

Initial Therapeutic Results of Visual Feedback Manipulation in Robotic Rehabilitation

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Abstract— Visual feedback is provided to patients in most robotic rehabilitation applications, and this feedback has the potential to influence patient performance in therapy. We have explored the use of visual feedback manipulation (by distortion or progression) in rehabilitation with 3 subjects, each of whom participated in a 6-week rehabilitation protocol. Patients' performances during the initial assessment at each therapeutic session were found to be an underestimate of their actual abilities and were a poor metric for setting the difficulty level of therapeutic exercise. All three patients were willing and able to improve their performance by following distortion or progression, and all patients showed functional improvements after participation in the study. Visual feedback manipulation could provide a way to go beyond patients' self-assessment performances, improving the outcome of robotic rehabilitation.

I. INTRODUCTION

ROBOTIC therapy has been proposed as an addition to traditional rehabilitation in order to enable new types of therapeutic exercise and to increase the amount of therapy available to each patient. Our goal is to examine how manipulation of the visual feedback given to a patient can be used to make robotic therapy more effective than traditional human-assisted therapy and previous robotic rehabilitation applications. Due to entrenched habits [1] or low self-efficacy [2], patients may show reluctance in therapy to move beyond an established level of performance. We hope to overcome this reluctance by using two visual feedback manipulations: visual progression and visual distortion. "Visual progression" means veridical visual feedback emphasizing and encouraging gradual improvement in performance. "Visual distortion" refers to visual feedback that gradually changes by imperceptible amounts to encourage improvement of patient performance. Visual distortion has been successfully used in rehabilitation to address spatial neglect [3]. In addition, Wei et al. showed that visual error augmentation can speed learning, while visual distortion via a constant offset can both speed and increase the magnitude of learning [4].

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We hypothesize that manipulating visual feedback to encourage improvement in rehabilitation tasks will result in performance better than that observed during rehabilitation sessions in which the visual feedback is not manipulated. In preparation for the work described here, we conducted several experiments with unimpaired controls. For a therapeutic program involving distortion to be most effective, patients must not detect the visual distortions as they interact with the robot. Thus, the first set of experiments we conducted addressed the limits of imperceptible visual distortion with unimpaired subjects [5]. Further experiments with unimpaired subjects were conducted to show that vision dominates kinesthetic feedback in our robotic rehabilitation environment and that gradual visual distortion can be used to control force production and movement distance within a single experimental session [6].

Based on our previous work, we have designed paradigms using visual feedback manipulation for the rehabilitation of chronic stroke and traumatic brain injury patients. Though visual feedback manipulation could be applied to any rehabilitation task, we have chosen to focus on tasks devised to improve fine motor control and function in the hand. In this paper, we show the initial results from a 6-week therapy protocol completed by three subjects with chronic stroke or traumatic brain injury. We found that a subject's performance when initially asked to complete a task was not representative of his or her abilities later in the same session of therapy. We demonstrate patients' willingness to be guided by manipulated visual feedback. In addition, all patients showed functional improvements after therapy in our robotic environment.

II. METHODS

Three subjects participated in this experiment; they are denoted P3, P4, and P7. All three patients had suffered a stroke or traumatic brain injury that limited their use of at least one hand. Each injury happened at least one year prior to participation in the study, and each subject used an impaired hand to complete the rehabilitation protocol. P3 was a 25-year-old female TBI subject who participated with her right hand. P4 was a 76-year-old female stroke subject who used her right hand in the experiment. Both P3 and P4 experienced a protocol with visual distortion. Subject P7 was an 82-year-old male stroke subject who participated with his left hand in a visual progression paradigm.

The robotic environment for this experiment included two PHANTOM™ Premium 1.0 robots and is shown in Figure 1. The index finger was coupled to one robot, and the thumb was

coupled to the other. A custom-made finger cuff with 3 passive DOF was used to link each finger to its robot. In this environment, the subject practiced pinching the fingers together and extending the fingers to separate them, as though releasing an object. Performance in pinch formation and release was measured by the distance between the end of the index finger and the end of the thumb. We denote this measurement by d_{it} . The patient was asked to minimize d_{it} when pinching and maximize it when extending the fingers to release.



Fig. 1. The robotic environment with which the subject interacted in our rehabilitation protocol. Two PHANTOM™ robots were used, one coupled to the index finger and one to the thumb.

A. Calibration

Each rehabilitation session began with a short calibration program that measured the patient’s minimum and maximum values for d_{it} , denoted d_{min} and d_{max} , respectively. During this program, patients were told to “pinch fingers together as much as you can” and then to “move fingers as far apart as you can.”

The next part of the calibration program was designed to measure the degree of tremor inherent in each subject’s control when the distance between the fingers was halfway between d_{min} and d_{max} . In this part of the calibration program, the subject saw a screen containing a white box bisected by a blue line (Figure 2). The blue line represented a distance of $(d_{max} - d_{min})/2$, and the white box indicated a window of 5 mm on either side of this distance. The variable d_{it} was shown on the screen as a green ball. The ball moved to the left as d_{it} decreased and to the right as d_{it} increased. The subject was asked to keep the green ball as close as possible to the blue line. One second after the green ball entered the white box, the program began to measure d_{it} . It recorded d_{it} for 3 seconds and then calculated the standard deviation of the distance between the thumb and index finger.

B. Hangman Game

After completing the calibration program, the patient practiced pinching and extending in the context of a game of hangman (Figure 3). The subject saw a screen with a designated number of blanks indicating the number of letters in the word to be guessed, which we refer to as the target word.

The letters from which the patient selected, which we call the letter set, were shown across the top of the screen. As the subject moved the fingers from flexion to extension, letters from left to right were highlighted for selection. The number of letters in the letter set was calculated based on the standard deviation measured during the calibration program, with the caveat that this number was not allowed to decrease from session to session. Our goal was for the screen position of each letter to be unambiguously mapped to the distance between the index finger and thumb; thus, patients with more tremor were presented with fewer letters. All five vowels were always shown, as were all consonants present in the target word. Other consonants were chosen randomly as necessary to complete the letter set. The consonants were listed alphabetically. Vowels were made available at either the right or the left extreme of the letter set, depending upon the deficit (flexion or extension) for which the subject needed the most



Fig. 2. An example of the screen shown during the final part of the calibration program run at the beginning of each rehabilitation session. The ball represented the distance between the subject’s index finger and thumb. The subject brought the fingers closer together to move the ball to the left and separated them to move it to the right. The subject was instructed to keep the ball as close as possible to the blue line centered in the white box. This part of the calibration program measured the tremor in the subject’s movements as he or she tried to maintain a constant distance between the fingers.

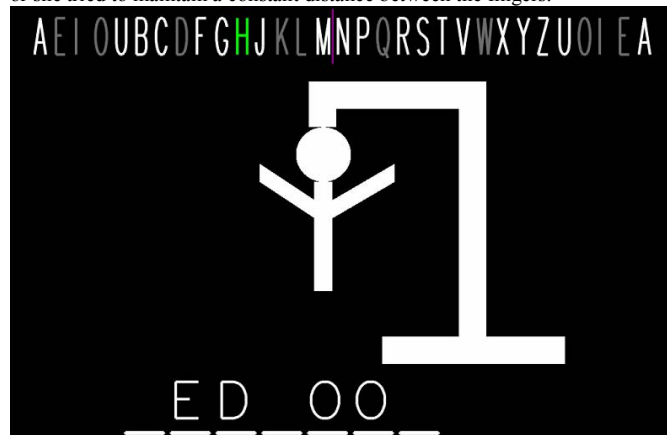


Fig. 3. An example of the appearance of the screen as the subject played the hangman game (in the distortion condition). The letter set was shown horizontally across the top of the screen. The subject moved between letters by changing the distance between the index finger and thumb. When the subject selected a letter, either that letter appeared in the target word at the bottom of the screen or another segment of the hangman appeared.

therapy. Vowels were presented at both extremes for subjects with deficits in both flexion and extension.

The subject selected different letters by changing the distance between the index finger and thumb. We denote the range of distances mapped to the letter set by (d_{mapmin}, d_{mapmax}) . This list was subdivided so that a subinterval corresponded to each of the letters in the letter set. When the subject was within a subinterval corresponding to a given letter, that letter was highlighted. The subject selected a letter by remaining within that letter's subinterval for 2 seconds. The letter then appeared in the target word, or a new segment of the Hangman appeared. A round of hangman ended when the user selected all of the letters in the target word (winning the round) or when all seven segments of the hangman appeared (losing the round).

After each word, the patient was asked to flex and extend the fingers in the absence of feedback. The first goal of these no-feedback periods was to encourage transfer of pinching skills to activities of daily living (ADL). In addition, these no-feedback periods allowed us to measure the subject's voluntary maximum in the absence of feedback. We then examined these data for trends over time and compared it to data measured during the hangman game.

As the subject flexed and extended the finger while playing the hangman game, he or she had to resist a small amount of force. This force was particularly important in extension, because resistance to extension has been shown to improve the active range of motion of stroke patients more than resistance to grasp or ballistic extension [7]. The magnitude of the force was based on the square root of the absolute difference between d_{it} and $(d_{max} - d_{min})/2$. To obtain the magnitude of the force exerted against each finger, this factor was multiplied by a scaling factor that differed for flexion and extension (in general, subjects could resist more force in flexion than in extension). These scaling factors were such that the subject resisted $F_f = 2$ N when the distance between the fingers was d_{mapmin} . When d_{it} was equal to d_{mapmax} , the subject resisted $F_e = 1$ N. The direction of the force was determined in such a way that when d_{it} was less than $(d_{max} - d_{min})/2$, the subject experienced a force pushing the fingers apart. When d_{it} was greater than $(d_{max} - d_{min})/2$, the subject experienced a force pushing the fingers together. The force feedback was removed from the game for P3, because she could not select a letter while resisting any level of force. P4 experienced force feedback in flexion through the six-week protocol, but was only able to play the hangman game while resisting force in extension during the last five rehabilitation sessions. P7 received force feedback in both flexion and extension throughout the six-week protocol.

C. Implementation of Manipulation

Each patient received 18 90-minute rehabilitation sessions, 3 per week for 6 weeks. Each patient experienced visual feedback manipulation in odd-numbered sessions. Visual manipulation was implemented in this robotic environment by manipulating the range of distance (d_{mapmin}, d_{mapmax}) that was mapped to the letter set. For each rehabilitation session, the initial values of d_{mapmin} and d_{mapmax} were chosen to be $1.2d_{min}$ and $0.8d_{max}$, respectively. These proportions of the calibration

maximum and minimum distances were chosen as limits that normal subjects could reach comfortably and repeatedly. During even-numbered sessions in which no manipulation was present, d_{mapmin} and d_{mapmax} remained constant throughout the session.

During sessions with manipulation, d_{mapmin} and d_{mapmax} were made gradually smaller and larger, respectively, over the course of the first 14 words in the hangman game. Thus, to reach all of the letters in the letter set, the patient had to gradually move the index finger and thumb closer together when pinching and further apart when extending. The details of the manipulation will be described for extension; the manipulation for flexion was implemented similarly. The total amount of manipulation experienced during a rehabilitation session varied from subject to subject and was determined based on the difference between the subject's range of motion at the beginning of the experiment and an estimate of what a normal range of motion would be for that subject. During each manipulation session, the upper bound of the distance mapped to the letter set for P3 changed from 80% of the maximum extension measured by the calibration program to 113% of the calibration maximum. P4 was manipulated to 108% of her calibration maximum during the appropriate sessions. P7 was encouraged to increase his maximum extension distance to 105% of his calibration maximum. As visual manipulation encouraged patients to improve their performance, each patient was given the option of asking the experimenter to contract the range of distance mapped to the letter set. This ensured that no patient was required to move beyond his or her physical abilities.

The total amount of manipulation experienced during a rehabilitation session was reached via a series of steps of equal size. Words were presented in sets of three, with a break given between each set. For the second and third words of a set of three, d_{mapmax} was increased by one manipulation step. After the break, d_{mapmax} was decreased by one step. This method was followed until the fourteenth word was reached. For the fourteenth word and all subsequent words, d_{mapmax} was kept constant at the maximum level of manipulation. There were 24 words for each rehabilitation session, but we expected that the subject would not complete all of them.

D. Type of Visual Feedback Manipulation

Rehabilitation sessions for the two types of visual feedback manipulation were identical, except that the subject experiencing visual progression was told that the range of motion required to play to game would gradually increase. In addition, for the visual progression subject, a scale of distance in millimeters was shown along the bottom of the letter set.

E. Measurement of Effects

Before and after the six-week period, each patient was evaluated by an occupational therapist who administered two functional tests, the Arm Motor Ability Test (AMAT) and the Action Research Arm Test (ARAT). The AMAT tested the patient's performance of a variety of everyday activities, such as cutting meat with a knife and fork [8, 9]. For each part of a

task, the patient was given a score from 0 to 5 for both Functional Ability and Quality of Movement. The ARAT, on the other hand, focused on a variety of pinching and grasping tasks more directly related to the movements practiced in our robotic environment [10, 11]. The ARAT is divided into four subtests. Two of these, the Grasp and Pinch subtests, were given once a week throughout the six-week period.

III. RESULTS

For P3 and P4, we focus on performance in extension, for which each had a significant deficit. P7 had deficits in both pinching and extension. However, while we located vowels on both ends of the letter set to give P7 the choice to pick vowels using pinching or extension, he chose to use extension to select vowels 94.7 % of the time. Thus, the visual feedback manipulation was primarily applied in extension, and we confine our analysis to P7's performance in extension. The following sessions were omitted because insufficient data were collected: session 12 for P3, sessions 2 and 12 for P4 (session 2 omitted only from analyses examining variables as a function of time within a session), and session 7 for P7 (omitted only from analyses of periods with no visual feedback).

A. Calibration Measurements

Each subject's maximum extension distance was measured by the calibration program at the beginning of each rehabilitation session (Figure 4). No significant increase with time was found for this distance over the six-week participation period for P3 and P7 (P3: $p = 0.94$; P7: $p = 0.99$). On the other hand, P4 exhibited a significant downward trend in the maximum extension distance measured during calibration ($p < 0.001$).

Recall that the standard deviation of d_{it} measured the instability of the patient's hand position midway between the extremes of flexion and extension. A marginally significant positive slope in this measure was found over the duration of P3's participation in the experiment ($p = 0.060$; Figure 5). This effect was countered by the fact that by the third week of the six-week period, P3 was playing the game with the entire alphabet shown on the screen. However, there was a significant upward trend with session in the time it took P3 to select each letter ($p < 0.001$), which may have been due to the increase in the number of letters in the letter set. For P4, we observed a significant downward trend in the standard deviation of d_{it} ($p = 0.049$; Figure 5). This coincided with P4's ability to play the Hangman game with a larger letter set without increasing the mean time needed to select a letter ($p = 0.23$). At the beginning of the 6-week paradigm, P7 was capable of playing the hangman game with the vowels presented on both the left and right sides of the screen and with all consonants shown (31 letters total). For this reason, we do not discuss the standard deviations in distance measured for P7.

B. Effects of Manipulation

The maximum extension distances measured during the calibration program did not appear to be representative of the

true abilities of our subjects. All three subjects followed the visual feedback manipulation. P3 never requested that the experimenter contract the range of distance mapped to the letter set. P4 chose to contract the distance range during 3 of the 9 sessions with manipulation, but also tried to contract the distance range during 3 of 9 sessions without manipulation (when this request had no effect). P7 chose twice to reduce the range of distance mapped to the letter set. In both cases, he struggled for some time to reach the far right of the display before allowing the experimenter to reduce the range of distance required.

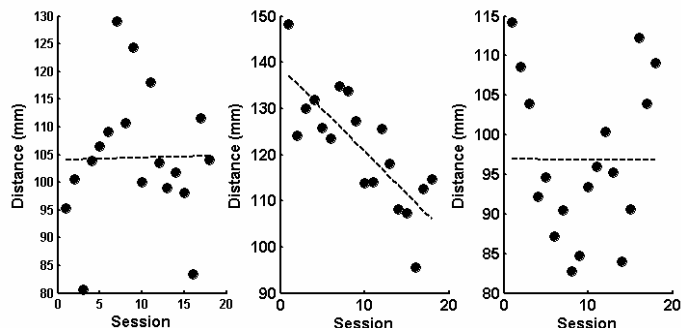


Fig. 4. From left to right, the maximum extension distance measured during calibration in each session for P3, P4, and P7. A significant downward slope was found for P4.

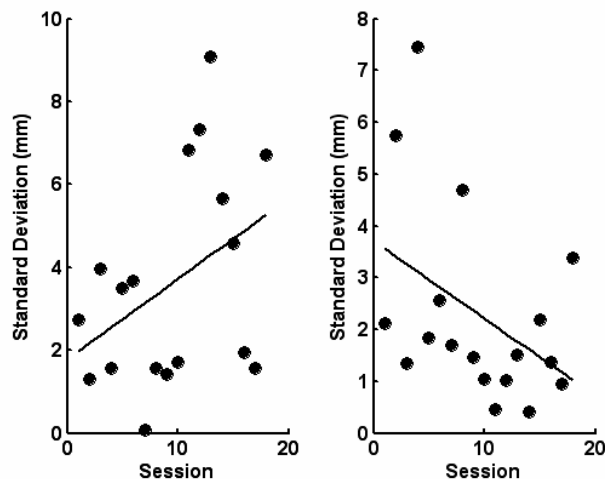


Fig. 5. The calibration program measured the standard deviation in the distance between the thumb and index finger as the subject tried to keep this distance at the midpoint between the minimum and maximum distances measured during calibration. This standard deviation as a function of session number for P3 is shown on the left, and the data for P4 are shown on the right. A regression line is shown for each subject's data. This line had a marginally significant positive slope for P3 and a significant negative slope for P4.

The effects of the distortion and progression can be seen in Figure 6. For each subject, we first found n_{min} , the minimum number of words completed in a session. For each of the first n_{min} words in a session, we calculated the maximum extension distance used to select a letter during that word. We then averaged these distances across manipulation sessions to find how the maximum extension distance evolved as a function of time during a rehabilitation session with manipulation. A significant upward trend with visual manipulation was

observed in the maximum extension distance for each subject (P3: $p = 0.020$; P4: $p = 0.0051$; P7: $p < 0.001$). There were no significant linear trends for the first n_{min} words of sessions

TABLE I

Patient	With Feedback	No Feedback	p -value
P3	110.6	103.1	0.098
P4	119.2	120.2	0.91
P7	99.88	112.4	0.74

The mean maximum extension (in mm) between the fingers measured with and without feedback for each patient in the manipulation condition. For each patient, the mean with-feedback maximum was compared to the mean no-feedback maximum.

TABLE II

Patient	With Feedback	No Feedback	p -value
P3	98.19	104.3	0.64
P4	100.6	106.6	0.64
P7	79.72	115.1	0.0078

The mean maximum extension (in mm) between the fingers measured with and without feedback for each patient in the no-manipulation condition. For each patient, the mean with-feedback maximum was compared to the mean no-feedback maximum.

with no distortion or progression (P3: $p = 0.79$; P4: $p = 0.28$; P7: $p = 0.56$).

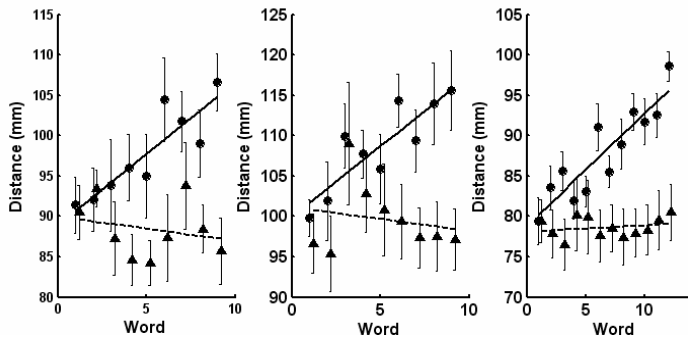


Fig. 6. Each patient (from left to right: P3, P4, and P7) consistently followed the visual feedback manipulation, causing an upward trend in his or her extension during sessions with manipulation. Circles (triangles) represent the mean over manipulation (no-manipulation) sessions of the maximum extension distance used to select a letter in each word. No-manipulation data is slightly horizontally offset from distortion data for clarity. Regression lines for each data set are shown. All error bars represent standard error.

C. Performance in the Absence of Visual Feedback

Recall that periods with no visual feedback were interposed between words in the hangman game. We examined whether the no-feedback data exhibited a tendency toward greater extension over the course of a manipulation session, as was the case for data taken during the hangman game. For each subject, we found n_{minnof} , the minimum number of no-feedback periods completed in a session by that subject. Then, for each of the first n_{minnof} no-feedback periods, we averaged the maximum extension across sessions with visual feedback manipulation. No significant linear trend was found for P3 and P4 for the no-feedback maximum extension as a function of time within a session ($p = 0.32$ for P3; $p = 0.26$ for P4). This analysis could not be performed for P7.

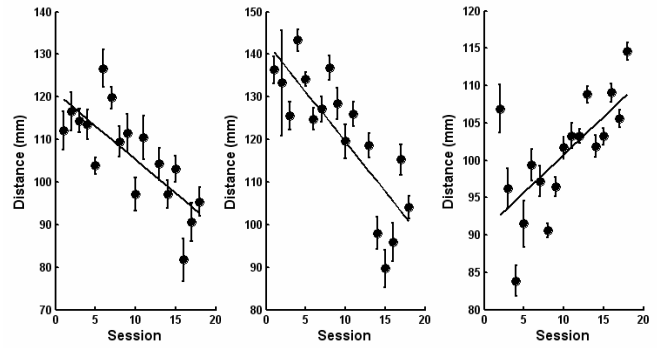


Fig. 7. The mean maximum extension measured during the periods with no visual feedback is plotted as a function of session number. From left to right, the graphs correspond to subjects P3, P4, and P7. A regression line is shown for each subject, and the bars represent standard error. Significant downward trends in maximum no-feedback extension with session number were found for P3 and P4, but a significant upward trend was found for P7.

Next, we compared each subject's performance with and without visual feedback. The comparisons were made at two points: at the beginning of a rehabilitation session and at the point in the session where the visual manipulation reached a maximal level. When we compared the first no-feedback maximum extension of each session to the first with-feedback maximum extension (the first distance used to select 'A'), the no-feedback extension was found to be significantly higher for all three subjects ($p = 0.0019$ for P3; $p < 0.001$ for P4 and P7). That result occurred because in the no-feedback condition, subjects extended beyond the distance of $0.8d_{max}$ that was initially required by the hangman game. We then compared the maximum extension during the last no-feedback period with the last maximum extension with feedback (last 'A' selected). The results of these tests are shown in Table I for sessions with visual feedback manipulation and, for comparison, in Table II for sessions without visual feedback manipulation. Even though patients were performing near or above their calibration maximum in the with-feedback condition, their performance did not degrade in the no-feedback condition.

Table III.

Patient	ARAT Score		AMAT Functional Ability Score	
	Initial	Final	Initial	Final
P3	26/57	32/57*	2.11/5	1.61/5*
P4	38/57	40/57	2.29/5	2.86/5*

The initial and final scores of each subject for the ARAT and the Functional Ability score of the AMAT. An asterisk denotes clinically important differences.

To examine whether practice in our robotic environment resulted in an increase in voluntary extension, we also looked at the change over sessions in the maximum no-feedback extension. For each session, we averaged the maximum extension distances measured during the first n_{minnof} no-feedback periods. Contrary to expectations, there was a significant downward slope in the mean maximum extension distance over the six-week period for P3 and P4 ($p < 0.001$ for both; Figure 7). However, we observed a significant upward trend over the 6-week period for P7 ($p < 0.001$).

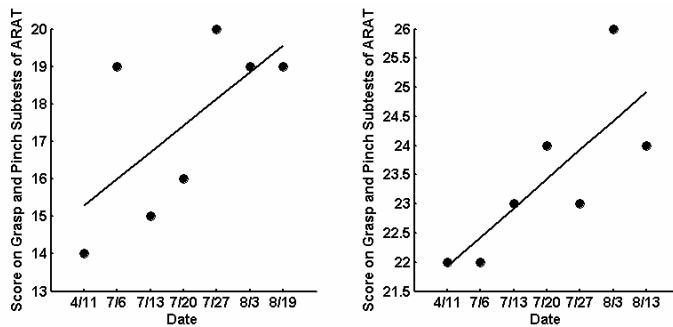


Fig. 8. Throughout the 6-week period, P3 (left) and P4 (right) improved their functional pinching skills, as measured by a subtest of the ARAT. The slope of each regression line is significantly greater than 0.

D. Functional Tests

We observed a variety of functional improvements in our subjects. Figure 8 shows, as a function of time, the scores of P3 and P4 on the Grasp and Pinch subtests of the ARAT. A significant upward slope was found in the subtest score of each patient (P3: $p = 0.023$; P4: $p = 0.0013$). Table III shows the ARAT score and Functional Ability score on the AMAT before and after the 6-week protocol. Clinically important changes are marked with an asterisk; we assumed a clinically important difference to be 10% of the maximum possible score [11]. Results for the Quality of Movement score of the AMAT were similar.

IV. DISCUSSION

A. Effects of Manipulation

We explored the effects of visual feedback manipulation with three patients. At the beginning of each session, a patient was required to extend to 80% of his or her calibration maximum to reach the far right of the list of letters used in the hangman game. We chose a starting point of 80% of the calibration maximum because we anticipated that a subject would expend considerable effort reaching the calibration maximum and would find it difficult to reach this distance repeatedly. We felt 80% of the calibration maximum would approximate a comfortable maximum distance for the subject. However, all patients readily followed distortion or progression to levels of extension well above this starting point. By the end of each manipulation session, the patient was reaching or exceeding his or her initial maximum. This is particularly notable for P3 and P4, because they were required to reach, but not hold, their maximum extensions during calibration, while a given level of extension had to be held 2 seconds to select a letter in the hangman program. One might assume that without the requirement to hold, these patients would have produced something close to their true maximum during calibration; yet, even these levels were readily exceeded.

B. Underperformance in Calibration

The results of these experiments indicate that a patient's initial performance should not be assumed to represent that patient's actual abilities. Had the patients exhibited a true maximum in pinch performance during calibration, visual

feedback would not have induced them to reach more extreme postures, but in fact, the feedback was highly successful. Underperformance during calibration is also indicated by the data measured during the no-feedback periods. The mean no-feedback maximum extension did not increase over the course of a rehabilitation session, yet it was similar to the with-feedback maximum extension at the highest level of manipulation. If the calibration maximum were the subject's absolute maximum, he or she would not consistently reach similar levels of extension in the no-feedback condition. Increasing the starting point for the distortion or progression would allow us to obtain a clearer picture of the patient's actual abilities and the effects of visual feedback manipulation.

Underperformance by P3 during calibration is also implied by the standard deviation used to determine the number of letters shown on the screen. There was a marginally significant upward trend with session for the standard deviation, possibly caused by P3 becoming bored with the calibration program. Despite the fact that the standard deviation increased, P3 successfully played the Hangman game with more letters as the six-week period progressed, finally playing with all 26 letters shown on the screen (Note: Before her participation in the experiment, P3 attempted the Hangman game with all 26 letters, and was unable to play successfully). However, the upward trend with session in search time per letter indicates that P3 did find it more difficult to select letters when more letters were presented on the screen. This upward trend could also reflect the increased cognitive load of playing the game with more letters.

The gap between calibration performance and actual ability is consistent with Taub's work with Constraint-Induced Movement Therapy (e.g., [12]). This technique addresses learned nonuse by restraining the unaffected limb of hemiplegic patients. Patients are often surprised to find that they can use the impaired arm for many activities that they usually perform with the unimpaired arm. In general, the underperformance of subjects during calibration has important implications for rehabilitation in general, and for robotic rehabilitation in particular. Robotic rehabilitation systems must be calibrated for each individual, and the activities a patient is asked to perform are based on this calibration. One way to overcome this problem is to use visual feedback manipulation to encourage a patient to improve his or her performance.

C. Performance in the Absence of Visual Feedback

Maximum extension during no-feedback periods indicates the patient's voluntary level when he or she is not trying to cause a particular visual outcome. We assessed improvement in capability by examining this measure over the six-week participation period. We observed a significant downward trend for P3 and P4 in the mean maximum extension measured during the no-feedback periods presented throughout the Hangman game. This is contrary to the expectation that voluntary extension would improve. Moreover, we did not observe increases in maximum extension during calibration for any patient, with P4 even decreasing over the six weeks. On

the other hand, we found a significant upward trend over the six-week period in the mean maximum extension measured for P7 during no-feedback periods. With our limited data, we have no way of accounting for these contrasts, but two differences in the experimental protocols should be noted. P7 had to hold his no-feedback maxima and minima for 2 s each, while P3 and P4 did not. The 2 s hold reduced variation in the no-feedback maxima and minima, making it easier to observe any trends. It may have also induced P7 to pay more attention to the measure. In addition, P7 encountered a resistive force in extension, while P3 and P4 were unable to play the Hangman game while experiencing such a force (P4 did experience resisted extension during her last 5 sessions). Resistance in extension has been shown to improve active range of motion in patients more than resistance in flexion [7]. It is possible that countering resistive force, particularly in extension, helped P7 to strengthen his hand enough that we observed an improvement in his range of motion.

D. Functional Improvements

Exercise in our environment led to clinically significant functional improvements in all three of our patients. Our initial data with only three subjects (without control) cannot show how these improvements were related directly to the visual feedback manipulation, but practice in our robotic environment did transfer to functional grasping tasks. Future experiments will investigate whether visual feedback manipulation can lead to greater functional gains.

E. Comparison of Distortion and Progression

When we began these experiments, we expected that patients who experienced the progression protocol might choose more frequently than distortion patients to contract the range of distance mapped to the screen. Alternately, we hypothesized that they might be highly motivated by observing their progress. However, these preliminary results show few differences between the two protocols, possibly because P7 did not seem very interested in watching his improvement on the distance scale. More experiments with patients will be required to determine whether the effects of distortion differ from those of visual progression. In future experiments, it may be helpful to change the visual display so as to make the progression more striking, thus ensuring that the subject pays attention to it.

F. Visual Feedback Manipulation in Rehabilitation

Previous applications involving visual distortion in rehabilitation [4, 13] relied on the effects of distortion being maintained after the conclusion of the rehabilitation session. In part, this is true of our paradigm as well. Ideally, a subject who follows the visual manipulation to obtain a larger range of motion will continue to utilize the larger range after the conclusion of the rehabilitation session. This is likely, given that the effects of distortion have been found to wash out more slowly in stroke patients [13, 14]. However, the main goal of

the manipulation is to encourage the subject to perform at a higher level during the rehabilitation session. We expect that even if the effect of the manipulation is short-term, practicing at a higher level during each rehabilitation session will improve the outcome of rehabilitation.

While these data are only an initial exploration of the effects of visual feedback manipulation, we have many indications that patients are capable of performing better than they may demonstrate when asked to execute a task. These indications are strong support for using visual feedback manipulation to encourage patients to improve their performance during rehabilitation.

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