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Improving fine motor function after brain injury using gesture recognition biofeedback

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***Purpose*: We developed a gesture recognition biofeedback (GRB) device for improving fine motor function in persons with brain injury using surface muscle pressures of the forearm to provide real-time visual biofeedback. The GRB apparatus is easy to don by moderately impaired users and does not require precise placement of sensors. *Method*: The efficacy of GRB training with each subject was assessed by comparing its effectiveness against standard repetitive training without feedback. The outcome was measured using a nine-hole peg test (HPT) administered before and after each condition, in a cross-over study design. *Results*: GRB was shown to be effective for short-term improvement of fine motor function of 12 impaired participants, reducing their average time to completion of the HPT by 15.5% (S.D. 7.14%). In a subset of impaired subjects, this effect was significant in comparison to similar training without biofeedback ($p < 0.05$). Control subjects experienced negligible change in HPT time. *Conclusions*: This pilot study of a heterogeneous group shows that GRB may offer a simple means to help impaired users re-learn specified manual tasks.**

Keywords: Biofeedback, brain injury, fine motor control, grasp, stroke

Implications for Rehabilitation

- Grasp Recognition Biofeedback (GRB) is a novel technology for biofeedback in fine motor function.
- Surface Muscle Pressure in the forearm is used to record hand activity and give simple, real-time feedback.
- In a relatively small sample, training with GRB yields short-term improvements in brain-injured subjects.

Introduction

Grasping is fundamental to activities of daily living (ADL) and is usually impaired following stroke and traumatic brain injury [1]. In the absence of grasping, the impaired arm tends to be neglected, retarding its recovery [2]; accordingly, grasp training is a high priority for rehabilitation of the upper limb [3,4].

Repetitive training tasks are often difficult for brain-injured individuals, due not only to their motor deficits, but also to their tactile and proprioceptive deficits [5]. Although there are reports in the literature of inconclusive evidence [5], many studies have documented the efficacy of electromyographic (EMG) biofeedback [6]. For example, a group of hemiplegic patients who were given occupational therapy plus EMG-biofeedback improved their upper limb function relative to a control group receiving only occupational therapy [6]. Biofeedback from the EMGs of the *extensor carpi radialis* and *extensor digitorum communis* improved the wrist and finger extension of stroke subjects [7]. EMG-biofeedback has even been proposed as a therapy for remotely supervising home users [8]. The method, however, remains a challenge, as EMG requires expertise and is difficult for self-application and interpretation [8]. Reviews of biofeedback modalities suggest that existing augmented feedback may have an added value for rehabilitation therapy following brain injury as compared to standard repetitive training [9,10].

Here we report on a new biofeedback modality, gesture recognition biofeedback (GRB), wherein visual feedback relays the accuracy of specific gestures rather than specific muscular activation amplitudes, and uses a simpler interface. The method uses surface muscle pressure (SMP) to record muscle activation during fine motor tasks. SMP registers voluntary effort during grasping with a sensorized cuff worn on the forearm, and its accuracy and utility have been demonstrated in previous studies [11,12]. GRB operates by calculating the difference between current SMP sensor outputs and a gesture template, which is

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set prior to training by recording the user's performance of the desired movement with a clinician's instruction or assistance. This comparison provides the user with real-time guidance in repetitive task performance that can be remotely monitored. The resulting value is displayed on a computer monitor in real time, providing visual knowledge of performance feedback that may be comparable to previous methods [11,13].

Here, a cohort of brain-injured subjects trained in a single session with two conditions: one with GRB and one without feedback. Testing with the nine-hole peg test (HPT) was done before and after each training condition [14]. We tested the hypothesis that training with GRB will enhance performance, independently of the order of training conditions, in comparison to repetitive training without feedback.

Methods

Participants

The experimental group consisted of both stroke (n = 4) and traumatic brain injury (TBI) (n = 8) subjects, eight male and four female. Ten of the subjects were right-hand dominant. Their mean age was 39.8 years, with a range of 21–69 years. All had mild to moderate spasticity, as assessed by an Occupational Therapist, and could complete the HPT. In addition to the experimental group, seven healthy subjects participated as a cohort of control subjects, approximately age-matched to the experimental group, with a mean age of 46.4 years ranging from 25 to 67 years. None of the control subjects reported any neurological or biomechanical impairment in either upper extremity. Informed consent was obtained from each subject, as approved by the IRB of Rutgers University and the JFK-Johnson Rehabilitation Institute.

Biofeedback

SMP was recorded with a sensorized therapeutic cuff placed comfortably around the forearm, as described previously [11]. Seven individual force-sensitive resistors (*Interlink Electronics*), 1.2 cm in diameter, were moveable within the cuff, so that they could be evenly spaced around each subject's forearm. While the sensors were distributed uniformly, they were not targeted to specific locations on the arm. Signals were acquired at a sampling rate of 25 Hz. The cuff was applied around the forearm with a comfortable static pressure, providing a positive baseline that allowed detection of local pressure changes in the limb, as in previous SMP studies [15].

Biofeedback was generated as a comparison between real-time SMP values and those previously recorded as a template for desirable activity. To set the template, subjects were instructed to continue resting while the "relax" state was captured. Subjects were then instructed to "pinch", producing a thumb-index opposition, with attention to the posture of the hand. SMP values from the final 200 ms of capture were averaged to generate a template value for each sensor.

For training, subjects were given auditory cues to pinch and relax, alternately presented every 4 s. Biofeedback was generated as a scalar value which was derived from the multi-dimensional information from all seven SMP sensors. The pinch template was defined as a static point in sensor space whose location was defined during template setting. The real-time SMP values defined a point in the sensor space representative of forearm muscle activity.

To resolve the real-time and template SMP values into information about performance, their locations were compared using the Euclidean distance, a simple spatial metric that decreased as the real-time SMP approached the template in sensor space. The distance was calculated by the following formula:

$$\mathrm{GRB} = 10 - \sqrt{\sum_{i=1}^{7}\left(\mathrm{Target}_{\mathrm{i}} - \mathrm{SMP}_{\mathrm{i}}\right)} \quad (1)$$

where $\mathrm{Target}_{\mathrm{i}}$ is the i^{th} sensor's value in the pinch template and $\mathrm{SMP}_{\mathrm{i}}$ is the ith SMP sensor's real-time value. By subtracting the resultant distance from 10, the GRB feedback value decreased from 10 as the distance increased. Conversely, feedback increased as thumb-index opposition more closely met the clinician-directed template. Feedback was delivered visually as a partially "filled" rectangle of height 10, such that its fullness was determined by the GRB feedback value. Subjects were instructed to keep the feedback rectangle as full as possible.

Protocol

During training, subjects were instructed to pinch as in template setting. In the *With Feedback* (WF) condition, visual feedback was given as described above. In the *No Feedbac*k (NF) condition, the subject was instructed to either pinch or rest according to the auditory timing cues, but no visual feedback was given. Sessions included approximately 30 repetitions per condition with two rest periods provided as necessary.

Participants were assigned to one of two groups which determined the order that feedback conditions were used in training. One group (WF–NF) had biofeedback in the first training session and *No Feedback* during the second session. The NF–WF group was trained in the opposite order. The same grouping scheme was used for the control subjects.

Fine motor function was assessed by the HPT which was administered using standard pegs and peg board. Subjects were instructed to fill the board peg-by-peg, then to remove pegs one at a time. They were instructed to complete this test as quickly as possible and using only the affected hand. The HPT was performed three times during the study: first as a pre-training baseline, then after each of the two training conditions.

Analysis

In order to measure the effect of each session of training, results from the HPT were compared within subjects as

$$(\mathrm{post} - \mathrm{pre})/\mathrm{baseline} \quad (2)$$

The difference between the time to completion of an HPT (post) and that of the preceding HPT (pre) was normalized within subjects by dividing by the baseline time from the subject's first HPT. For example, for the WF–NF group, the effect of NF training is calculated as the difference between

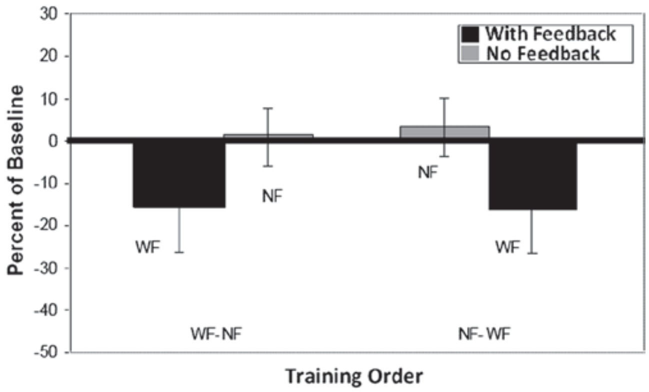

Figure 1. Effect of training order on nine-hole peg test (HPT) change across all impaired subjects (mean ± S.E.). Note that independent of order, HPT times decrease *With Feedback* (WF) and increase slightly in standard repetitive training (NF).

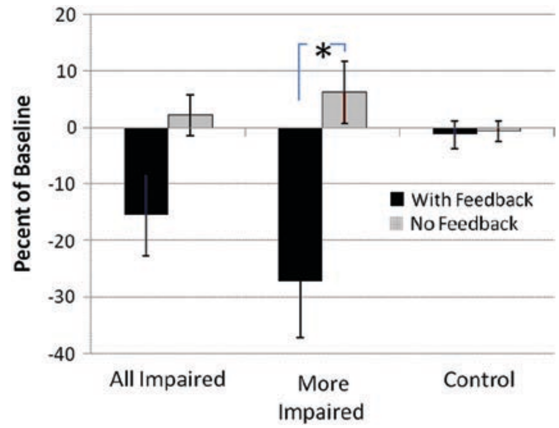

Figure 2. Change in performance time, as percent of baseline for three subgroups (mean ± S.E.). Left: results from all impaired subjects; Center: improvement *With Feedback* in more impaired subset; Right: minimal change in control subjects. *Statistical significance ($p < 0.05$).

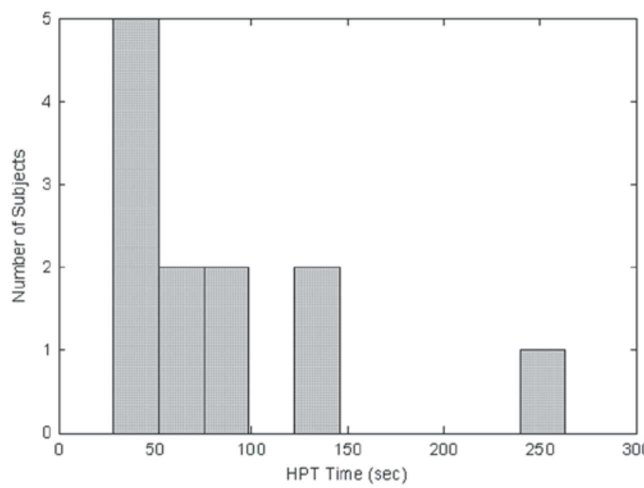

Figure 3. Histogram of baseline HPT times for impaired subjects (10 bins). Note that five subjects had times less than 50 s, while, the remaining seven were distributed between 50 and 260 s, prompting the post-hoc analysis of the more impaired subgroup.

HPT after NF training (post) and HPT following WF training (pre), divided by the baseline HPT time. To measure the independence of effects from training order, HPT times were compared between the two training order groups. This analysis was performed both for WF training and for NF training using the non-parametric Mann–Whitney test. Low significance from this analysis would indicate that the training order was irrelevant and the two groups could be combined.

HPT times following both NF and WF training were compared using the Wilcoxon signed-rank test, as data were collected in two conditions for each subject. A two-tailed Student's t-test was used to compare training effects between the stroke and TBI subgroups. In all cases, the null hypothesis of these tests was the expectation that the two experimental conditions yielded identical times on the HPT.

Results

Baseline HPT scores ranged from 28.6 to 263 s for the impaired subjects and from 15.78 to 25.56 s for the control subjects. No significant effect of training order was found ($p > 0.7$), as shown in Figure 1, and no significant differences were seen between the stroke and TBI groups ($p > 0.9$). Based on these results, subsequent analyses were conducted independently of training order or brain injury type. After training WF, the average decrease in impaired subjects' HPT time to completion was 15.5% (S.D. 7.14%). In contrast, training with NF slightly increased the HPT time by 2.07% (S.D. 3.61%) (Figure 2).

A subset of the impaired subjects was established using the criterion of a minimum of 52 s to complete the baseline HPT (Figure 3). This resulted in a cohort of seven subjects (6 TBI, 1 stroke) treated as a single cohort regardless of training order. Results from the cohort of more impaired subjects were compared to the results from the entire impaired group (Figure 2). GRB training yielded an improvement of 27.3% (S.D. 9.93%, $p < 0.05$). In the absence of GRB training, there was a 2.07% (S.D. 3.61%) decline in performance.

For the control group, GRB training had minimal effect, as seen in Figure 2. Control subjects' HPT times were significantly faster than those of impaired subjects at baseline ($p < 0.01$), after WF training ($p < 0.004$) and after NF training ($p < 0.05$).

Discussion

Experimental design

Analysing the efficacy of therapies for brain injuries due to trauma or stroke is complicated by the range of associated impairments. Here, fine motor function was assessed using an independent rater, the HPT, a commonly used outcome for stroke rehabilitation [16,17]. The impaired group included eight subjects with traumatic and four subjects with ischemic brain injuries. Since no difference in trend was noted between the two injury types, we combined both types into a single group, similarly to a previous approach [18], and used non-parametric statistical analysis, not based on the assumption of normal distributions. In this way, subjects' changes in HPT time after WF training were compared to their own control (NF) condition.

Approximately 30 repetitions of the thumb-index opposition were performed in each training condition, split evenly into three sets by resting periods of approximately one minute. This number of repetitions was sufficient to facilitate the improvement of fine motor function during training with biofeedback. However, without feedback, thirty repetitions were not likely to improve performance even in the most impaired subjects.

It is possible that additional training time might have facilitated some improvement in the NF condition. The total number of 60 repetitions seemed to be the best compromise possible between avoiding fatigue and maximizing training time [19]. While some studies have used more repetitions during training, as many as two hundred [20], some have used only 30–60 repetitions [21,22].

Although the effects of stroke and TBI are thought to be generally dissimilar, the non-parametric, paired Wilcoxon signed-rank analysis used here treats improvements within subject.

We selected thumb-index opposition as a representative task, as a prehensile movement critical to ADL and a common task in studies of motor control [23]. The NF condition is representative of a typical rehabilitation protocol, in which a subject repetitively performs a task without a therapeutic device. It is similar to the control condition in a number of studies comparing new rehabilitative methods to standard training [24]. Using both NF and WF training for each subject in a cross-over experimental design allowed the use of a repeated-measures statistical analysis. The randomization of training orders accounted for the possibly confounding effects of fatigue or other changes during an experimental session. The close parallel between training effects for the WF–NF group and the NF–WF group can be seen in Figure 1, indicating the lack of effect of training order. For this reason, the possibility of a confounding effect from fatigue, cognition, or other artifactual influences as detailed above can be dismissed as negligible.

Among our impaired subjects, there was a diversity of impairment level, as indicated by a wide range of baseline HPT time, from 28 to 263 s (Figure 3). Selecting a threshold of 52 s as a separation criterion resulted in a subset of seven more impaired subjects. As can be seen in Figure 2, the more impaired group improved by 27.3% (S.D. 9.93%) with GRB which was significantly more efficacious than NF training. The correlation between the degree of improvement and the severity of participants' impairments has been previously noted in subjects training with robotic assist therapies [25].

Clinical implications

Herein we tested the efficacy of acute training with GRB in a pinching task with brain-injured subjects including those with stroke and those with TBI. Results from HPT testing showed that subjects decreased their time to completion of the HPT to a greater extent after training with the biofeedback than after the NF condition. GRB provides real-time visual feedback during repetitive grasping tasks that yields acute improvement in a single session of training. Since SMP does not require the precise placement of sensors on specific muscles [11,12,15], GRB is easily donned and simple to interpret.

In the present pilot study, we have demonstrated that GRB may offer individuals with moderate impairment due to brain injury a technological aid for improving fine motor function of the hand in the short-term with only minimal supervision. Future testing will validate and expand on the present results using a larger, homogeneous sample of participants in a long-term training study.

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Declaration of interest

The authors report no conflicts of interest.

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