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Effects of Visual Feedback Distortion for the Elderly and the Motor-Impaired in a Robotic Rehabilitation Environment

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Abstract—**In order to design a robotic rehabilitation environment using visual feedback distortion, we investigated in this study the limits and effects of visual feedback distortion for the elderly and the motor-impaired. To determine the minimum imperceptible amount of visual distortion, we measured the Just Noticeable Differences (JNDs) for force and position for elderly, unimpaired subjects; values of 31.0% (0.619 N) and 16.1% (5.01 mm), respectively, were obtained. JNDs of 46.0% (0.920 N) and 45.0% (14.8 mm) were measured for a motor-impaired individual. These JNDs were larger than corresponding measurements previously taken with young subjects, showing a decrease in discrimination ability with age and impairment. Visual distortion based on these values caused elderly subjects and the motor-impaired individual to increase their force production levels by 72.5% and 97.7%, respectively. These results were similar to those obtained with young subjects, but differences were observed on interspersed trials with no visual feedback. Poor discrimination abilities in elderly and impaired subjects and visual dominance in our environment for this subject group support our hypothesis that visual distortion can be an effective tool for rehabilitation in a robotic environment.**

Keywords-robotic rehabilitation, feedback distortion, just noticeable difference, stroke, traumatic brain injury

I. INTRODUCTION

Robotic therapy has been shown to increase the range of motion, strength, and velocity of arm movements in chronic stroke patients [1, 2]. Robotic therapy may improve the condition of such patients because it focuses on intensive, repetitive movements, which have been shown to counteract the detrimental effects of a habitual decrease in movement [3].

We have constructed a robotic environment to combine the repetitive movements of robotic therapy with visual feedback distortion [4, 5]. When an individual performs a task repeatedly, his or her performance on a given attempt is predicted largely by the previous performance [6]. If feedback received by the individual is distorted so that the level of performance appears less than the level previously achieved, the individual will improve performance until the feedback indicates (falsely) that the previous performance level has been reached [7, 8]. The use of feedback distortion to improve performance has been investigated in the context of single-session improvements in weight-lifting [6-9]. We plan to extend the use of feedback distortion to continuous, progressive distortion during rehabilitation activities with chronic stroke and traumatic brain injury (TBI) patients. Feedback distortion may be particularly useful for these chronic patients because an extended period with little or no improvement may discourage a patient from attempting tasks beyond his or her usual level of function. A robotic environment is appropriate for this research since it allows systematic distortion of the visual feedback relative to the interaction with the robot.

To prevent patients from dismissing the visual feedback as unreliable, we must ensure that the visual distortion in our environment is imperceptible. To that end, we measured the Just Noticeable Difference (JND) for force and position in young (ages 18-31), unimpaired subjects (preliminary results in [10]). The JND for a physical dimension is the smallest change in that dimension that can be reliably perceived. Thus, the JNDs for force and position provide a lower bound on the amount of visual distortion that we can expect to be imperceptible. We found a mean force JND of 19.7% ± 1.85% (0.296 ± 0.028 N) (mean ± standard error) and a mean position JND of 13.3% ± 1.4% (3.99 ± 0.434 mm). These numbers are higher than those previously measured for similar quantities by other researchers [11-15], because we vary background dimensions that these researchers fixed [16, 17]. We vary the background dimensions (spring constant and either force or position) in our experiments to increase the amount of visual distortion that will be imperceptible.

In addition to measuring the JNDs for force and position in young, unimpaired subjects, we examined the use of visual distortion to increase force production in this subject group [5]. We found that gradual visual distortion increased the forces that subjects produced. Subjects did not detect the distortion, even when the total distortion was twice the JND for force.

In the work described here, we expanded our subject pool to include elderly, unimpaired subjects (stroke age-matched group) and a motor-impaired patient. We present in this paper the JNDs and the response to visual distortion for our new subject population. This information will allow us to understand the effects of aging and motor impairment on kinesthetic sensitivity and the integration of visual and motor information. Furthermore, we will use this information to design new rehabilitation paradigms utilizing visual feedback distortion.

II. EXPERIMENTS

Our experimental environment is shown in Figure 1. We use a PHANTOM™ Premium 1.5 force-feedback robot

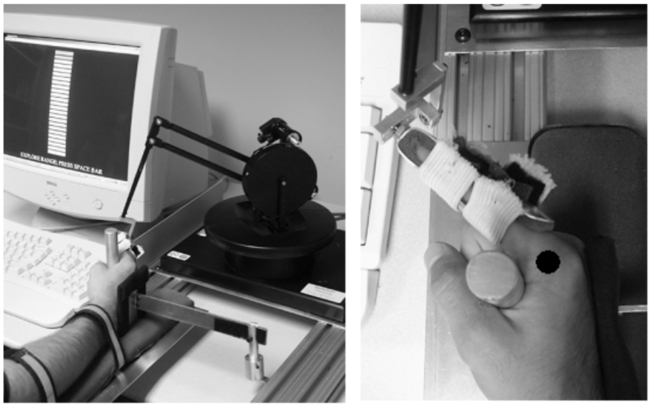

Figure 1. A) The subject interacts with the 3-DOF PHANTOM™ robot by moving the index finger about the metacarpo-phalangeal (MCP) joint. All other joints are restrained. B) A close-up of the custom-made 3 DOF finger cuff. The MCP joint is indicated with a black dot. The screen that conceals the subject's hand from view during the experiment is not shown.

SensAble Technologies, Inc.). This robot has 3 DOF, and the largest continuously exertable force is approximately 5 N. We attached a custom-made 3 DOF finger-cuff to the robot (Figure 1B). Subjects placed the index finger in the finger cuff and made movements about the metacarpo-phalangeal (MCP) joint. The robot simulated a spring during each experiment, with the amount of force exerted by the subject dependent upon the amount of movement about the MCP joint. The force was always exerted tangential to the path of the subject's fingertip. Joints apart from the MCP joint were restrained, and the subject's hand was concealed behind a screen during each experiment. More details about the experimental environment can be found in [4].

All elderly subjects were between 61 and 81. They were right-handed with no history of known neurological trauma affecting the right side of the body. Each performed the appropriate experiment with the right hand. Subjects whose results were more than 2 standard deviations from the mean were excluded. The TBI patient denoted SKL was a 34-year-old female who was eight years post-injury. She performed the experiments with her left hand, which fit our inclusion criteria for rehabilitation training.

A. Force JND Experiment

1) Methods

The force JND experiment was performed to determine the minimum amount of visual distortion of force information that is imperceptible. Ten elderly subjects (5 females and 5 males) and SKL participated in the force JND experiment. Four of the elderly subjects had previously participated in the distance/position JND experiment, but there was no significant difference in JND between the two groups (p = 0.268). This experiment consisted of 100 trials. A break lasting at least 4 minutes was given every 25 trials. On each trial, the subject sampled two forces. The first force was always the base force $F_0 = 2.0$ N. On half of the trials, the second force was also 2.0 N. On the other half, the second force was $F_0 + \Delta F =$ 2.7 N ($\Delta F = 0.8$ N for SKL). ΔF was chosen to be larger than the previously measured force JND for young subjects. After sampling both forces, the subject was asked if the two forces

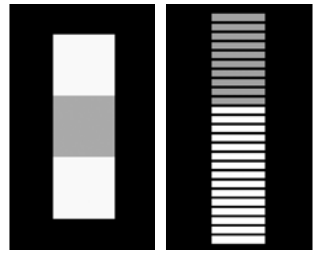

Figure 2. A) The visual display used for the force and distance/position JND experiments. The middle box was shaded when the subject was at the target value for force or distance, respectively. B) The visual display used during the visual distortion experiment. The number of shaded boxes indicated the magnitude of the force exerted by the subject. The direction of increasing force or distance was vertically downward for both A) and B).

were the same or different and responded by pressing 's' or 'd' on the keyboard. The subject was told the correct answer after each trial.

A visual display (shown in Figure 2A) guided the subject to each target force. The middle box on the display was shaded when the subject was in the desired force window. The direction of increasing force was vertically downward, because this provided a more intuitive relationship between the subject's movements and the visual feedback. Each target force was defined by the nominal force plus a window on either side of this force. The window was 1, 2, or 3%; the size of the window was determined by ten calibration trials that measured the ability of the subject to maintain a constant force. After the subject had stayed within the desired force window for 2 seconds, the middle box changed color and the subject returned to the origin of the virtual spring in preparation for sampling the next target force.

The spring constant of the virtual spring varied from trial to trial and also within a single trial. The five possible values for the spring constant were 58.5, 72.0, 85.5, 99.0, and 112.5 N/m. The subject was instructed to disregard information about the spring constant or the position of the fingertip and concentrate only on the force felt in the target window. The spring constant was varied to prevent the subject from performing the discrimination task using position instead of force.

2) Analysis

The Just Noticeable Difference for force was computed using the method described by Berliner and Durlach [18] and Pang et. al. [12]. The JND is computed using the proportion p_F of false positives (trials in which the forces were the same but the subject answered 'different') and the proportion p_H of hits (trials in which the forces were different and the subject answered 'different'). The method assumes that for each sampled force, the subject experiences a sensation *S*. For a given force value, the probability density of the random variable *S* is normally distributed with mean μ and variance σ^2. The JND can be computed using the formula

$$\mathrm{JND} = \frac{\Delta F}{F_{norm}^{-1}(1 - p_F) - F_{norm}^{-1}(1 - p_H)}, \tag{1}$$

where F_{norm}^{-1} is the inverse of the cumulative distribution function for the standard normal distribution.

The sensation distributions for F_0 and $F_0 + \Delta F$ overlap, and a subject chooses a particular sensation level C as the decision boundary. The bias β of each subject was computed by finding the ratio of the height of the $F_0 + \Delta F$ distribution to the height of the F_0 distribution at that point C. If behavior is unbiased, the point C will be where the two normal distributions intersect, and β will be equal to 1. If β is greater than 1, the subject is biased in favor of choosing the response 'same.' If β is less than 1, the subject is biased in favor of choosing 'different.' The bias is given by the formula

$$\beta = e^{\frac{1}{2}\left[\left(F^{-1}(1-p_F)\right)^2-\left(F^{-1}(1-p_H)\right)^2\right]}. \quad (2)$$

3) Results

The mean force JND for elderly subjects was 31.0% ± 3.99% (0.619 ± 0.0797 N) (mean ± standard error). This JND was significantly different from that previously measured for young subjects (p = 0.0133) (Figure 3A). The mean bias was 0.989 ± 0.146, and a Wald test showed that the mean bias was not significantly different from 1 (p = 0.942). Individual JNDs ranged from 12.3% (0.246 N) to 50.5% (1.01 N). Subject SKL's JND was 46.0% (0.920 N) with a bias of 1.14.

B. Distance/Position JND Experiment

1) Methods

The distance/position JND experiment was conducted to determine the minimum amount of visual distortion of positional displacement that is imperceptible. Ten elderly subjects (5 females, 5 males) and SKL participated in this experiment. Five of the elderly subjects had previously participated in the force JND experiment, but there was no significant difference between the JNDs of the two groups (p = 0.564). The protocol for this experiment was similar to the one used in the force JND experiment. On each of 100 trials, the subject sampled two displacements of the finger from the origin of the spring. The visual display used in the force JND experiment was used here to direct the subject in moving the finger through the desired distance. Subjects were required to stay within ± 1, 2, or 3 % of the target displacement, depending upon the result of the calibration procedure.

During the first part of each trial, the subject always moved a distance of $D_0 = 30\,\text{mm}$ from the origin of the spring. During the second part of the trial the displacement was either $D_0 = 30\,\text{mm}$ (50 trials) or $D_0 + \Delta D =$ 40.5 mm (50 trials). As in the force JND experiment, the spring constant of the virtual spring varied from trial to trial. The five possible values for the spring constant were 32.5, 40.0, 47.5, 55.0, and 62.5 N/m. These spring constants differed from those used in the force JND experiment due to the force limitations of the PHANTOM™ robot.

2) Results

The distance/position JND and the bias for each elderly subject were computed using the method described in Section 3.1.2. We refer to this JND as the distance/position JND because the distance moved and the terminal position of the finger were correlated in our experiment. Subjects could have used either quantity to perform the discrimination task. The mean JND for elderly subjects was 16.1% ± 1.18% (5.01 ± 0.370 mm), and the mean bias was 2.01 ± 0.692. The mean bias was not significantly different from 1 (p = 0.143). The mean distance/position JND for elderly subjects was not significantly different at the 5% level from the previously measured mean JND for young subjects (p = 0.0893), though there was a trend for the elderly JND to be larger (Figure 3B). Individual JNDs for elderly subjects ranged from 12.4% (3.95 mm) to 23.0% (7.27 mm). SKL's JND was 45.0% (14.82 mm), and her bias was 1.40.

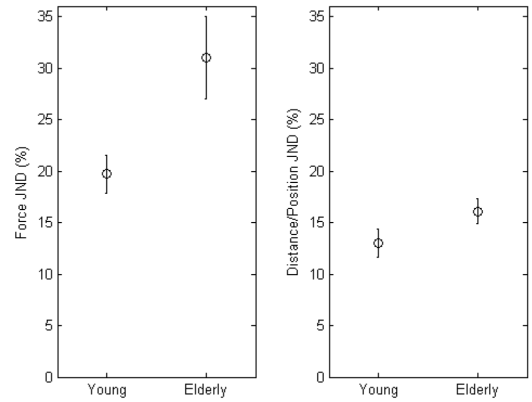

Figure 3. A) A comparison of the mean and standard error of the force JNDs for young and elderly subjects. The mean force JND for elderly subjects was significantly larger than that of young subjects. B) A comparison of the mean distance/position JNDs. The mean distance/position JNDs were not significantly different.

C. Visual Distortion Experiment

1) Methods

The visual distortion experiment was performed to determine whether distortion could be used to increase force production beyond the JND for force in one training session. Six elderly subjects (3 females, 3 males) and SKL participated in this experiment. It consisted of 100 trials. The experiment lasted approximately 20 minutes, and no breaks were given. On each trial, the subject was asked to produce a particular level of force from 1 to 5. Level 5 was the largest force level, and level 1 was the smallest. Subjects were instructed to be as consistent as possible in the force that they produced for each level, though each subject independently chose the magnitude of force corresponding to each level. Before the trials of the experiment began, the subject was allowed to explore the range of force and decide on the magnitude of force that he or she felt should correspond to each level.

The visual feedback provided to the subject is shown in Figure 2B. The number of shaded boxes denoted the magnitude of the force exerted by the subject. We chose to use a visual feedback bar composed of discrete blocks in order to make it more difficult for a subject to associate a particular force with a specific point along the feedback bar.

The visual feedback bar was gradually distorted throughout the experiment. The range of force represented on the bar changed in four steps from 0.500-3.22 N to 0.815-5.25 N for the elderly subjects and from 0.500-2.73 N to 0.960-5.25

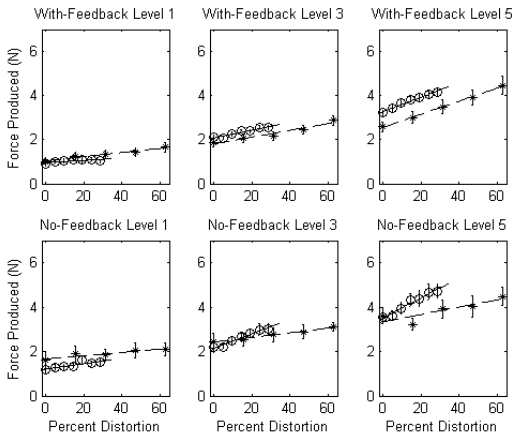

Figure 4. The results of the visual distortion experiment for force levels 1, 3, and 5. The mean produced force is plotted as a function of the percentage distortion for both feedback conditions. Open circles represent young subjects, and asterisks represent elderly subjects. Error bars indicate the standard error. The average regression lines for each force level/feedback condition are also shown for each subject group.

N for SKL. Each distortion step was accomplished by increasing the force represented at each end of the visual feedback bar by one half of the JND multiplied by the original value of the corresponding endpoint (For elderly subjects, a preliminary force JND value of 31.5% was used.) It is important to note that the appearance of the visual feedback bar did not change; only the range of forces represented on the bar changed. Since each distortion step was less than the JND for force, we anticipated that the distortion would be imperceptible.

Each subject experienced twenty trials for each level of distortion (including 0% distortion). In each block of twenty trials, the subject produced each level of force four times, twice with visual feedback and twice without. Each force level/feedback condition was experienced once with a spring constant of 90.0 N/m and once with a spring constant of 120.0 N/m. The order of the trials within each block of twenty was random. We measured the effects of visual distortion on the forces that the subject produced for each force level.

We hypothesized that as the distortion increased, the subject would gradually increase the force produced for each level in order to maintain the approximate position of that force level along the feedback bar. We further hypothesized that there were two possible reasons this could occur. Either the subject could ignore the force and focus only on the visual feedback bar, or the visual distortion could influence the subject's perception of force, making a larger force seem equivalent to the previously produced smaller one. To distinguish between these two possible alternatives, we included the no-feedback trials. If the visual distortion influenced the subject's perception of force, then we would expect to see an upward trend with distortion in the subject's produced forces on the trials with no visual feedback.

2) Results

For each force level/feedback condition, linear trend analysis was performed for produced force as a function of the percentage distortion. An adjustment was made for multiple

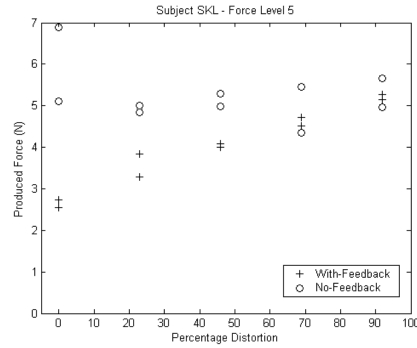

Figure 5. The results of the visual distortion experiment for force level 5 for subject SKL. The produced force is plotted as a function of distortion for the with-feedback (plusses) and no-feedback (circles) conditions. Her produced force rises in the with-feedback condition, but not in the no-feedback condition.

testing to minimize the false discovery rate [19]. Linear regression was also performed for produced force as a function of percentage distortion for each subject for each force level/feedback condition.

Linear trends significant at the 5% level were seen for all force levels for elderly subjects in the with-feedback condition (Figure 4). For force level 5, distortion increased the produced force by 72.5% for the with-feedback trials. In addition, linear trend analysis revealed the slope of the average regression line to be linearly related to the force level for elderly subjects in the with-feedback condition ($p < 0.001$). When a t-test was used to compare the average slope of produced force with percent distortion for force level 5 to the corresponding data taken with young subjects [5], no significant difference was found ($p = 0.707$).

Significant linear trends were seen only for force levels 1, 2, and 5 in the no-feedback condition for elderly subjects. The slope of the mean regression line was not linearly related to the force level ($p = 0.156$). For young subjects, on the other hand, significant linear trends were seen in force levels 3-5 in the no-feedback condition. For force level 5, the difference between young and elderly subjects in the slope of produced force with distortion was close to significant in the no-feedback condition ($p = 0.0557$).

The forces produced by SKL for force level 5 are plotted as a function of distortion in Figure 5. Her mean force rose linearly in the with-feedback condition for force level 5, but not in the no-feedback condition. This result was typical of SKL's performance at other force levels. Visual distortion of 92.0% increased her produced force for force level 5 by 97.7% in the with-feedback condition.

When asked whether the forces represented on the bar changed during the experiment, four elderly subjects answered in the affirmative. However, only one of those subjects correctly identified the direction of the distortion. The other three claimed that the distortion went in both directions, that the force required to reach the bottom (high-force end) of the bar was sometimes greater and sometimes less. We determined that those subjects had not actually detected the distortion. Most subjects stated that they were consistent in the force that they produced for each level. Subject SKL did not notice the distortion and stated that she was "very consistent" in the force that she produced for each level.

III. Discussion

A. JND Experiments

Because we plan to use visual distortion to encourage stroke and TBI patients to exert more force or expand their range of motion, we have measured unimpaired subjects' JNDs for force and distance/position in order to discover the lower bound on the amount of distortion that will be undetectable. For example, we should be able to distort the visual display of force by at least the force JND without the subject detecting the distortion. This information can be used to design a general rehabilitation paradigm that can be customized using each patient's JND, as we customized the visual distortion experiment for subject SKL. Based on the large range of JNDs that we observed for elderly subjects, such customization will be more appropriate than using a single paradigm based on the average JND.

The force JND of 31.0% (0.619 N) that we found for elderly subjects was significantly greater than that of young subjects. To our knowledge, we are the first to measure the force JND for elderly subjects. The JND we measured for elderly subjects may be larger than that measured for young subjects due to reduced afferent input with age [20] or to deterioration of the brain's discriminatory mechanisms.

Researchers interested in other dimensions have also found increased JNDs in elderly subjects. For instance, Fitzgibbons and Gordon-Salant [21] measured the Just Noticeable Difference for young and elderly subjects for the rate of auditory pulses in a sequence and for a single interval between two pulses. They found that the JNDs for elderly subjects were roughly twice those of young subjects. Similarly, Shinomori et al. [22] found that age increased the JND in wavelength for some optical channels. Gescheider et al. [20], on the other hand, found no significant difference in the JNDs for young and elderly subjects for vibrotactile amplitude. However, the test amplitudes used for each subject were expressed in terms of that subject's sensory threshold, and the thresholds for elderly subjects were significantly larger than those of young subjects.

We observed a greater difference between the young and elderly force JNDs than between the young and elderly distance/position JNDs. This may be because the difference between the largest spring constant and the smallest spring constant was 54.0 N/m in the force JND experiment but only 30.0 N/m in the distance/position JND experiment, even though the percent change in the spring constant was the same for both. This means, effectively, that the position varied more in the force JND experiment than the force did in the distance/position JND experiment. It may be that elderly subjects are more affected by varying background dimensions than young subjects.

While we cannot draw strong conclusions from a single patient, it seems, based on the JNDs measured for subject SKL, that we can reasonably expect the JNDs for stroke and TBI patients to be much larger than those of the appropriate control group. Since SKL is 34, her data are comparable to our young subject control group. Yet her distance/position JND is more than twice as large as the largest young subject JND, and her force JND is almost 1.5 times the largest young subject JND. This is encouraging from the point of view of our proposed rehabilitation paradigm, because larger JNDs mean that larger amounts of visual distortion will be imperceptible.

Because the JNDs for SKL were so much larger than the corresponding JNDs for unimpaired subjects, it may be possible to use the JND measurements as an assessment tool for motor deficits. We expect that training and recovery would decrease the JNDs, and these measurements may be a good indication of the progress of recovery.

Finally, it should be noted that the above discussion assumes that we vary the background dimensions, changing position and stiffness when force is the target dimension and varying force and stiffness when position is the target dimension. If we choose not to vary the spring constant, so that force and position are always related in the same way, subjects will be able to combine these two sources of information to possibly increase their ability to detect any visual distortion [15].

B. Visual Distortion Experiment

The force and distance/position JNDs indicate the *minimum* amount of distortion that should be imperceptible; in fact, much larger amounts of distortion may go unnoticed by subjects. Vision dominates the kinesthetic sense in many tasks ranging from the identification of shape [23] to the discrimination of stiffness [24]. Ernst and Banks [15] have proposed that subjects combine sensory inputs by weighting each input with the reciprocal of its variance. Since vision is more precise than the kinesthetic sense, vision dominates the kinesthetic sense in most situations.

The significant linear trend that we see on the with-feedback trials of the visual distortion experiment is attributable to visual dominance. On the with-feedback trials, elderly subjects relied primarily on visual feedback rather than force feedback. The produced force rose with distortion, and because each distortion step was less than the JND, subjects were not aware that the distortion had occurred. The total distortion in this experiment was more than 2 JNDs, but only one subject detected it. Subject SKL did not detect a 92% distortion. The slope of the rise in produced force with distortion was linearly related to the force level. Because the distortion was implemented as a percentage of the force, the absolute distortion was greater at larger force levels. Thus, the linear trend in slope means that larger amounts of distortion led to larger increases in force. These results were similar to our previous observations with young subjects; no influence of age was seen in the with-feedback trials.

For young subjects, a significant upward trend in force was seen even on the no-feedback trials. This means that the distortion influenced subjects' perception of force, rather than simply distracting them from the value of the force on the with-feedback trials. We observed fewer significant upward trends on the no-feedback trials for elderly subjects (and SKL), and larger amounts of distortion did not lead to larger increases in force for these trials. In addition, the slope of produced force with distortion tended to be smaller for elderly subjects than for young subjects. We believe that this may be due to the large discrepancy between the initial with-feedback force and the initial no-feedback force for each level for elderly subjects. For 0% distortion, the mean level 5 no-feedback force was 1.01 N higher than the mean level 5 with-feedback force for elderly subjects. This difference was only 0.336 N for young subjects. At maximum distortion, the difference between the mean level 5 no-feedback force and the mean level 5 with-feedback force was 0.545 N for young subjects, but it was only 0.0228 N for elderly subjects. The larger difference for elderly subjects between the no-feedback and the with-feedback forces at the beginning of the experiment is attributable to the larger force JND of elderly subjects. Throughout the experiment, the elderly subjects and SKL produced no-feedback forces that were perceptually equivalent to the with-feedback forces. As they increased the with-feedback forces to match the visual distortion, the elderly subjects and SKL had to increase their no-feedback forces by only a small amount, because the no-feedback forces started at a higher level. The visual feedback may have changed subjects' perception of force, but we cannot observe that change due to the initial force discrepancy. It is interesting that young subjects maintained the discrepancy between feedback conditions throughout the experiment. This may not occur in elderly and impaired subjects because they become more easily fatigued. While this difference in performance on the no-feedback trials has theoretical value, it will not affect the implementation of our rehabilitation paradigm, in which visual feedback will always be given.

We have measured the lower limits of imperceptible visual distortion and shown that vision dominates kinesthesis in our robotic environment for elderly subjects and an impaired individual. Elderly subjects and a TBI patient adjusted their performance of the force production task based on gradual visual distortion, and they did not recognize the distortion. The dominance of vision for our expanded subject pool in this force production task supports our hypothesis that we will be able to use visual distortion to encourage stroke and TBI patients to improve their performance of various physical tasks. Because subjects rely primarily on the visual feedback, a patient may work harder if the feedback is gradually distorted so that better performance is required to achieve the same visual result. This improvement due to distortion should enhance the outcome of the rehabilitation.

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