



## Background

Humans use and interact with objects everyday, from turning a key in a keyhole



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# Why You Don't Spill Your Coffee

Julia Ebert<sup>1</sup>, Albert Mukovskiy<sup>2</sup>, Tjeerd Dijkstra<sup>3</sup>, and Dagmar Sternad<sup>4</sup> <sup>1</sup>Behavioral Neuroscience, Northeastern University; <sup>2</sup>Centre for Integrated Neuroscience, Eberhard Karl University, Tübingen, Germany; <sup>3</sup>Institute for Computing and Information Sciences, Radboud University, Nijmegen, Netherlands; <sup>4</sup>Biology, Electrical & Computer Engineering, Physics, Center for Interdisciplinary Research on Complex Systems, Northeastern University

# **Behavioral Results**

# Northeastern University

Given the virtual implementation of the cup-and-ball model, the humanobject interactions corresponds exactly to the system equations. This correspondence offers a unique opportunity for analysis of human trajectories: each measured sample of the state vector from the human trial can be inserted into the dynamic model as initial conditions. The model initialized with different conditions can then be analyzed with mathematical techniques.

### **Angle Between Trajectory and Flow**

Instantaneous angle between subject's trajectory and flow of the unforced system.

Subjects generally follow the flow when unperturbed and return to the flow following a perturbation.



### **Contraction Analysis**

Measure of the relative stability of the system's state in response to noise or small perturbations: do nearby trajectories converge or diverge?



Lohmiller, W. & Slotine, J.-J. E. (1998) On Contraction Analysis for Nonlinear Systems, Automatica, 34(6).

Subjects successfully generalized understanding of the system's dynamics to new perturbations.

This experiment is a successful first test of using a virtual system with known dynamics to allow model-based analysis of human trajectories. Two novel mathematical analyses, flow direction and contraction analysis, provide a theoretical framework for assessing stability in human movements.

Learning stable trajectories is useful to handle perturbations arising from internal sources (noise), external sources (applied perturbations), and the object's complexity.



# **Analytical Methods**

**Contracting** and expanding directions eigenspaces of symmetrized Jacobian Generalize final distributior initial spherical cloud of virtual displacements

# Conclusions