Feedback Distortion to Overcome Learned Nonuse: A System Overview

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Abstract—**We constructed a virtual environment that is designed to use visual feedback distortion to address Learned Nonuse in stroke patients. The system is intended to rehabilitate finger movements, and it includes haptic and visual displays. The virtual environment includes custom-made hardware and software that allow the force feedback to adapt to different individuals and to movement changes over time for a single individual. Using this environment, we conducted a preliminary experiment with unimpaired subjects to show that it is possible to extend the range and strength of movements without subjects recognizing the visual feedback distortion.**

Keywords—**Robotic Rehabilitation, Virtual Environment, Feedback Distortion, Learned Nonuse, Stroke**

I. INTRODUCTION

The use of robotics for rehabilitation applications is often represented as a way to decrease the cost of rehabilitation and increase the efficiency of therapists [1]. However, robotic therapy can be more than simply a substitute for conventional therapy; robots make new kinds of therapy possible [1,2].

The goal of our research is to show that robotics technology combined with virtual reality can augment conventional therapy not only by providing novel physical exercises, but also by addressing perceived limitations that hinder the rehabilitation process. About 25% of stroke patients are affected by a condition called Learned Nonuse [3]. Immediately after a stroke, cortical damage severely limits a patient's range of motion and the forces that a patient can produce. Patients learn to move only within these limits, and they may perceive themselves as being incapable of moving beyond them. This habit of decreased movement is called Learned Nonuse. As cortical reorganization progresses, patients should be able to relearn larger, stronger movements, but patients experiencing Learned Nonuse may be reluctant to move beyond their perceived limits, which can impede their progress in rehabilitation. We want to use virtual reality to encourage patients to move beyond their perceived limits on mobility and strength without directly challenging these limits.

This paper describes the virtual robotics environment that we have constructed to rehabilitate stroke patients who may be experiencing Learned Nonuse. We present preliminary results showing that this environment can be used to increase force production and movement distance without the awareness of the subject.

II. THERAPEUTIC ENVIRONMENT

Fig. 1. The therapeutic environment includes a haptic display and a visual display (right). Our software simulates a virtual compression spring between *O* and the index finger (left). A virtual wall is placed at the finger's full extension (*S*). The spring's rest length is *SO.*

A. Hardware

Our therapeutic environment consists of haptic and visual displays, as shown in Figure 1. The subject moves his or her index finger against a resisting force while receiving visual feedback on the display. The force feedback is provided by a Premium 1.5 model PHANTOM™ robot (SensAble Technologies, Inc., Woburn, MA). This robot has 3 active degrees of freedom (DOF) and can measure position to within 0.03 mm. The maximum exertable force is 8.5 N, while the largest continuously exertable force is approximately 5 N. This robot was chosen because of its inherent design to safely interact with human subjects.

We removed the PHANTOM™ stylus provided by SensAble Technologies and designed a custom-made finger cuff. Our finger cuff adjusts easily to fit a wide range of finger sizes and restrains the finger so that it moves only about the metacarpo-phalangeal (MCP) joint. Three pairs of ball bearings give this finger cuff 3 passive DOF. When combined with the 3 active DOF inherent to the robot, the 6 DOF of our system allow the finger to move comfortably in any direction within the robot's workspace. The total weight of the finger cuff is 39 g. The finger cuff was tested with an elderly subject (age 71, female), and it was light enough to allow the subject to move the finger freely. To accurately track the orientation of the finger pad, we have incorporated a rotary potentiometer into our finger cuff.

In order to isolate the movement about the MCP joint and eliminate movements of other fingers or the wrist, we instruct the subject to grasp a post with the remaining fingers and thumb throughout the experiment. In addition, the subject's forearm is restrained in a horizontal position.

B. Environment Design

Our software consists of a graphics thread that runs at 30 Hz and haptics thread that runs at 1 kHz. This program is written in Visual C++ and uses the GHOST® tool kit provided by SensAble Technologies. This tool kit provides functions to send force commands to the robot and receive position information about the endpoint of the robot from encoders on the motors. The tool kit, however, provides no information about the actual forces generated by the robot; only the commanded forces are known. To calibrate the relative encoders, the tool kit assumes that the robot is initialized approximately in a neutral position. We built a custom-made initialization fixture to make this calibration accurate and repeatable. The software uses a Cartesian coordinate frame with the origin located at the endpoint position of the robot during initialization. All position and force information is given in terms of this Cartesian coordinate frame.

Each subject begins a session in our environment by moving back and forth between the two positions marked *O* and *S* in Figure 1. Point *O* is the position of the index finger at the small metal post, and point $S = (x_S, y_S, z_S)$ is the point at which the subject has extended the finger a Euclidean distance of 65 mm from *O*. The distance of 65 mm was chosen because it is the distance that all subjects can comfortably extend the index finger without shifting the hand position. Because the arc that the fingertip makes is relatively small, this Euclidean distance is a good approximation for the distance that the fingertip travels along an arc from *S* to *O*. While the subject moves between *S* and *O*, the path of the finger is recorded. The path is an arc between *S* and *O* that lies largely in the *xz*-plane, though a significant path component in the *y*-direction has been observed for elderly subjects (see Section 2.2.3). This path is used to determine the force that is exerted on the finger during the session, as discussed in Section 2.2.3.

In our experimental environment, we create a virtual compression spring and a virtual wall, as shown in Figure 1. One end of the virtual spring is fixed at the point marked *O*, and one end is attached to the subject's index finger. The subject can move only between *O* and the virtual wall at $x = x_S$, and the values of y_S and z_S are reset each time the subject reaches the virtual wall, in order to adjust the position of *S* for any small changes in the subject's hand position. The Euclidean distance between *S* and *O* is the rest length of the virtual spring, and the force produced by the robot increases as the subject moves the finger from *S* toward *O*. The force experienced by the subject is $F = k\sqrt{(x - x_S)^2 + (y - y_s)^2 + (z - z_S)^2}$, where *k* represents the spring constant and (x, y, z) is the current finger position.

C. Visual Feedback and Distortion

We provide visual feedback using OpenGL that allows us to assess the effect of distortion. It consists of a bar that represents the force produced by the finger or the Euclidean distance moved by the finger. The number of colored blocks indicates the magnitude of the subject produced force or distance. The direction of increasing magnitude is vertically downward to provide a more intuitive mapping between the visual display and the actual movements of the subject. Feedback distortion is implemented by surreptitiously changing the range of forces or distances represented on the bar. For example, if a bar that represents 0 to 2 N of force is distorted by + 20%, it would represent 0 to 2.4 N. This means that when the feedback distortion is present, the subject has to exert 20% more force to produce the same change in the visual display. The amount of distortion used is based on the Just Noticeable Differences (JNDs) for force and distance. These were previously measured to be 14.4% and 18.0%, respectively, for our system [4]. These values set a lower bound on the amount that the force or distance can be changed between two successive exposures, while the visual feedback remains identical, without the subject's noticing the distortion. Our preliminary results with a visual feedback bar indicated, however, that considerably larger distortions of up to 35.9% are not reliably detected by subjects [5].

D. Force Assignment

Assuming that the robot accurately produces the force commanded (validation of this below), then the force assigned tangential to the finger path determines the force generated by the subject. The component of the path that lies in the *xz*-plane (the horizontal plane) and the component that lies in the *y*-direction are considered separately because the *y*-component of the path was found to be more variable than the horizontal component. The horizontal path is found by approximating *z* as a quadratic function of *x*, $z = ax^2 + bx + c$. The coefficients *a*, *b*, and *c* are computed using the method of least-squares fit. This least-squares fit is initialized at the beginning of the experiment using an array of 1000 position data points recorded while the subject moves the finger back and forth in the absence of the virtual spring force. This allows the force assignment to adjust to each subject's individual finger path. The least-squares fit is updated throughout the experiment to adjust for any slight changes in the finger path that may occur during the experiment. Every time the subject's index finger moves 2 mm in the *xz*-plane, a new data point is added to the position array, and the oldest data point in the array is deleted. Then the least-squares fit is recalculated, yielding a new set of coefficients.

We observed that the elderly subjects, in general, had a stronger tendency than younger subjects to tilt the hand downward instead of moving entirely in the horizontal plane. To model this downward movement, we assume that the displacement in the *y*-direction is proportional to the distance moved by the finger in the *xz*-plane. The distance moved by the finger in the *xz*-plane is approximated by the Euclidean distance in the *xz*-plane from *S* to the finger, so $y = m\sqrt{(x - x_S)^2 + (z - z_S)^2}$ where *m* is a constant that can be found using the point S and the position of the finger. This method of approximating the vertical component of the subject's finger path allows the force assignment to be adjusted for path deviations in the y-direction that occur during a single trial.

The path $\vec{P}$ of the finger can be written as

$$\vec{P} = x\hat{i} + m\sqrt{(x-x_S)^2 + (z-z_S)^2}\,\hat{j} + (ax^2 + bx + c)\hat{k}\,\cdot \tag{1}$$

Substituting for z in the y-component and taking the derivative, we find that the tangent to the finger path lies along the vector,

$$\vec{t} = \hat{i} + \frac{m(x-x_S) + (2ax+b)(z-z_S)}{\sqrt{(x-x_S)^2 + (z-z_S)^2}}\hat{j} + (2ax+b)\hat{k} \tag{2}$$

By normalizing this vector, we can find the direction in which the force should be applied. We combine this with previously calculated force magnitude, and the result is a virtual spring with the force, $\vec{F}$, applied perpendicular to the fingerpad. Finally, assuming that the least-squares fit for z in terms of x is accurate, small errors in the y-direction force are corrected using the output of the rotary potentiometer in our finger cuff. The potentiometer measures the orientation of the fingerpad normal $\vec{h}$. If $\vec{F}$ and $\vec{h}$ lie in the same vertical plane, then the force that is actually exerted perpendicular to the fingerpad is $\vec{F} \cdot \vec{h}$. This is the force that is used to determine the visual feedback.

III. VALIDATION

A. *Validation of Force Feedback*

As mentioned above, the PHANTOM does not provide feedback information about the forces produced. In order to investigate the relationship between the commanded force and the actual force exerted on the finger, we placed a Kistler 9712 quartz Piezotron® load cell against the endpoint of the PHANTOM™. We designed a validation experiment in which the PHANTOM™ was programmed to execute a sequence of six forces eight times while the Kistler load cell recorded the force produced. This procedure was repeated for forces along the x-axis and at 45° to the x-axis in the xz-plane of the robot. Measurements were made at four arbitrary positions of the robot's endpoint in the yz-plane. The average error in the force produced by the PHANTOM™ was calculated to be ± 0.150 N by finding the mean average difference between the force measured by the load cell and the nominal robot force. None of our experiments use forces or force differences under 0.4 N. Therefore, we determined that the commanded force of the PHANTOM™ estimates the true force exerted on the fingerpad accurately enough for our experimental purposes.

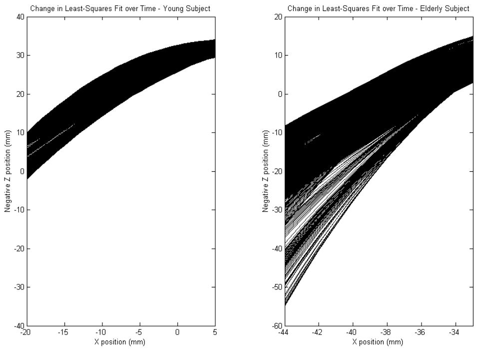

Fig. 2. The change over time of the least-squares quadratic fit of z in terms of x for a young subject (left) and an elderly subject (right). The least-squares fit is continually updated to account for small path changes.

TABLE I
THE MEAN VALUE AND STANDARD DEVIATION OF THE TWO RELEVANT LEAST-SQUARES COEFFICIENTS.

	Young Subject	Elderly Subject
Mean Value of a	0.0192	0.0493
Standard Deviation of a	0.00625	0.0471
Mean Value of b	-0.849	1.16
Standard Deviation of b	0.111	3.43

B. Validation of Force Assignment

As discussed in Section 2.2.3, the least-squares fit of $z = ax^2 + bx + c$ is updated throughout the experiment so that the force exerted by the robot is normal to the fingerpad. To assess the variability of the least squares fit, we examined the change in the quadratic fit over approximately 5 minutes of experiment time for both a typical young subject (age 18) and a typical elderly subject (age 71). During the five minutes, the least-squares fit was updated 2340 times and these data are shown in Figure 2. The mean and standard deviation for coefficients a and b for both subjects are shown in Table 1. Because only the derivative of the finger path is used to assign the direction of the force, the coefficient c is irrelevant for our analysis. The variance of both a and b is significantly greater for the elderly subject ($p < 0.001$). This shows that the adaptation of the least squares fit is more important for elderly subjects than for young subjects. However, for both the young and the elderly subject, the slope of the tangent line to the least squares fit at a given x-value is consistent, which means that the direction of the force in the xz-plane at that x-value is consistent.

Because the least squares fit for z is continually updated and the slope of the path tangent is consistent, we can be confident that the direction of the force in the xz-plane is a good approximation to the true horizontal component of the path tangent. Any errors in the y-direction that shift the direction of the exerted force away from the fingerpad normal are measured using the rotary potentiometer, and the force used to determine the visual feedback is $\vec{F} \cdot \vec{h}$, the portion of the force that is normal to the fingerpad. Figure 3

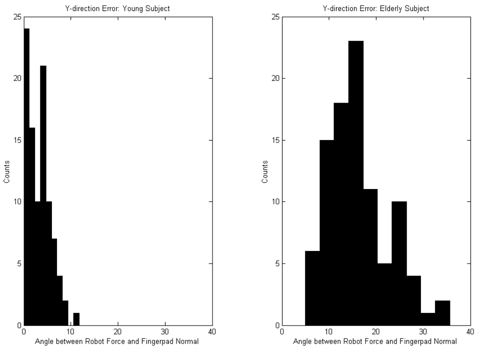

Fig. 3. Histograms of the y-direction error for both a young subject (left) and an elderly subject (right). This error was measured using the rotary potentiometer. The force used to determine the visual feedback was the component of the robot force normal to the fingerpad.

shows the angle between the robot force and the fingerpad normal for 95 forces experienced during an experiment by a young subject (age 21) and an elderly subject (age 71). The mean difference angle for the young subject is 3.30°, which means that 99.8% of the robot force is exerted perpendicular to the fingerpad. The mean difference angle for the elderly subject is 16.4°; 95.9% of the robot force is exerted perpendicular to the fingerpad. The 4.1% of the robot force that is not exerted normal to the fingerpad is not considered when the visual feedback is determined.

IV. PRELIMINARY RESULTS

Using the system described above, we have conducted preliminary experiments to show that visual feedback distortion can be used to change the perception of force and distance in unimpaired subjects [6]. Each experiment consisted of 140 trials. On each trial, the subject was asked to produce a force or distance corresponding to a level from 1 to 5. The actual force at each level number was determined by the subject. During the experiment, the range of forces or distances shown on the visual feedback bar was distorted gradually. We determined the effect of this distortion on the forces produced for each level.

Figure 4 shows a portion of the results when the subject was asked to produce force level 5. As the force corresponding to the end of the bar (the largest force represented on the bar) increased, the average force produced for force level 5 also increased. This increase was even seen for trials with no visual feedback that were inserted among the trials in which feedback was present. In addition, the increase in produced force occurred without the knowledge of the subject. The effect did not occur in control subjects for whom the feedback bar did not change, and the effect occurred even when subjects were warned about the possibility of distortion. A similar effect occurred when subjects were asked to produce levels of distance instead of force.

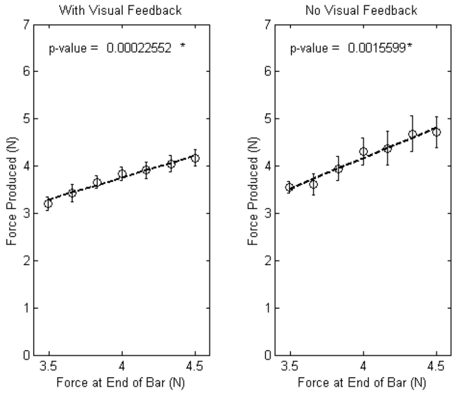

Fig. 4. Preliminary results showing the influence of visual distortion on force perception. As the force at the end of the bar (the largest force represented on the bar) increased, the subject produced more force for both with (left) and without (right) visual feedback.

V. DISCUSSION

Our preliminary results indicate that our new virtual robotic environment can be utilized to encourage stroke victims to make larger and stronger movements without the patients recognizing the distortion. Its ability to alter movements without patients' awareness makes this an ideal environment to help patients overcome Learned Nonuse. There are a few key features that make our therapeutic environment appropriate for stroke rehabilitation. First, our environment provides a straightforward way to set the distortion of the visual display relative to the actual movement of the subject's finger. Second, the adaptive mechanisms included in our software allow the environment to adjust easily to different subjects and to movement changes for an individual subject. Third, both the robot forces and our force assignment routines are accurate. Currently, this environment is limited to training finger movements, but we plan to extend our environment to include larger joints and multi-joint movements.

REFERENCES

[1] Krebs, H. I., B. T. Volpe, M. L. Aisen and N. Hogan, "Increasing productivity and quality of care: robot-aided neuro-rehabilitation," J Rehabil Res Dev 37(6), pp. 639-52, 2000.

[2] Burgar, C. G., P. S. Lum, P. C. Shor and H. F. Machiel Van der Loos, "Development of robots for rehabilitation therapy: the Palo Alto VA/Stanford experience," J Rehabil Res Dev 37(6), pp.663-73, 2000.

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

[4] Allin, S., Y. Matsuoka and R. Klatzky, "Measuring just noticeable differences for haptic force feedback: implications for rehabilitation," Proceedings of the 10th IEEE Symposium on Haptic Interfaces for Virtual and Teleoperator Systems. pp.99-303. 2002.

[5] Matsuoka, Y., S. Allin and R. Klatzky, "The Tolerance for Visual Feedback Distortions in a Virtual Environment," Physiology & behavior, 77(4-5), pp.651—655. 2002.

[6] Brewer, B.R., R. Klatzky, and Y. Matsuoka, "Feedback distortion to increase strength and mobility," International Conference on Rehabilitation Robotics, April 2003.