocks Test; FM = Fugl-Meyer; RLA = Rancho Los Amigos Functional Test of the Hemiparetic Upper Extremity; ROM = range of motion; N-m = Newton-meter.

transferred was averaged across the three trials for the BB test. Grip strength for the impaired hand was normalized by the grip strength for the hand ipsilateral to the lesion.

Repeated measures analysis of variance (ANOVA) statistical tests were performed for the dependent variables of interest using SPSS software (SPSS Inc., Chicago, IL). The within-subject variable was evaluation session (pre, post, and follow-up), and the between-subject variable was subject group (CO, PO, control).

Results

Fifteen adult participants completed the study: 5 CO, 5 PO, and 5 controls. Two participants with-

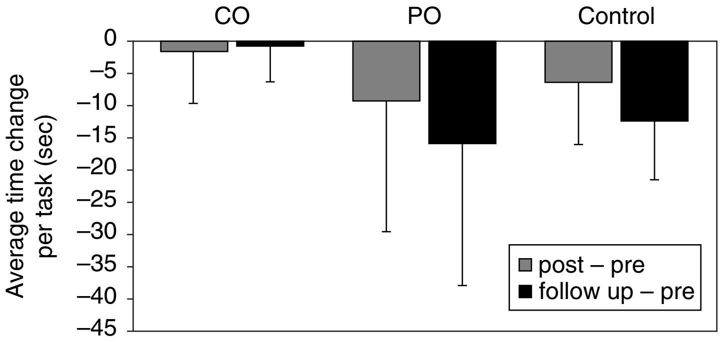

Figure 4. Test results from the Wolf Motor Function Test showing decreases in time between pre and post evaluations and pre and follow-up evaluations (p = .02). Error bars indicate 1 *SD*.

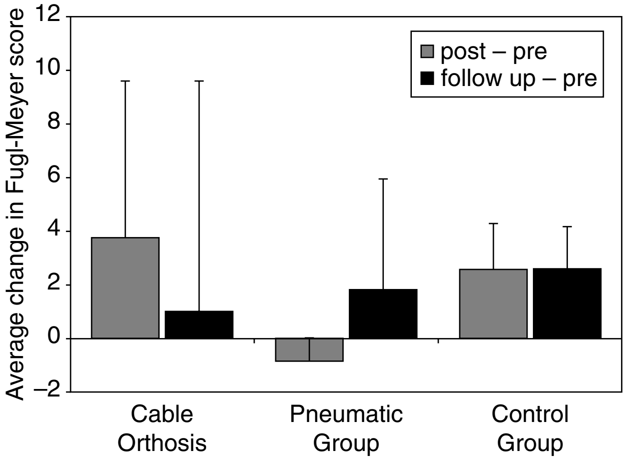

Figure 5. Fugl-Meyer test scores showing the differences in performance at pre, post, and follow-up evaluations (p = .08). Error bars indicate one standard deviation.

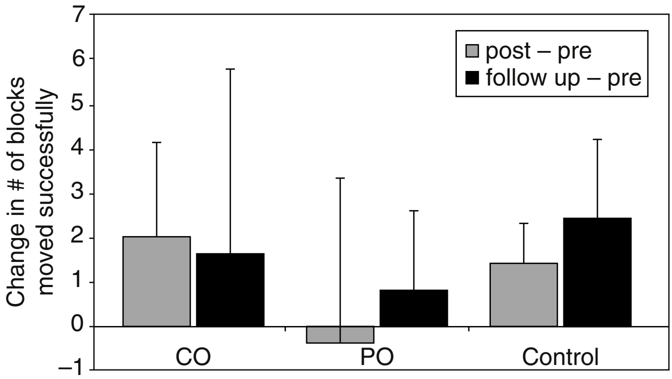

Figure 6. Box and Blocks Test results showing the change in performance between pre and post evaluations and pre and follow-up evaluations (p = .09). Error bars indicate 1 *SD*.

drew from the study; one withdrew for health reasons and the other chose not to continue after the first session. Average values and standard deviations per group for measurements from pre, post, and 1-month follow-up sessions are presented in **Table 2**.

There were no significant changes for normalized grip strength, isometric flexion, isometric extension, peak extension velocity, or extension ROM across evaluation sessions or for session-group interactions ($p > .20$). Initial maximum MCP flexion torque was roughly 10 times greater than initial extension torque across participants, and this changed little after training. The CO group showed a slight (nonsignificant) increase in active MCP extension after training (2.8°), but this was largely dissipated at the 1-month follow-up. Training did not lead to any change in spasticity ($p > .20$).

Across participants, there was a significant decrease in time to perform functional tasks for the WMFT ($p = .02$; see **Figure 4**). Average time for task completion decreased from 84.9 seconds pre training, to 77.9 seconds post training, to 75.3 seconds at 1-month follow-up, demonstrating a 10-second decrease. The increase for the upper extremity FM score (**Figure 5**) approached significance ($p = .08$). Scores increased from 23 pre training to 25 post training and 25 at 1-month follow-up (out of a total of 66). This increase demonstrates 3% of the total score. The increase in the number of blocks successfully grasped and released during the BB test (**Figure 6**) approached significance ($p = .09$). Number of blocks increased from two at pre to three at post and four at 1 month. This two-block increase represents only 5% of the average (45) blocks retrieved with the ipsilesional hand. There were no statistically significant changes in time to complete tasks on the RLA, and there were no significant differences among the groups.

Discussion

Fifteen stroke survivors with chronic hemiparesis completed the grasp-and-release training integrating virtual reality with mechatronic devices to assist hand opening. Specifically, we compared self-assistance (CO) with automated assistance (PO). We did not incorporate resistance training into the protocol as the ability of the participants to extend was either very weak or nonexistent. Overall, the responses to the orthoses and the virtual reality were positive. Despite the flexion tone and flexed hand posture of many of our participants, they were able to utilize the orthoses and to move the arm while wearing them. Of the two participants who withdrew, one was compelled to do so for unrelated health issues while the other elected not to continue participation after the first session.

Across groups, we observed small yet significant gains in task performance, as measured with the WMFT. These improvements following repetitive, active use of the affected limb suggest functional adaptation of the nervous system even in the chronic stages of stroke. In addition, participants were able to generalize learning from the grasp-and-release tasks of the training paradigm to performance of functional tasks in the clinical evaluations. However, no significant change was seen in the biomechanical measurements of hand performance, such as active finger extension or torque generation. This disparity suggests that improvement may have resulted primarily from the development of new movement strategies or from improvement in proximal arm control, not from improvements in finger extension or strength. Additionally, there were no statistically significant differences among groups.

The gains that were observed were quite modest. The 2-point increase in upper extremity FM scores was less than the 3- to 5-point increases reported in other studies of robotic or constraint-induced training.[25,28,29,50–52] Our participants, though, typically had somewhat greater initial impairment, with minimal active finger extension. Additionally, these studies specifically addressed arm movement, which constitutes a large portion of the FM scale.

One study of similarly impaired participants did report large gains (15 points) in FM after training, but the participant's population was in a subacute phase, only 4 to 8 weeks post-stroke.[30] For our participants, the average time post-stroke was 7 years. It is interesting to note that when the same mechatronic device used in that study was employed in a prior study with participants who had chronic hemiparesis, the observed change in Rivermead Motor Assessment was minimal.[20]

Thus, it may be important to target participants for training while they are still in the subacute phase.

That study also emphasized massive practice of simple tasks, namely 800 repetitions of forearm pronation/supination or wrist flexion/extension per session. Due to the taxing nature of the reach-to-grasp tasks of our study, only 30 repetitions were performed during each session. The intensity of this training program may not have been sufficient to induce changes in hand function. The reaching demands may have overshadowed the hand rehabilitation. Although task-oriented rehabilitation seems to be beneficial,[4] greater repetition of simplified tasks may be preferable for moderately to severely impaired stroke survivors.

Our experiences suggest important modifications to the current system before a larger trial is undertaken. Participants were generally enthusiastic about the incorporation of virtual reality into the training. The virtual reality system did provide faster transition between tasks and provided more opportunity to practice grasp of objects not readily available in a traditional treatment setting. However, the limited field of view for the Glasstron head mounted display (28° about the horizontal plane) was an issue for some. A number of participants had trouble independently controlling the neck and the shoulder, so it was difficult for them to lift their arm while still looking down to see their hand and the virtual object. A different head-mounted display with a much wider field of view could reduce the demands on motor control of the neck to position the eyes. Donning the CO was cumbersome. As few participants could actually use elbow extension to generate hand opening, the device could be simplified by eliminating the arm cuffs, which also had a tendency to slide. With modifications, it could be made available for home use.

The current PO provides equal pressure to all of the fingers during hand opening and measures only two joints of the hand. Introduction of independently controlled air bladders for each digit has the potential to provide more precise feedback of hand function to the clinician and the client during task performance. Additionally, the tubing and cables from the glove are also cumbersome during task performance and may limit the client's performance.

Both devices incorporate gloves that change the sensory stimuli that one would normally experience. There could be both a reduction in sensory input from external objects and a potentially undesirable increase in stimuli across the palm or dorsum of the hand. A recently completed study, however, showed no impact of cutaneous stimuli on either the dorsal or palmar surface of the hand on spasticity.[53]

In summary, we believe that it is feasible to incorporate mechatronic devices and virtual reality into rehabilitative hand training, even for individuals with severe hand impairment following stroke. Efficacy of these devices, however, remains to be shown in a severely impaired population. For participants at this level, it may be necessary to enhance compensatory skills or incorporate assistive devices rather than focusing on restoring motor control.

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