

# Limitations of Human Force Control when Physically Tracking Robot Movements

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## I. INTRODUCTION

In physical human-robot interaction (pHRI) tasks, the control of interaction forces by each partner is critical. While robots can be programmed to independently control force and motion [3], two recent studies demonstrated that humans cannot decouple their control of force from motion when collaboratively tracing a path with a robot partner. Maurice and colleagues showed that humans applied significant interaction forces against the robot’s predefined elliptic path, despite being instructed to minimize any interaction forces [2]. A follow-up study demonstrated that humans were unable to maintain a constant instructed force during the robot’s motion, but exhibited periodic force modulations around the elliptic path [5]. As these findings highlighted important limitations for humans collaborating with robots, a third study on the same ellipse tracing task showed that augmented feedback enabled humans to better regulate their interaction forces. However the forces were still significant even after 3 days of practice [1]. The present study aims to identify the specific features of the robot motion that lead to the lingering undesired interaction forces in the physical human-robot interaction task.

This study used the same ellipse tracing task in which the robot’s trajectory around the elliptic path obeyed or violated the so-called *2/3 power law* in human trajectory control[4]: humans tend to slow down in highly curved path segments and speed up in straighter segments. Based on this *2/3 power law*, a robot was programmed to move with three distinct velocity profiles around an ellipse in the horizontal plane. One profile followed the *2/3 power law*, consistent with human preferences. Two additional profiles challenged participants to deviate from their preferred velocity: one condition exaggerated the human-like velocity modulation, another condition kept tangential velocity constant. We tested three specific candidates that may elicit undesired forces: curvature (Hypothesis 1, **H1**), tangential velocity (**H2**), or angular velocity (**H3**) of the movement. Our findings will help understand the limitations of human motor control to inform robot controllers that can better accommodate the human partner.

## II. METHOD

*a) Experimental Task and Procedure:* 22 participants were recruited and grouped into 3 cohorts (IRB#10-06-19). Participants interacted with a 3-DOF robotic manipulandum (HapticMaster, Motek) that was programmed to trace out an elliptic path in a horizontal plane (Fig. 1A). They were instructed to firmly hold and follow the robot handle around the ellipse, while exerting minimal

force on the handle. Interaction forces were measured with a 3-axis force sensor embedded in the robot end-effector, and tangential and normal components were derived.

Experiments were performed in 3 sessions on 3 consecutive days; each session presented 8 blocks of 10 trials each (total 240 trials). In each trial the robot traced the ellipse 6 times (3 s per ellipse, total 18 s). Visual feedback about the force was shown on a screen in front of the participant. A cursor moved on the ellipse and its color indicated the applied force against the elliptic constraint (green = good, red = bad) (Fig. 1B).

*b) Robot Velocity Profiles:* The *2/3 power law* can be written as  $\omega(t) = Kc(t)^\beta$ , with  $\omega$  the hand’s angular velocity,  $c$  the path’s curvature,  $K$  a gain factor used to adjust for the overall duration of the ellipse, and  $\beta$  the power determining the velocity variation. Three different velocity profiles were created by setting  $\beta$ : *biological* ( $\beta = 2/3$ ), *constant* ( $\beta = 1$ ), and *exaggerated* ( $\beta = 1/3$ ). The obtained angular velocities for each profile are shown in Fig. 1C. 8 participants were assigned to the *biological*, 7 to *constant*, and 7 to the *exaggerated* profile. Each participant only performed the task with their assigned velocity profile.

*c) Data Analysis:* To explore force patterns after extensive practice, only the last 10 trials of the last session were analyzed. The time series of the forces exerted against the robot were examined to determine whether force depended on curvature (**H1**),

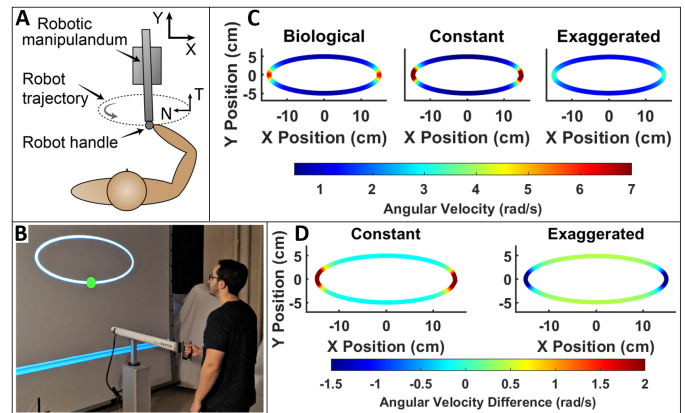


Fig. 1. A: Top-down view of the experimental setup; positive normal and tangential forces shown as N and T, respectively. B: Participant interacting with the robot and the visual display on the projector screen. C: Angular velocity of the three robot profiles across the ellipse. D: Difference of angular velocity in the constant and exaggerated velocity conditions from the biological profile, respectively.

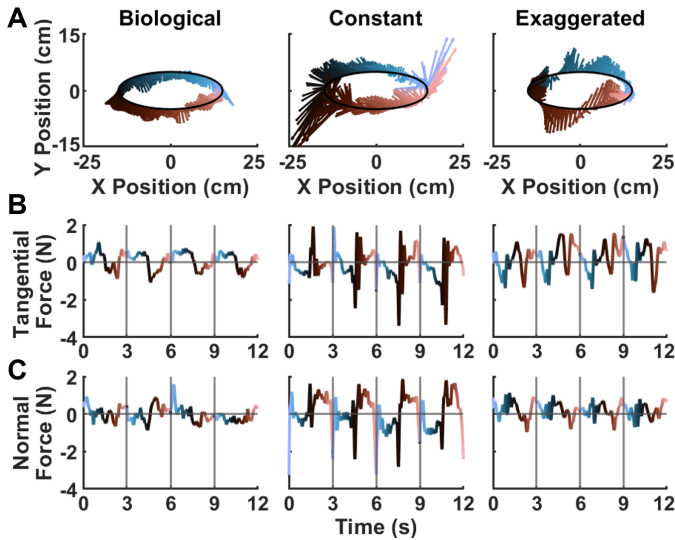


Fig. 2. A: Interaction forces (direction and magnitude) exerted on the robot across the ellipse in the 3 velocity profiles from 3 representative participants of the respective groups. Vectors represent medians across 4 ellipses of one trial. Color indicates the progression of time matching the time series below. B: Time series of tangential forces across 4 ellipses of the same trial as above. C: Time series of corresponding normal forces.

tangential velocity (**H2**), or angular velocity (**H3**) of the robot trajectory. To test these hypotheses, tangential and normal forces were calculated at each point along the ellipse (discretized across 360 points); the median at each point along the ellipses of each participant was further analyzed. For each participant, the median forces were regressed against the 3 hypothesized variables. The obtained regression slopes and their 95% confidence intervals quantified the dependency.

### III. RESULTS AND DISCUSSION

Fig. 2 illustrates the spatial and temporal pattern of the tangential and normal forces from 3 representative participants in the 3 velocity profiles. The force patterns highlight how different segments around the ellipse elicited different interaction forces. Despite instruction, the magnitude of force did not reach 0 N. Most notably, the *biological* condition only elicited small fluctuating forces around the ellipse, while the forces were visibly higher in the two non-biological conditions: in the *constant* condition the forces were high in the curved segments, while in the *exaggerated* condition, the forces were high in the linear segments.

From inspection of these time series, **H1** could be rejected as the 3 velocity profiles elicited different force patterns, even though the ellipses' curvature was identical for all profiles. Further, the observation that the *constant* velocity profile exhibited a clear modulation of forces, even though the tangential velocity was constant, led to a rejection of **H2**.

To evaluate **H3**, linear regressions were conducted as illustrated in Fig. 3. First, force was plotted against angular velocity for each trial (Fig.3A&D); second, the median trajectories were determined (Fig.3B&E); third, the linear regression was conducted to obtain a slope and its 95% confidence interval. Fig. 4A shows the linear regression slopes and confidence intervals for all participants in the 3 velocity profiles. While consistent within one profile, the patterns differed across profiles; hence, **H3** was rejected.

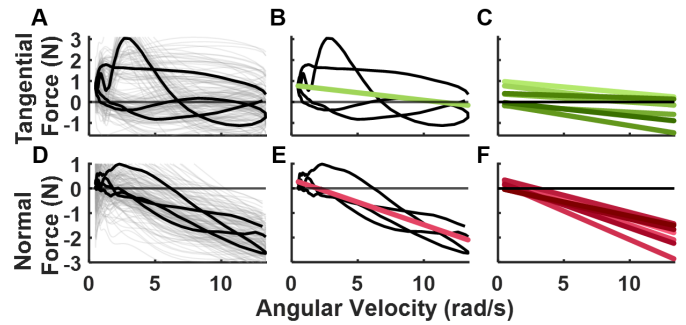


Fig. 3. Measured tangential (A) and normal (D) forces plotted against angular velocity at each time sample for the last 10 trials (gray lines) in the *constant* velocity profile; median of the forces (black line) for a representative participant. Linear regression fitted (colored line) to the median (black line) of tangential (B) and normal (E) forces versus angular velocity for the same participant. Linear regressions of tangential (C) and normal (F) forces for all participants in the *constant* velocity profile.

Further inspection revealed that forces were higher when the robot's motion differed from the *biological*, i.e. humans' preferred profile [2]. To specify how deviations from this velocity profile were responsible for the observed modulations, forces were regressed against the velocity difference from the biological profile, computed at every spatial point around the ellipse (Fig. 1D). Then, regressions were conducted against this *angular velocity difference*, see Fig. 3. Results in Fig. 4B show consistent regression slopes for the *constant* and *exaggerated* velocity profiles. Larger angular velocity differences were linked with higher applied forces. Fig. 4 summarizes the slopes obtained for all participants in the 3 groups. Notably, they were consistently negative for angular velocity differences for both tangential and normal forces.

In conclusion, this study examined the interrelation of force and motion in a pHRI task and showed that deviations of angular velocity from the *biological* velocity profile elicit higher tangential and also normal interaction forces. These results may inform the development of robot controllers that accommodate for their human partners by appropriately modulating angular velocity.

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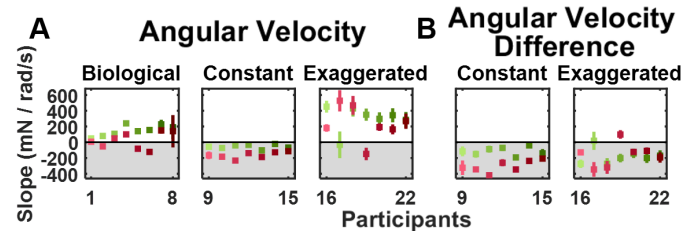


Fig. 4. A: Regression slopes with their 95% confidence intervals fitted to each participants applied tangential (green) and normal (red) forces versus angular velocity. B: Regression results for tangential (green) and normal (red) forces versus angular velocity difference.