Massachusetts Institute of Technology

The Action Lab

Newman Laboratory for Biomechanics
and Human Rehabilitation

Collaborative Research:
Towards Robots with Human Dexterity

Neville Hogan and Dagmar Sternad

Massachusetts Institute of Technology **Northeastern University**

Disclosure: Neville Hogan holds equity in Bionik Laboratories,
which manufactures human-interactive technologies for rehabilitation

NRI- 1637824 (Hogan)
NRI- 1637854 (Sternad)

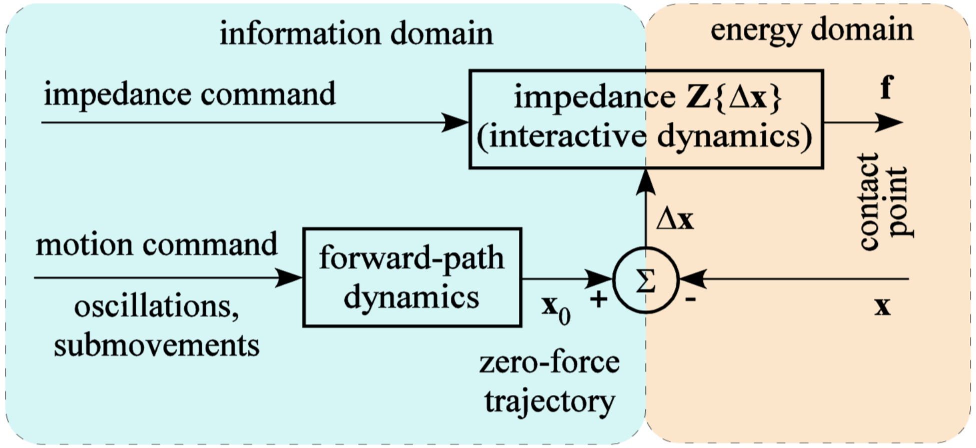
Understanding Human Dexterity

- **Premise: Studying humans may facilitate**
  - Improved robot control
    - Scale-up to many DOF
  - Physical human-robot collaboration

- **Hypothesis: Humans use dynamic primitives**
    - To work around neural limitations

- **Dynamic primitives: Robust attractors of low-level dynamics**
    - Limit cycle (rhythmic oscillation)
    - Trajectory (stereotyped submovement)
    - Mechanical impedance (interactive behavior)

Combine Primitives in a Nonlinear Equivalent Network



The 'equivalent source'
- Describes forward path dynamics
- Composed of motion primitives

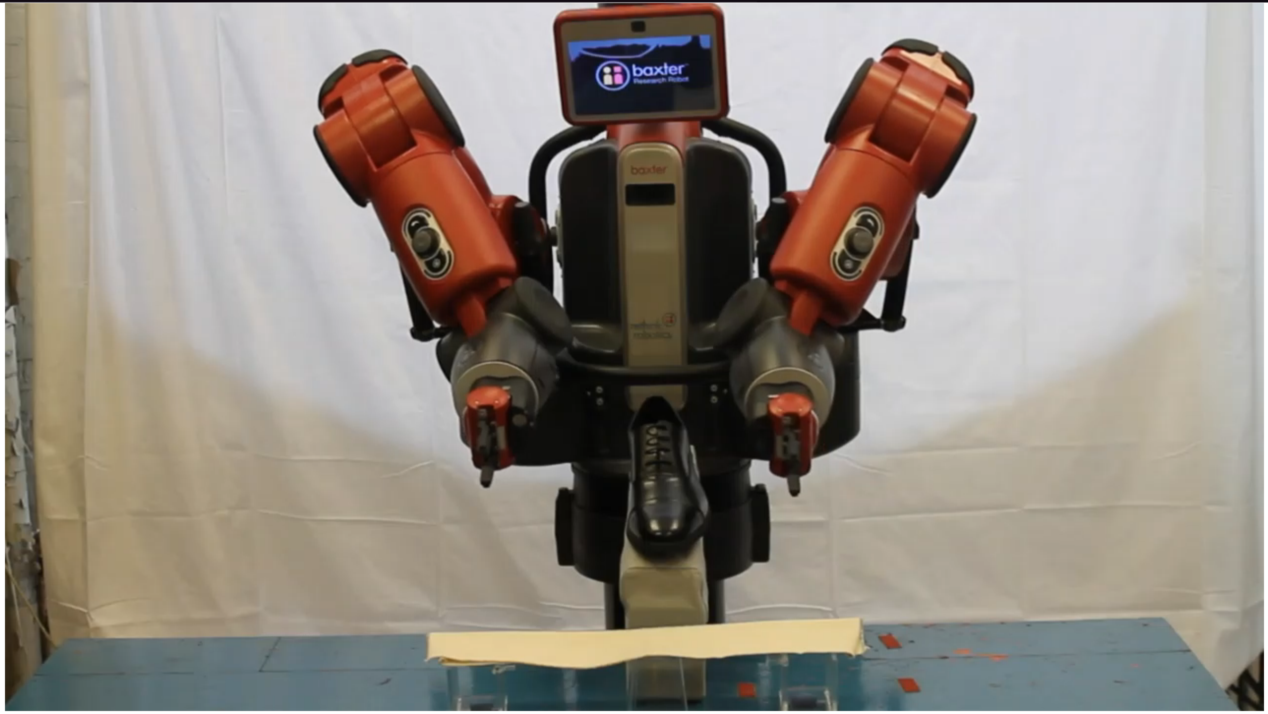
The 'equivalent resistance'
- Describes interactive dynamics
- Composed of impedances

A 'neo-classical' approach?

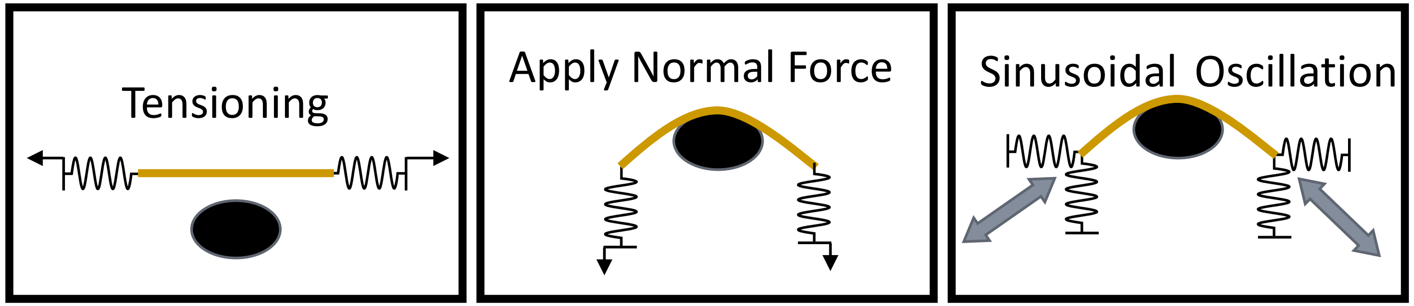
Hogan, *Geom and Num Foundations*, Springer, 2017
Hogan, *IEEE/ASME Trans on Mechatronics*, 2014
Schaal, Kotosaka, Sternad, *Humanoid Robotics*, 1998
Sternad, *Coordination*, Springer, 2008
Hogan & Sternad, *Biol Cybernetics*, 2012
Hogan & Sternad, *Front Comp Neurosci*, 2013

Mechanical Impedance Compositionality

- **Compositionality: Impedances superimpose even if non-linear**
  - Map desired end-point stiffness $f = k(x_0 - x)$ to configuration space $\tau = J(\theta)^T k\big(x_0 - L(\theta)\big)$
  - Define configuration controller $\tau_j = K(\theta_n - \theta)$ and add $\tau_{net} = J(\theta)^T k\big(x_0 - L(\theta)\big) + K(\theta_n - \theta)$



- **Notable features:**
  - No inverse kinematics—works at singularities
  - Makes control modular and versatile
    - Flexible object
    - Multi-arm coordination
    - Contact and non-contact phases



Human Interaction with a Kinematic Constraint

Subjects turned a crank while instructed to:

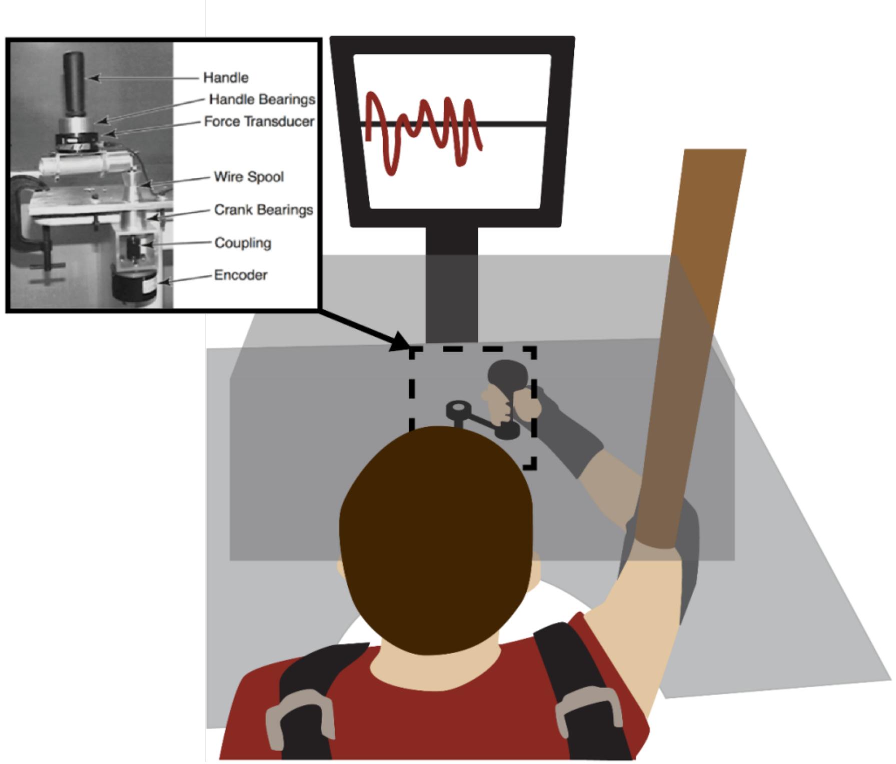
- Turn at different constant speeds: slow, medium, fast
- CW or CCW
- The hand was occluded from view
- Visual speed feedback was provided

Main result: Despite instruction and feedback

- Speed varied systematically with crank angle
- Normal force varied systematically about zero

Underlying motion command:

- Describe interaction dynamics as mechanical impedance $Z\{\cdot\}$
  - $F(t) = Z\{\Delta\, x(t)\}$
  - $\Delta x(t) = x_0(t) - x(t)$
- Subtract off interaction dynamics
  - $x_0(t) = x(t) + Z^{-1}\{F(t)\}$



$\boldsymbol{x_0(t)}$ = **zero-force trajectory (ZFT)**

Hermus, Masters Thesis, Mech Engineering, MIT, 2018

Hermus, Doeringer, Sternad, Hogan, *J Neurophysiology*, revised

Zero-Force Trajectory Revealed Underlying Structure

Zero-Force Trajectory

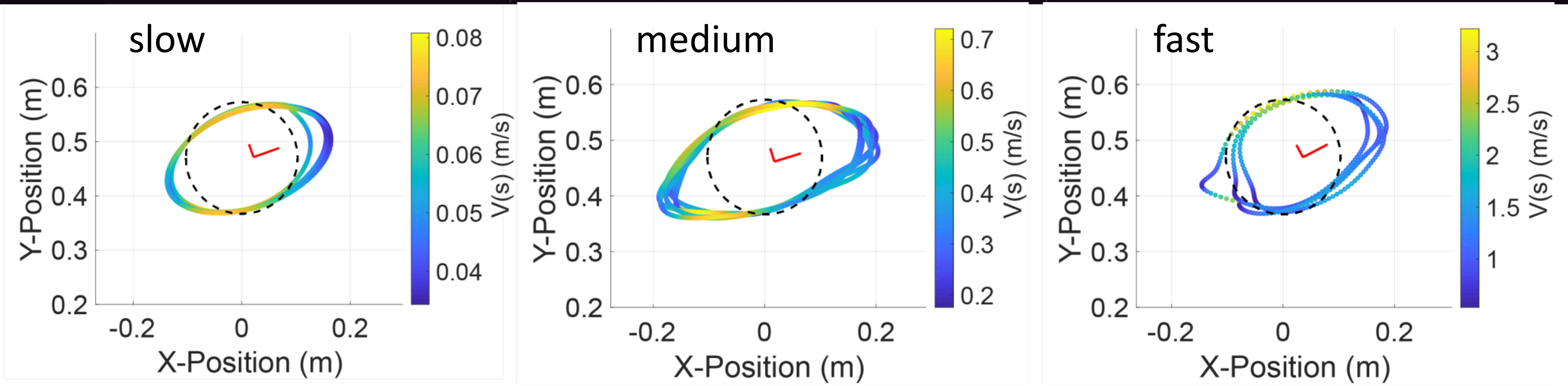
- Roughly elliptical path
- Speed minima and curvature maxima coincided

Similar to a speed-curvature relation widely reported in unconstrained motion

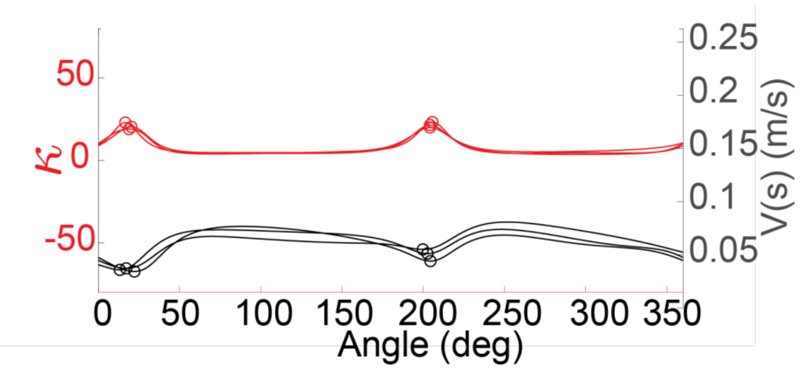
- **The "1/3 power law"**

Dynamic Primitives

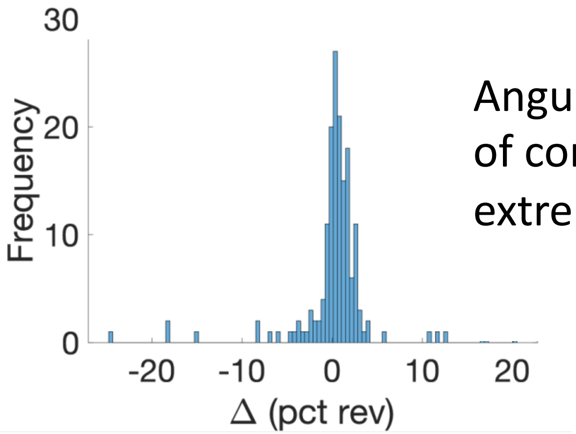
- Consistent with underlying motion composed of two primitive oscillations



Zero-force trajectories. Red lines denote major & minor axes of best-fit ellipse



Zero-force trajectory speed and curvature



Angular separation of corresponding extrema

Hermus, Doeringer, Sternad, Hogan, *J Neurophysiology*, revised

Human Interaction with a Moving Constraint: 1/3 Power Law

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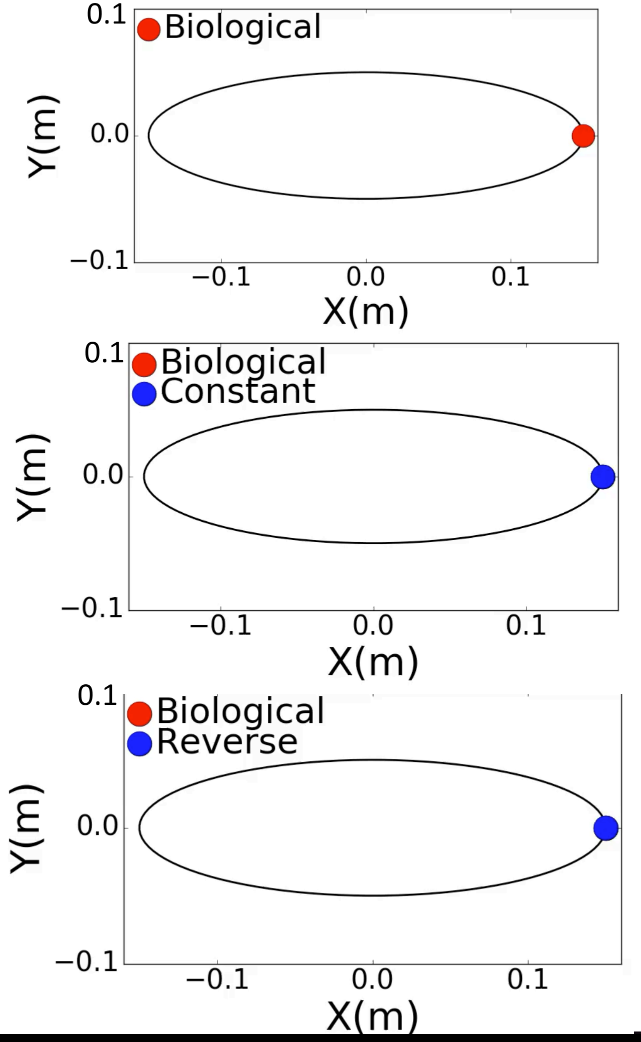


b = 1/3

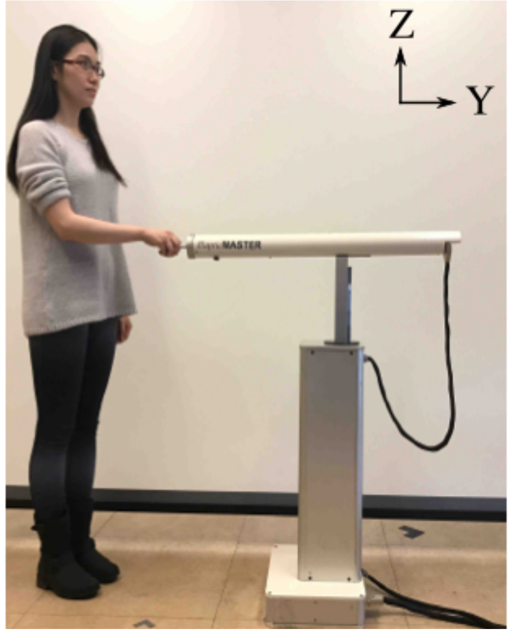
b = 0

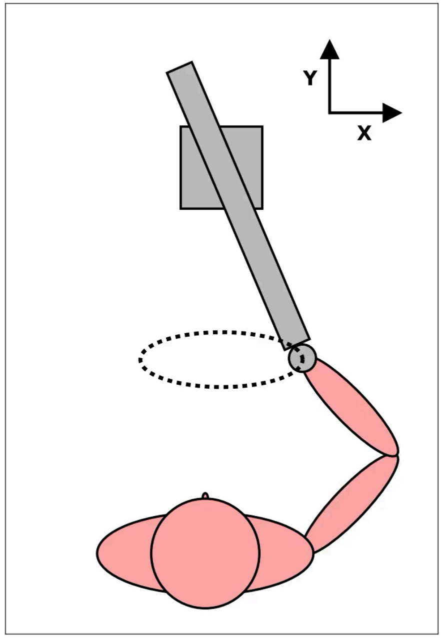
b = -1/3

Humans display a specific scaling of velocity with curvature

$$v(t) = K\ r(t)^{b}$$

v: tangential velocity, **r**: radius of curvature, **b: 1/3**

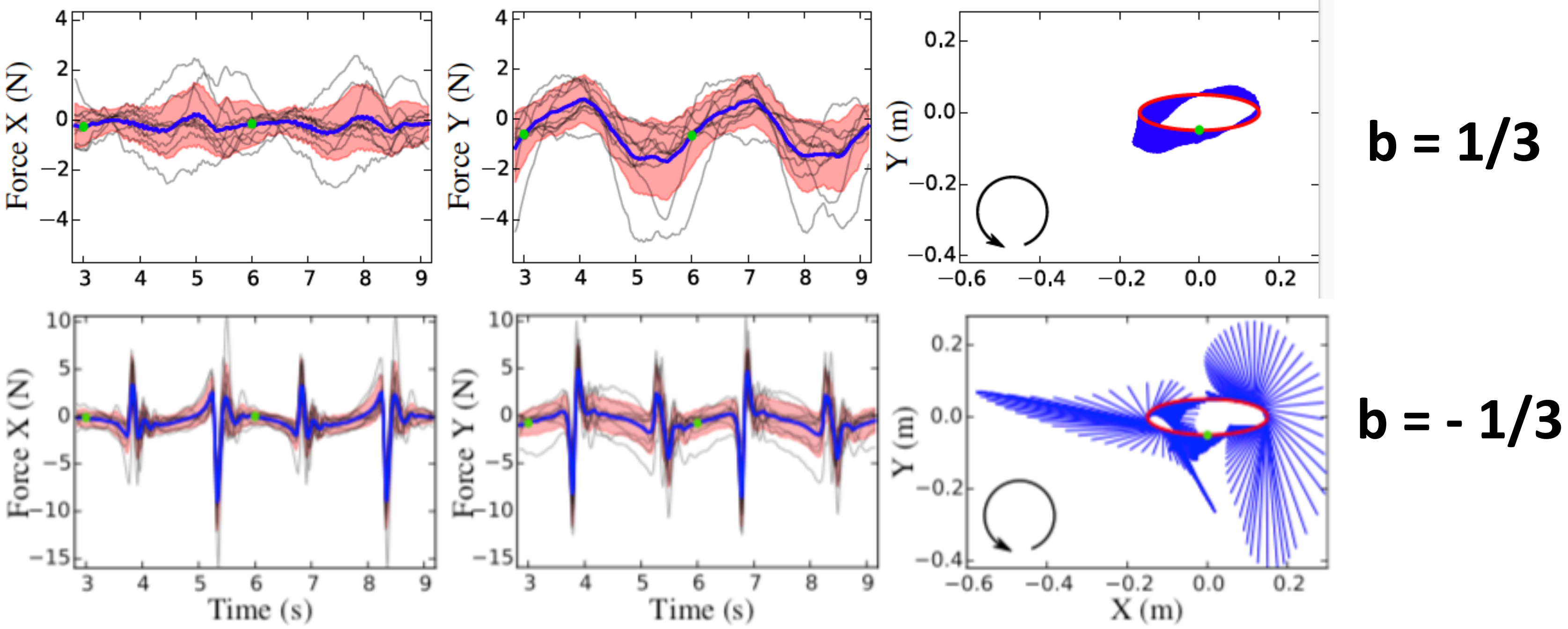


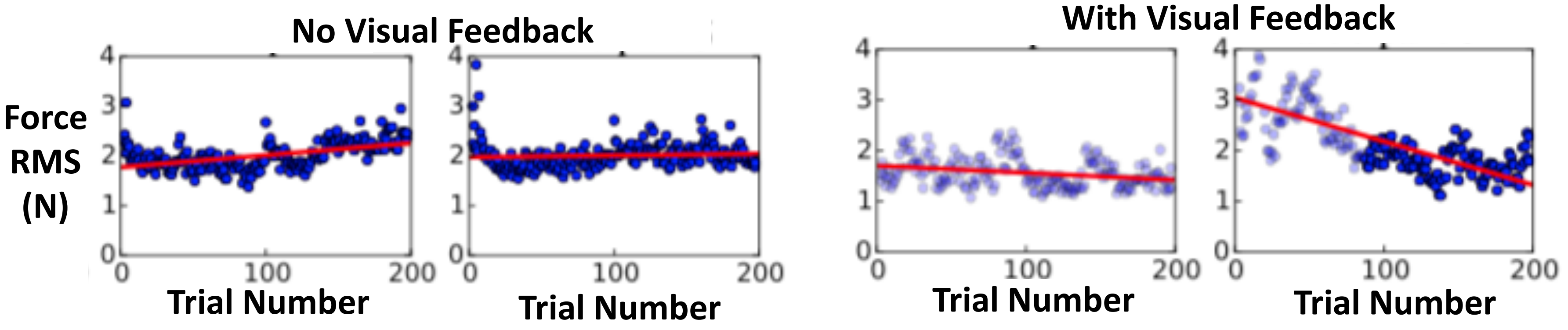


[redacted]

Maurice, Huber, Hogan, Sternad, *Robotics and Automation Letters*, 2017

Humans Cannot Perform Non-Biological Velocity Patterns





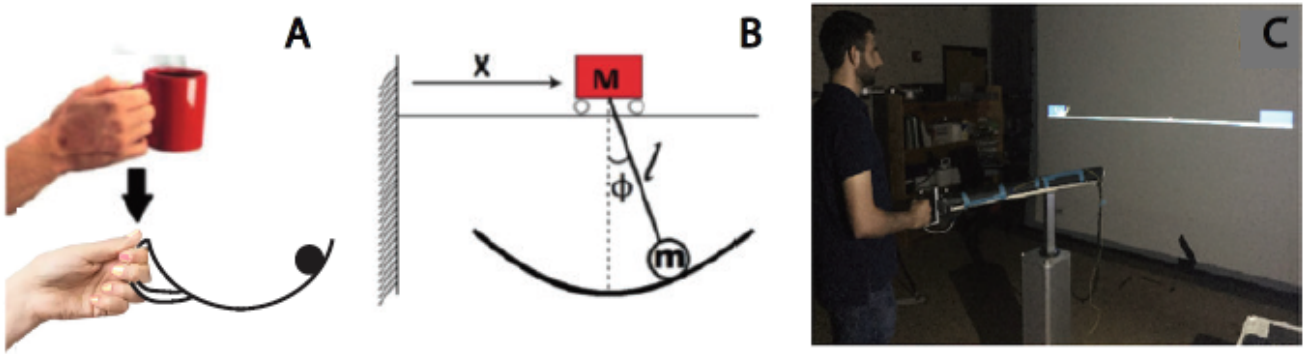
- Humans exert greater forces with greater deviations from b = 1/3.
- Humans do not learn non-biological velocity-curvature patterns without visual feedback.

Maurice, Huber, Hogan, Sternad, *Robotics and Automation Letters*, 2017

Human Interaction with a Complex Object

How Do Humans Manipulate Complex Objects?

- Long delays imply heavy reliance on predictive control based on an internal model
- But complex internal models seem unlikely



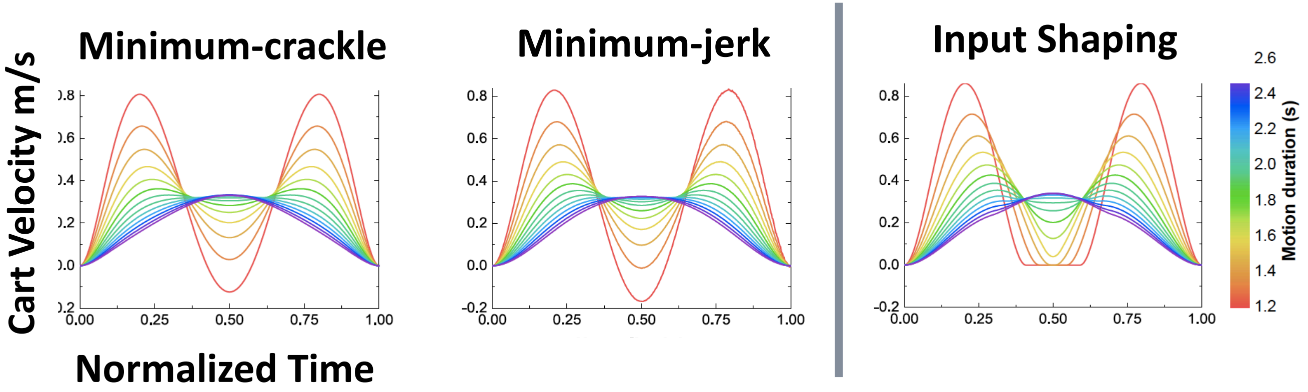
Overall Hypothesis:

Humans simplify control by using dynamic primitives

- Control via Input Shaping eliminates residual vibrations

Alternative Hypotheses:

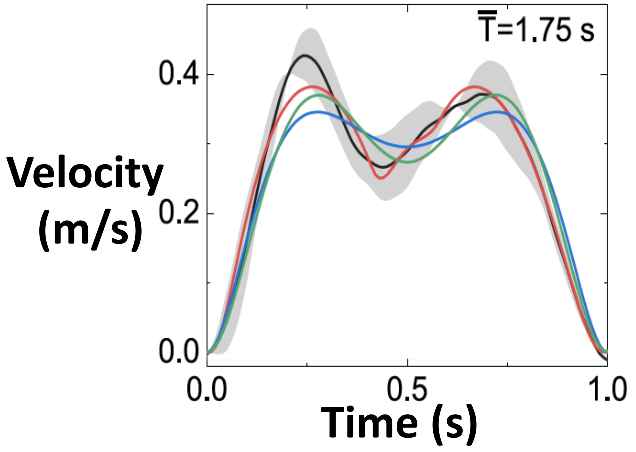
- Using optimization



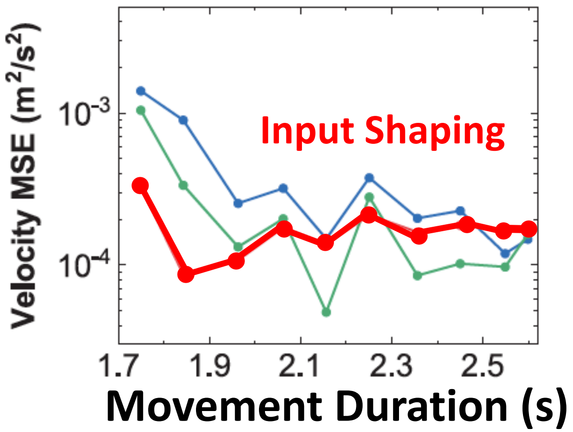
Bazzi, Ebert, Hogan, Sternad, *ICRA*, 2018
Guang, Bazzi, Sternad, Hogan, *ICRA*, 2019

Input Shaping with Two Submovements is the Best Control Strategy

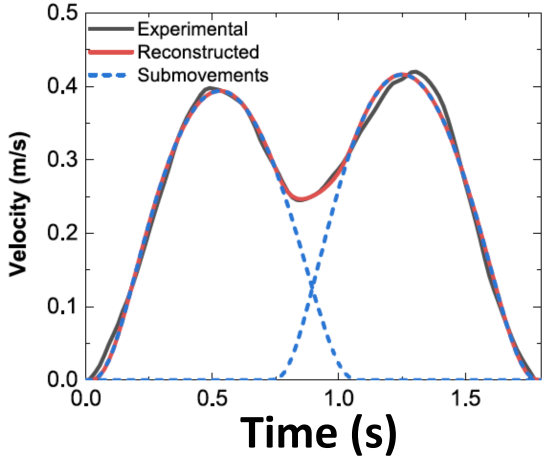
Data and Models



Different Model Fits



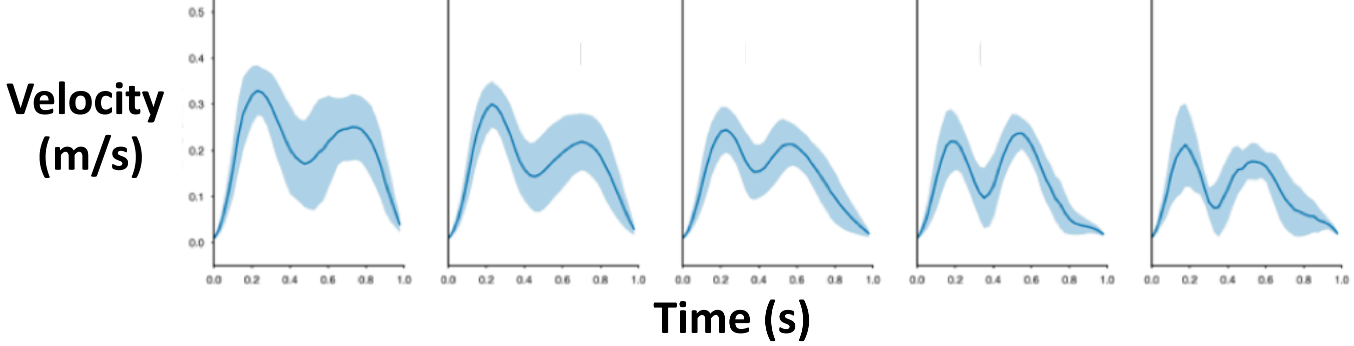
Submovement Fitting

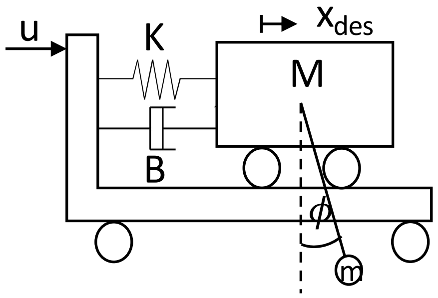


Two submovements fit the human velocity profile

Input shaping ➡ **Dynamic Primitives**

Different Movement Durations





Next Step: Asymmetric profile indicates presence of impedance

Bazzi, Stansfield, Sternad, Hogan (in preparation)

Bazzi, Ebert, Hogan, Sternad, *ICRA*, 2018
Guang, Bazzi, Sternad, Hogan, *ICRA*, 2019

Compositionality Simplifies Scale-Up to Many DOF

- **Readily extends to two (or more) arms**
    - Connected at a common end-point
    - Interacting with a common object
  - Net end-point stiffness is $k_{both} = k_l + k_{j,l} + k_r + k_{j,r}$

- **Superimpose open-chain single arm controllers**
  - Left arm: $\tau_{net,l} = J(\theta_l)^T k_l \left(x_{0,l} - L(\theta_l)\right) + K_l(\theta_{n,l} - \theta_l)$
  - Right arm: $\tau_{net,r} = J(\theta_r)^T k_r \left(x_{0,r} - L(\theta_r)\right) + K_r(\theta_{n,r} - \theta_r)$

- **No closed-chain kinematic computation**

- **No inverse kinematic computation**