Control of complex objects: Impedance control around an optimal reference trajectory

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Highlights:

Complex object manipulation as a testbed for models of human motor control

Hand impedance is vital to model human manipulation but a fixed reference trajectory is insufficient

Complex object control requires optimal reference trajectories that consider interaction dynamics

For decades, point-to-point reaching in the horizontal plane has served as a testbed to gain insight into human motor control. Except when adaptation to force-fields was examined, these experiments studied free unconstrained movements. However, interactions with objects create sensorimotor challenges that go beyond simple reaching, particularly when the objects have intrinsic dynamics. This research examines physical interactions with a non-rigid object, inspired by carrying a cup of coffee. Safe control of such a complex object needs to predict, preempt, or compensate for self-generated perturbations from the liquid that act back onto the hand. Major computational frameworks that have accounted for key features in human movements are stochastic optimal feedback control (OFC), kinematic smoothness (minimum-jerk), and impedance control for physical interaction. This study tests these models for interactions with non-rigid objects and introduces a new control framework for modeling such interactions.

In a virtual environment interfaced with a haptic robotic manipulandum, participants transported a cup with a ball inside on a horizontal line to a target. The ball rolling inside the circular cup represented the sloshing liquid in the cup and was simulated as a pendulum suspended from a cart in the virtual environment. For comparison, the ball was also fixed inside the cup, rendering a solid object; as the object only added mass to the movements, this condition was equivalent to free reaching. Subjects performed 100 trials in each condition in block 1. Block 2 was the same, but subjects encountered an additional resistive impulse-like perturbation mid-way to enhance the challenge. As expected, moving the rigid object exhibited a smooth bell-shaped velocity profile. However, when moving the cup with the moving ball, the cup trajectory significantly deviated from the bell-shaped velocity profile due to the internal dynamics of the ball. Further, the perturbation significantly disrupted the cup and ball trajectory exhibiting characteristic deviations.

To account for the observed behavior, we constructed models with three different modeling components: minimum-jerk cup trajectories, OFC, and arm impedance (stiffness/damping). All models could replicate human behavior in the rigid object condition. In the non-rigid object condition, minimum-jerk trajectories, with or without arm impedance, could not realistically replicate data. OFC without arm impedance predicted a two-peak cup velocity profile for the non-rigid object that deviated from the data; its response to perturbation was also stiffer than participants' response. Only an OFC that included arm impedance could reproduce data in all test conditions. In this new model, OFC flexibly produced the reference trajectory for arm impedance in place of a preplanned profile. These results demonstrated that both the object and the arm dynamics should be included in OFC to replicate key features of the behavior.