

Robot Motion Affects Human Force Regulation in Physical Human-Robot Interaction

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I. INTRODUCTION

The regulation of interaction forces is critical when humans physically interact with a robot. While robots can be programmed to independently control force and motion [2], two recent studies demonstrated that humans are unable to decouple their control of force from motion when they held the endeffector of a robot and tracked its motion. A first study by Maurice and colleagues showed that humans generated interaction forces that varied with the geometric and kinematic features of the robot’s motion [1]. As the robot traced out an elliptic path subjects exerted significant forces against the robot’s predefined path, even though they were instructed to minimize any interaction forces. In a follow-up study, West and colleagues highlighted that humans were unable to produce a constant instructed force during the robot’s motion but exhibited periodic modulations around the elliptic path of the robot [4]. Neither of the two studies observed any significant improvements in humans reducing or controlling the undesired forces. These findings highlighted that for physical human-robot interaction (pHRI), it is important to understand the limitations of human motor control to develop robot controllers that can better accommodate the human partner. This study aims to identify the specific features of the robot motion that leads to undesired interaction forces in a physical human-robot interaction task.

Previous research in motor neuroscience showed that human endpoint trajectories exhibit a systematic relation between hand velocity and curvature of the associated path, the so-called $2/3$ power law [3]: humans tend to slow down in highly curved path segments and speed up in straighter segments. When interacting with a robot, violations of this velocity-curvature relation caused undesired interaction forces as the two previous studies indicated. However, the exact determinants in the robot motion that elicited the undesired human forces have not been specified. This is the goal of this study.

Based on the $2/3$ power law, a robot was programmed to move with three distinct velocity profiles around an ellipse path. One profile followed the power law consistent with human preferences; two other profiles either exaggerated the human-like velocity modulation or kept tangential velocity constant to challenge participants to deviate from their desired velocity profile. Specific candidates that may elicit forces were curvature (Hypothesis 1, **H1**), tangential velocity (**H2**), or angular velocity (**H3**) of the movement. Understanding the aspects of motion that determine forces in humans would allow for improved design of robot controllers in pHRI scenarios.

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 Medical) that was programmed to trace out an elliptic path in a horizontal plane with (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 (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 colored cursor traced the ellipse and its color indicated applied force (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 ω the hand’s angular velocity, c the path’s curvature, $\beta = 2/3$, and K a gain factor used to adjust the overall duration of the ellipse. By varying the exponent β , 3 different velocity profiles were created: *biological* ($\beta = 2/3$), *constant* ($\beta = 1$), and *exaggerated* ($\beta = 1/3$). The obtained angular velocities for each profile are shown in Fig. 1C (more details in [1]). 8 participants were assigned to the *biological*, 7 to *constant*, and 7 to the *exaggerated* profile.

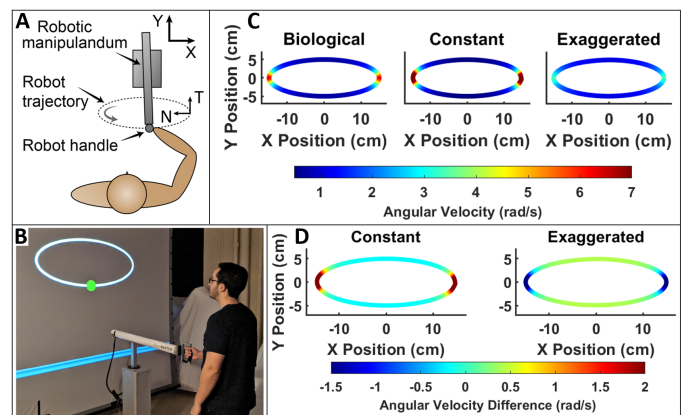


Fig. 1. A: Birds-eye view of the experimental setup; positive normal and tangential forces shown as N and T, respectively. B: Participant interacting with the robot and the visual feedback on the projector screen. C: Angular velocity of the three profiles across the ellipse. D: Angular velocity difference for the 2 non-biological velocity profiles.

