

# Feedback Distortion to Augment Controllability of Human Limb Motion

B. Dellon and Y. Matsuoka

**Abstract**— Virtual robotic rehabilitation is beginning to show its efficacy in motor function recovery for stroke survivors. However, due to the lack of understanding in the potential danger imposed by large energetic actuators safety for intimate interaction is typically not taken into account beyond software. For this reason the ability to extend virtual robotic rehabilitation to hospital or domestic settings is limited. Our group has constructed a safer, purely dissipative, robotic device for rehabilitation of large whole body movements. Consequently, shifting to passive actuation fundamentally changes common control strategies that work well for active devices. In this paper, we present a method that distorts visual feedback to the subjects as a first step to achieve the desired controllability hereto limited by passivity constraints. With visual distortion we demonstrate how a subject’s arm trajectory can be altered in a way that passive actuation alone cannot. Our results show that subjects involuntarily changed their path motion up to 30% with distortion applied; this ability to steer user’s movements can be harnessed to offset controllability issues.

**Index Terms**—passive actuation, haptic, visual feedback distortion, brake actuated manipulator, virtual environment, rehabilitation.

## I. INTRODUCTION

Virtual reality possesses many desirable qualities which make it highly compatible for rehabilitation regimes [1]. The breadth of techniques pertaining to rehabilitation in virtual environments is long and diverse. Much of the work focuses on the assessment of cognitive abilities, but recently a trend is geared towards physical retraining [2]. Virtual reality systems for training fall into two categories. The first are desktop setups using a robotic device and either computer or head mounted display [3]. The second encompasses video or motion capture systems that can be paired with or without robotic interaction and a suitable graphic display [4, 5]. We focus on the former called the virtual robotic environment.

Robotic devices present rehabilitation opportunities for both upper and lower extremities. When such devices are coupled with virtual reality it provides features that are not possible with human therapists alone, such as: real-time limb position and force measurement, fine control of repetitious movement, programmable stimuli, and finally enabling a patient to work at home away from the clinic.

Large robotic devices have been built and used for rehabilitation paradigms in a lab setting (MIME [6], WAM [7], Phantom 3.0 [8], and HapticMaster [9]). Currently, these devices contain active actuators that store energy and can move with unexpectedly high velocity or force during a failure

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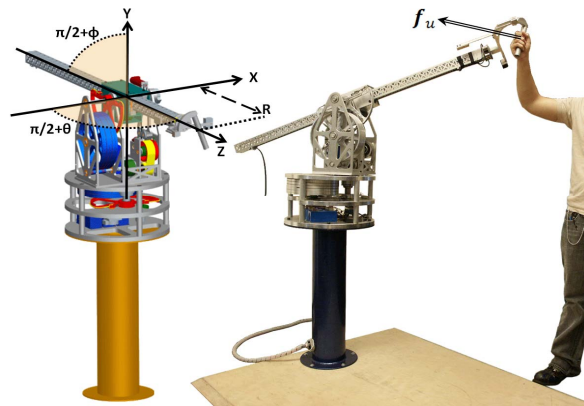


Fig 1. Left: The six degree of freedom Brake Actuated Manipulator (BAM), shown with Cartesian and spherical coordinate system orientations. Right: Standing operation of the BAM with  $2m^3$  workspace sufficient for whole limb/body interactions.

mode. Safety is typically taken care of in software, or by limiting force/speed and range of motion (to counteract possibly hazardous situations). However, this process can make the haptic interaction too weak for whole arm and body therapies. To solve this problem, we need to design a robotic device that’s strong and fast while remaining inherently safe under software or power failure.

To alleviate these safety concerns we take a *passive* actuation approach to system design. Fig. 1 shows our 6 DOF dissipative life sized haptic device called the Brake Actuated Manipulator (BAM) [10]. There are three types of passive devices: hybrid, steerable, and dissipative. Hybrid devices couple motors with dissipative elements to enhance stability [11]. Steerable devices (Cobots) use a continuously variable transmission to reorient their kinematic freedoms [12]. Dissipative devices, like the BAM and planar trajectory enhancing robot (P-TER) [13] use either brakes or clutches to redirect energy and are inherently stable enabling virtual constraints as stiff as the device’s transmission allows. The inherent safety of dissipative devices affords much larger workspaces that permit whole body free motion interaction useful for sports medicine, rehabilitation, and large-scale object design applications.

While passive systems provide many advantages, the shift to braked actuation fundamentally changes common control strategies, and in some cases it limits important capabilities. For example, passive devices can only apply joint torques satisfying  $\tau_i \dot{q}_i \leq 0$ ; note that torques from a motor can satisfy either  $\tau_i \dot{q}_i \leq 0$  or  $\tau_i \dot{q}_i > 0$ . This results in challenges for providing arbitrary path constraints and rendering soft springs [14]. Work has been done on path following control with dissipative devices using both velocity and force control [13,

15]. However performance is hampered by poor visual information when following complex three dimensional paths, and these techniques cannot currently overcome the passivity constraints.

In order to provide an inherently safe virtual robotic environment with the ability to guide patients' limbs in any desired path, we need a method of creating movement to temporarily relax the passivity constraint as a way to augment the passive device's lack of controllability. There are two ways this can be accomplished; either directly with the incorporation of energy storage elements into the mechanical subsystem, or indirectly by affecting the operator to generate a response. The addition of springs or motors, creating a hybrid device, may enhance haptic effects but decreases overall safety and increases device bulk, complexity, and power requirements. In light of this we seek an alternate solution by manipulating the user's perception through visual feedback distortion to make the user self-steer their movement based on visual cues which differ from reality. This is a first attempt to alter a robot's ability to interact with humans using neuropsychological effects.

The objective of this paper is to illustrate the concept of visual feedback distortion as a means of controlling a user's limb trajectory without their awareness and beyond the actuation capability of the passive robotic device in use. We conduct an experiment that introduces visual feedback distortion. And observe how much a given motion path can be altered, then examine our ability to distort with respect to the body coordinates of the user.

## II. RELATED WORK

In order to affect the user's movement through false perception, we rely on our brain's ability to convolve multi-modal sensory information into a correct perception. The combination in the nervous system of visual and haptic/movement information (sensory fusion), has been found to be similar to maximum likelihood estimation [16]. Results showed that visual feedback dominates sensory fusion when the variance associated with visual estimation is smaller than that of the haptic mode. This is caused by the disparity between our acute visual feedback and dull kinesthetic (muscle) feedback. Therefore, humans tend to believe visual cues over kinesthetic ones even if the visual cues are providing false information.

Classic work on sensory fusion has been investigated as far back as the 60's. In one study, spectacles, made from Risley prisms were used to shift a subject's gaze while they judged their hand position both visually and haptically [17]. The results confirmed that the subjects perceived their hand position to be consistent to what was seen visually over what was felt kinesthetically.

Related to sensory fusion and visual distortion is simulated force feedback through the use of an isometric device similar to a mouse [18]. The force-feedback is perceived through the internal mechanical characteristics of the device in combination with force controlled visual feedback. The result of this was termed pseudo-haptic feedback. Experiments investigating pseudo-haptics tend to focus on the haptic

analogues of visual illusions such as the Bourdon [19] or Muller-Lyer illusions [20].

While studies of sensory fusion, pseudo-haptics, and illusion are well documented, no evidence has been shown relating to their utility explicitly in the control mechanics of a virtual environment. The methods and phenomena above are embodied through visual feedback distortion and its relevance towards actively controlling a subject's perception with respect to the virtual environment.

The first successful use of contextual feedback distortion in a virtual robotic environment was demonstrated in our laboratory for rehabilitation [21] using a Phantom [8] robotic device. The goal was to increase the hand strength and finger mobility in chronic stroke survivors through exercises beyond their perceived ability. This was accomplished by manipulating a visual error feedback metric within the range dictated by both the position and force just noticeable differences of the index and thumb. The distorted feedback pushed the subject to produce greater force or range of motion without their awareness. Therapeutic results show that the subjects learned to spread their fingers further and became stronger because of the exposure to this environment.

In this work we use visual feedback distortion as a way to overcome some of the inherent limitations of the passive robotic environment, expanding on [21] to include the entire arm. When the passive environment is incapable of producing forces to redirect user's movements, the visual feedback to the user can be distorted to redirect the limb's motion. To gauge the efficacy of feedback distortion schemes on the BAM a preliminary experiment was conducted.

## III. EXPERIMENTAL METHOD

An experiment was designed to test the effects of visual distortion on point to point reaching motions. We evaluated the subject's perception of motion (distorted or not) in the virtual environment with a discrimination task.

### A. Conditions

Experimental trials were randomized between direction (left, right, down) and level of distortion applied (0%, 15%, 30%, 45%) with ten trials for each condition. Each pairing of distortion level, direction, and trial number was given in a random order. Breaks were given every thirty trials to allow the subject a rest. During each reaching trial hand position was measured in the Cartesian frame (figure 1) using the BAM's encoders.

### B. Participants & Setup

Four healthy subjects were asked to participate in this experiment. Each subject sat in front of a computer screen displaying the virtual environment. Subjects held on to the BAM's handle with their left hand and the specified path was over the left shoulder, starting over the head as shown in Fig. 2B. Subjects were told not to look at their arm movement, and to pay attention to the computer screen. This path position was chosen so that subjects could not see their precise arm position without the aid of an occlusion device. Each subject was allowed to sample the lateral movement between targets

without any distortion as many times as they wished before the experiment started. Figure 2 shows the visual feedback the subjects received on the computer screen. The go signal was indicated by an upper right circle turning green. The target circle (lower left) faded from red to green in 1.5 seconds then faded to blue in the next 1.5 seconds. Subjects were instructed to reach the target when it was green. In between each trial subjects were asked a yes or no question to determine if they could sense any distortion (in relation to what they consider no distortion), and then to rate their confidence in this decision from one to five, with five being the most confident.

This data allows us to calculate the frequency, over distortion levels, that the subjects were able to correctly identify distortion. We used the confidence value of three to be significant. The weighted responses from all subject's perceptual data were compared against chance (50%), and the confidently noticeable distortion level (75%).

### C. Visual Feedback distortion

To provide the specified distortion conditions, the visual distortion (the difference between the actual and displayed movements) was created by moving the "camera" location where the virtual screen is shot. Figure 3 shows how moving the "camera" while a subject performs the movement provides a graduated distortion.

Camera movement, or distortion, was linearly introduced with a single component of motion along one of three primary directions left (positive x motion), right (negative x motion), or down (negative y motion) as the subject traversed the reaching motion. Thus the camera acts as if tethered by a 2D spring to the fixed frame and forced by user movement.

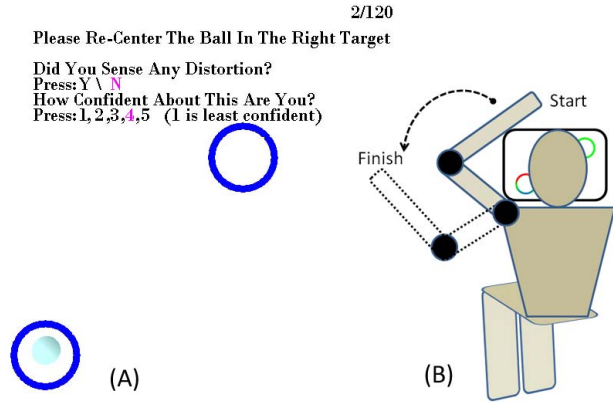


Fig 2. A. Screenshot of the experimental virtual environment in the phase between trials. The subject was asked to answer perceptual questions involving the previous trial. B. Cartoon of a Subject performing the reaching motion from upper right to lower left targets.

Path length of the reaching motion under zero distortion was chosen to be 10 inches long.

The coordinate position of the subject's hand is defined to be  $T_u$ , and the subject's starting position  $T_{u0}$  is at the origin. The final target position  $T_l$  is defined by the distortion levels in each direction,  $l_x$  &  $l_y$  along with the final target position with no distortion  $T_{l0}$ . The distortion levels,  $l_x$  and  $l_y$ , are percentages of the undistorted path along the tested directional component of camera movement.

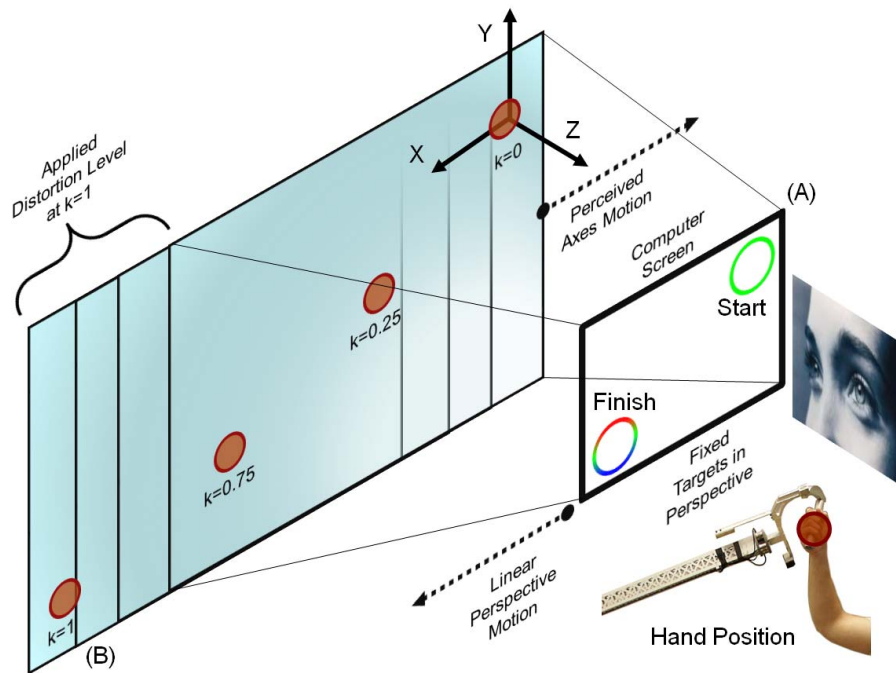


Fig 3. A. The screen of a computer monitor, depicting start and finish targets fixed in the subject's field of view. The color of the final target changes from red to green and then blue to give the subject a sense of velocity feedback. B. The virtual environment with four stages of camera perspective displacements, shown while a subject traverses the path between the initial and final position with the camera moving to the left. Each stage of traversal, parameterized by  $k$ , correlates to a shift in camera position and hence a shift in the opposite direction of the world coordinate frame. The world coordinate frame is hidden from view during experimentation.

$$-1 \leq l_{x,y} \leq 1 \quad (1)$$

$$T_{t0} = \begin{bmatrix} -10 \frac{\sqrt{2}}{2} & -10 \frac{\sqrt{2}}{2} \end{bmatrix} \quad (2)$$

$$T_t = \begin{bmatrix} (1+l_x)T_{t0,x} \\ (1+l_y)T_{t0,y} \end{bmatrix} \quad (3)$$

The parameterization,  $k$ , of the path is found using (2) and (3), starting from the origin:

$$k = \begin{cases} 0, & \frac{\|T_u\|}{\|T_t\|} < 0 \\ 1, & \frac{\|T_u\|}{\|T_t\|} \geq 0 \\ \frac{\|T_u\|}{\|T_t\|}, & \frac{\|T_u\|}{\|T_t\|} < 1 \end{cases} \quad (4)$$

The instantaneous distortion magnitude is proportional to the distance traveled from the start location, reaching its maximum level at the final target. The camera position,  $T_c$  is calculated by multiplying the parameterization (4) with the distortion levels (1) and components of overall path length.

$$T_c = k \begin{bmatrix} l_x |T_{t0,x}| \\ l_y |T_{t0,y}| \end{bmatrix} \quad (5)$$

With  $T_c$  defined in this way the camera slides along the distortion vector as the user traverses the path and ultimately reaches  $T_t$ . The initial and final targets appear fixed in the

camera frame at the origin and  $T_{t0}$  respectively, and when  $k=1$  the goal target has reached  $T_t$  even though there was no visual movement of the targets.

#### IV. RESULTS & ANALYSES

Figure 4A shows that distortion was unnoticed by the subjects up to the 15% distortion level for the left camera movement and the 30% level for the right and down camera movements. These allowable distortion values are in agreement with similar measures calculated in [21] for pinching motions between the thumb and index finger.

Figure 4B shows that the trajectories with distortion are significantly different than the control (central target). In most cases the subject smoothly transitioned to reach the target, but in one case overshoot can be seen (right distortion). The causes for this overshoot are chiefly due to timing constraints imposed by the experimental setup coupled with the direction of distortion. When the camera moved to the right the effect was to shorten the overall path length, thus increasing the velocity of the hand movement on the computer screen.

The distortion to the left was detected faster ( $p < 0.05$ ) while the remaining direction's weights were statistically insignificant from one another. In order to understand this difference, we evaluated the movement's manipulability and the subjects' body mechanoreceptor sensitivities for the left distorted path against other movements.

The manipulability ellipse indicates which directions motion or force are easily permitted [22]. A derivation of the manipulability ellipse can be found in Appendix A. Along the major axis of the manipulability ellipse large movements can be made, and motion along the minor ellipse axis is more difficult. If the difference in our ability to distort is related to manipulability then we should find a relationship between the manipulability ellipse's angle and the subject's ability to detect distortion. Fig. 4B shows the resulting trajectories for the 45% distortion level with manipulability ellipses. The result indicates that distortion to the left should be difficult to detect as motion is aligned along the major axis of the ellipse,

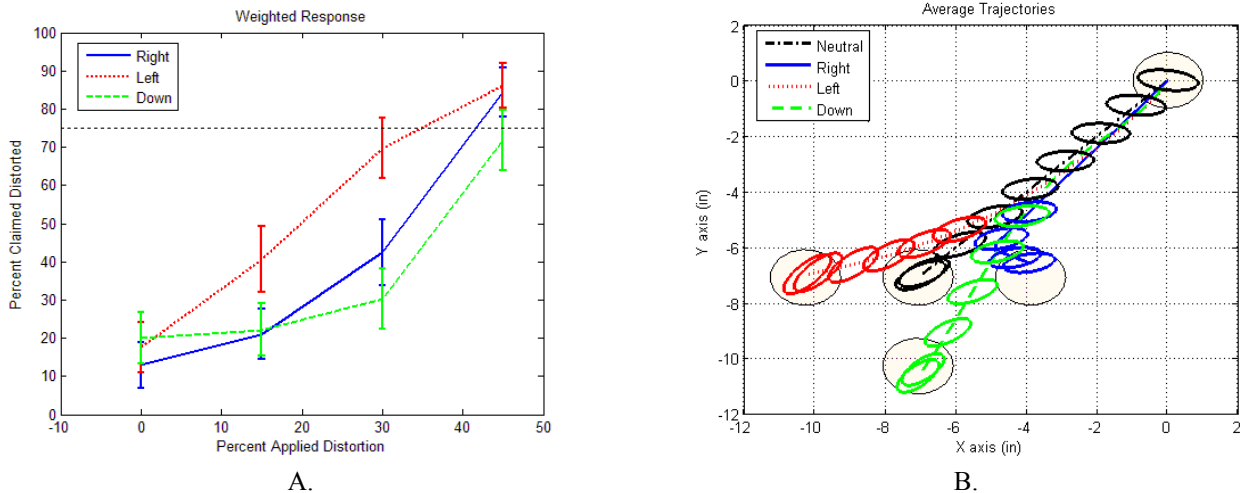


Fig. 4. A. Graph of the mean and standard error associated with the binary distributions gathered from perceptual data. Each line shows how frequently subjects were able to discern distortion at a particular level. Fifty percent marks random guesses, and the 75% level is defined to be just noticeable. B. Resulting trajectories for the 45% level of distortion across all tested camera movement directions. The manipulability ellipse for a planar 2-link arm is plotted along the average trajectories; the ellipses for all trajectories are similar in the starting region of the motion.

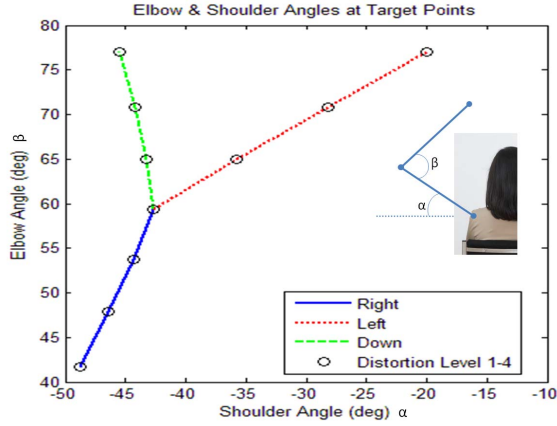


Fig 5. The shoulder and joint angles from the inverse kinematic model are plotted for all of the final target positions across all distortion levels and camera movement directions.

showing that the manipulability ellipse is a poor estimator of distortable directions.

To investigate this further, we paid attention to the mechanoreceptor sensitivity in the elbow and shoulder. It is known that joints proximal to the body give us a better perception of their angle than those distal [23]. The shoulder is reported to be approximately three times more sensitive to position than the elbow [24]. This can be understood by realizing that the central nervous system must perform a coordinate system transformation between our hand position and joint angles. Thus the farther away from the body a joint resides the larger the error incurred through this process. Looking at the joint angles from the inverse kinematic model of a 2-link arm for each target position across all levels of distortion gives an idea of the proportion of motion associated with each joint away from the zero-distortion target (figure 5). Inverse kinematical model for the 2-link arm can be found in Appendix B.

All three directions of camera motion incurred similar amounts of elbow motion, as indicated by figure 5, while only distortion to the left created a large shoulder displacement. Since the shoulder is more proximal to the body than the elbow, it affords us with a higher precision thus resulting in quicker detection of our visual distortion.

## V. CONCLUSION

We have shown that we can utilize visual feedback distortion in the virtual environment as a way to “actively” move a subject’s arm in a different manner from the intended movement without their awareness. This manipulation is conditioned upon the subject’s posture as evidenced by the inverse kinematic analysis. Although the visual feedback distortion presented here is simple, it provides a foundation on which to improve on the controllability of passive devices for virtual robotic environment.

## VI. APPENDIX A: MANIPULABILITY ANALYSIS OF SUBJECT’S ARM

Consider the set of all end effector velocities,  $v$  which are realizable by joint velocities,  $\dot{q}$  such that  $\dot{q} < 1$ . This set is an ellipsoid which describes the manipulability of a linkage by

both size and orientation. The Euclidean norm of  $\dot{q}$  can be written as,

$$\|\dot{q}\| = \dot{q}^T \dot{q} \quad (6)$$

And through the Jacobian relationship,  $v = J\dot{q}$  it can be shown (6) is equal to,

$$\dot{q}^T \dot{q} = v^T J^{-1T} J^{-1} v \quad (7)$$

The quantity  $J^{-1T} J^{-1}$  gives the matrix which defines the ellipsoid. The axes of the ellipsoid are defined by its eigenvectors, and their magnitudes are equal to the eigenvalues of  $J^{-1T} J^{-1}$ . A similar method is used to find the force ellipsoid which has the form of,

$$\tau^T \tau = f^T J J^T f \quad (8)$$

These ellipsoids depend heavily on the Jacobian, and hence posture. We used a 2-link serial robot as a model with the link lengths  $l_1 = 10$  inches and  $l_2 = 13$  inches, and shoulder centered at (3, -13) inches.

## VII. APPENDIX B: INVERSE KINEMATICS TO ESTIMATE SHOULDER AND ELBOW ANGLES

The inverse kinematics for the 2-link arm (figure 5) are found using the law of cosines and similar geometric principles:

$$l_3^2 = (T_{u,x} - T_{s,x})^2 + (T_{u,y} - T_{s,y})^2 \quad (9)$$

$$\beta = \cos^{-1} \left( \frac{l_3^2 - l_2^2 - l_1^2}{-2l_1 l_2} \right) \quad (10)$$

$$\gamma = \sin^{-1} \left( \frac{l_2 \sin \beta}{l_3} \right) \quad (11)$$

$$\varepsilon = a \tan 2(T_{u,y} - T_{s,y}, T_{u,x} - T_{s,x}) \quad (12)$$

$$\alpha = \pi - \gamma - \varepsilon \quad (13)$$

$\alpha$  is the shoulder angle relative to the horizontal, and  $\beta$  is the inner angle at the elbow. Although this is a non-canonical formulation for the joint angles,  $\alpha$  &  $\beta$ , it provides an intuitive relationship for quick physiological comparison as seen in figure 5.

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