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 ere 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.

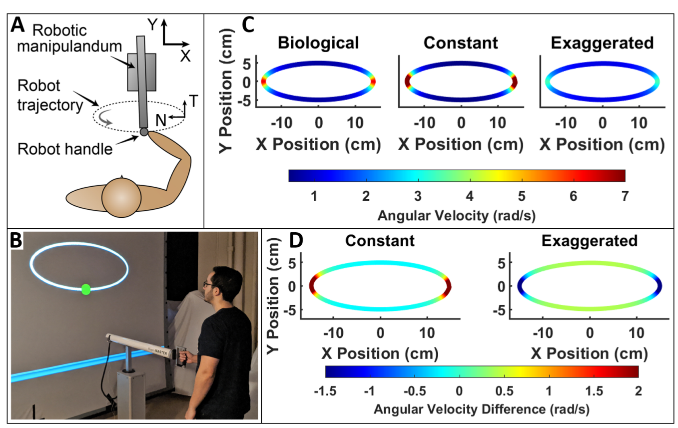

Fig. 1. A: Birds-eye view of the experimental setup; positive normal and tangential forces shown as N and T, respectively. B: Participant interacting with the robot and the visual feedback on the projector screen. C: Angular velocity of the three profiles across the ellipse. D: Angular velocity difference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

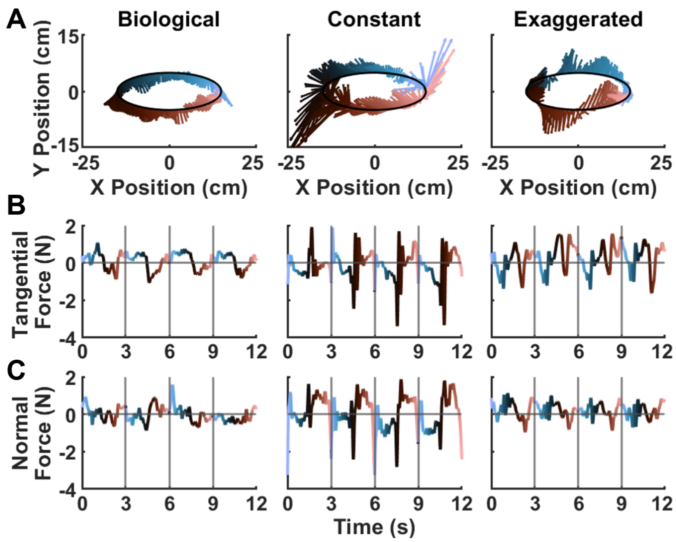

Fig. 2. A: Interaction forces (direction and magnitude) exerted on the robot across in the 3 velocity profiles from 3 representative participants of the respective groups. Vectors represent medians across 4 ellipses of one trial. Color indicates the progression of time matching the time series below.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

c) Data Analysis: To eliminate any familiarization effects, 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**), tangential velocity (**H2**) of the path, or angular velocity **H3**. 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 across all ellipses of each participant was further analyzed. For each participant, a linear regressions were fitted to the median forces against the hypothesized variables. The obtained regression slope and its 95% confidence interval quantified the dependency.

III. Results & Discussion

Fig. 2 illustrates the spatial and temporal pattern of the tangential and normal forces from 3 representative participants in the 3 velocity profiles. While the subsequent analysis focuses on the normal force, similar results were obtained by evaluating the tangential force. 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, normal force was plotted against angular velocity for each trial (Fig.3A); second, the median trajectories were determined (Fig.3B); third, the linear regression was conducted to yield a slope with 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.

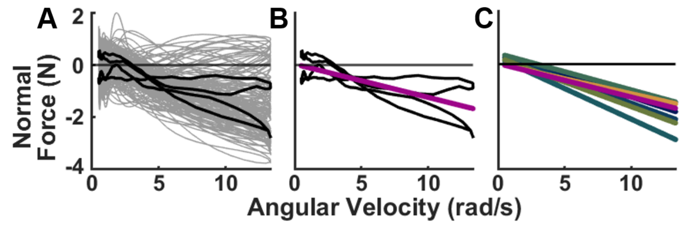

Fig. 3. A: Measured normal force plotted against angular velocity at each sample time for the last 10 trials (gray line) and the median of the force (black line) for a representative participant in the *constant* velocity profile. B: Linear regression (purple line) fitted to the median of force versus angular velocity for the representative participant. C: Linear regression for all participants in the *constant* velocity profile.

Further inspection revealed that forces were higher when the robot's motion differed from the *biological* profile, i.e., the profile that humans prefer [1]. To specify how deviations from this velocity profile were responsible for the observed modulations, forces were regressed against the difference between the angular velocity of the biological and the constant or the exaggerated profile. *Angular velocity difference* was computed at the same spatial point around the ellipse (Fig. 1D); regressions were conducted as in 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. Positive angular velocity differences equated to outward normal forces, and negative angular velocity differences led to inward normal forces applied by the participants.

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

References

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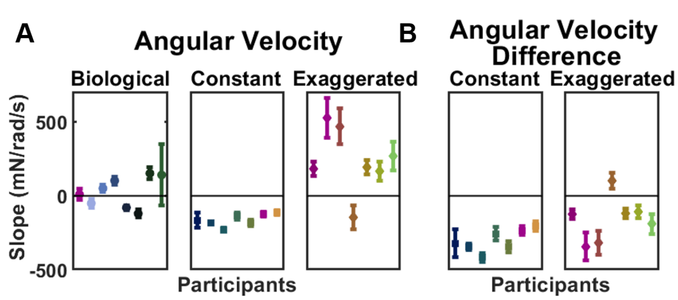

Fig. 4. A: Regression slopes with their 95% confidence intervals fitted to each participants applied normal force versus angular velocity. B: Regression results for normal force versus angular velocity difference.