Human control of complex objects: Stochastic optimal feedback control and beyond

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For several decades, goal-directed reaching in the horizontal plane has served as testbed to gain insight into human control and adaptation of movements. A prominent model that has successfully accounted for a variety of observations is stochastic optimal feedback control that minimizes muscular effort and kinematic accuracy given signal-dependent noise. This body of research simplified the movement to free pointing tasks, excluding any real-world interactions with objects and the environment. Our research extends the sensorimotor challenge and examines 'reaching' while transporting a non-rigid object, such as carrying a cup of coffee. Safe control of such underactuated objects need to predict, preempt or compensate for self-generated perturbations of the liquid that presents forces acting back onto the hand.

In our experiment, participants transported a semicircular cup with a heavy ball rolling inside (simulating the sloshing coffee) in a virtual environment, interfaced with a robotic manipulandum. They moved the cup-and-ball on a horizontal line to a target box. Due to the internal dynamics, the cup trajectory significantly deviates from a bell-shape velocity profile common in unconstrained movements. It also deviates from the two-peaked profile that is predicted by an effort-minimizing optimal controller that minimally intervenes with forces generated by the rolling ball. To reproduce the observed cup velocity profile (which has small positive acceleration in the middle), two modifications of the optimal feedback controller were needed: First, hand impedance accounts for the participants' compliant behavior when facing perturbations (included as a linear spring/damper at the cup). Second, the controller seeks to regulate the zero-force trajectory of the spring/damper with maximal smoothness. As long as the object dynamics is simple, as for a rigid object, both the original and the modified control models result in bell-shaped velocity profiles. However, when coping with interaction forces from the object, the dynamically-informed smoothness criterion is superior as it penalizes changes in cup velocity. These findings show that to gain insight into human control, we need to go beyond the highly simplified tasks to gain insights into human behavior with real-life challenges.