Dynamic Stability in the Control of Complex Objects

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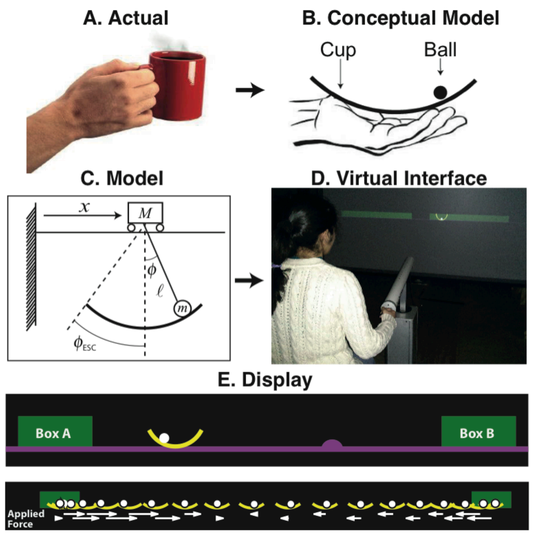
INTRODUCTION

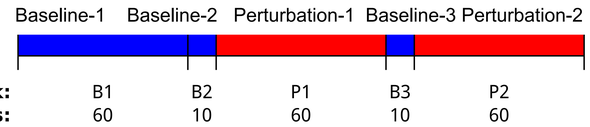
- From swinging a hammer to drinking a cup of coffee, interaction with objects – tool use – is an essential skill for daily activities.
- Manipulating complex objects, such as guiding the cup of coffee to the mouth, requires precise control to preempt and compensate those complex interaction forces to avoid spilling.
- Prediction based on internal models for such complex nonlinear dynamic objects seems implausible.
- Slow neural transmission and neuromotor noise makes error correction insufficient.
- **Hypothesis: Humans make hand-object interactions predictable.**
- **How: Humans exploit the stability properties of the task to obviate errors and attenuate noise.**
- Self-stabilizing or convergence properties can obviate error correction, which are likely insufficient due to long delays.
- Thereby, the model-based closed-loop control of object dynamics becomes less important.
- **Specific Objective: Analyze stability of human-object interaction using contraction analysis.**

The Task



- **Subjects**: 5 right-handed healthy individuals.
- **Task Goal**: Move the cup from Box A to Box B as quickly as possible, without letting the ball escape.
- A perturbation (40 N, 20 ms) was applied at a ***fixed visible location***, acting either ***in*** or ***against*** movement direction.

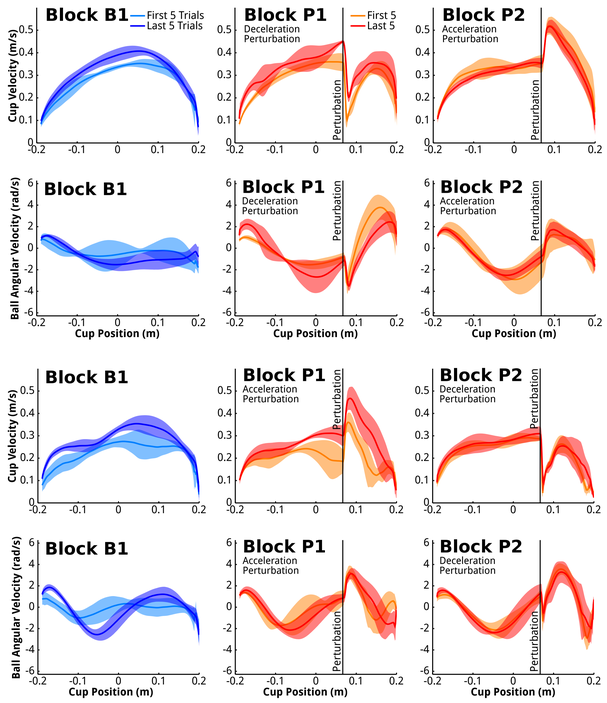
Design and Specific Hypotheses



1) Human make trajectories ***stable*** when facing ***resisting*** perturbations.

2) Human make trajectories ***unstable*** to exploit ***assisting*** perturbations.

Trajectories of 2 Exemplary Subjects



Subject 1 (rows 1 & 2): P1 – resisting, P2 – assisting.

Subject 2 (rows 3 & 4): P1 – assisting, P2 – resisting.

Participants learned to move faster during practice in 60 baseline trials B1.

There is a clear decrease or increase in the cup velocity dependent on the perturbation.

In P1, cup velocity improved further. Note that sequence of assisting and resisting trials differed between subjects.

In P2, there is no further increase in cup velocity.

The variabilities of cup and ball velocities are reduced at the moments preceding perturbations after the extensive training.

Literature

- Nasseroleslami, B., Hasson, C.J., & Sternad, D. (2014). Rhythmic manipulation of objects with complex dynamics: Predictability over chaos. *PLoS Computational Biology, 10(10),* e1003900.
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- Sternad, D. (2016). Control of intermittent and continuous objects. In J.-P. Laumond, *Geometric and numerical foundations of movements.* New York: Springer.
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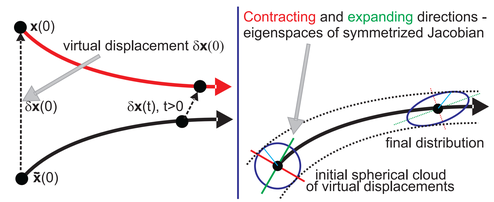
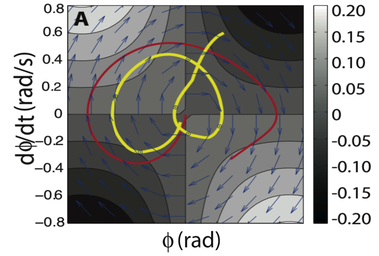
Contraction Analysis

Given the virtual implementation of the cup-and-ball model, human-object interactions exactly correspond to the system equations. The model system can be analyzed using contraction analysis. Contrary to Lyapunov analysis, contraction analysis is not restricted to stable states of the nonlinear dynamic system. This offers the unique opportunity to analyze "dynamic stability" of human trajectories as they perform the task.



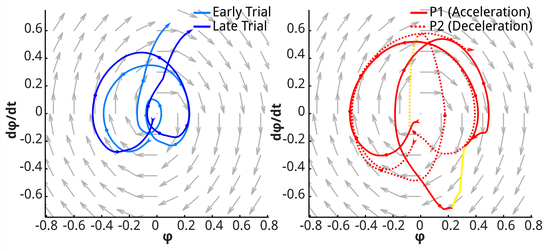
Lohmiller, W. & Slotine, J-J. (1998). On contraction analysis for nonlinear systems. Automatica, 34, 2, 683-696.

Exemplary Results



Ball trajectories from human performance plotted against total contraction values. Negative contraction exponents (dark grey) denote contracting states.

Yellow trajectory early in practice, red trajectory late in practice.



Left: Ball trajectories during baseline block.

Right: Ball trajectories during perturbed trials. Trajectories travel with flow after perturbation. Onset is such that post-perturbation segments are in contracting regions.

CONCLUSIONS

- Subjects successfully learnt the task and generalized across the two types of perturbations.
- First application of contraction analysis to assess dynamic "stability" during complex object manipulation.
- Some first evidence that subjects position the perturbation onset such that the subsequent trajectory falls in a contraction region of state space.