Analysis of Human Control in an Effort to Improve Robot Dexterity

A. Michael West Jr. [1], James Hermus[2], Meghan Huber[2], Dagmar Sternad[3, 4, 5], and Neville Hogan[2, 6]

[1] Department of Mechanical Engineering, Yale University [2] Department of Mechanical Engineering, Massachusetts Institute of Technology [3] Department of Biology, Northeastern University [4] Departments of Electrical & Computer Engineering and Physics, Northeastern University [5] Center for Interdisciplinary Research of Complex Systems, Northeastern University [6] Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology

Introduction

Human neural pathways and muscles are orders of magnitude slower than computer processors and robotic actuators, yet humans outperform robots in tasks requiring agile or dexterous movements [1], [2]. Simple everyday tasks requiring physical interaction, such as opening a door or turning a crank, present complex dynamic challenges. However, humans can do these tasks quickly, and subconsciously. How do humans perform these "complex" constrained motion tasks with such ease? To understand what humans do will not only aid in better physical interaction but also better robot-aided neurorehabilitation. It has been shown that robot-aided neurorehabilitation can be useful in improving the recovery process for stroke patients [3]. One way Krebs et al. [3] has done this is by requiring patients to exert an assistive force—even a small force—on the robot while it generates a physiologically relevant movement. If forces healthy subjects exert are understood, robots can be better equipped to reteach them to stroke patients. One of the well-established approaches to manage physical interaction is compliant force control. We **hypothesized**: Humans use force control to manage physical interaction during a robot following task. This hypothesis yields several testable predictions. It can be predicted that humans exert a constant force during the robot following task, and error in tangential force will decrease to zero with practice. Large position dependent errors in tangential force were observed. Additionally, subjects' error in their tangential force direction did not converge to zero. These observations are inconsistent with the hypothesis that humans use force control to manage physical interaction during a robot following task.

Methods

- Eleven healthy right-handed subjects were instructed to apply a constant force in the direction of the robot's motion (i.e. the tangential direction).
- The Haptic Master (Figure 1) moved a handle along an elliptical path (Figure 2) following the two-thirds power law [4].
  - The two-thirds power law is a velocity profile that has been proven to be the easiest for humans to follow [5].
  - $A = KC^{2/3}$ where A is angular velocity, K is a constant C is the curvature and $C = 1/R$ [4].
- The experiment consisted of 5 blocks. Each block contained 15 trials, and each trial contained 4 revolutions.
  - In alternating blocks, subjects were given tangential force visual feedback (Figure 3). Visual feedback and force specifications are detailed in Table 1.
- Data Analysis
  - The first revolution was excluded to avoid transients from the start of the robot.
  - The tangential force was interpolated to a degree value from 1 to 360 degrees, and then averaged to one revolution.
  - To assess learning, linear regressions were computed and an one sample t-test was performed on the slope .

Table 1

Block 1	Block 2	Block 3	Block 4	Block 5
No Visual Feedback	Visual Feedback	No Visual Feedback	Visual Feedback	No Visual Feedback
Comfortable Force	5 N	5 N	5 N	5 N

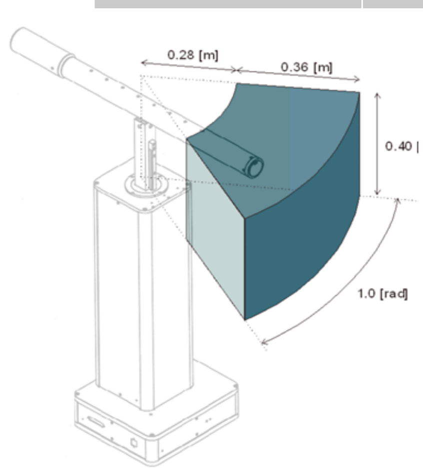

Figure 1: The Haptic Master has three degrees of freedom (one rotational and two prismatic). It was used to move an attached handle in a counter-clockwise elliptical path in the transverse plane [6].

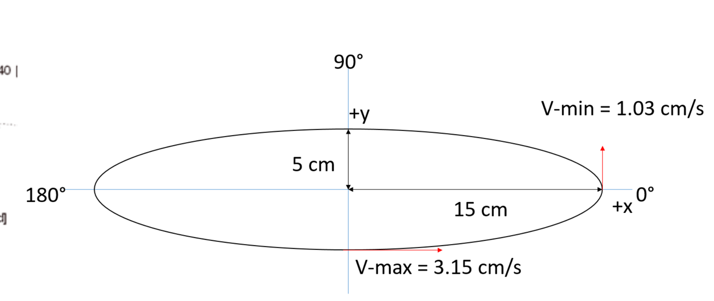

Figure 2: Top view of the elliptical trajectory the Haptic Master followed. The direction was counterclockwise where the velocity profile was in accordance with the two-thirds power law. The maximum velocity was 3.15 cm/s and the minimum velocity was 1.03 cm/s. The coordinate axis, seen in blue, had 0 degrees on the positive x-axis. The major axis was along the x-axis with an a value of 15 cm and the minor axis was along the y-axis with a b value of 5 cm.

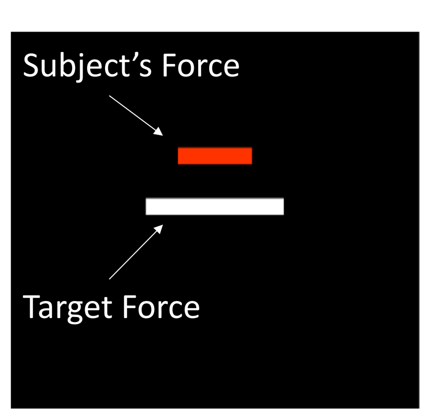

Figure 3: Visual Feedback given during blocks 3 and 5. The screen was 183 cm in height and 236 cm in width. Subjects sat approximately 218 cm away from the visual display. The target force of 5 N was depicted statically, and the subjects' force was depicted by the moving red bar.

Results

Were subjects able to apply a constant tangential force of 5 Newtons?

- Subjects were instructed to apply a constant force in the direction of the robot's motion, the tangential direction.
- If subjects were able to successfully use a force controller, there would be a constant force of 5 N solely in the tangential direction.
- Figure 4 shows that subjects exerted radial forces. In contrast, Figure 5 shows that subjects were able to apply a 5 N force along certain areas of the elliptical path.
- Additionally, highlighted in Figure 5 are peaks in error, which occur near the area of maximum curvature (i.e. 0 and 180 degrees).

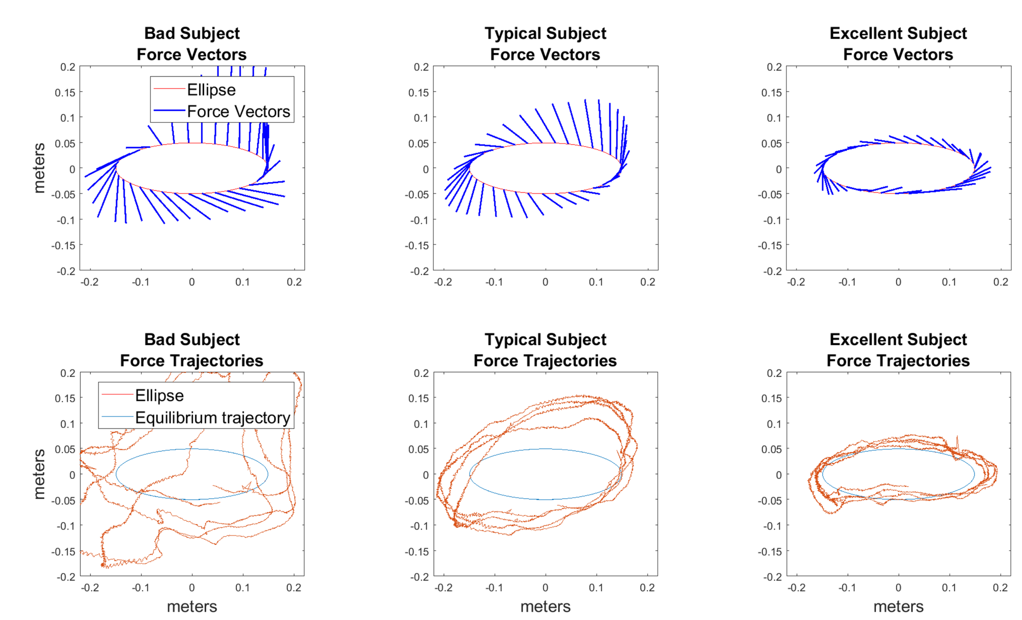

Figure 4: Top row: Force vectors exerted by a representative [poor, typical, and excellent] subject in a given trial were plotted to demonstrate the directions forces were applied. These forces were scaled by 0.01. Bottom row: Force trajectories by a representative [poor, typical, and excellent] subject in a given trial were plotted. These forces were scaled by 0.01.

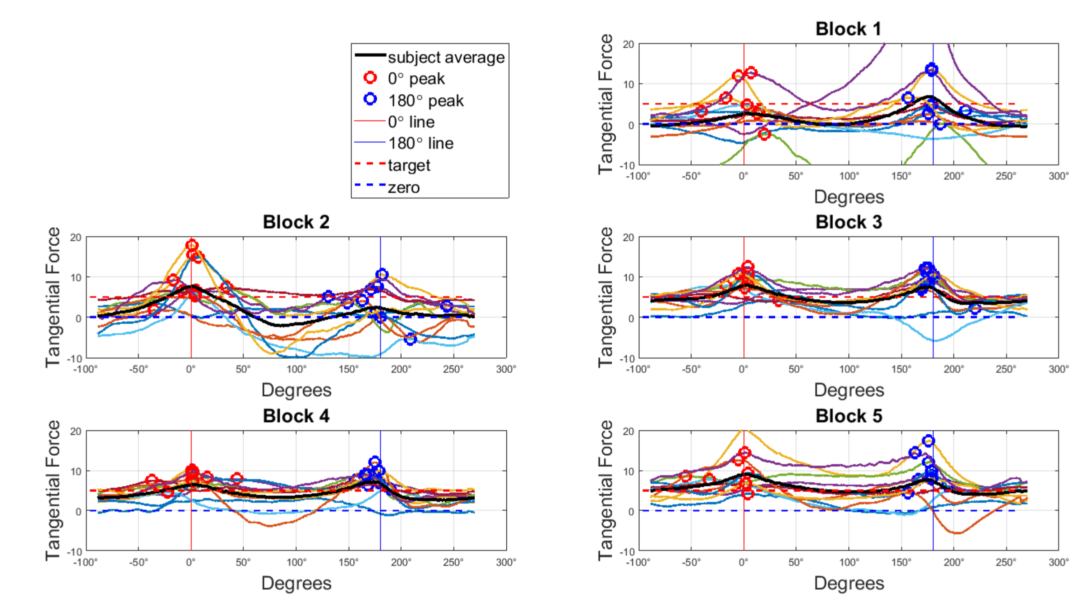

Figure 5: The average position-dependent tangential force exerted by each subject across a single block was plotted as a function of position for trials 6 -10 in a given block. The target was depicted by the dashed red line at 5 N. Every subject was plotted, and the average of all 11 subjects was shown by the black line. Peaks in force are highlighted by the red and blue circles for values near 0 and 180 degrees respectively.

Where along the ellipse did subjects struggle?

- It was noticed that there are position dependent errors (Figure 5) where the area of curvature is maximized (i.e. 0 degrees and 180 degrees).
- To quantify the likelihood that these peaks in error occurred at either 0° or 180°, a 95% confidence interval was computed (Table 2).

Table 2

	0 degree range	180 degree range
Overall 95% Confidence Interval	-7.5° to 3.7°	171.1° to 182.1°
Visual Feedback 95% Confidence Interval	-10.8° to 8.1°	165.6° to 184.5°
No Visual Feedback 95% Confidence Interval	-9.7° to 5.1°	170.6° to 184.7°

How has learning affected our data?

- To examine how subjects were able to learn the task it had to be determined how a subject varied in performance across trials, and across blocks.
- To compare performance across trials, the average root-mean-square-error was plotted as a function of trial. Linear regressions were computed to the first 5 trials, the middle 5 trials, and the last 5 trials. If the slope was significantly less than zero, learning occurred.
- The slope was statistically significant from zero only in the linear regression of the first 5 trials of block 2, t(10) = -3.310, p = .008 (Table 3).
- It can be noted that beyond block 2 the subjects' tangential direction error did not noticeably decrease, and that tangential direction error was greater than zero.

Table 3

One-Sample Test

	Test Value = 0					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference: Lower	95% Confidence Interval of the Difference: Upper
Block 1	-2.114	10	.061	-.52296	-1.0742	.0283
Block 2	-3.310	10	.008	-1.17474	-1.9655	-.3839
Block 3	-.519	10	.615	-.04801	-.2539	.1579
Block 4	.427	10	.679	.02837	-.1198	.1765
Block 5	-.541	10	.600	-.07102	-.3635	.2214

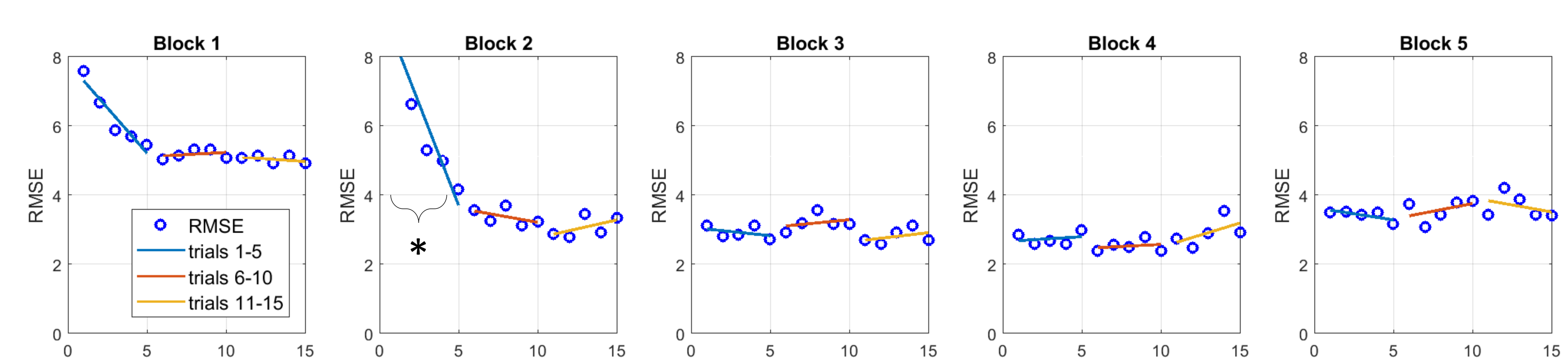

Figure 6: The average of all subjects' tangential force root-mean-square-error, RMSE, was plotted as a function of the trial number in each block. The data, subjects' RMSE, was represented by the blue circles. The blue, orange, and yellow lines were linear fits to trials 1-5, trials 6-10, and trials 11-15 respectively. The asterisk denotes that the linear regression of trials 1-5 in block 2 was the only statistically significant slope.

Results

Were subjects able to perceive the shape of the robot's trajectory?

- After the experiments, subjects were asked what shape they believed they were following. Results are summarized in Table 4.

Table 4

Subject	Perceived Shape
Subject 1	Triangle
Subject 2 (Average Subject)	Square
Subject 3	Oval
Subject 4	Oval
Subject 5	Oval/Circle
Subject 6	Circle
Subject 7 (Excellent Subject)	Oval
Subject 8	Oval/Circle
Subject 9 (Poor Subject)	Triangle/Oval
Subject 10	Circle
Subject 11	Oval

Discussion & Conclusion

The **hypothesis**: Humans use force control to manage physical interaction during a robot following task, was tested. More specifically, it was predicted that humans exert a constant force during the robot following task, and error in tangential force will decrease to zero with practice. It was found that subjects were not able to exert a constant force. Position dependent errors were observed near the area of maximum curvature (i.e. 0 and 180 degrees). Even though the velocity was not constant, due to the two-thirds power-law a linear relationship between position and time is observed. Research by Maurice et al. [5] has shown that subjects collaborate better with robots who move according to biological (two-thirds power law) velocity profiles. Thus, incorporating the two-thirds power law in this experiment gave subjects the best chance to follow the robot. Subjects' inability to apply a constant force in areas of maximum curvature was inconsistent with our predictions. Also inconsistent with our predictions, subjects were unable to reduce the error in their tangential force to zero. Lastly, it was observed that subjects do exert radial forces. These three observations, are inconsistent with the hypothesis that humans use force control to manage physical interaction during a robot following task. Further analysis of variance will be done to quantify the effects of learning across trials and across blocks, as well as to quantify the position dependent errors. Future work will further investigate motor planning strategies consistent with these observations in constrained motion tasks.

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