From *The Eighth International Conference on Rehabilitation Robotics*, pp.258--261, 2003.

Feedback Distortion to Increase Strength and Mobility

Bambi R. Brewer[1], Roberta Klatzky[2], and Yoky Matsuoka[1]
[1]Robotics Institute, [2]Psychology Department
Carnegie Mellon University
Pittsburgh, PA 15213
E-mail: bambi@andrew.cmu.edu

Abstract

A method for using visual distortion to overcome Learned Nonuse in stroke victims is described, and results from a preliminary experiment on unimpaired subjects are presented. A visual display was used to present increasingly distorted feedback about the force exerted by a subject. Visual distortion encouraged unimpaired subjects to increase their force production by more than 30%. In addition, the effects of different amounts of distortion on force production were analyzed; visual feedback distortions of up to 28.8% linearly increased the force exerted by subjects.

1. Introduction

An estimated 20-25% of stroke victims exhibit a phenomenon called "Learned Nonuse," in which cortical damage causes patients to develop movement deficits by learning to move only within certain limits [1]. With rehabilitation and cortical reorganization, patients relearn larger and more powerful movements to a certain extent, but the habit of decreased movement may prevent them from regaining their original mobility and strength. Also, patients may perceive themselves as being incapable of moving beyond their learned limits and may be reluctant to try to do so.

Currently, therapists attempt to overcome Learned Nonuse with Constraint-Induced Movement Therapy or concentrated conventional therapy. Intensive, repetitive practice using the impaired extremity appears to be the key factor in overcoming Learned Nonuse, which suggests that robotic rehabilitation could be a useful addition to conventional stroke rehabilitation [2]. In addition, the use of a robot combined with a visual display suggests the possibility of using distortions in visual feedback to help stroke patients overcome their self-imposed limits on mobility and strength. The long-term goal of this research is to investigate that possibility. Stroke patients will interact with a force-feedback robot while observing a computer display. During each therapy session, the visual feedback will become increasingly distorted in such a way that the subject has to move further or exert more force to cause the same response in the visual display. This process will encourage the subject to relearn larger, stronger, and more coordinated movements without directly challenging his or her perceived limits.

The experiment described here investigated the basic idea of this paradigm, which is that distorted visual feedback can be used to encourage the production of progressively larger forces. This experiment was conducted with unimpaired individuals, but a parallel procedure will be used with stroke victims.

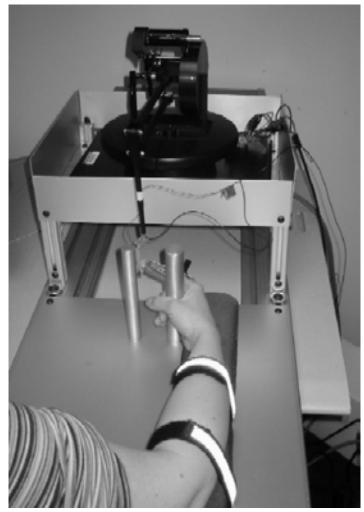

Figure 1. The experimental setup. The subject placed the finger in a cuff attached the PHANTOM™ robot. The subject moved the finger at the MCP joint while grasping a post to prevent movement of the hand. A closeup of the finger cuff is shown. The screen that concealed the hand during the experimental trials is not shown.

2. Methods

We conducted the experiment with 10 subjects between 18 and 28 years of age. All subjects were right-handed and did not appear to have any neurological problems. The experimental setup is shown in Figure 1. We asked each subject to sit in front of a computer screen with the index finger of the right hand in a 3 DOF custom-made finger cuff attached to a 3 DOF force-feedback robot called the PHANTOM™ (Premium 1.5 model, SensAble Technologies, Inc., Woburn, MA.). The subject moved the index finger at the metacarpo-phalangeal joint while the robot exerted a force perpendicular to the arc of the finger. The force output of the robot behaved much like a spring, in that the further the subject moved, the more force had to be exerted against the robot. The subject's hand was concealed behind a screen throughout the experiment.

The experiment consisted of 150 trials. On each trial, the user was asked to generate a particular level of force from 1 to 5, with level 1 being the smallest force and level 5 being the largest. Subjects determined their own force

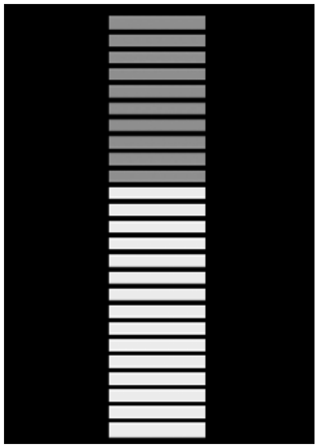

Figure 2. The discrete visual feedback display seen by the subject on half of the experiment trials. The direction of increasing force was vertically downward.

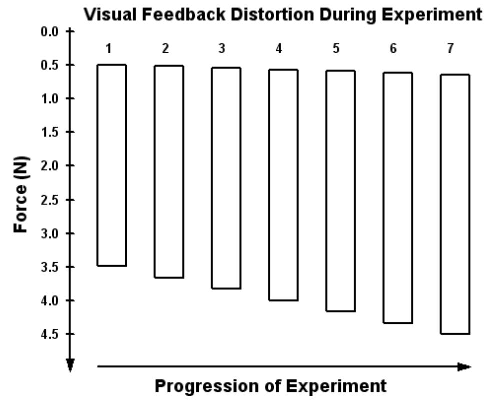

Figure 3. The forces represented by the endpoints of the feedback bar were distorted gradually throughout the experiment. The original range of forces represented by the feedback bar was 0.50 – 3.49 N, but by the end of the experiment, the feedback bar represented 0.64 – 4.5 N.

levels corresponding to each target number but were instructed to keep the forces they produced for a given level as consistent as possible. Visual feedback throughout the experiment was in the form of a bar made up of 25 discrete blocks (as shown in Figure 2). The number of colored blocks on the feedback bar indicated the magnitude of the force. The direction of increasing force was vertically downward because this provided a more intuitive mapping between the visual display and the actual movements of the subject's finger as the force was produced. A feedback bar made up of discrete blocks was used instead of a continuous feedback bar so that subjects would not associate each level of force with a particular point along the feedback bar.

The forces represented by the endpoints of the feedback bar changed throughout the experiment, as shown in Figure 3. Seven different pairs of endpoints were used during the course of the experiment so that the range of force shown on the feedback bar was gradually distorted from 0.50 – 3.49 N to 0.64 – 4.50 N. The intervals between successive pairs of endpoints were based on the Just Noticeable Difference (JND) for force in our experimental setup, which was previously determined to be 14.4% (preliminary results in [3]). For each step, the endpoints were increased by 1/3 of the JND until the last set of endpoints differed from the first by 2 JNDs. Previous experiments indicated that each of these incremental changes should be imperceptible [4]. The visual feedback was distorted only by changing the range of forces represented on the feedback bar. The appearance of the bar itself did not change.

Twenty trials were conducted for each feedback bar before the experiment advanced to the next distortion level. Within each block of twenty trials, each force level appeared four times in a random order, twice with visual feedback and twice without it. One of the trials for each force level/feedback condition used a spring constant of 0.09 N/mm in the PHANTOM spring model, and the other used a spring constant of 0.12 N/mm. A break was given after 80 trials to prevent fatigue of the subject's finger and overheating of the robot. The break coincided with the end of the twenty trials for the fourth feedback bar. After the break, 10 of the trials for the fourth feedback bar were repeated before the trials for the fifth feedback bar began. We hoped in this way to minimize the effects of the break on the subject's self-determined force levels.

We hypothesized that gradually increasing the endpoints of the feedback bar would cause the subject to produce larger forces without his or her awareness for each force level in an attempt to approximately reach the previous location of that level along the feedback bar. We hypothesized that this upward trend would occur because the feedback change would actually influence the subject's perception of force, not because the subject would ignore the force felt and rely entirely on the visual feedback. To test this hypothesis, we interleaved trials with no visual feedback. If the visual feedback distortion caused changes in the subject's perception of force, then the upward trend should exist even in the trials without visual feedback.

3. Results

Early in our analysis, we realized that the presence of a break halfway through the experiment was dramatically influencing our data. For the larger force levels, we saw a distinct drop in the produced forces after the break (as shown in Figure 4), and we had to correct for this effect. We took the difference between the mean produced force for each force level/feedback condition for the fourth successive feedback bar before the break and the mean produced force for each force level during the 10 repeated trials for the fourth feedback bar that took place after the break. We then added this difference to the forces produced during trials of the appropriate force level/feedback condition that occurred after the break. This adjustment eliminated the drop in the produced forces after the break, indicating that the break was indeed responsible for this

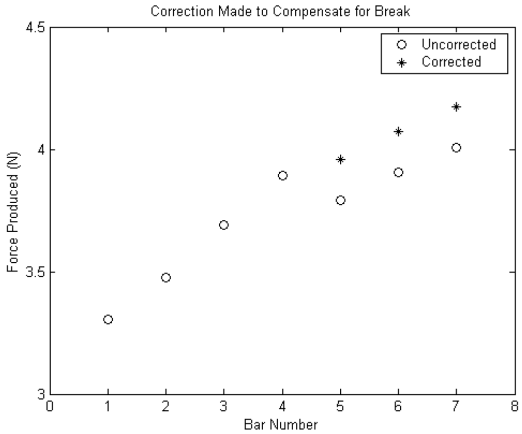

Figure 4. A break occurred after feedback bar 4, and as a result, the produced force dropped between bar 4 and bar 5 (open circles). We used bar 4 trials repeated after the break to correct for this effect (asterisks). Shown here is representative data from one subject.

effect. The corrected data were used for the rest of the analysis.

For each force level/feedback condition, the mean and standard deviation of the produced force for each feedback bar are plotted in Figure 5. Linear trend analysis was performed for both feedback conditions for force levels 3-5. Because the data did not appear to satisfy the condition of sphericity, a method of trend analysis that did not use a pooled error term was utilized [5]. The results of this analysis are presented in Figure 5. The starred p-values were significant at the 5% level after a Bonferroni adjustment was made. The distortion in the endpoints of the feedback bar clearly caused an increase in the forces produced for levels 3, 4, and 5 in both the feedback and the no feedback conditions. The maximum increases in produced force occurred for force level 5. The produced force increased by 30.0% in the with-feedback condition and by 33.0% in the no-feedback condition.

Trend analysis is not presented for force levels 1 and 2. Because the visual display was distorted by a percentage, the lower force levels were only distorted by a small magnitude (see discussion). Since trend analysis is only useful for detecting linear trends with slopes that are not close to zero, this analysis would be fruitless for force levels 1 and 2.

For each force level/feedback condition, linear regression was performed on each subject's data. The average of the resulting regression lines is plotted as a dashed line in the subplot of Figure 5 for that force level/feedback condition. For comparison, Figure 5 also contains solid lines that correspond to the force represented by a particular location on the feedback bar. In the graphs for each level of force, the solid line represents the following: for level 1, the bottom (low-force end) of the feedback bar; for level 2, one fourth of the length of the bar; for level 3, the middle of the bar; for level 4, three fourths of the length of the bar; and for level 5, the top (high-force end) of the bar. These lines are shown only for comparison, since each subject chose his or her own force levels and did not necessarily space them evenly along the bar.

Qualitatively, the slopes of the average regression lines appear to be larger for the larger force levels. Trend analysis was performed to assess the significance of this tendency. The upward trend in slope was found to be significant for both the feedback (p-value < 0.0001) and the no feedback (p-value < 0.01) conditions.

4. Discussion

In this experiment, visual distortion was used to persuade subjects to exert more force than they perceived themselves to be exerting. Subjects were specifically instructed to keep their responses for a given force level as consistent as possible, yet as the visual feedback changed, subjects produced larger forces for each requested force level. This occurred even though a discrete visual display discouraged subjects from relying entirely on visual matching.

Given the dominance of vision in the human sensory system, it is perhaps not surprising that this occurs on the trials with visual feedback. However, the same trend was seen in the trials with no visual feedback. Distortion of the visual display seems to affect not simply the particular force produced while the subject is seeing the distorted feedback, but the subject's general perception of force. As the visual feedback becomes more distorted, the subject becomes accustomed to producing larger forces and adjusts his or her perceived magnitude levels accordingly. Thus, when the subject is asked to demonstrate those magnitude levels, the produced forces rise with increased visual distortion, even on no feedback trials.

The distortion in this experiment was implemented by increasing by a constant percentage the forces represented at the endpoints of the visual feedback bar. This meant that the position on the feedback bar of a specific force changed more for a high force than for a low force. For instance, the visual position of 3 N changed more than the visual position of 1 N as the distortion increased. This is reflected in the fact that the solid lines in Figure 5 that correspond to the top of the bar have greater slopes than those that correspond to positions near the bottom of the bar. We observed that produced forces for higher force levels have greater slopes than produced forces for lower force levels. Since there was more visual distortion for the higher force levels, we can infer that larger amounts of visual distortion lead to larger increases in force production.

It is interesting to note that our data show no evidence of an upper limit on the total amount of visual distortion that can be used to encourage the production of larger forces, provided each successive visual distortion is sufficiently small. By the end of this experiment, the visual feedback was distorted 28.8% from the feedback at the beginning of

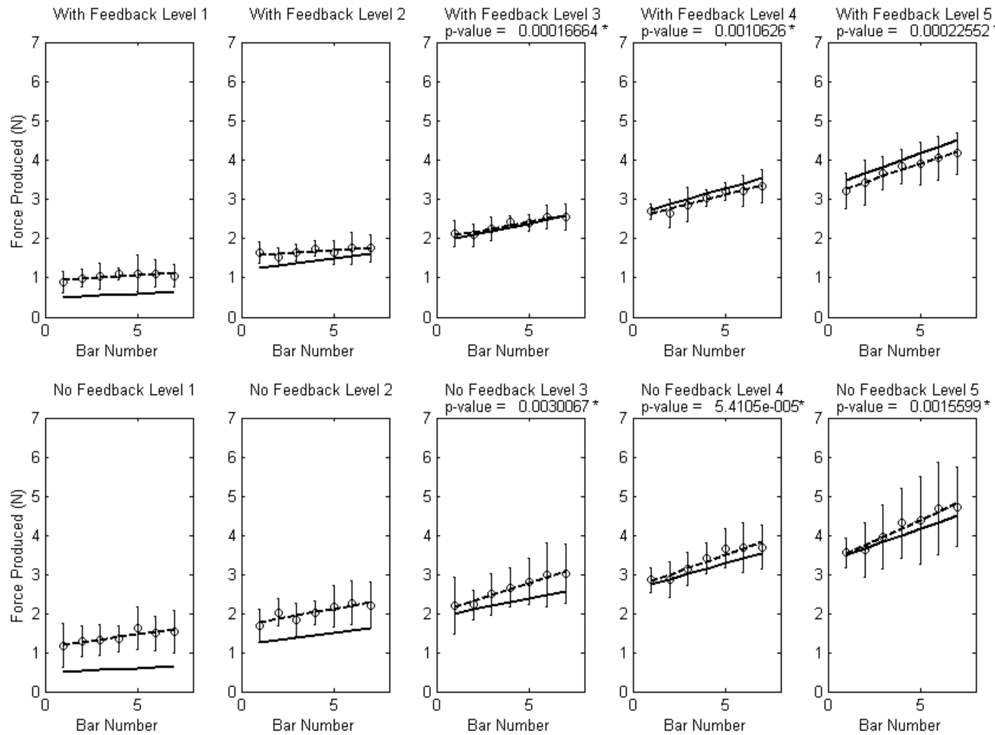

Figure 5. The results of the experiment. Each graph shows the means and standard deviations for a given force level/feedback condition. The solid lines show the forces represented at different points along the feedback bar (see text). The dashed lines are the mean regression lines for the data. Linear trend analysis was performed for force levels 3-5, and the p-value is shown at the top of each graph. Starred p-values were significant.

the experiment. This distortion is twice the size of the force JND, yet the forces produced for each force level continued to rise linearly with distortion. A questionnaire given at the end of the experiment indicated that most of the subjects did not notice any change in the visual feedback or attributed it to a wide variety of reasons besides deception, e.g., fatigue.

5. Conclusions

Visual distortion was used to increase the mean force produced for level 5 by 30.0% in the with-feedback condition and 33.0% in the no-feedback condition. These increases are more than twice the force JND of 14.4%, and they occurred without the knowledge of the subjects. Since the protocol used in this experiment was similar to the one we will use with stroke victims, these results demonstrate that we may be able to use visual distortion to significantly increase, within a single rehabilitation session, the amount of force generated by stroke patients. It should be possible to do this without the patients recognizing the visual distortion. This method of therapy will allow patients to move beyond the limits they have unconsciously set for themselves due to Learned Nonuse.

6. References

[1] E. Taub, "Overcoming Learned Nonuse: A new approach to treatment in physical medicine," *Clinical Applied Psychophysiology*, Editors J. G. Carlson, A. R. Seifert and N. Birbaumer, New York, Plenum Press, pp. 185-220, 1994.

[2] E. Taub, J.E. Crago, and G. Uswatte, "Constraint-Induced Movement Therapy: A new approach to treatment in physical rehabilitation," *Rehabilitation Psychology*, vol. 43(2), pp.152-170, May 1998.

[3] S. Allin, Y. Matsuoka, and R. Klatzky, "Measuring Just Noticeable Differences for haptic force feedback: A tool for rehabilitation," 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2002.

[4] Y. Matsuoka, S. Allin, and R. Klatzky, "The tolerance for visual feedback distortions in a virtual environment," *Physiology & Behavior*, vol. 56(6), pp. 651-655, 2002.

[5] M. J. Roberts, personal communication, Jan. 2003.