Research report

Visual feedback distortion in a robotic environment for hand rehabilitation

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Abstract

Robotic therapy offers a means of enhancing rehabilitation for individuals with chronic stroke or traumatic brain injury. The present research targets members of this population who demonstrate learned nonuse, a tendency to use affected limbs below the level of the individual’s true capability. These individuals may not strive for difficult goals in therapy, which ultimately hampers their progress and the outcome of rehabilitation. Our research uses a paradigm called visual feedback distortion in which the visual feedback corresponding to force or distance is gradually changed by an imperceptible amount to encourage improved performance. Our first set of experiments was designed to assess the limits of imperceptible distortion for visual feedback concerning the force exerted or the distance moved by the index finger. A second set of experiments used these limits to gradually distort visual feedback in order to manipulate a subject’s force or distance response. Based on this work, we designed a paradigm applying visual feedback distortion to the rehabilitation of individuals with chronic stroke and traumatic brain injury. Initial tests are reported for two subjects who participated in a six-week rehabilitation protocol. Each patient followed visual feedback distortion to levels of performance above that predicted by her performance during an initial assessment. Both patients showed functional improvements after participating in the study. Visual feedback distortion may provide a way to help a patient move beyond his or her self-assessed “best” performance, improving the outcome of robotic rehabilitation.

Keywords: Visual distortion; Visual feedback; Hand rehabilitation; Robotic rehabilitation

1. Introduction

A variety of robotic systems have been proposed for rehabilitation of the upper limb. These include systems designed to address large movements of the whole arm [36], robots for practice of primarily planar reaching movements [21], and systems to improve fine motor control in the hand [5]. One benefit of using these systems as an addition to traditional rehabilitation is that they provide high-precision measurements that can be used to evaluate patient performance and progress [22]. Robots can also produce controlled, repeatable stimulation of the upper limb, for example, by passively moving the limb along a target trajectory [10] or by providing targeted forces to the arm that result in a desired aftereffect [24].

Robotic systems for rehabilitation can provide visual feedback to individuals interacting with the robot [5,21]. Our work examines how this visual feedback can be used to improve performance during rehabilitation. Patients may resist making progress in rehabilitation due to entrenched habits [34] or psychological barriers [1,2]. This problem may be particularly pronounced in individuals with chronic stroke and traumatic brain injury (TBI), who have the capacity to make functional improvements but have lived with disability for long periods of time. We have designed a paradigm we call visual feedback distortion to help such an individual overcome a reluctance to move beyond his or her established level of performance. The subject receives visual feedback that is mapped to some movement variable, such as force or range of motion. Then, the range of the movement variable mapped to the visual feedback is gradually increased to encourage the subject to improve his or her performance. This remapping is imperceptible in order to ensure that the subject does not realize that he or she is being asked to advance. Otherwise, the subject may judge the visual feedback to be unreliable and rely less upon it [13]; a subject might even actively resist improving his or her performance beyond an established level.
This paper reviews some of the initial work that we have done to build a body of work for researchers interested in incorporating visual distortion into rehabilitation. We chose to research the effects of visual distortion in the context of fine motor tasks involving the hand and fingers. This work could be extended to include other tasks and other parts of the body.

We began by measuring the Just Noticeable Differences (JNDs) for force and position. The Just Noticeable Difference for a physical variable indicates the smallest change in that variable that a subject can reliably perceive. This gives us a lower bound on the amount of distortion that should be imperceptible in our robotic environment. The JND is a lower bound because larger amounts of distortion may be imperceptible if time passes or the subject is distracted.

After determining the JNDs for force and position, we used these quantities to design an experiment to show that visual distortion can be used to increase a subject’s force production and movement distance in a robotic environment. When asked to produce constant levels of force or distance, subjects’ responses were dominated by the distorted visual feedback, rather than kinesthetic feedback from the hand. In this experiment, subject performance was affected by a series of imperceptible distortion steps resulting in a cumulative level of distortion well above the JND.

In addition to reviewing the experiments described above, this paper also describes how we used our results to design a six-week rehabilitation protocol using visual distortion. Two preliminary subjects, a chronic stroke subject and a chronic TBI subject, completed this protocol, and we review those results here. Each subject used distorted visual feedback to guide performance during rehabilitation. This was possible because the performance of each subject during calibration did not reflect her true ability. Both subjects showed functional improvements after completing the rehabilitation protocol.

2. Lower bound on distortion

2.1. Methods

We measured the Just Noticeable Differences for force and position to obtain a lower bound on the amount of distortion that is imperceptible in our robotic environment. The experimental environment used in this experiment in shown in Fig. 1 and consisted of a Premium 1.5 model PHANTOM™ robot coupled to the subject’s index finger with a custom-made finger cuff. The robot had three active degrees of freedom and could exert continuous forces up to approximately 5 N. The custom-made finger cuff had three passive degrees of freedom. The subject was restrained so that he or she moved the hand only about the metacarpophalangeal (MCP) joint of the index finger. In this environment, we created a virtual spring; as the subject flexed the index finger about the MCP joint, he or she had to push harder against the robot. The robot exerted force in a direction tangent to the path of the subject’s finger.

The force JND experiment consisted of 100 trials, and the subject sampled 2 forces on each trial. The first force was always a base force $F_0$, while the second was either $F_0 + \Delta F$ or $F_0$. The values of $F_0$ and $\Delta F$ varied for the different subject groups, but [23] found that such variations did not affect the force JND considered as a percentage of the base force. The visual display shown in Fig. 2 guided the subject to the target force. When the subject was within an acceptable window of the target force, the middle box was shaded. Otherwise, the top or bottom box was shaded. The subject sampled each force for 2 s. To ensure that distance was not correlated with force, the spring constant of the virtual spring implemented on the robot varied from trial to trial and also between stimuli within a single trial.

After sampling both forces, the subject was asked whether they were the same or different and responded by pressing ‘s’ or ‘d’ on the keyboard. After the subject completed the experiment, the force JND was calculated using the number of hits (trials on which the forces were different and the subject answered “different”) and the number of false positives (trials on the forces were the same and the subject answered “different”) [4,23]. We computed the force JND as a percentage because it has been found to be a constant fraction of the starting force [15,23].

![Fig. 1. The experimental environment used in the experiments described in Sections 2 and 3. The subject’s index finger was coupled to a PHANTOM™ robot via a custom-made finger cuff. The robot simulated a spring as the subject moved the finger about the metacarpophalangeal joint (reprinted from ref. [6] © 2005 IEEE).](image-url)
Fig. 2. The visual display used in the experiments designed to measure the lower bound on the amount of distortion that is imperceptible (Section 2). The middle box of the display was highlighted when the subject was within the target window for force or position. Otherwise, the top or bottom box was highlighted (reprinted from ref. [6] © 2005 IEEE).

The position JND experiment was similar. In this experiment, subjects were asked to move the finger through two distances from a given starting point and then distinguish whether these distances were the same or different. Previous work suggests that this discrimination was likely based on the endpoint position of the finger, rather than the distance moved [17]. Thus, we consider this measurement a JND for position and computed it in terms of millimeters.

Both experiments were conducted with both young and elderly subjects without disability. In addition, two young individuals with TBI (P1 and P5) and one elderly individual with stroke (P4) also participated in both experiments.

2.2. Results

The results of the force and position JND experiments can be seen in Figs. 3 and 4. The mean force JND measured for young, unimpaired subjects was 19.7 ± 1.85% (mean ± standard error), which was significantly smaller than the JND of 31.0 ± 3.99% that was measured for elderly, unimpaired subjects. The two results were compared using a t-test. The results for the motor-impaired subjects were as follows: P1’s JND was 46.0%, P4’s JND was 54.8%, and P5’s JND was 24.0%.

The mean position JND for young, unimpaired subjects was measured to be 3.99 ± 0.434 mm. A t-test indicated that this was not significantly different from the value of 6.32 ± 1.38 mm measured for elderly, unimpaired subjects. The results for the motor-impaired individuals were as follows: P1’s JND was 14.8 mm, P4’s JND was 13.6 mm, and P5’s JND was 11.2 mm.

2.3. Discussion

The force and position JNDs for young subjects provide us with a lower bound on the amount of distortion that is imperceptible for these physical dimensions. For example, if a visual display of force is distorted by 15%, then subjects will be unable to detect this amount of distortion because it is below the force

Fig. 3. Force JND results for young and elderly subjects without disability. Error bars represent standard error. The force JND for elderly subjects was significantly greater than that of young subjects. The force JND results for two TBI subjects and one stroke subject are shown for comparison (portions reprinted from ref. [6] © 2005 IEEE).

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Fig. 4. Position JND results for young and elderly subjects without disability. Error bars represent standard error. The position JND for elderly subjects was not significantly different from that measured for young subjects. The position JND results for two TBI subjects and one stroke subject are also shown (portions reprinted from ref. [6] © 2005 IEEE).
JND of 19.7%. The JND is a lower bound for the amount of distortion that is imperceptible because it represents a subject’s performance when two stimuli are presented sequentially and the subject is concentrating his or her attention on distinguishing them. If the forces are separated in time or the visual feedback is in the form of a game that diverts the user’s attention, then levels of distortion well above this lower bound may be imperceptible.

Our value for the force JND of young subjects is much larger than the values measured by other researchers for various muscle groups in the arm and hand [9,18,23,25,27]. For example, Raj et al. [25] measured a JND of 11–12% for weights lifted by the middle finger about the MCP joint, while Pang et al. [23] measured a JND of 7% for pinch force exerted between the index finger and thumb. However, in these experiments, the only dimension that was varied was the force. This contrasts with our experiment, in which we also varied the spring constant of the virtual spring. As a result, distance was uncorrelated with force; a dimension, such as distance, that varies independent of the target dimension (force) is termed a background dimension. Similar variations in background dimensions have been shown to increase JNDs for force and displacement [32,33].

We also varied the spring constant during the position JND experiment, but due to force limitations, the range of spring constants used was less than that used in the force JND experiment. In effect, position varied more in the force JND experiment than force did in the position JND experiments. This may be why the position JND of 3.99 mm that we measured for young subjects is close to the range of 1–3 mm reported for the JND of a similar quantity, the finger span (the distance between the index finger and thumb) for studies in which no background dimensions were varied [12,13]. When considering the use of distortion in a rehabilitation environment, varying any available background dimensions is advantageous because it increases the amount of distortion that is imperceptible.

Our force JND results with elderly subjects show that age tends to decrease perception of force differences. This result is similar to previous studies showing that age decreases the tactile sensibility of the hand as measured by two-point discrimination, the distance by which two contact points must be separated before they are perceived as distinct [28,31]. Age has also been found to increase JNDs relevant to auditory discrimination [14] and wavelength discrimination [29]. The position JND that we measured for elderly subjects was not significantly larger than that observed for young subjects, though there was a tendency in this direction. This may indicate that elderly subjects are more affected than young subjects by variations in background dimensions; there may be a larger difference between the JNDS of the young and elderly in the force experiment because the background dimensions varied more in that experiment.

So far, we have worked with only a few individuals with chronic stroke and TBI, yet already our results indicate that these disabilities tend to decrease perception of force and position differences. On average, position JNDS measured for individuals with motor disabilities were about three times greater than those of the appropriate age-matched control group. The force JND of one TBI subject was close to the range of JNDS measured for age-matched individuals without disability, while those for the other motor-impaired individuals were much higher than those measured for the control groups. It is worth noting that the TBI subject with the low force JND (P5) possessed a high degree of hand function, i.e., full range of motion with considerable grip strength. The effect of stroke or TBI on the JND for the hand for force and position has not been studied by other researchers, but our results are similar to a previous result showing that stroke decreases a patient’s ability to discriminate joint position on the impaired side [19]. The high JNDS that we measured for individuals with stroke and TBI suggest that large amounts of distortion can be used imperceptibly in robotic rehabilitation paradigms for these individuals. For further details about the experiments described in this section, see ref. [6].

3. Use of distortion to manipulate force production and movement distance

3.1. Methods

After measuring the JNDS for force and position for a variety of subject groups, our next goal was to show that gradual distortions beyond these lower bounds could manipulate subject performance during a single session.
in a robotic environment. We first considered the use of distortion to increase force production. The experimental test bed described above was used for this experiment. Each subject completed 140 trials, and on each trial, he or she was asked to produce a particular level of force from 1–5, 5 being the largest. The subject flexed the index finger against the virtual spring until the desired force was reached, then pressed the space bar to record the force. The subject was allowed to choose the magnitude of the force that corresponded to each level but was asked to be as consistent as possible in the force he or she produced for each level. For example, throughout the experiment, the subject tried to produce the same force every time he or she was asked for force level 3.

During half of the trials of the experiment, a visual feedback bar (Fig. 5) was shown on the computer screen. On the other half of the trials, the screen displayed only the requested force level. The feedback bar consisted of 25 boxes, and the number of shaded boxes indicated the magnitude of the force exerted by the subject. We implemented distortion in this experiment by gradually changing the range of force that was mapped to the visual feedback bar. The subject experienced twenty trials for each of seven levels of distortion, including 0% distortion. Each distortion step was accomplished by increasing the force represented at each end of the visual feedback bar by one third of the force JND multiplied by the original value of the endpoint. To ensure that the JNDs measured in the previous experiment were valid for this design, the spring constant of the virtual spring was varied from trial to trial.

The experiment described above was conducted with young, unimpaired subjects. Similar experiments were conducted with elderly subjects without disability, two subjects with chronic TBI, and two subjects with chronic stroke. In addition, a control experiment with no distortion was conducted with young unimpaired subjects. Finally, this experimental paradigm was expanded to include a variation in which subjects were warned that the visual display might be distorted and a variation with distortion designed to increase movement distance.

3.2. Results

The results of the initial experiment (distortion designed to increase force production in young, unimpaired subjects) are shown in Fig. 6. For each force level and feedback condition (with or without visual feedback), we performed linear trend analysis to test for an upward trend in the force produced as a function of increasing distortion. Because this resulted in a series of ten tests, an adjustment was made to minimize the false discovery rate [3]. For the trials with visual feedback, we observed an upward trend in force with distortion for force levels 3, 4, and 5. In addition, linear trend analysis also showed that the slope of produced force versus percent distortion increased significantly as a function of force level, showing that greater absolute amounts of distortion led to greater absolute changes in force. For each force level, a t-test showed that the mean slope of force versus percent distortion was not significantly different from the slope that would be expected if the subject ignored kinesthetic feedback and relied only on the visual feedback bar (total visual dominance). Again, an adjustment was made for multiple testing. The results for trials without visual feedback were similar, indicating that distortion during trials with feedback affected performance even when the feedback was removed. These results were very different from those observed for subjects in the control experiment with no distortion (Fig. 7). The data for control subjects were divided into seven blocks of twenty trials to correspond to the seven distortion conditions.
that their performance did not differ from that predicted by total visual dominance. The data collected with elderly subjects and individuals with disability confirmed that distortion increased the force produced by these individuals (Fig. 8), though the elderly subjects and the two TBI subjects exhibited smaller increases in force with distortion for the trials with no visual feedback. In an alternate version of the experiment, distortion was also used to increase movement distance during a single experimental session.

3.3. Discussion

This set of experiments showed that visual feedback distortion could be used to increase force production within a single experimental session. Though subjects tried to be consistent in the force that they produced for each level, upward trends in force with distortion were seen for the trials with visual feedback for young and elderly unimpaired subjects, as well as for four subjects with stroke or TBI. In fact, distortion was used to encourage specific increases in force, as evidenced by the fact that larger absolute amounts of distortion led to larger absolute changes in force production. Our results indicate that subjects used the visual feedback bar to set a visual goal for each level and responded in such a way as to keep the visual goal constant, even though the actual force or distance corresponding to the visual goal was increasing. In this sense, vision dominated kinesthesia in our robotic environment. These results are similar to reports of visual dominance for tasks ranging from shape perception [26] to perception of stiffness [30] and limb position [39].

Vision tends to dominate kinesthesia in tasks for which the subject judges that vision provides more precise feedback [13]. Thus, it is noteworthy that by the end of the experimental session, we had distorted the visual display of force or distance by approximately two JNDS, yet subjects still followed the distortion. This large amount of distortion, which would be easily detectable if reached in a single step, went unnoticed because it was accomplished over a series of steps, each of which was less than the JND for force. This result suggests that large distortions can be used in rehabilitation, provided they are reached gradually.

From a rehabilitation perspective, it is also important that the results of the experiment did not change when subjects were informed that the display might be distorted. To be a useful addition to rehabilitation, distortion must be used over multiple sessions, and a verbal slip or technical error could make the user suspect that the visual display is being manipulated. Our results indicate that distortion should still be effective in this situation.

The trials without visual feedback that were included in this experiment provide insight into the effect of visual feedback manipulation on the somatosensory representation of the force goal. For young subjects without disability, significant upward trends in force with distortion were observed across trials with no visual feedback. As a subject maintained a constant visual goal, their performance did not differ from that predicted by total visual dominance. The data collected with elderly subjects and individuals with disability confirmed that distortion increased the force produced by these individuals (Fig. 8), though the elderly subjects and the two TBI subjects exhibited smaller increases in force with distortion for the trials with no visual feedback. In an alternate version of the experiment, distortion was also used to increase movement distance during a single experimental session.

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Such increases were not consistently found for elderly, unimpaired subjects and individuals with disability. We hypothesize that this difference may be caused by the tendency of elderly subjects and some motor-impaired individuals to overestimate the force in the absence of visual feedback. Due to overestimation of the force in the initial trials without visual feedback, the subject did not need to adjust the somatosensory representation of the visual goal to keep pace with the distortion. A similar overestimation phenomenon has been observed for grip force [11,16].

While this set of experiments focused primarily on force production, an experiment with young, unimpaired subjects using distortion designed to increase movement distance yielded similar results. Thus, we expect that our results concerning the use of visual distortion to increase force production can also be applied to movement distance. For more information on the experiments described in this section, see ref. [7].

4. Distortion in a rehabilitation paradigm

4.1. Methods

After conducting the experiments described above, we designed a preliminary rehabilitation protocol using the same experimental environment and distortion to increase force production about the MCP joint. While exercise in this environment did increase strength and range of motion in a single test subject with TBI, we observed no clinically significant functional improvements due to the focus on movement about a single joint [7]. To increase the functional benefit to individuals with stroke and TBI, we expanded our experimental environment to include two PHANTOM™ Premium 1.0 robots, one coupled to the index finger and one coupled to the thumb (Fig. 9). Two subjects, P3 and P4, participated in a preliminary experiment in this environment. P3 was a 25-year-old subject with chronic TBI, and P4 was a 76-year-old subject with chronic stroke. Both were female.

In the robotic environment, each subject practiced pinching the index finger and thumb together and extending the fingers to separate them, as though releasing an object. Thus, the variable of interest was the finger span, the distance between the tip of the index finger and the tip of the thumb. While we have not specifically measured the JND for this quantity, it has been measured by other researchers to be 1–3 mm for unimpaired subjects in the absence of varying background dimensions [12,13]. Our position JND results for stroke and TBI subjects indicate that we should expect the JND for these subjects to be approximately three times the value measured for subjects without disability, giving us an expected maximum JND of about 9 mm. Background dimensions were not consistently varied in our rehabilitation protocol because the subjects were not consistently capable of extending the fingers against a resistive force.

Each subject practiced pinching and extending the index finger and thumb in the context of a game of hangman (Fig. 10). Along the bottom of the screen, the subject saw a number of blanks indicating the target word, the word to be guessed. Across the top of the screen, the subject saw a letter set from which she could select. The subject’s finger span was mapped to the letter set in such a way that as she moved the fingers from flexion to extension, letters from left to right were highlighted for selection. The subject selected a letter by keeping that letter highlighted for 2 s. The discrete display used in this game was similar to the visual feedback bar used in the experiment described in Section 3, but the discrete items were letters instead of blocks. The subject won a round of the game by completing the target word before all segments of the hangman appeared.

After each round of the game, the subject was asked to pinch and extend the fingers in the absence of visual feedback concerning the finger span. These periods without visual feedback were included to encourage transfer to activities of daily living (ADL) and to measure the subject’s voluntary maximum and minimum finger span.

Each subject received eighteen 90-min rehabilitation sessions, 3 per week for 6 weeks. The subject experienced distortion in only the odd-numbered sessions. At the beginning of every session, a short calibration program measured the subject’s minimum pinch and maximum extension. For each session, the initial limits of the finger span range mapped to the letter set were 120% of the calibration minimum (lower limit) and 80% of the calibration maximum (upper limit). These limits were chosen as the minimum and maximum distance between the fingers that the subject could achieve comfortably and repeatedly.

During sessions with distortion, the finger span range mapped to the letter set was gradually expanded over the course of the rehabilitation session. We will describe the implementation of the distortion for the upper limit of the finger span range; distortion for the lower end was analogous. For P3, the upper limit of the finger span range changed from 80% of the calibration maximum to 113% of the calibration maximum over the course of a rehabilitation session with distortion. This change occurred over five steps distributed over the first 14 words of a session. Given P3’s mean calibration maximum of 104 mm, the size of each distortion step was approximately 6.86 mm. For P4, the upper limit
of the finger span range was distorted from 80\% of the calibration maximum to 110\% of the calibration maximum, again via a series of five steps. P4’s mean calibration maximum was 122 mm, meaning that the size of each distortion step was approximately 7.32 mm. Thus, for both subjects, each distortion step was less than the estimated maximum JND for this experiment, which was 9 mm. For safety, each subject was always given the option of asking the experimenter to reduce the finger span range required to play the game.

Before and after the six-week rehabilitation protocol, each subject was given two functional tests by an independent occupational therapist. The first was the Arm Motor Ability Test (AMAT), which quantifies performance of everyday activities such as cutting meat [20, 35]. The second functional test was the Action Research Arm Test (ARAT), which quantifies performance of various grasping and pinching tasks [37, 38]. A subtest of the ARAT was given weekly during the rehabilitation protocol. We assumed a clinically important change on each test to be 10\% of the maximum possible score [38].

4.2. Results

P3 and P4 had significant deficits only in extension, so we focus on their performance in extension. Each of the subjects was guided by the distortion during sessions in which it was present. For each subject, linear trend analysis indicated a significant upward trend with word number (i.e., time-point within the session) in the maximum extension distance used to select a letter in the word (Fig. 11). No significant trend was observed during sessions without distortion.

We compared data taken while playing the hangman game to data recorded during the interposed periods with no visual feedback. At the beginning of the rehabilitation session, non-parametric Mann–Whitney tests showed that each subject’s maximum finger span while playing the hangman game was significantly less than the maximum finger span measured with no visual feedback. This result occurred because in the absence of visual feedback, each subject extended beyond 80\% of the calibration maximum, which was the upper limit that was initially required by the hangman game. At the end of the rehabilitation session, Mann–Whitney tests showed no significant difference between the maximum finger span measured during the hangman game and that measured with no visual feedback. This was the case
for both subjects for sessions with and without distortion.

Both subjects showed functional improvements over the course of the study. The occupational therapist measured improvements for both on the ARAT, though the change was only clinically important for P3. There was also a significant positive slope for score with time for both subjects for the subtest of the ARAT given throughout the rehabilitation protocol (Fig. 12). On the AMAT, the occupational therapist measured a clinically important improvement for P4, but a decrement for P3 that was also clinically important. At a six-month follow-up, P3 maintained her improvement on the ARAT, while P4 did not maintain her gains on the ARAT and AMAT.

4.3. Discussion

This rehabilitation paradigm was a culmination of our foundational work concerning the use of visual distortion in a robotic environment. We estimated the maximum JND for finger span (similar to the JND for position) and used distortion steps less than this bound to encourage each subject to increase her finger span. As we expected based on our experiments using distortion to manipulate force and distance production, each subject increased her finger span under the guidance of visual distortion. This trend was not seen in rehabilitation sessions with no distortion.

Each subject was able to increase her finger span to keep pace with the visual distortion because her performance during calibration was not representative of her actual ability to extend the index finger and thumb. We expected that a subject would exert substantial effort during the calibration program, and that, because of this, she would be unable to repeatedly reach the maximum finger span measured during calibration. Thus, the maximum finger span required to play the hangman game was initially set to 80% of the calibration maximum at the beginning of each session; we expected that this point would be a comfortable maximum for the subject. However, each subject followed the distortion to much larger finger span values. In addition, each subject extended beyond 80% of the calibration maximum during the first period with no visual feedback. Even at the largest levels of distortion, each subject’s performance in the absence of visual feedback was comparable to her maximum finger span with visual feedback. Taken together, these results suggest that when calibrating a robotic rehabilitation system, a subject’s initial performance should not be assumed to represent the extent of his or her ability. Visual distortion is one way to address this problem of underperformance during calibration.

We observed for both subjects a significant upward trend on the subtest of the ARAT given throughout the rehabilitation paradigm, and each subject showed a clinically important improvement on one of the functional tests administered by an independent occupational therapist. Practice in our robotic rehabilitation environment transferred to improvements on functional pinching tasks. In addition, our results with P3 indicate that it is possible for subjects to maintain these gains over time. Further research is needed to determine whether the use of visual distortion can lead to greater functional gains than rehabilitation without distortion. Further details of this experiment can be found in ref. [8].

5. General conclusions

We began to study the use of visual distortion in rehabilitation by performing a series of general studies concerning the limits and effects of distortion in a robotic environment. For maximum effect, visual distortion should be imperceptible, and measuring the Just Noticeable Differences for force and position provided a lower bound on the amount of distortion that should be indiscernible. The JNDs were then used to design an experiment demonstrating that distortion can be used to increase force and distance production in a robotic environment. The results of these experiments culminated in an environment for robotic rehabilitation in which visual distortion encouraged subjects to increase the finger span. Preliminary tests in this environment indicated that visual distortion guided subjects to levels of performance above that predicted by their performance in calibration. This suggests that calibration performance is a poor gauge of subject ability and that visual distortion could be a way to encourage a subject to move beyond his or her self-assessed maximum.

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