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Assessing the Role of Preknowledge in Force Compensation During a Tracking Task

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***Abstract*— Considerable research has been done looking at the asymmetries between the dominant and nondominant arms. However, one area that has received less attention is how information about a perturbation affects these upper limb asymmetries. Our study sought to determine whether foreknowledge of a perturbation can affect the compensation from each arm. In addition, we examined the differences in compensation for perturbations parallel with the line of action and perpendicular to it. Results showed that the nondominant arm was largely unaffected by the visual condition. The dominant arm showed a comparatively smaller improvement between visible and invisible forces.**

I. Introduction

The subject of upper limb motor control has been an important topic over the last few decades for several reasons that include furthering the understanding of the burgeoning fields of humanoid robotics, haptics, and the human brain. This work has disproven the general assumption among the public that their dominant arm is the better or more desirable arm. Research has shown that each arm has a performance bias toward certain types of tasks arising from each arm's control scheme bias. Thus, although the dominant arm may seem to outperform its counterpart in general, the performance advantage of an arm is task specific [1]. The aim of this study is to further explain the function of the dominant and nondominant arms by quantifying their ability to respond to visible and invisible force field perturbations.

II. Background

Research has revealed that there are asymmetries between the two arms' performance in a given task, and several studies have shown that the dominant arm relies more heavily on a predictive control strategy while the nondominant arm tends to use an impedance control strategy [1], [2], [3]. This has led to a general consensus that the dominant arm "can achieve more varied and flexible control over movement trajectories" [4]. This is why reaching and movement tasks requiring quick, fluid motions like writing one's name, throwing a baseball, or using a computer mouse are most easily accomplished with the dominant arm. The nondominant arm has advantages in stability and posture: attributes that are less apparent in the subjective, but nonetheless essential to bimanual motor control and task completion [2].

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Bagesteiro and Sainburg [3] conducted a study in which they investigated the ability of each arm to compensate for a load during elbow flexion movements. They found that the nondominant arm was able to compensate for the load very well with the final endpoint accuracy being almost the same as the baseline (no load) trials. However, when the dominant arm was loaded, drastically different results were experienced, which showed "a large and systematic overshoot" of the end point position compared to the baseline (no load condition). This illustrates the predictive and impedance natures of each arm. The nondominant arm is more capable of compensating for unknown effects of the load because of its more effective integration of sensory feedback and proprioception [5].

Several studies have been conducted to compare the performance of arms with and without visual feedback. Carson et al. [6] studied the asymmetries in manual aiming where subjects moved from a starting point to a target location. They found that the nondominant arm held advantages in reaction time for all tested visual conditions including full vision and no vision. The dominant arm was seen to hold advantages in movement time. Przybyla et al. [7] found that the dominant arm depended more heavily on visual feedback than the nondominant arm did when comparing their final position accuracies in a reaching task.

In a study on the dominant and nondominant arms' adaptation to a velocity dependent curl field, Schabowsky et al. [2] determined that the arms learned at a similar speed when exposed to a novel dynamic environment. Despite the symmetry between the arms' adaptation capabilities overall, a contrast between the arms became apparent when the errors early in the adaptation process (first 25 trials) were examined. Additionally, asymmetries arose in the after affects from adaptation. The peak errors in both the early and after affect cases from the nondominant arm were found to be significantly less compared to the dominant arm. This corresponds in a more general sense to the findings of Carson et al. [6] that showed reaction time advantages in the nondominant arm.

When a motor action is planned in the brain, the subgoals are planned in addition to the final objective. These subgoals provide a predicted sensory response that is compared with afferent signals from sensory information to determine the error [8]. Given the dominant arm's bias toward a predictive control system discussed previously, our hypothesis is that knowing specific information about a perturbation before encountering the disturbance could affect this feedforward control for the dominant arm. This could augment the initial trajectory and/or velocity, thereby improving force compensation. For the nondominant arm, we concur with existing work [7] and do not expect a significant performance difference with or without visual feedback due to its bias toward impedance control and integration of haptic feedback. To the best of our knowledge, neither of these hypotheses have been tested for a tracking task.

III. Methods

A. Experimental Design

In order to investigate how foreknowledge of perturbations affects the control strategies of both arms, we presented participants with two cases. In the first case, subjects were shown when, where, and in what direction the force fields would perturb them (a colored block with directional arrows was displayed as seen in Figure 1). In the second case, no information about the force fields was given other than that perturbations would be encountered along the path. Examples of the visual display in these two cases can be seen in Figure 2. Both the left and the right arm were subjected to these conditions.

The motion was from left to right for the right hand and vice versa for the left. This direction of motion was chosen in order to reduce asymmetries arising from crossing into the opposite region (e.g., left hand in right field or vice versa). This has been shown to increase the error associated with similar movements [5], [7].

B. Experimental Setup

The experimental setup consisted of a haptic device and a display, as shown in Figure 1. Our haptic device was a Geomagic Touch, which has 6 degrees of freedom (DoF) and 3 DoF of force feedback. The display was a 23 inch flat screen computer monitor with a refresh rate of 60 Hz.

The desktop computer ran a C++ program at 1000 Hz to communicate and control the haptic device and to dictate what the subject saw on the display. The haptic device was constrained to 2 DoF by the program: making the Geomagic's workspace a vertical plane that was parallel with the computer display. 'Sticking' the participant's virtual and physical positions to a vertical plane was done in order to reduce the learning curve with the haptic device and to limit unwanted errors as they should never have deviated from the vertical plane.

C. Procedure

Participants were instructed to hold the Geomagic's stylus as they would a pencil or pen. This was done to ensure grip consistency and prevent participants from overpowering the device during the trials. They were also instructed to get as close to the center of the circle as possible but more importantly to stay within the target circumference. The larger target circle was implemented because precision on the screen (staying within the target) was more important than staying at the center of the target for a tracking task such as the one presented. The outer target had a diameter of 15 mm and the inner target had a diameter of 3 mm. The total length of the track was 30 cm.

Fig. 1: The experimental setup with desktop computer and Geomagic Touch is shown here for the right hand configuration.

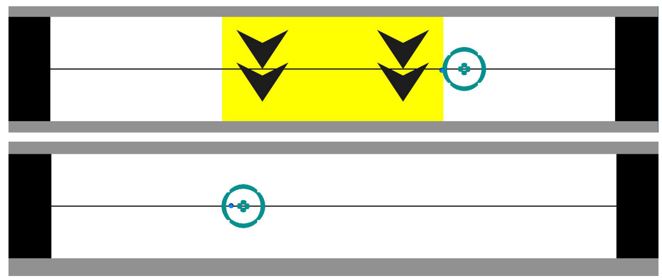

Fig. 2: Trials depicted are with a force field (top) and without a force field (bottom). The black boxes at each end represent the start/end positions.

Each trial lasted approximately 9 seconds, which was the time it took the participant to get from the start box to the finish box. Participants self-initiated each trial by pressing a button on the Geomagic's stylus. The target (shown in Figure 2) would wait one second after the button press to allow the subject to focus on the target and then begin moving at a constant rate of 27.5 mm/s across the screen. Forces were applied via the Geomagic's force feedback programmed in C++. Each trial had a single direction force field, but all four coordinate directions in an xy-plane were included in the experiment. A color-coded block and directional arrows denoted the direction of each force field. The forces were equal in magnitude in all four directions and were set at a constant force of 3 N.

Subjects were given a training period of 8 trials without force feedback to allow them to become comfortable with the system and procedure. The recorded trials consisted of a total of 32 trials: equal blocks of 16 visible and 16 invisible force fields, followed by 8 trials with no perturbations. During recorded trials, blocks of 4 trials were executed on each hand. This was done to limit intermanual transfer of skill, which has been shown to occur in other studies [9], [10]. The length of the experiment provided the subjects adequate time to adapt to the perturbations such that their trial-to-trial improvement began to plateau. The order in which the force fields were placed on the display was chosen randomly as was the choice of hands.

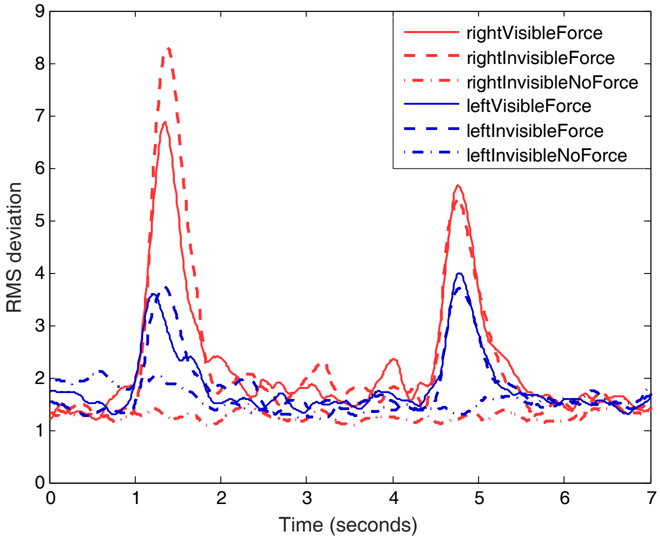

Fig. 3: RMS deviation versus time for parallel perturbations for right and left hands. The two peaks represent the subjects entering and exiting the force field.

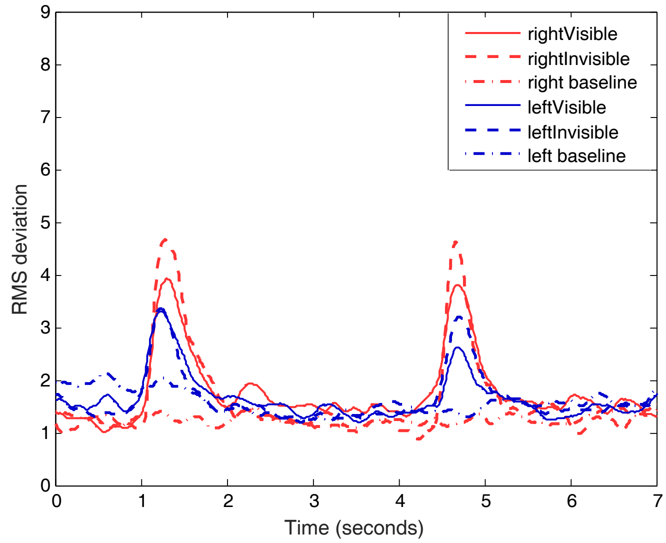

Fig. 4: RMS deviation versus time for perpendicular perturbations for right and left hands. The two peaks represent the subjects entering and exiting the force field.

D. Participants

Participants were healthy, right-handed, ranged in age from 19-28 years old, and included eight males and two females. Subjects were restricted to right-handed individuals because it has been shown that arm asymmetries in left-handers are not as pronounced as in right-handed individuals [11]. All participants signed an informed consent form for this study approved by the University of South Florida's Institutional Review Board.

IV. Results

The participants were scored based on their RMS deviation with respect to the center of the target. Since they were constrained to an xy-plane and they only received 2-D visual feedback, the z direction was assumed to be negligible for the purposes of error calculation. Equation 1 was used to calculate the error and is given below where actual denotes the subject's cursor position and target corresponds to the position of the center of the target.

$$RMS = \sqrt{(x_{actual} - x_{target})^2 + (y_{actual} - y_{target})^2} \quad (1)$$

Figure 3 shows the RMS errors for trials that had a left/right (parallel) perturbation (and no force for comparison) Figure 4 shows the RMS errors for trials that had an up/down (perpendicular) perturbation (and no force for comparison). Two peaks are seen in Figures 3 and 4; these peaks correspond to the entrance and exit of the force fields during the trials, respectively. The flat portion between the peaks is where subjects had compensated for the force and had almost returned to baseline performance. The plots of RMS deviation vs. time are shifted 2 secs, which was after the initial phase where the subject would begin the initial motion, but before the perturbation was felt.

We performed a repeated measures one-way ANOVA with peak RMS deviation after the onset of the force as the dependent variable and a single independent variable consisting of the trial type. The trial type has ten factors consisting of visible up/down force, visible left/right force, invisible up/down force, invisible left/right force, and no force where each of these was completed with both the left and right hands. We treated these trial types as ten separate cases instead of running a multi-way ANOVA since the interaction effects are large and it is clearer to determine the differences with this setup. The ANOVA determined that there is a statistically significantly difference among the trial types ($F(9,81) = 20.3$, $P<0.00001$). Post hoc tests using a Bonferroni correction revealed that the right hand with both visible and invisible left/right forces were statistically significantly different than all other cases, but not from each other. The invisible cases with the left and right hands were statistically significantly different than all other cases, but not from each other. There were no statistically significant differences among the other cases.

The left arm proved to be much more effective than its counterpart at compensating for perturbations parallel to the direction of motion regardless of foreknowledge (see Figure 3). The two max error peaks corresponding to entering and exiting the force field (seen in Figures 3 and 4) are fairly symmetrical and have similar max error values. This symmetry is expected because the second peak is a perturbation of the same magnitude, but opposite direction, as the first peak; the participants had adapted to a near constant error approaching the baseline performance while they were still in the force field. Thus, leaving the force field has a similar effect as entering it.

The visual condition had little affect on the nondominant hand's performance in either the parallel or perpendicular perturbation cases. These results agree with our hypothesis that the nondominant arm would be less affected by the lack of foreknowledge and visual feedback due to its bias toward impedance control and its advantages in proprioceptive and haptic feedback integration.

In the first red peak seen in Figure 3 for the right hand, we see an improvement when subjects had visual feedback. This is consistent with previous studies [6], [7] and our expectations. This improvement is also evident in Figure 4 where the peaks are more symmetrical and both exhibit improvements when the force was visible. Although an improvement was seen in the plots, the difference in error for the right arm between the visible force and the invisible force was not statistically significant.

A comparison of the perpendicular and parallel perturbation results in Figures 3 and 4 (plots have the same scale) yields much higher error for the dominant hand in both visible and invisible cases when compensating for a parallel force perturbation: for visible, the parallel max error is almost double the max error seen in the perpendicular case. The nondominant hand saw only marginal differences between parallel and perpendicular forces. This suggests that the dominant arm is less efficient at dealing with parallel force perturbations than perpendicular ones. Further trials and analysis are necessary to confirm this.

V. Discussion

The right arm's error from parallel perturbations was strikingly larger than the left arm's error, especially when the force field was entered. This might be partially explained by the dominant arm's slower reaction time as compared to the nondominant [6]. Nonetheless, this does not explain the evident decrease in peak radial error between the entering and leaving force field phases for the right hand. If this is compared with the same phases for the right arm in the perpendicular condition, the peak errors are very symmetrical and do not exhibit the same decrease in error between peaks. One reason for this decrease might be because of some participants' behavior during the experiment. When a subject was pushed ahead of the target, they tended to wait for the target to catch up instead of retreating back inside the target boundaries. This would cause unnecessary errors that were purely behavioral in nature and not arising from the motor control system.

Although previous research has shown that both arms adapt at approximately the same rate, it was also shown that peak errors in early adaptation (first 25 trials) for the nondominant arm in a novel environment (curl field perturbations) were significantly less than the dominant arm's peak errors [2]. Velocity dependent curl field perturbations are a more complex environment than our constant, one directional force perturbations. However, early adaptation errors may still have played a factor in the results since most of our trials are within the 25 trial bracket.

A tracking task differs from a reaching task with end point target in that the errors between start and end points are measured and analyzed. The high level of symmetry between visible and invisible perturbations assert that the nondominant arm can make continuous corrections such as those necessary for a tracking task. Our results also indicate that the right arm may have relied more heavily on visual feedback than on foreknowledge; i.e., the focus was on the cursor position rather than an impending perturbation. This is evidenced by the difference in performance between the dominant and nondominant arms. Although there was a difference, it was not statistically significant in three out of four peaks. A more in depth experiment and analysis are necessary to confirm or deny a potential advantage of the nondominant arm in a tracking task.

VI. Conclusion

Our results for the nondominant (left) arm show little difference between visible and nonvisible forces. The dominant (right) arm did show improvement in the visible force condition, but these improvements were not statistically significant. This has led us to conclude that there may have been unforeseen aspects of the experiment, which disrupted the procedure and impaired the natural compensation of each arm.

We plan to continue this work by comparing when the screen is moving while the target remains fixed versus a moving target and fixed screen as seen in this study. In addition, we will augment the program to include an additional case that will switch the direction of motion to be vertical. These additions will enable us to further test the tracking task case and the affects of parallel vs. perpendicular forces, as well as to eliminate some of the potential undesirable errors introduced into the experiment.

Acknowledgments

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