Features of Free Motion Persist in Constrained Actions

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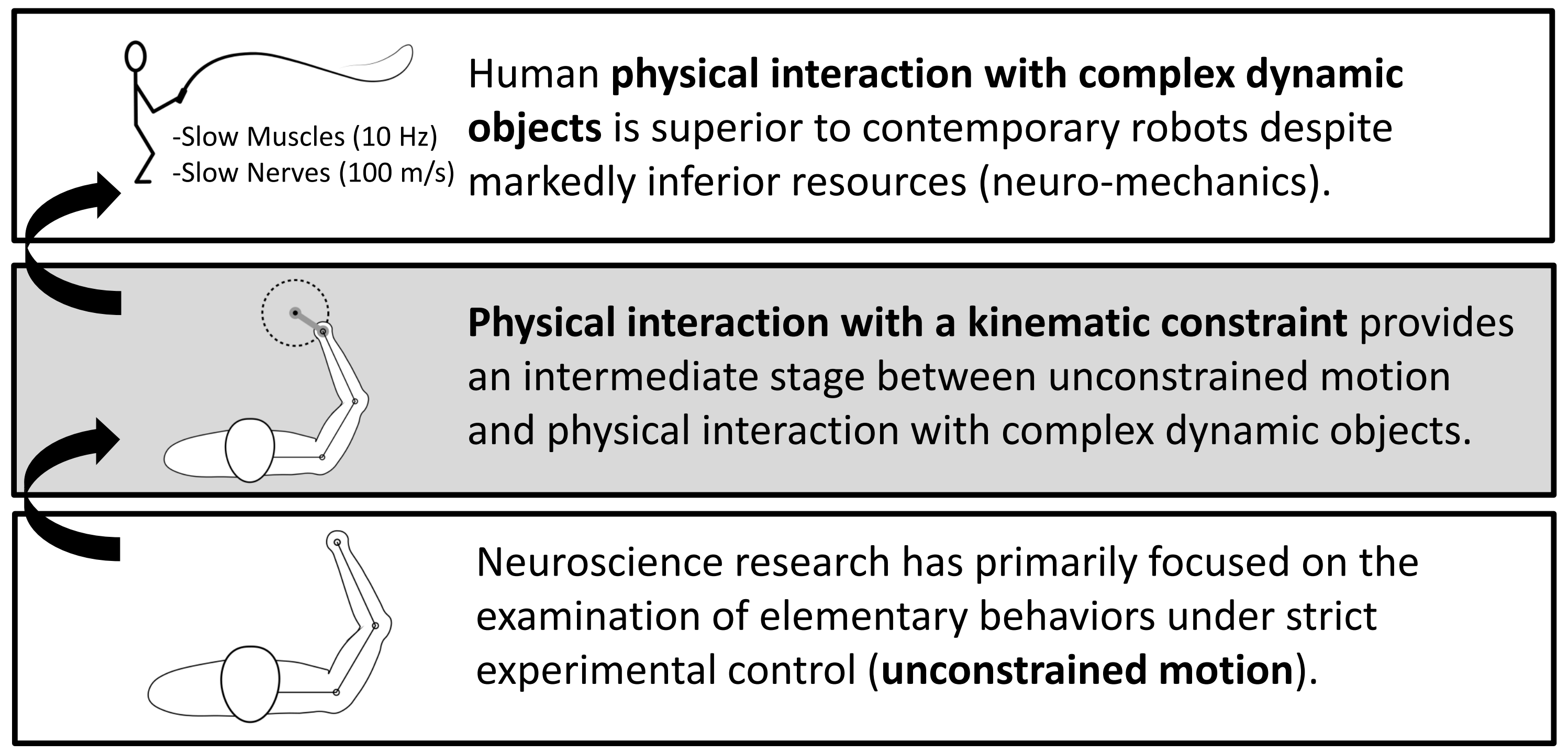
Abstract

We examined arm movements while interacting with a crank, a horizontal planar circular constraint. As kinematically-constrained actions necessarily involve significant physical interaction, disentangling the influences of biomechanics and neural control is a challenge. The approach used here was to assume a plausible mathematical model of interactive dynamics and use it to 'subtract off' peripheral biomechanics to uncover underlying neural control of motion. We called this quantity the zero-force trajectory. It can loosely be interpreted as the trajectory the hand would take if zero force impeded motion, i.e. the constraint was removed. In unconstrained motion hand movements are well described by minimum jerk trajectories, which results in a power law relating speed and curvature. The physiological origin of this speed-curvature relation has been debated. It has been attributed to skeletal kinematics, to neuro-muscular dynamics, or to neural processes. The mechanical design of our experiment suppressed any variation of hand path curvature (a circular constraint has constant curvature). By experimental design, any variation of hand tangential speed was discouraged via visual feedback. Nevertheless, the widely-observed synchrony between speed and curvature extrema re-emerged as estimated by the zero-force trajectory.

Motivation

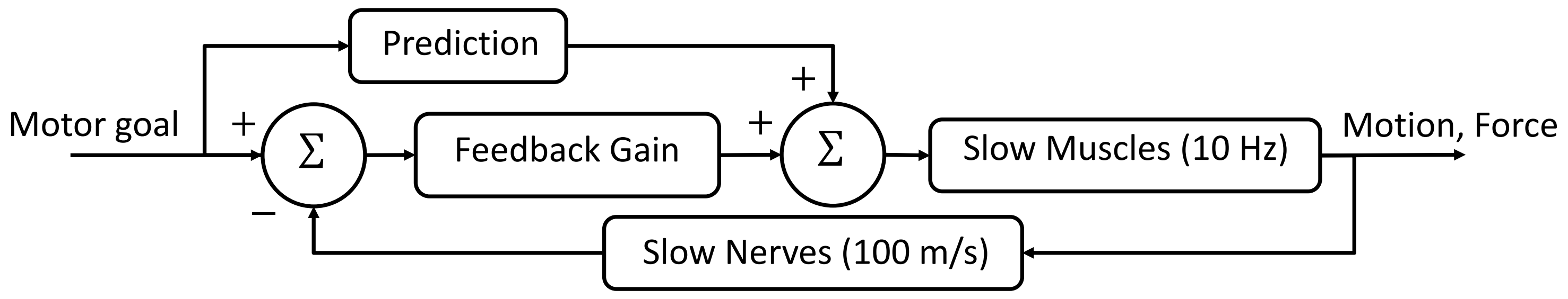


Human **physical interaction with complex dynamic objects** is superior to contemporary robots despite markedly inferior resources (neuro-mechanics).

Physical interaction with a kinematic constraint provides an intermediate stage between unconstrained motion and physical interaction with complex dynamic objects.

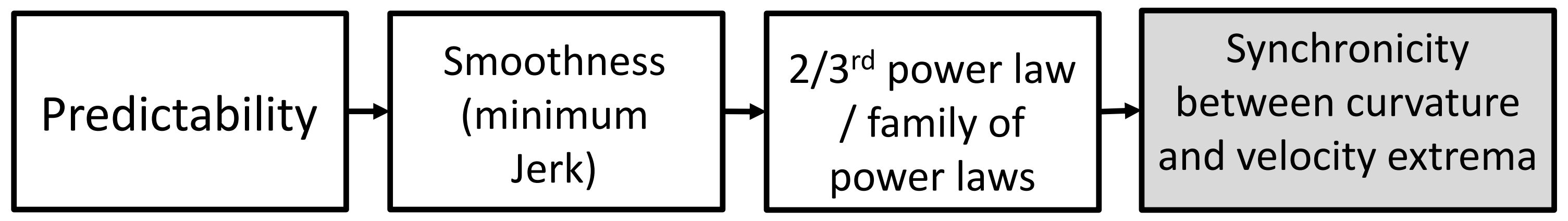
Neuroscience research has primarily focused on the examination of elementary behaviors under strict experimental control (**unconstrained motion**).

Background



A relationship between velocity and curvature has been widely reported:

- Hand writing (Abend et al. 1982)
- For ellipses this is the so-called '**two-thirds power law**' (Lacquaniti et al., 1993)
- Neuronal populations (Schwartz, 1994)
- In more complex shapes (Huh & Sejnowski, 2015)
  - **A family of power laws** was observed
  - **Predicted by maximizing smoothness (minimum jerk)**



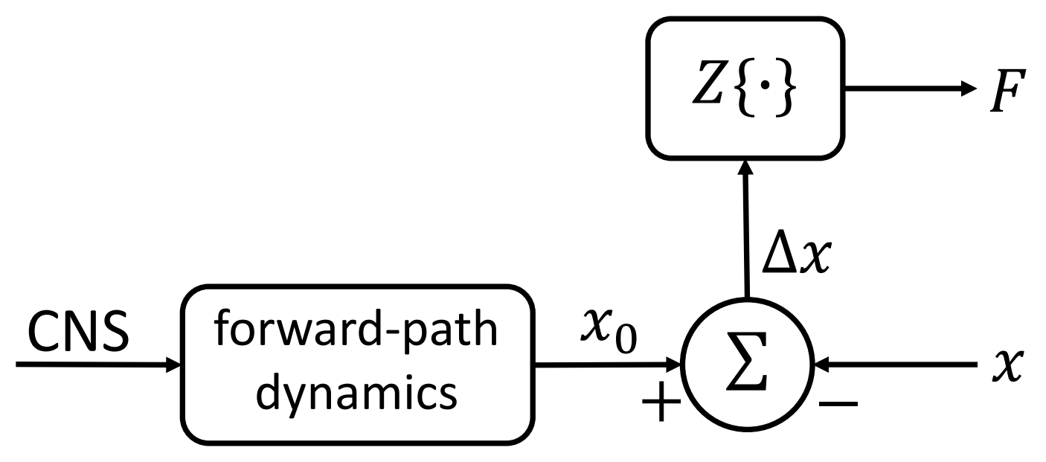
Predictability → Smoothness (minimum Jerk) → 2/3rd power law / family of power laws → Synchronicity between curvature and velocity extrema

The Zero-Force Trajectory

Hypothesis: The underlying neural command will exhibit the same patterns evident in unconstrained motions, i.e. curvature-velocity relationship.

The Zero-Force Trajectory

- **Goal**: Uncover underlying neural control
- Model interaction dynamics
- Describe interaction dynamics as mechanical impedance $Z\{\cdot\}$.
  - $F(t) = Z\{\Delta x(t)\}$
  - $\Delta x(t) = x_0(t) - x(t)$
  - $x_0(t) = x(t) + Z^{-1}\{F(t)\}$
- 'Subtract' off peripheral biomechanics
- Express the result in terms of motion
- The **zero-force trajectory (ZFT) =** $\boldsymbol{x_0(t)}$



In practice this relationship is implemented in joint space and assumes the impedance to be linear, first-order, and time-invariant.

$$\boldsymbol{\tau} = \boldsymbol{K}(\boldsymbol{q}_0 - \boldsymbol{q}) + \boldsymbol{B}(\dot{\boldsymbol{q}}_0 - \dot{\boldsymbol{q}})$$

Methods

- Subjects were instructed to move with constant velocity
  - Circular constraint eliminates curvature variation
  - Visual speed feedback was provided online on a display
- Subjects were instructed to turn:
  - In the CW/CCW direction
  - At different speeds: slow, medium, and fast
- In all trials the hand was occluded from view

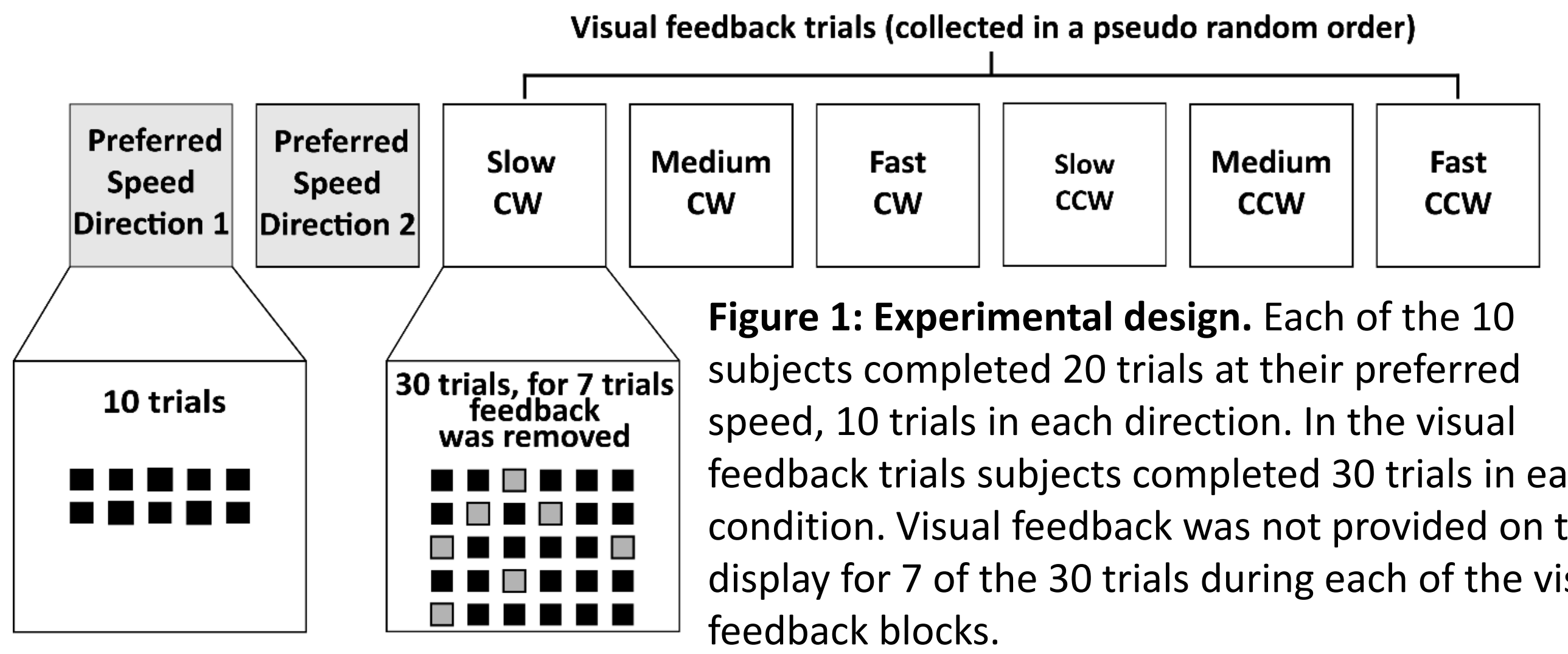


Figure 1: Experimental design. Each of the 10 subjects completed 20 trials at their preferred speed, 10 trials in each direction. In the visual feedback trials subjects completed 30 trials in each condition. Visual feedback was not provided on the display for 7 of the 30 trials during each of the visual feedback blocks.

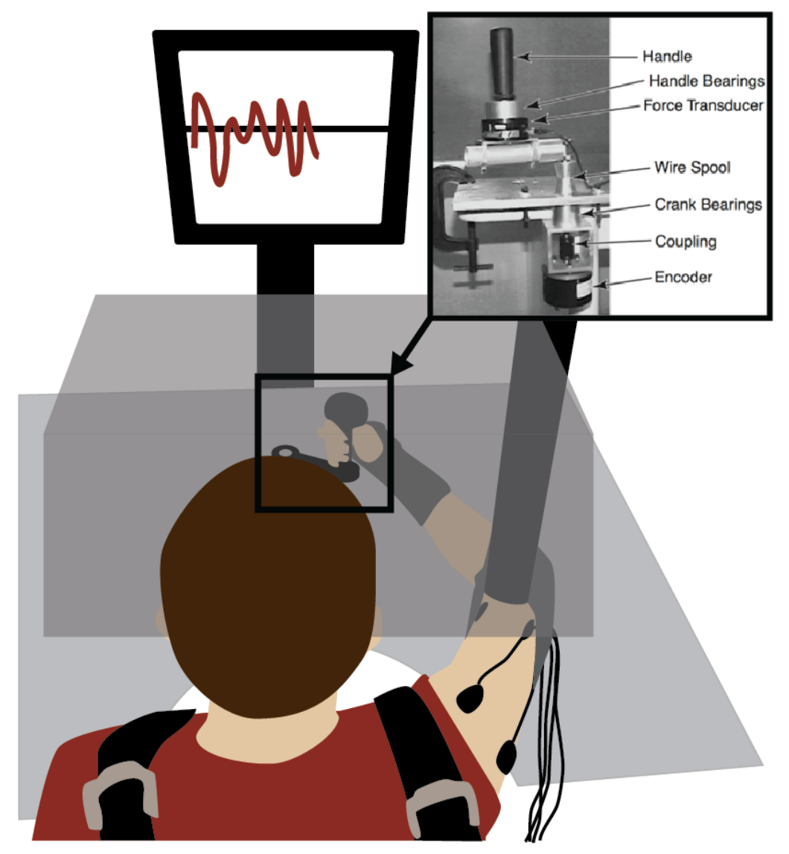


Figure 2: Experimental setup. The crank displayed in the inset was used to provide a circular constraint. The subject was provided with visual velocity feedback. The wrist was be braced, the elbow was supported by a sling, and the shoulders was be strapped to the chair.

Results

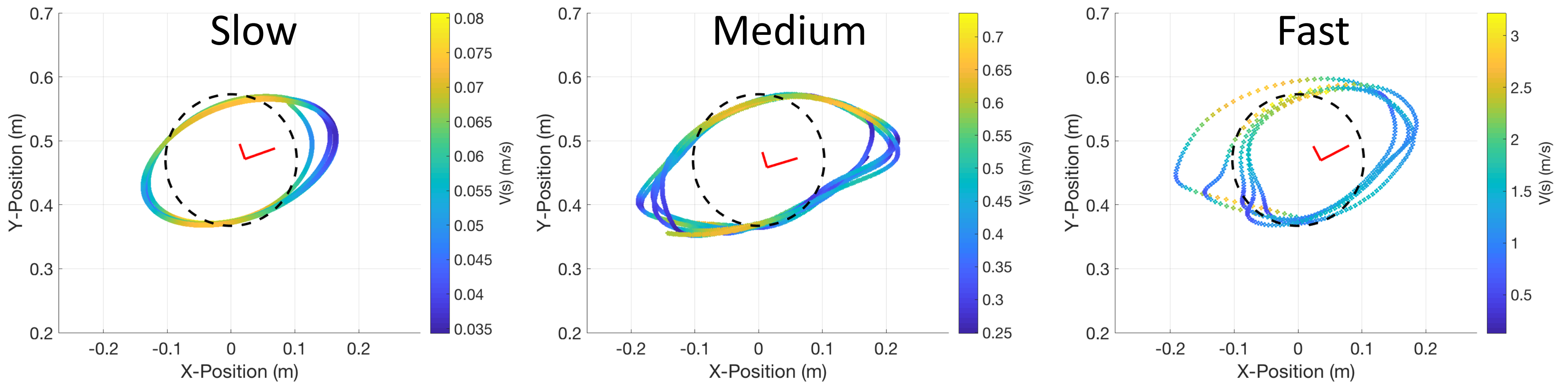


Figure 3: Representative trial from one subject in each of the speed and in the CCW direction conditions: zero-force trajectory (variable color line), path defined by the constraint (black dashed lines), and covariance major and minor axis direction (red lines).

Results (Continued)

- We computed the angular difference between corresponding curvature peaks and velocity valleys normalized by period.
- The 95% confidence interval was less than 3% from zero

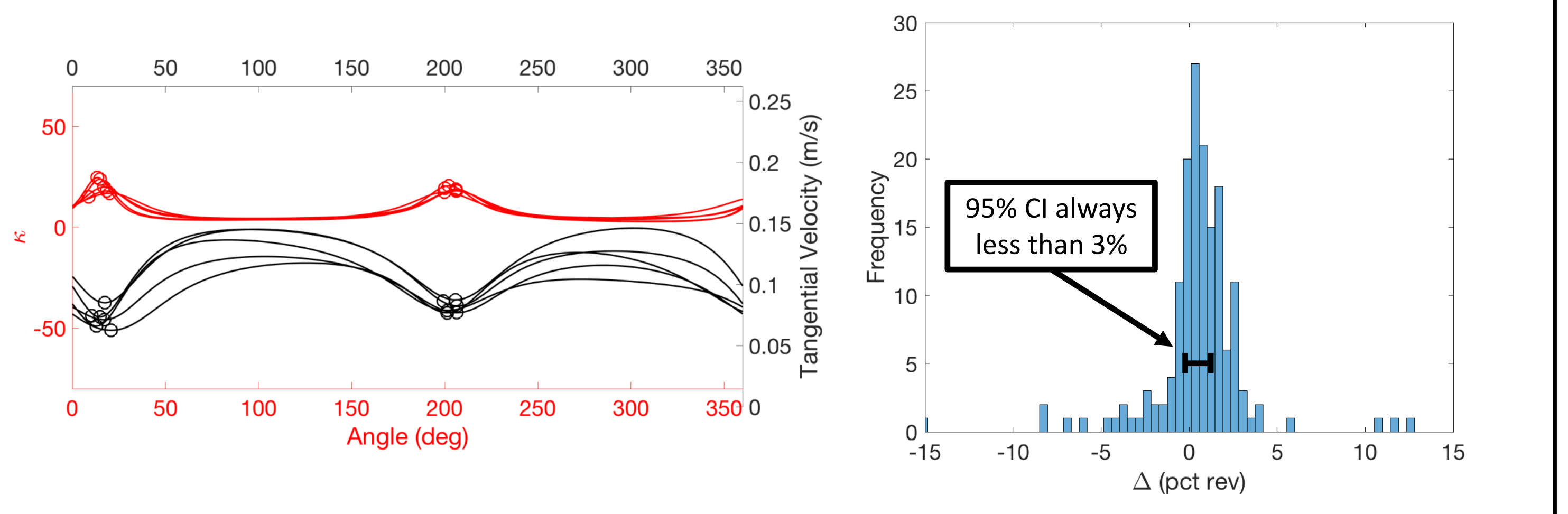


Figure 4: Speed and curvature of zero-force trajectory for a single trial, and histograms of the angular difference between corresponding extrema for all trials performed by one subject in the slow speed condition in the CW direction.

- Was this an artifact of the assumed impedance?
  - The result is robust to changes in the impedance. The 95% confidence interval was less than 4% even when the stiffness and damping gains were varied over a 3:1 range.

Conclusions

- A temporal coincidence of speed and curvature extrema has been observed in unconstrained reaching motions. This coincidence is believed to arise, at least in part, from the neural control architecture.
- In our study, subjects were instructed to move with a constant speed while the mechanical constraint confined their hand path to a circle (constant curvature) which therefore implied no incentive to vary speed. However, hand tangential speed was not constant.
- Unlike the actual hand path, the zero-force trajectory was not confined to a constant-curvature (circular) path. Strikingly, the curvature and tangential speed of the zero-force trajectory exhibited a coincidence of extrema. The angular difference between corresponding extrema often slightly led or lagged zero but, remarkably, all 95% confidence intervals were always less than 3% of a revolution from zero.
- These findings strongly indicate that neural commands contribute to the coincidence of speed and curvature extrema. In fact, this observation is consistent with maximizing smoothness, and therefore predictability, which facilitates feedforward control.

References

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