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

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Motivation

- Regulation of interaction forces is critical in physical human-robot interactions (pHRI).
- Maurice et al.¹ showed that human force regulation is better when robot movements exhibit human-like features.
- In human movements, velocity v scales with radius of curvature r obeying the power law, with K as gain factor:

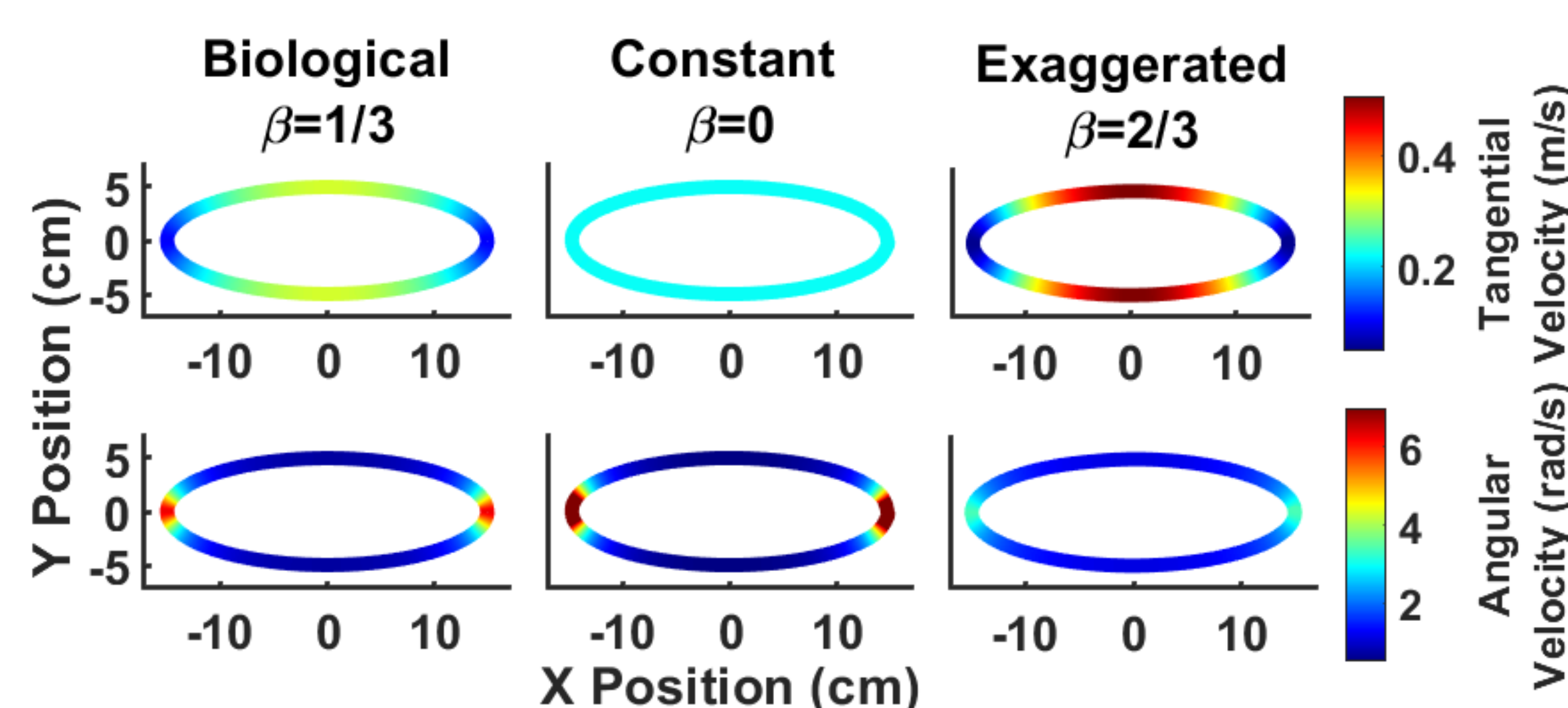
$$v(t) = Kr(t)^\beta, \beta = 1/3$$

- West et al.² showed that applied force of humans cannot be decoupled from the robot's motion.
- Understanding this coupling allows for developing robot controllers that accommodate their human partner.
- This study tests different profiles of robot motion to examine if the human applied forces depend on the:

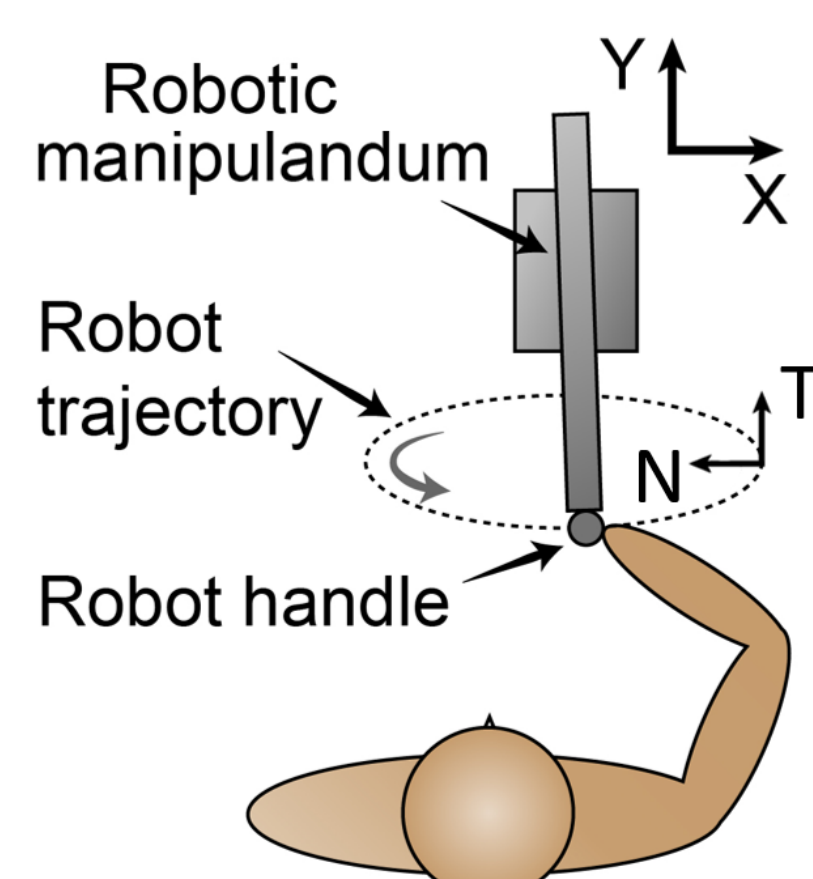
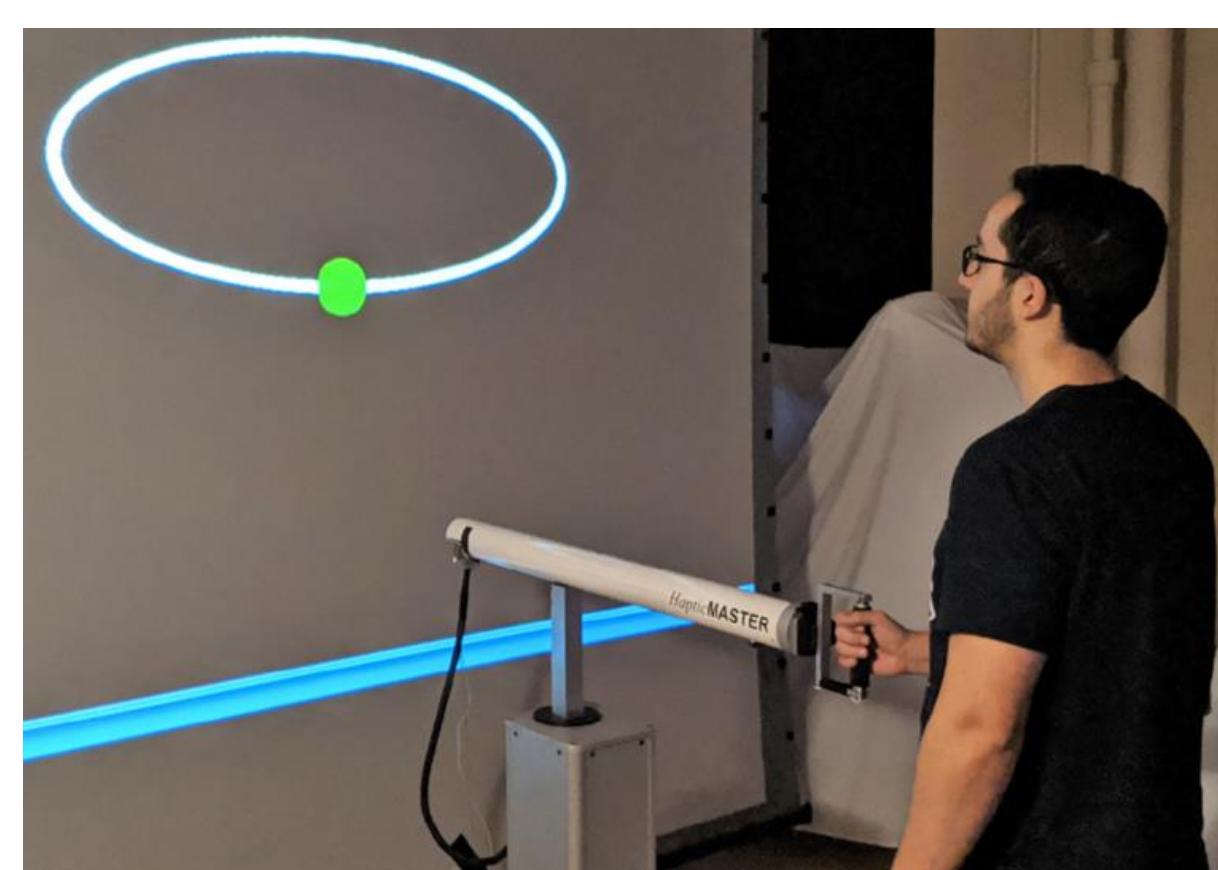
- trajectory's curvature (**H1**)
- tangential velocity (**H2**)
- angular velocity (**H3**).

Methods

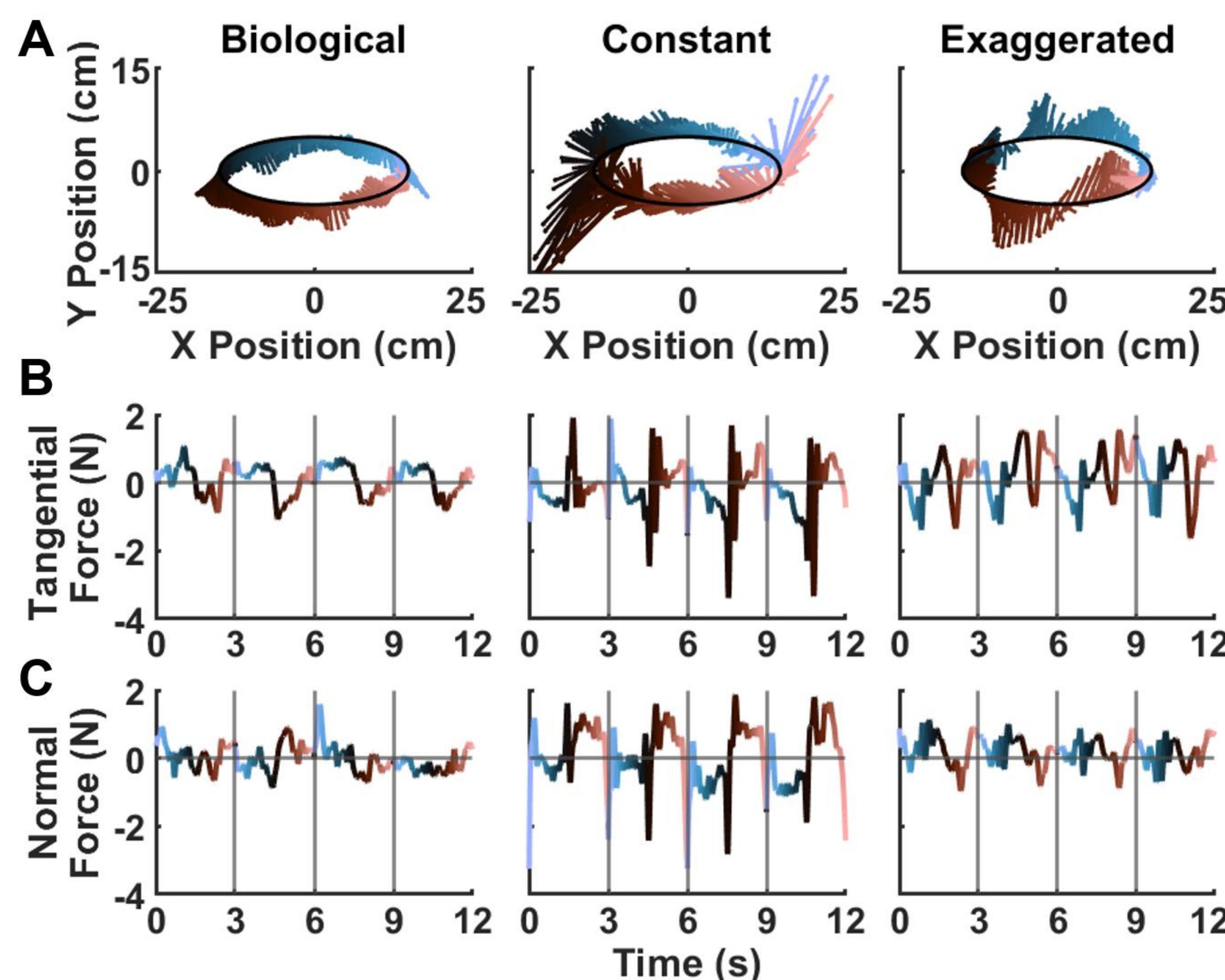
- Robot traced a planar ellipse (major axis = 15cm, minor axis = 5cm) with 3 different velocity profiles:



- 22 subjects were assigned to 1 of the 3 velocity profiles.
- 3 sessions - 80 trials each, analyzed last 10 trials.
- Dependent measures: Tangential and normal force applied by participants on the robot.

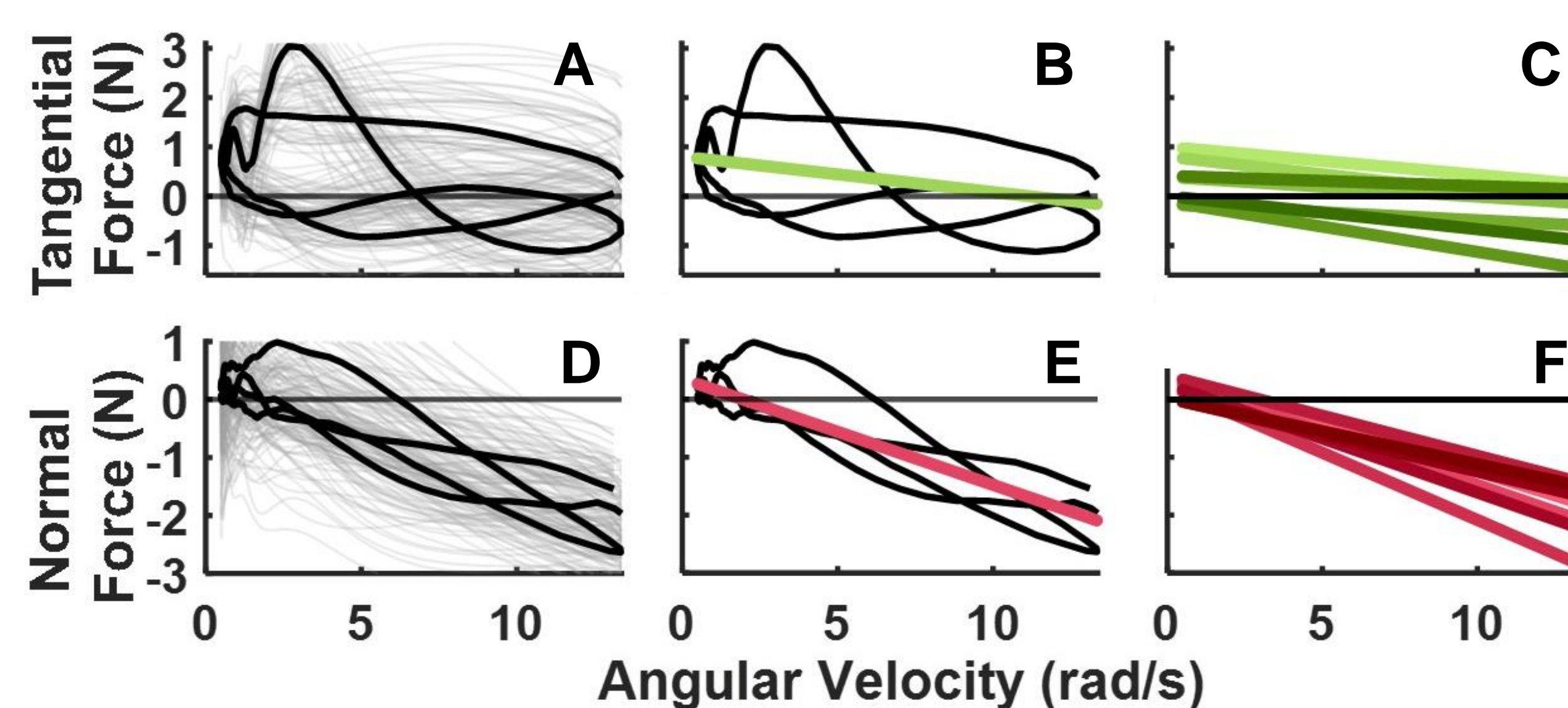


Force Patterns



- Different velocity profiles elicited different force patterns despite having the same curvature profile (**H1 rejected**).
- Large variations of applied force in the *constant* profile with fixed tangential velocity (**H2 rejected**).

Force vs Angular Velocity - Analysis

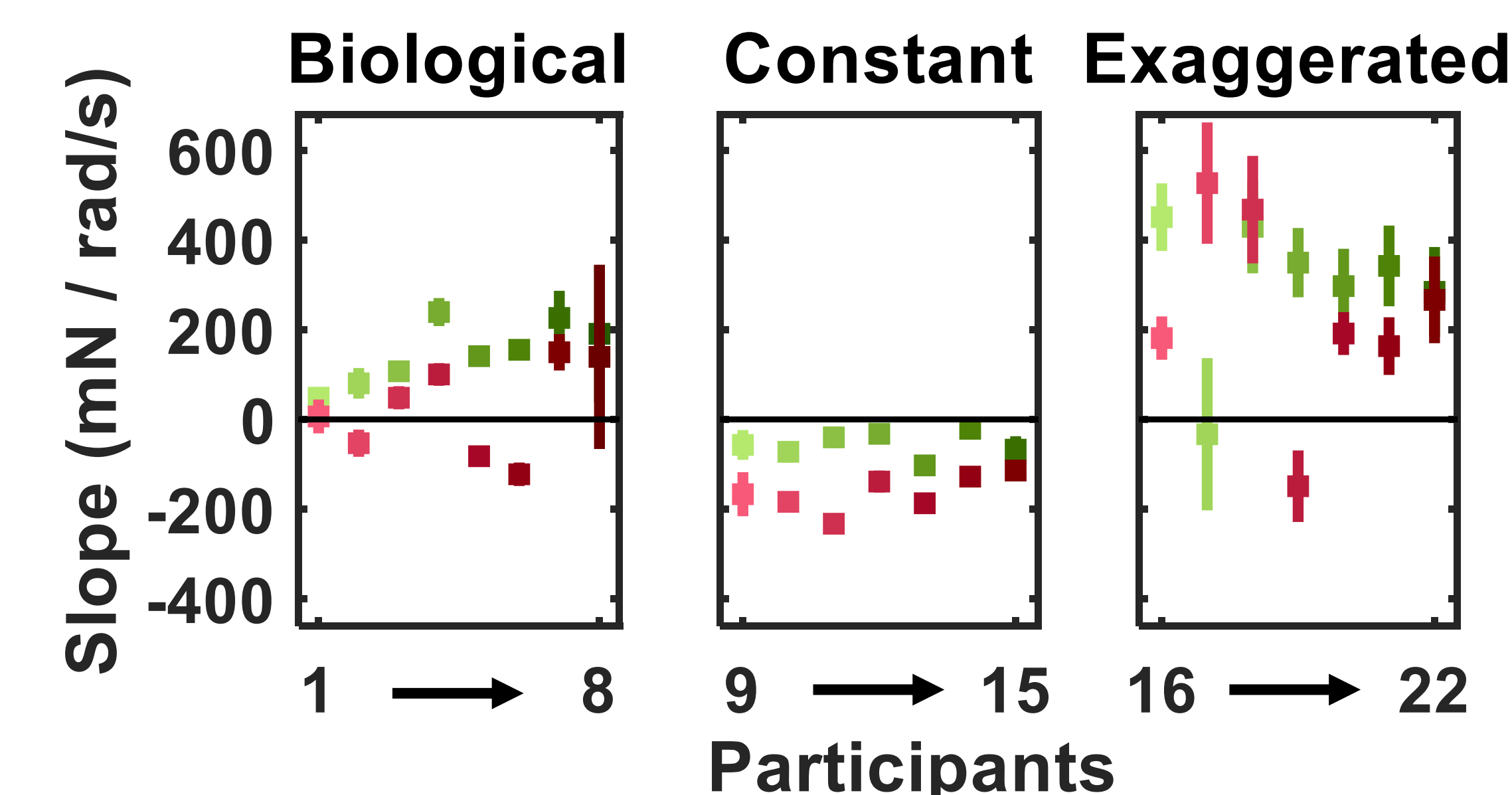


Slopes of linear regressions quantified how applied forces depended on the robot's angular velocity. Figures above show tangential and normal forces of the *constant* velocity profile.

References

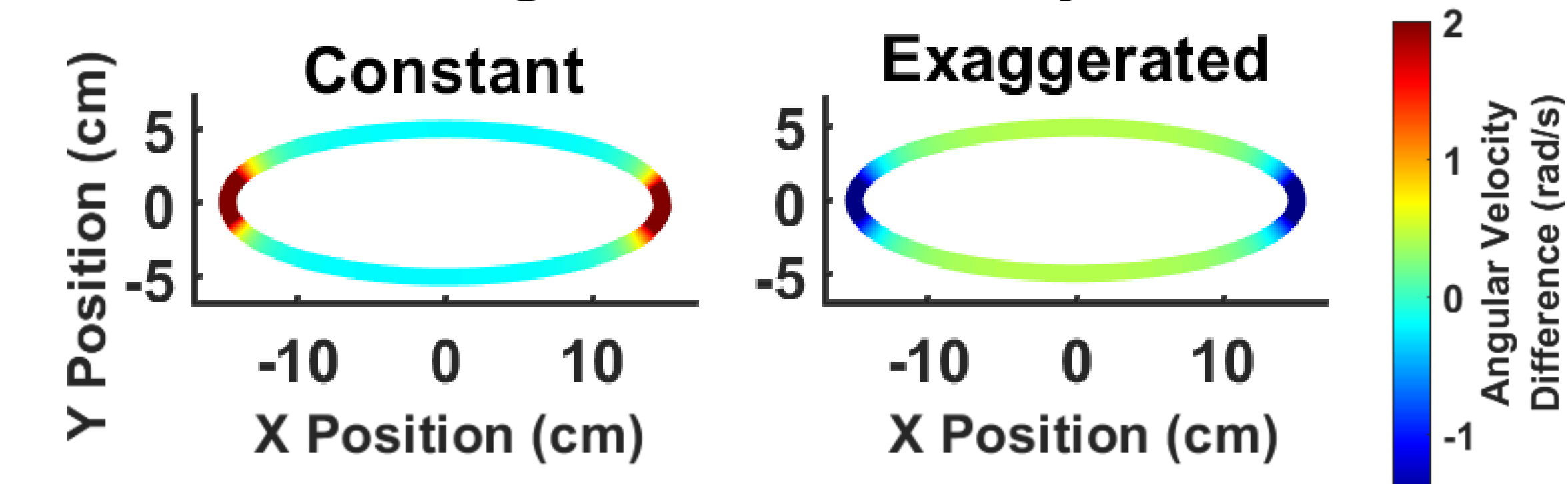
- P. Maurice, M. Huber, N. Hogan, and D. Sternad. Velocity-curvature patterns limit human-robot physical interaction. IEEE RAL, 2018.
- A. M. West, J. Hermus, M. Huber, P. Maurice, D. Sternad, and N. Hogan. Dynamic primitives limit human force regulation during motion. IEEE RAL, 2022.

Force vs Angular Velocity - Results

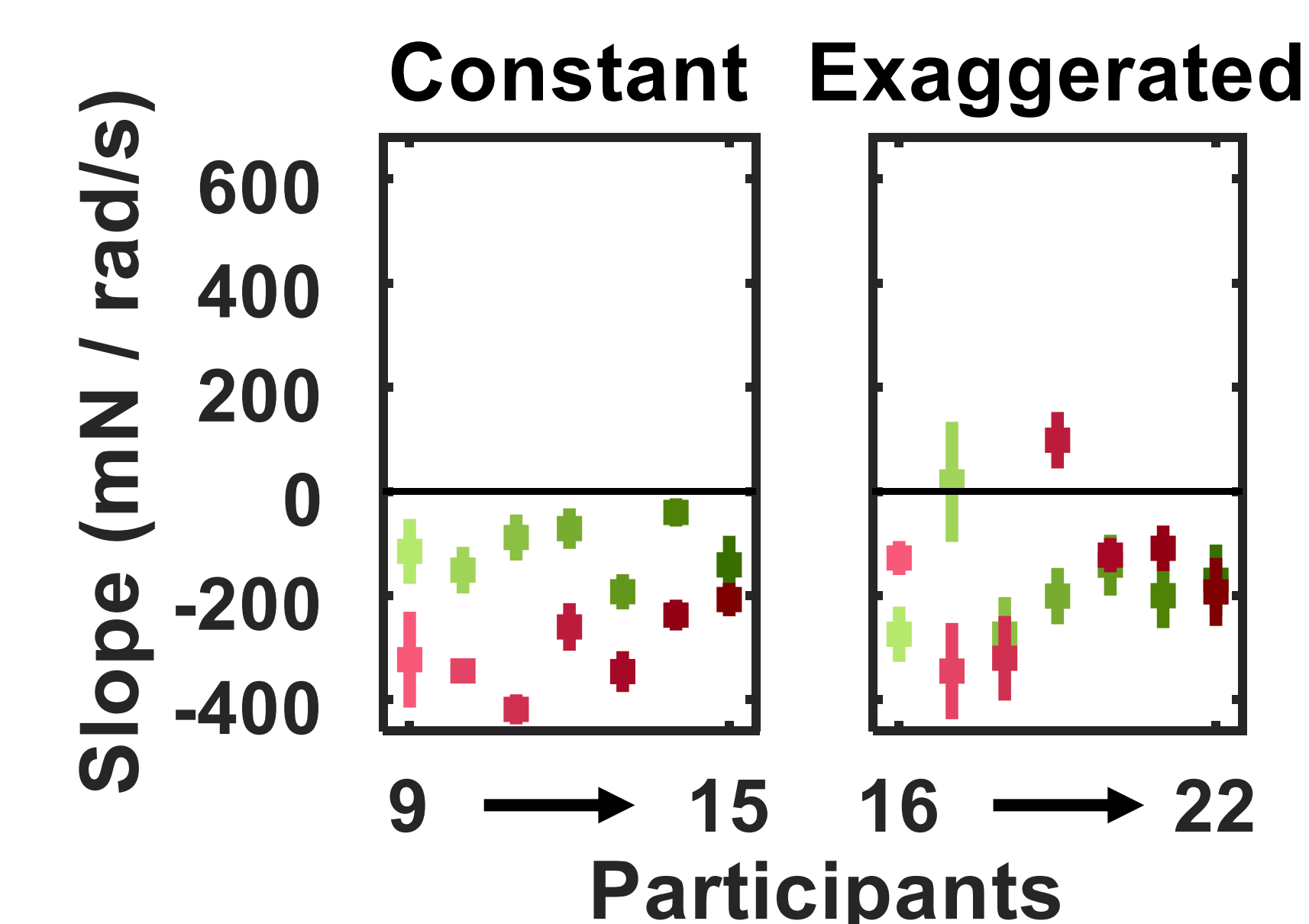


Magnitude of applied force correlated with the robot's angular velocity (**H3 supported**).

Force vs Angular Velocity Difference



Additional question: Do deviations in angular velocity from the *biological* profile lead to higher applied forces?



All slopes show a negative relation with *angular velocity difference*. In both conditions, magnitude of force depended on deviations of angular velocity from the biological profile.

Conclusions

- Human movement has certain limitations that need to be recognized for pHRI tasks.
- Robot movement profiles that deviated from the power law led to higher interaction forces applied by the human partner.
- Robot motion that incorporates the human preferred movement features enables more efficient and safer pHRI.