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Arm control recovery enhanced by error augmentation

Farnaz Abdollahi, Sylvester V. Rozario, Robert V. Kenyon, James L. Patton
University of Illinois at Chicago
Chicago, IL, U.S.A.

Emily Case, Mark Kovic, Molly Listenberger, James L. Patton
Sensory Motor Performance Program
Rehabilitation Institute of Chicago
Chicago, IL, U.S.A.

***Abstract*—Here we present results where nineteen stroke survivors with chronic hemiparesis simultaneously employed the trio of patient, therapist, and machine. Massed practice combined with error augmentation, where haptic (robotic forces) and graphic (visual display) distortions are used to enhance the feedback of error, was compared to massed practice alone. The 6-week randomized crossover design involved approximately 60 minutes of daily treatment three times per week for two weeks, followed by one week of rest, and then repeated using the alternate treatment protocol. A therapist provided a visual target using a tracking device that moved a cursor in front of the patient, who was instructed to maintain the cursor on the target. The patient, therapist, technician-operator, and rater were blinded to treatment type. Several clinical measures gauged outcomes at the beginning and end of each 2-week period and one week post training. Results showed incremental benefit across most but not all days, abrupt gains in performance, and a benefit to error augmentation training in final evaluations. This application of interactive technology may be a compelling new method for enhancing a therapist's productivity in stroke-rehabilitation.**

Keywords- human stroke rehabilitation therapy; robotics control; virtual reality; error augmentation; biofeedback; arm reaching; hemiparesis

I. INTRODUCTION

Recent research points to intensive therapy, or "massed practice," for functional recovery after stroke [1-3]. Research also shows that "task-specific" retraining provides better overall improvement for the upper extremity, in which activities of daily living (ADLs) are practiced [3-5] and training on a variety of tasks are used [6, 7]. Because of these diverse requirements, employing technology to help in this process is not simple. In several studies, interactive technology has helped restore function to patients through repetitive training [8-13]. However, the question remains whether technology-facilitated training can provide superior improvements compared to simple massed practice.

Recent studies on prolonged adaptive training in the presence of appropriately designed visual distortions [14-16] or mechanical distortions [17-20] are ways to use this technology to foster beneficial changes in movement ability of stroke survivors. However, there is a clear need for clinical studies to examine the benefit these methods might offer beyond standard simple massed practice performed without such enhanced technology.

Among these techniques, a promising form of robotic training that leverages our understanding of neuro-plasticity is *error augmentation* [18, 19, 21]. In this paradigm the computer measures and magnifies the subject's movement errors from a desired trajectory, thus attempting to force the subject to strengthen his/her control. This magnification of movement error is sometimes counterintuitive and differs greatly from the standard level of care. However, such error-driven learning processes that are stimulated by this procedure are believed to be central to the neuroplasticity and acquisition of skill in human movement [22, 23].

One difficulty in implementing error augmentation is that during complicated functional 3-dimensional (3D) activities of the patient, the computer-controller must make an assumption of what the desired (or intended) trajectory of the subject is for each movement, which can be difficult to presume during independent practice. The solution we present in this study employs the therapist to specify the "presumed" trajectory in real time. This also allows the therapist to customize his/her therapeutic approach, focusing on what is critical for a particular patient's recovery (speed, range of motion, accuracy of movement, and access to environment).

In this paper, we present initial clinical results when using error augmentation on individuals with chronic stroke. We hypothesized that the error augmentation treatment phase with haptic and visual error augmentation in combination with massed practice would lead to the best functional recovery, and this blinded, 6-week randomized crossover study revealed a significant benefit of massed practice with error augmentation over massed practice alone.

II. METHODS

A. Participants

Nineteen participants (10 male and 9 female) were recruited from a Database of Stroke Patients at the

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Rehabilitation Institute of Chicago and from respondents to flier postings in the Chicago area. All participants were consented using approved IRB and university guidelines for protection of human participants and confidentiality protection of personal health information. Participants were aged 36 to 88 (mean age 59 ± 11). Participants' characteristics are summarized in Table I.

TABLE I- PARTICIPANT DEMOGRAPHICS

Subject ID	Age	Hand Dominance	Pathology	Affected Side	Months Post Stroke	Body Height (m)	Body Mass (kg)	Pre UE Fugl-Meyer Total
001	57	R	Ischemic	R	17	1.99	88.5	42
002	36	R	Ischemic	R	26	1.75	87.1	39
003	54	L	Ischemic	R	63	1.78	92.1	45
004	59	R	Hemmorhagic	R	61	1.71	76.2	41
005	69	R	Ischemic	R	236	1.52	62.1	26
006	65	R	Ischemic	R	25	1.70	83.9	41
007	57	R	Hemmorhagic	R	259	1.70	75.7	26
008	63	R	Hemmorhagic	R	158	1.68	77.1	17
009	88	R	Ischemic	R	205	1.60	54.4	26
010	54	R	Ischemic	R	21	1.60	88.5	50
011	51	R	Ischemic	R	19	1.68	81.6	36
012	61	R	Hemmorhagic	R	81	1.60	65.8	19
013	65	R	Ischemic	R	56	1.60	77.1	44
014	47	L	Ischemic	R	6	1.80	101.6	46
015	58	R	Ischemic	R	43	1.75	82.6	40
016	58	R	Hemmorhagic	L	157	1.45	58.1	22
017	63	R	Ischemic	L	92	1.63	72.6	24
018	69	R	Ischemic	L	141	1.80	100.2	13
019	45	R	Hemmorhagic	R	32	1.91	86.2	21
Mean	59				89	1.70	79.5	33
Min	36				6	1.45	54.4	13
Max	88				259	1.99	101.6	50

a. n =19

Participants were included if they were an adult (age >18), survived a single cortical stroke at least 6 months previously involving ischemia or hemorrhage of the middle cerebral artery (MCA), and demonstrated the presence of some active shoulder and elbow movement characterized by Arm Motor Fugl-Meyer (AMFM) scores in the range of 15 to 50. Exclusion criteria included diffuse or multiple lesion sites or multiple stroke events, bilateral paresis, severe spasticity or contracture (Modified Ashworth ≥3), severe concurrent medical problems, severe sensory deficits, severe ataxia, significant shoulder pain, Botox injection to the hemiparetic upper extremity (UE) within the previous four months, cognitive impairment (Mini Mental State Examination < 23/30) or affective dysfunction that would influence the ability to perform the experiment, depth perception impairment (< 3 on Stereo Circle Test), visual field cut or severe inattention that would influence the ability to participate in the activity, and the inability to provide informed consent. Initially, participants were excluded if they received any other skilled upper extremity rehabilitation in a clinical setting; however, we discovered that one participant did receive some outpatient therapy during enrollment in the study, yet we decided to include that individual in the analysis because values did not appear to differ.

B. Apparatus

We used a three-dimensional haptics/graphics system called the Virtual Reality Robotic and Optical Operations Machine (VRROOM) [24]. VRROOM is the union of a robotic system that can record wrist position and generate a force vector with a semi-immersive head-tracked virtual reality system providing 3D stereovision of the virtual environment (PARIS) [31] (See Figure 1). VRROOM allows practice of a variety of large, functional or pre-functional movements within a virtual environment, allowing both therapist and patient to work side-by-side. Open-source haptics software (H3D) package was used to program the haptics and graphics environment. A cinema-quality digital projector (Christie Mirage 3000 DLP) displayed the images that span a five-foot-wide 1280x1024 pixel display, resulting in a 110º wide viewing angle. Stereo images were provided using infrared emitters synchronizing separate left and right eye images through Liquid Crystal Display (LCD) shutter glasses (StereoGraphics, Inc). An Ascension Flock of Birds magnetic tracking system provided head position so that the visual display was rendered with the appropriate head-centered perspective. A 6-degree-of-freedom PHANTOM Premium 3.0 robot (SensAble Technologies), capable of generating 3 Newtons (N) with transient peaks of 22 N, provided forces over a workspace measuring approximately 0.9 x 0.9 x 0.3m. Since holding a robot handle may not be the same as free hand motion [25, 26], and since a large percentage of stroke patients have difficulty elevating their involved extremities against gravity as well as opening and closing their hand [27], we provided arm anti-gravity support and connected the robot near the wrist to allow the hand to open freely as well as pronate and supinate.

C. Experimental Protocol

We tested two experimental treatments in a crossover design: each participant received, in random order, a control treatment of massed practice with no error augmentation called the ***control treatment phase*** and an error augmentation treatment with the same amount of practice

but with combined visual and haptic error augmentation called the ***error augmentation (EA) treatment phase***.

Figure 1- Therapist(right), patient(left) demonstrating experimental set up

Each phase consisted of two weeks of training with participants receiving three, 60-minute treatment sessions per week (six sessions per phase). Each session began with five minutes of passive range of motion (PROM) and about ten minutes for setup and then five-minute blocks of movement training in random order with two-minute rest periods. The treatment protocol included the practice of specific movements for all participants; including forward and side reaching, shoulder-elbow coupling, and diagonal reaching across the body. Alternate treatment blocks consisted of customized training for each participant targeted at specific areas of weakness determined by the therapist based on the previous five-minute block (See Table II). Evaluations were performed at the beginning and end of each treatment phase as well as a week after for follow-up. Sandwiched between the two phases of treatment, participants received a one-week rest (See Table III).

TABLE II- SESSION LAYOUT

PROM	Setup	Activity 1	Rest	Custom Activity 1	Rest	Activity 2	Rest	Custom Activity 2	Rest	Activity 3	Rest	Custom Activity 3

During both treatment phases, participants were seated in a chair with the hemiparetic arm supported by the Wilmington Robotic Exoskeleton (WREX) gravity-balanced orthosis [28]. The hand was placed in an exotendon glove with a wrist splint, which assisted with hand opening and neutral wrist alignment to facilitate a more functional position. The WREX wrist support swiveled with forearm movement to allow pronation and supination during training. The PHANTOM robot was attached to the forearm with the center of the handle located above the radiocarpal joint. The robot only applied forces during the EA treatment phase; however, it was attached during both phases to assist in blinding the participant and treatment therapist as well as provide feedback regarding location within the 3D workspace.

TABLE III- EXPERIMENT LAYOUT

Evaluation	Treatment 1	Evaluation	Rest Week	Evaluation	Treatment 2	Evaluation	Rest Week	Follow up

During training, participants viewed two cursors on the stereo display. The treating therapist manipulated one cursor while the participant controlled the other cursor. Participants were instructed to follow the exact path of the therapist's cursor as it moved throughout the workspace. During the EA treatment phase, error augmentation was provided both visually and by forces generated by the robot. When participants deviated from the therapist's cursor, the error vector $\boldsymbol{e}$ was established as the instantaneous difference in position between the therapist's cursor and the participant's hand. Error was visually magnified by a factor of $1.5\boldsymbol{e}$ (m) as part of the error augmentation. Additionally, we applied an error augmenting force of $100\boldsymbol{e}$ (N/m), with the maximum limited to 4 N.

D. Evaluation Procedure

Subjects were tested immediately prior to the start of each treatment phase and again upon completion of the same phase. Follow-up testing was also performed one week after each treatment phase ended. A single blinded rater performed the following clinical assessments:

Free reaching ability was characterized by measuring a range of motion (ROM) reach value, which required subjects to use the impaired hand to reach 54 fixed targets throughout the workspace. This was assessed using data obtained with the Flock of Birds 3D electromagnetic motion capture system and the Phantom described earlier. Reaching ROM error was calculated as the linear distance between the position of the target and the final position of the cursor representing the subject's maximum reach in the direction of the target. Reach value was further calculated as the component of maximum reach made by the subject in the direction of the target normalized by the subject's arm length.

We use the Fugl-Meyer, specifically the arm motor function section, in this study as the main clinical outcome measure. The Fugl-Meyer Assessment is used to measure sensorimotor recovery from stroke and has proven to be a reliable and valid measure [32]. The arm motor section of the Fugl-Meyer (AMFM) is used to measure movement coordination and reflex action of the upper extremity. An individual completes a number of movements to determine his/her ability to move out of synergy patterns.

Other clinical tests utilized were the Wolf Motor Function Test (WMFT), Assessment of Simple Functional Reach (ASFR), and the Box and Blocks Assessment. The WMFT is a function-based motor assessment in which performance time of task, functional ability, and strength are documented. The test characterizes the motor status of subjects with chronic stroke and/or brain injury, and both reliability and validity are well established [32].

The ASFR was developed by therapists working on this study and has not yet been validated. It is a test which consists of reaching, grasping, and transporting a washcloth from four different locations in front of the participant at 75cm and 100cm in height. The time and success with reaching, grasping, and transporting the washcloth are recorded for each location.

The Box and Blocks Assessment has been found to be a reliable indicator of manual dexterity in which an individual grasps blocks and transports them over a partition in a box from one compartment to the other. The task is timed for 60 seconds. The goal is to move as many blocks as possible, testing both the unaffected and then affected arms.

III. Results

We chose to primarily analyze the improvement in the AMFM clinical score and ROM reach value as the main outcomes.

A. Range of Motion

Six of nineteen subjects showed significant improvement in ROM either immediately following treatment or at the follow-up phase of error-augmented treatment (See Figure 3A). Analysis of the ROM performance indicates a significant interaction effect between the sequence and type of treatment, from pre-treatment to follow-up ($p=0.04854$) and a moderate interaction effect from pre-treatment to post-treatment phase ($p=0.07056$). The p-values were generated using repeated measures ANOVA with the program R at the 10 percent level.

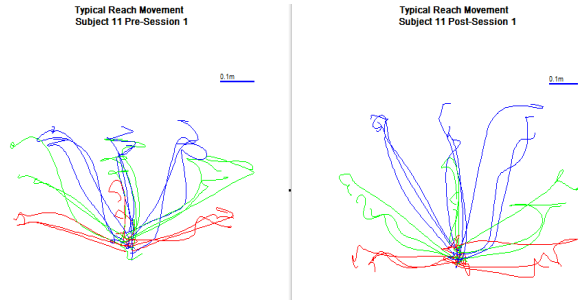

Figure 2- Reaching movement contrasting performance before (left) and after (right) error-augmented treatment session. Colors represent reach towards low (red), medium (green) and high (blue) level targets.

Typical reach movement by an individual subject (n=11) showing perceptible improvement in ROM of the impaired arm following error-augmented treatment phase is included as an example (See Figure 2).

B. Correlation with Clinical Measures

Error augmentation treatment elicited varied degrees of performance improvement as measured by the AMFM scores based on percentage change from pre-treatment base-line values to the follow-up evaluation (See Figure 3B). Control treatment on the other hand did not elicit any significant change. There was a marginal interaction effect between the type of treatment and the sequence of treatment given ($p=0.06792$). Other clinical measures showed no significant changes.

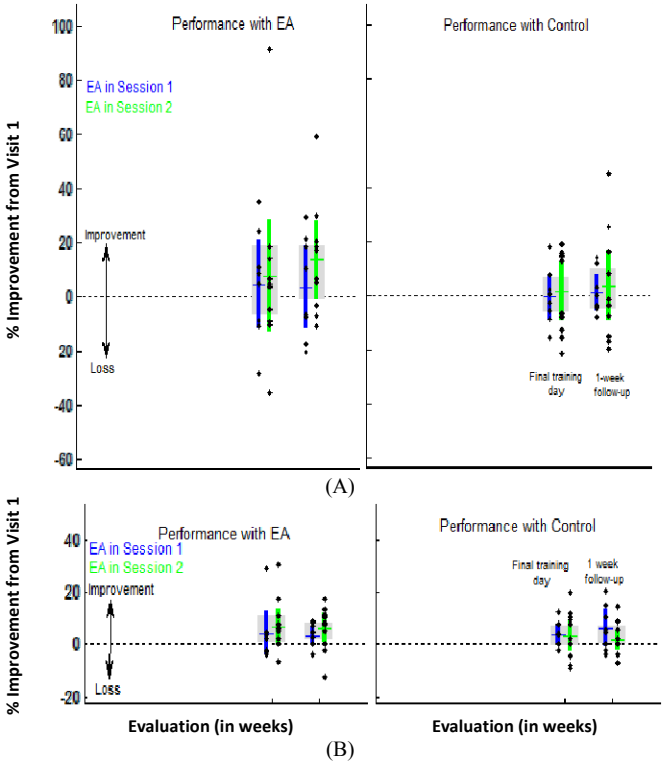

Figure 3- Reach value data grouped by condition (A), the 95% confidence intervals are shown as blue, green and grey bars. Individual data-points are overlaid. Fugl-Meyer scores are grouped and plotted with the same condition (B).

IV. Discussion

This blinded, 6-week randomized crossover study revealed a benefit of massed practice with error augmentation over simple massed practice. While ROM reach value and AMFM scores recorded percentage improvements when compared to the baseline, other clinical measures showed non-significant results.

The average gain in AMFM score of approximately 7 surpasses the minimal detectable change score of 5.2 found in the literature. This finding indicates that a real improvement in reaching performance occurred. However, this may not directly relate to an increase in function. The literature suggests a minimal clinically important difference score (i.e. enough change to be considered clinically meaningful) of 10 points. Since other clinical tests did not show significant change either, overall results indicate subjects may not have made any functional gains in the upper extremity. However, an increase in reaching performance is a critical precursor to improving function in everyday life tasks.

This study is one of the first to show clinical benefit of error augmentation that is superior to simple massed practice. However, we have exposed some boundaries on its effect on recovery. Although error augmentation shows significant signs of superior benefit over massed practice

alone, these benefits are quite modest. Clinicians may argue that the gains seen by subjects are in a range that is barely clinically meaningful. Even though the average AMFM gain was approximately 7, this does not indicate a removal of the majority of the motor deficit nor cause a direct link to increased function. Secondly, patients did not find the repetitive nature of the intervention particularly engaging. Several complained about the mundane, repetitive nature of the treatment while initially thinking that a virtual reality experience would be exciting despite the fact that they were informed that massed practice was precisely the goal. Thirdly, the glove and WREX, although placed in the experiment for good purposes, made the experience less than ideal because it increased setup time and some limitations in the usable workspace at the extreme locations. Future studies will attempt to assess the efficacy of such a system either without these added features or with modifications to them.

Because this study did employ blinding of investigators on all possible levels it provided a better test of the relative effect of a new software approach to therapy. The effectiveness of the blind was measured and showed no effect better than chance for any of the parties in ability to detect the blind. In fact, most were not concerned with trying to detect it. The robotic system enabled much of this ability by subtly applying error augmentation without any person involved being informed of the treatment. It is important to point out that in human therapy studies such blinding is not possible with the therapist. There was no way to determine whether the effects seen might be partly due to the placebo effect of the person believing there was some advantage to interacting with advanced technology for recovery. Nevertheless, the addition of haptic/graphic error augmentation appears to be superior to massed practice alone.

There appears to be clear benefit of this adaptive training paradigm that accumulates with repeated exposure. However, daily changes in performance from one day to the next that were not always an improvement, but were, on average, indicative of final clinical evaluations. These fluctuations could be attributed to gain or loss of capability as well to subjects experimenting with new strategies, exploring the limits of their abilities, temporarily loosing attention, or showing signs of fatigue. Clearly, while these within-training measures are important to inspect, one should judge these with great reservations. A better gauge of motor and functional recovery outcomes are in the evaluations pre to post training. Moreover, the most crucial outcome is the retention such benefits to the follow-up evaluations.

On average, subjects performed better in 1-week follow-up evaluations than they did at the end of the two weeks of training. This could be attributed to the fact that subjects were given only a 30-minute break before their evaluations at the end of the two weeks of training. Future work may dispense with this evaluation altogether, since the only clinically meaningful outcome is performance that persists.

The duration of training in this study is shorter than most published studies. The CIMT trial [1] for instance utilized two-week training periods with hours of intervention each day. Error augmentation combined with massed practice, however, shows some significant improvements during the ROM testing, and most importantly, there appear to be benefits of this adaptive therapist-mediated training paradigm that accumulates with repeated visits to the lab.

It is still not clear what underlying neurological mechanisms cause participants to respond to the error augmentation. It may be that the impaired nervous system does not react to nor does it try to learn from smaller errors, and the EA approach may promote learning by simply intensifying the signal-to-noise ratio for sensory systems, making errors more noticeable. Moreover, models of learning suggest that at least one mechanism of learning is driven by error [22, 29, 30]. The approach might also simply heighten motivation and/or attention.

While many mechanisms are not yet clear, this study provides early, practical, clinical evidence that can point to future studies that exploit the natural adaptive tendencies in the nervous system for restoring movement. In contrast to other robotic therapies that reduce or eliminate the role of therapists, this approach incorporates a skillful therapist working with the patient and a machine for a mode of therapy that has never been possible before. This and other unique applications of haptic/graphic environments can leverage therapists' skills to increase motivation, address specific needs, focus on individual goals, and enhance the overall rehabilitation experience for a variety of patients.

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