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Shaping Synergistic Pinching Patterns with Feedback Distortion in a Virtual Rehabilitation Environment

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Abstract— **Individuals with chronic disabilities often use compensatory coordination patterns learned during the recovery phase, even after their individual muscular control returns. Although these compensatory movements limit their ability to complete tasks, these individuals are not able to relearn the correct synergistic coordination patterns because doing so would temporarily compromise task performance. Following our previous work using feedback distortion in a virtual rehabilitation environment to increase the strength and range of motion of disabled individuals, we address the use of this same feedback distortion environment to alter movement coordination patterns. In this paper, we present the methodology and preliminary results showing that (1) able-bodied individuals could be trained to use a different coordination pattern to produce pinching movements, and (2) feedback distortion can alter movements for individual fingers separately during a coordinated movement. These results indicate that our distorted virtual environment may be a powerful rehabilitation tool to convert compensatory movements into movements that utilize all muscles in the normal synergistic patterns.**

Keywords—**Coordination; Feedback Distortion; Fingers; Rehabilitation, Robotics**

I. Introduction

Stroke and other neurological disorders affect more people as the general population ages. Early rehabilitation increases the chance that the patients can get around on their own, but this often means that the patients repetitively train themselves to use the compensatory strategies at home rather than the optimal strategies that they used before injury. Because of the repetitive training, the newly learned compensatory techniques often become the learned synergistic movement coordination. Unfortunately, these newly taught techniques do not allow as much flexibility and versatility as the original optimal strategies they used.

After patients' strength and range of motion have returned, there is nothing to prevent them from relearning the optimal strategies they used before injury. However, because they have learned compensatory movements that allow them to achieve their goals moderately well, they keep using and reinforcing the compensatory movements rather than relearning better techniques. This bottleneck is caused by the fact that modifying their movement strategies would temporarily impair task performance. To sidestep this problem, virtual rehab environments that can distort a patient's movements away from his or her current habit may be useful.

So far, virtual and robotic rehab environments have focused on increasing strength and range of motion [1-5]. Patton et al. [4] used the perturbation force profile to strengthen muscles and extend the range of motion. Our group has shown that visual feedback distortion in a virtual environment enables both able-bodied and traumatic brain injury (TBI) subjects to produce more force and move further than their perceived movements [5,6]. The distortion is the undisclosed discrepancy between the actual movements and the virtual visual feedback the subjects receive about their movements. The subject's Just Noticeable Difference (JND) defines the lowest bound of the feedback discrepancy between the actual movements and the virtual visual feedback. As long as the distortion is less than the JND, the subjects are unable to detect the distortion [7]. Subsequently, we showed that young, elderly, and disabled subjects were able to increase force and distance moved, without perceiving the difference and without an increased amount of perceived effort [6,8,9]. When this feedback distortion environment was used for rehabilitation, we were able to increase the maximum force production and range of motion of a chronic TBI subject [10].

None of the previous research, however, addresses either movement coordination or changing synergies. Unlike force production or range of motion, changing an individual's coordination patterns does not require pushing the limits of his or her physical ability, but rather requires altering the sub-optimal synergistic patterns learned during recovery. In this paper, we show how a feedback distortion environment can be used to alter movement coordination patterns. Specifically we investigated whether we could train able-bodied individuals to learn a prescribed pinching pattern that is different from their habitual pattern. In addition, we investigated whether subjects could be trained to produce these pinching movements with more precision with one of their fingers than with the others (we use the term "finger" to mean any digit including the thumb). Our methodology, which requires the use of two separate haptic devices to measure and control the motion of the thumb and index finger, together with preliminary results for young able-bodied subjects are reported below.

II. Methodology

Our experiment was conducted with 15 right-handed subjects with no known neurological disorders between 18 and 25 years of age. We used two PHANTOM™ robots (Premium 1.0 model, Sensable Technologies, Inc. Woburn,

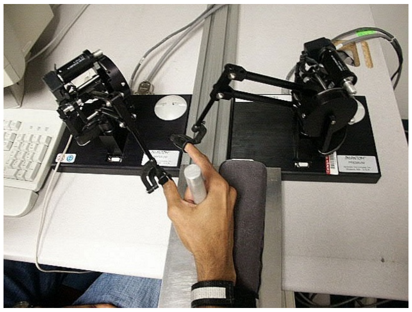

Fig. 1. Two PHANTOM™ robots were used to track and distort the index finger and thumb movement trajectories separately.

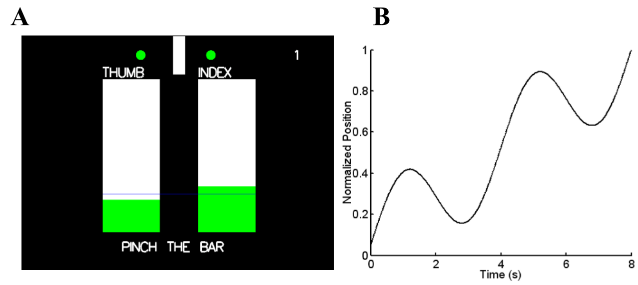

Fig. 2. The subjects' task was to pinch a virtual object displayed on the top of the screen (A) while they observed the normalized distance traveled displayed as a bar graph. For each trial, the blue line (the target movement) across both bars moved from the bottom to the top in the prescribed manner shown in B.

MA) to track the index finger and thumb movement trajectories separately (Fig. 1). The experiment was always conducted on the right hand. The subjects' right arm and wrist were strapped in and their palm kept in place by having the subjects hold onto a pole.

Once the pinching movement had been isolated from the rest of the hand and arm movements, subjects were told to pinch with their index finger and thumb back and forth starting from the widest pinch (100% pinch span) and ending with their fingers touching each other (0% pinch span). While subjects made these pinching movements, the mean trajectory was calculated. All of the subjects moved the index finger and the thumb different distances (usually the thumb was moved less than the index finger).

The subjects' task was to pinch a virtual object (displayed on the top of the computer screen shown in Fig. 2A) with a prescribed balance and timing between their thumb and index finger. The pinch was designed to start from 80% of their pinch span (virtual walls were placed to constrain people to stay within 80% of their initial pinch span). Hard virtual walls defined the object width of 26mm. While subjects moved their fingers from 80% of the pinching span to the surface of the virtual object, they observed the normalized distance traveled displayed as a bar graph on the computer screen (Fig. 2A).

A line through the bar graph displayed the desired pinching movement. In this experiment, the line was always at the same height for both fingers. The height of the line follows the trajectory in Fig 2B, generally increasing, but reversing direction twice before reaching the surface of the virtual object. For each pinching movement, the normalized mean absolute error was calculated for the thumb and index finger separately. At the end of each trial, the errors were displayed to the subject.

The experiment consisted of 200 trials. The subjects were divided into two groups: eight subjects (4 male, 4 female) for the experimental group and seven subjects (3 male, 4 female) for the control group. For the first 80 trials, neither groups experienced distortion. For the control group, the remainder of the experiment (120 more trials) had no distortion as for the first 80 trials. For the experimental group, the visual feedback representation of the index finger movement was distorted for the trials 81 to 120. In these trials, the error from the desired position was exaggerated by 20%. We distorted the index finger movement display relative to the thumb to test whether we could manipulate the index finger movement independently of the thumb during the coordinated pinching movement.

For the next 40 trials (trials 121-160), the visual feedback representation of the thumb movement was distorted by 20%. The distortion for the index finger movements was removed for these trials. For the final 40 trials (trials 161-200), both finger movements were distorted, i.e., the error band was increased relative to the original error signal, but there was no relative imbalance. To test whether the subjects retained what they had learned, a number of randomly selected trials were performed without feedback (the subjects saw the goal line moving across time but they did not see the bar graphs corresponding to the actual movement of their fingers). One such "no feedback" trial was inserted randomly in every 20 trials after the first 20 trials. At the end of the experiment, the subjects responded to a questionnaire that elicited their knowledge of the distortion.

III. Results

A. Learning Different Coordination Pattern

The pinching movement pattern recorded in the first trial was different from the learned pinching movement recorded in the last trial Each panel of Fig. 3 shows the first and last trial from a single subject. Five subjects lead their pinch with the index finger moving first, four subjects lead with their thumb, and six subjects alternating the leading finger throughout the trial.

All subjects learned the new coordination pattern over time. Most of the learning took place over the first 80 trials (approximately 20 minutes), however, a continuous reduction in the mean absolute error was observed throughout the entire 200 trials. While we made the task more challenging by including the direction reversals, the mean square error was not increased by adding the direction reversals. When the overall error was compared with the

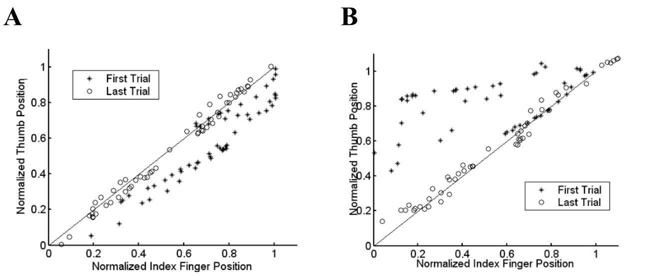

Fig. 3. The pinching movement pattern recorded in the first trial (*) was different from the learned pinching movement recorded in the last trial (o). Most of the subjects habitually lead their pinch with the index finger moving first (A), however, a few lead with their thumb (B).

error accumulated within one second after the direction reversals, the reversal error was significantly smaller (p = 1.2 e-4) than the overall error.

The learning curve over the "no feedback" trials showed that the subjects indeed learned to use the new coordination pattern even without the visual feedback.

B. Individual Finger Movement Distortion

None of the subjects in the experimental group indicated in the questionnaire that they detected the presence of distortion during the experiment.

Fig. 4 shows the mean absolute error of the normalized distance from the desired movement for each condition (no distortion (trials 41-80), index finger distortion (trials 81-120), thumb distortion (trials 121-160), and both distortion (trials 161-200)). The error is normalized to the mean absolute error of the latter half of the no distortion case (trials 41-80).

When the index finger movement was distorted (trials 81-120), the index finger error of the experimental subjects was reduced more than that of the control group despite the fact that the control group's index finger error also decreased as shown in Fig. 4A. While the index finger was being distorted, the error for the thumb did not decrease as much as for the control group (Fig. 4B).

The trend was the same when the distortion was added to the thumb and removed from the index finger. For the thumb, even though the error was larger for the experimental group than for the control group, the error was reduced to be about the same or smaller than for the control group within 40 trials. The difference in the thumb performance while it was distorted was significantly better (p = 0.01) than in the previous block when the index finger was distorted.

A contrast analysis was conducted to test whether the crossover trend between the increasing error in the index finger and the decreasing error in the thumb was significant. The result for the experimental group showed that the contrast was 0.17 and the crossover trend was significant (p = 2.9 e-4). For the control group, the contrast was –0.063 (negative contrast means the index finger dropped more than the thumb) and this trend was significant (p = 0.0029).

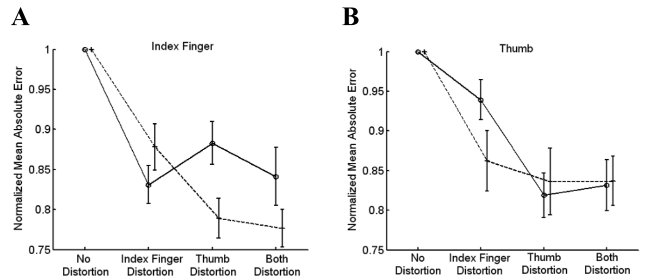

Fig. 4. The mean absolute error of the normalized distance from the desired movement for each condition (no distortion (trials 41-80), index finger distortion (trials 81-120), thumb distortion (trials 121-160), and both distortion (trials 161-200)). The error is normalized to the mean absolute error of the no distortion case. Each data point is the average of all the trials in each condition and the error bar indicates the standard error from the mean. The solid line (-) represents the experimental group and the dashed line (:) represents the control group.

C. Both Finger Movements Distorted Simultaneously

When both finger movements were distorted together (trials 161-200), there was no relative distortion. Fig. 4 shows that there was no difference in the performance of the control and experimental groups (p = 0.90 for the thumb and p = 0.17 for the index finger) when both fingers were distorted together.

IV. Discussion

Altering the coordination synergies among multiple fingers is considered to be a challenging problem. Latash et al. [11] conducted an experiment where subjects ramped up the sum of the static forces produced by all their fingers shown on the computer screen from zero to a designated force. When subjects were informed of the coefficients used for the fingers (i.e. some finger forces were multiplied by 0.5 or 2 before being summed), subjects immediately changed their force production pattern to compensate for those changes. When subjects were not informed of the coefficients, no adaptation to the distorted feedback was observed and they used the same coordination pattern as when all the coefficients were 1.

We have shown that we can change the dynamic coordination pattern between two fingers using visual feedback that provided information about them separately. When we presented a desired coordination pattern different from the habitual pinching pattern, subjects were able to adjust the movement of individual fingers to produce the desired coordination pattern. This learning was confirmed to have taken place even without the presence of the visual feedback during the interleaved trials with no feedback.

It is a common fear that the learned effect in a distorted environment would "wash out" to the baseline immediately after the training took place. However, when working with disabled individuals, these effects have been shown to not wash out (unlike for able-bodied individuals.) In our feedback distortion environment, we trained a traumatic brain injury patient to regain her range of motion and strength. During the six weeks of therapeutic sessions, the individual steadily increased the strength of her finger, and the range of motion at the end of the sessions was 70% more than at the beginning of the sessions [10]. In a separate study, Patton et al. [4] showed that the aftereffect of force perturbation therapeutic training does not wash out in the way it does in experiments with able-bodied individuals. These learned effects do not wash out for disabled individuals because they learn to activate different sets of muscles during the distorted feedback training. When the distorted feedback is removed, they are left with the new coordination patterns that they practiced repetitively during therapy, and which work to accomplish tasks in daily life.

For all subjects in our experiment, the habitual pinching pattern was not symmetric between the index finger and the thumb. Despite their different habitual coordination patterns, we were able to train all of the subjects to use the same new coordination pattern. In addition to changing the general coordination balance between the fingers, we were able to alter the movement accuracy of each finger separately. When the movement information on the computer screen was distorted to show more error on only one of the fingers (e.g. thumb), the subjects adjusted to reduce the error only for that finger (e.g. thumb). This implies that we can manipulate what is considered to be a synergistic activity one component at a time.

It is interesting to note that while the error for the distorted finger decreased, there was a trend for the non-distorted finger's (e.g. the index finger's) error to increase. It is possible that the subjects were unable to maintain the performance of the non-distorted while they were concentrating on reducing the error of the distorted finger. Alternatively, this effect may be caused by the fact that the central nervous system is controlling the total synergistic variability, rather than the index finger and thumb separately. Li et al. [12] have shown that the total variance of multiple finger forces is smaller than the sum of variances of individual finger forces. It is possible that by decreasing the variance of one of the fingers, the variance of the other finger must increase to optimize the total outcome. This is a key issue that must be addressed, in order to investigate and retrain synergistic coordination patterns.

When both finger movements were distorted together, the subjects learned the same amount as if they did not experience any distortion. There was no difference in performance between the index finger and the thumb because they were treated identically. However, the fact that the experimental group did not perform better than the control group shows that simply exaggerating the error for both fingers together may not be effective. It is possible that if we could prevent the performance deterioration of the non-distorted finger, distorting individual fingers one at a time may allow faster learning overall.

Our ultimate goal is to utilize our distorted feedback environment to steer away from suboptimal synergistic patterns that have become habitual. In the future, we plan to adjust the position and force production of one of the fingers with distortion rather than reducing the error of one of the fingers. Given the results of this current experiment, the methodology presented in this paper appears to be an excellent tool with which to rehabilitate individuals with chronic physical disabilities who cannot unlearn the compensatory movements that they learned during their initial rehabilitation.

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