# Dynamic Primitives Limit Human Force Regulation During Motion

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## MOTIVATION

Humans excel at physical interaction despite long feedback delays and low-bandwidth actuators. Yet little is known about how humans manage physical interaction. A quantitative understanding of how they do is critical for designing machines that can safely and effectively interact with humans, e.g. amputation prostheses, assistive exoskeletons, therapeutic rehabilitation robots, and physical human-robot collaboration. Practically speaking, this understanding should be in the form of a mathematical model that competently describes human interaction control with minimal complexity.

A majority of the robotics and human motor control literature has successfully focused on regulating motion during free-reaching tasks. However, to understand physical interaction, information about force must be incorporated as well. If humans regulate motion during free reaching, a simple extension of this idea to contact tasks may be to regulate force during contact. In robotics, this is the basis of hybrid position/force control (Raibert and Craig 1981); in motor neuroscience, this idea is often implicitly assumed, e.g., in the description of internal models (Chib et al. 2009).

### *HYPOTHESIS*

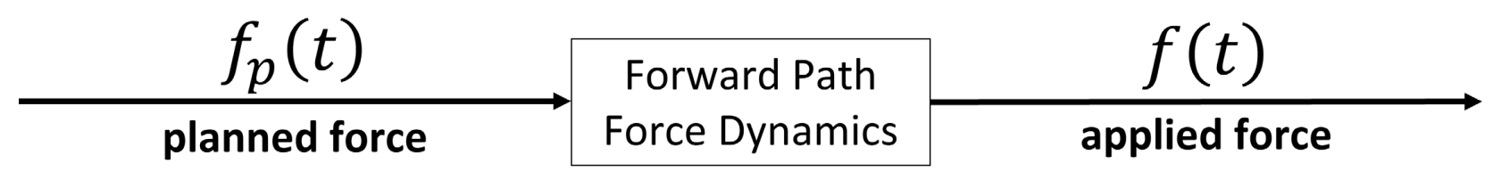
**This experiment tests the hypothesis that humans can directly regulate force independent of motion during physical interaction.**

## FORCE CONTROL

### *Direct Force Control*

*Formulation*

$f(t) = f_p(t)$

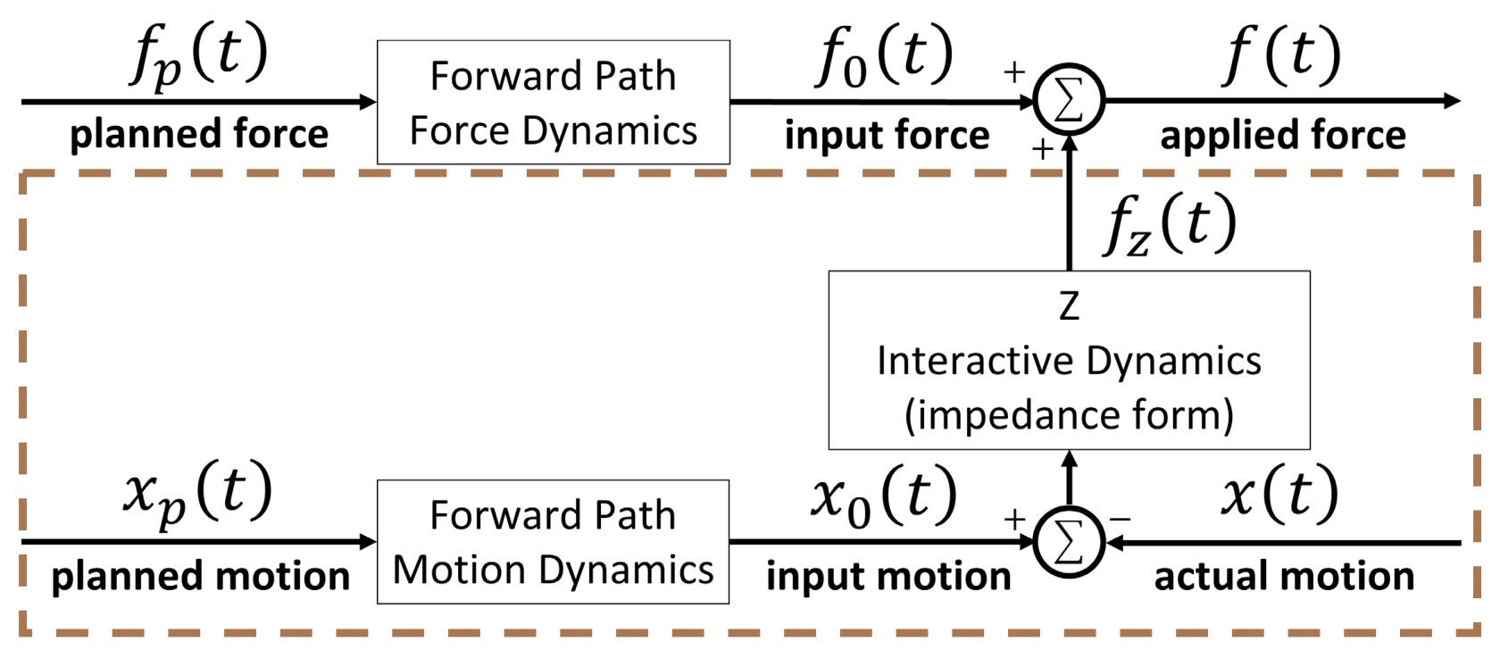


**Errors in contact force will be independent of motion.**

### *Indirect Force Control*

*Formulation*

$f(t) = Z\{x_0(t) - x(t)\} + f_0(t)$



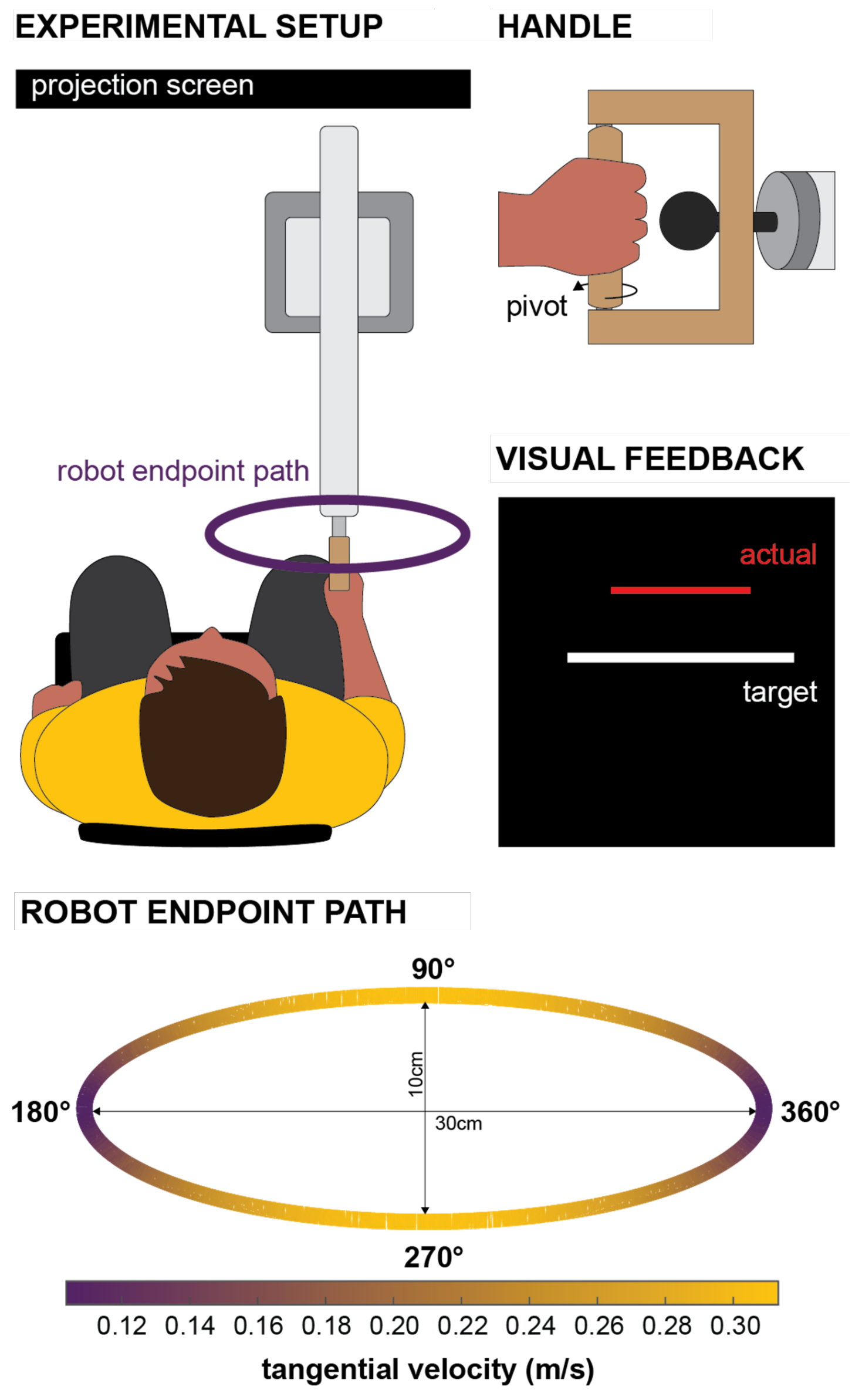
**Direct force control can be achieved if:**

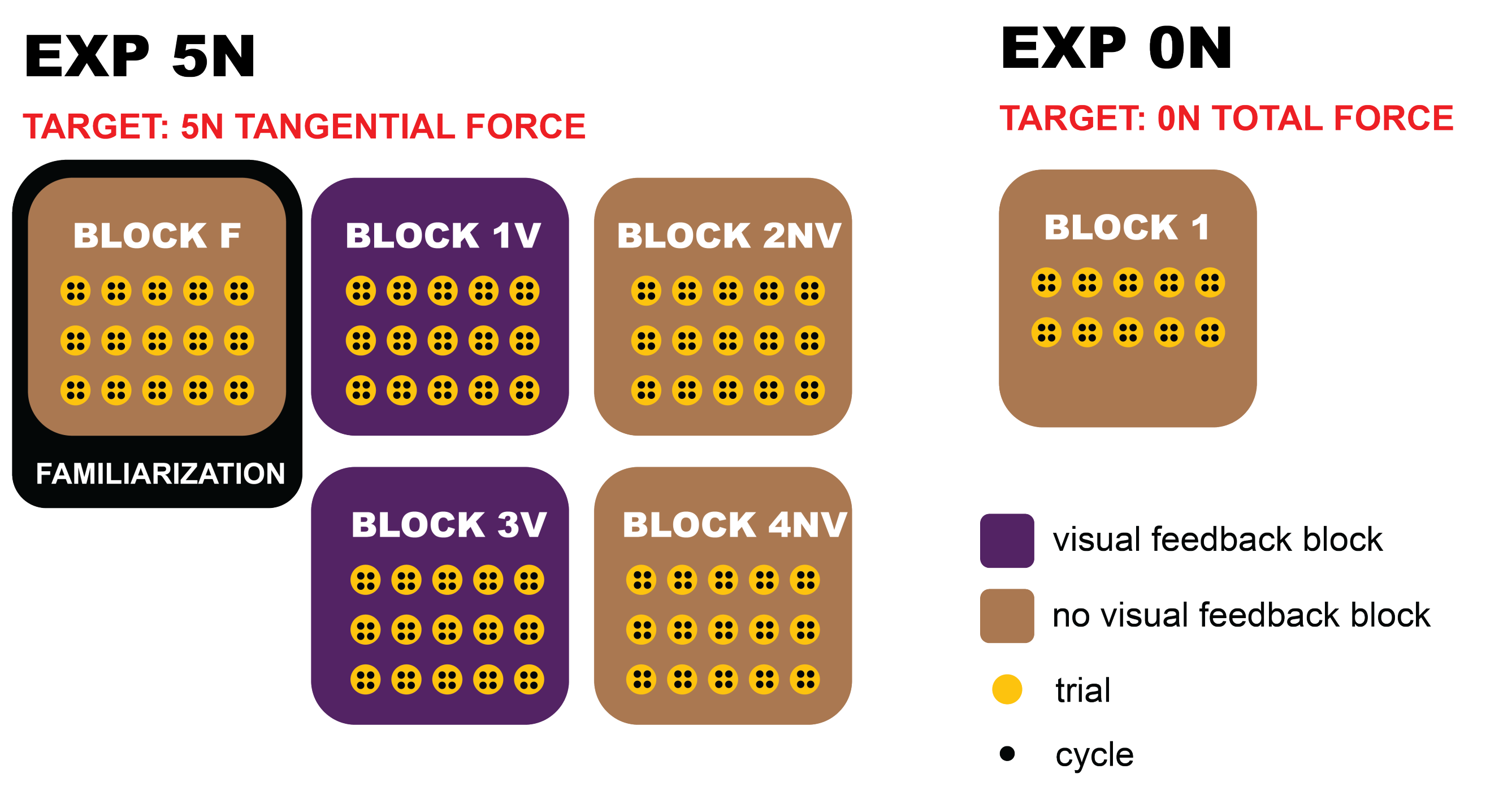
$Z\{\cdot\} \equiv 0$ or $x_0(t) - x(t) = 0$

**Otherwise, errors in motion control will affect force control.**

$f_p(t)$ planned force
$f_0(t)$ input force
$f(t)$ applied force
$x_p(t)$ planned motion
$x_0(t)$ input motion
$x(t)$ applied motion
$Z\{\cdot\}$ impedance mapping

## METHODS



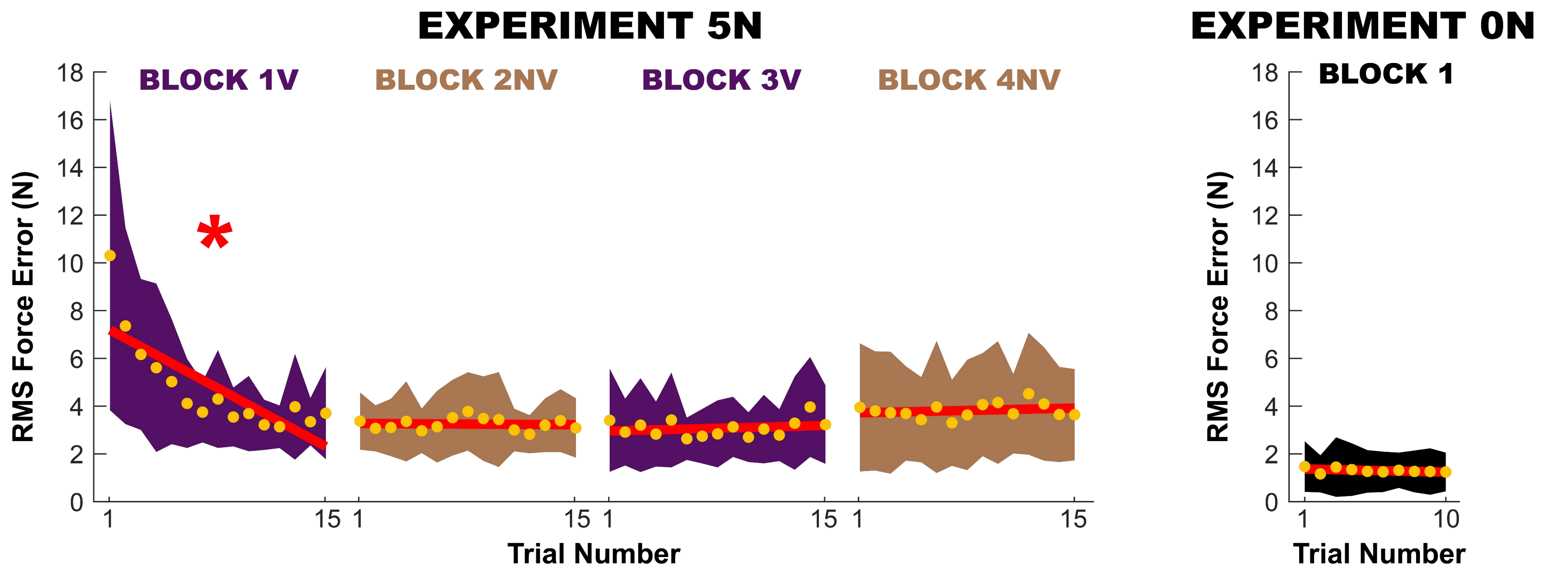


Subjects were instructed to apply either 5N tangential force (Experiment 5N, N=11) or 0N total force (Experiment 0N, N=6; from Maurice et al. 2018) on the robot handle, in its direction of motion.

To expedite learning, the robot handle moved along an elliptical path following the 2/3rd power law and visual feedback was added in some blocks in Experiment 5N.

## RESULTS

### *LIMITED IMPROVEMENT IN FORCE ERROR OVER PRACTICE*

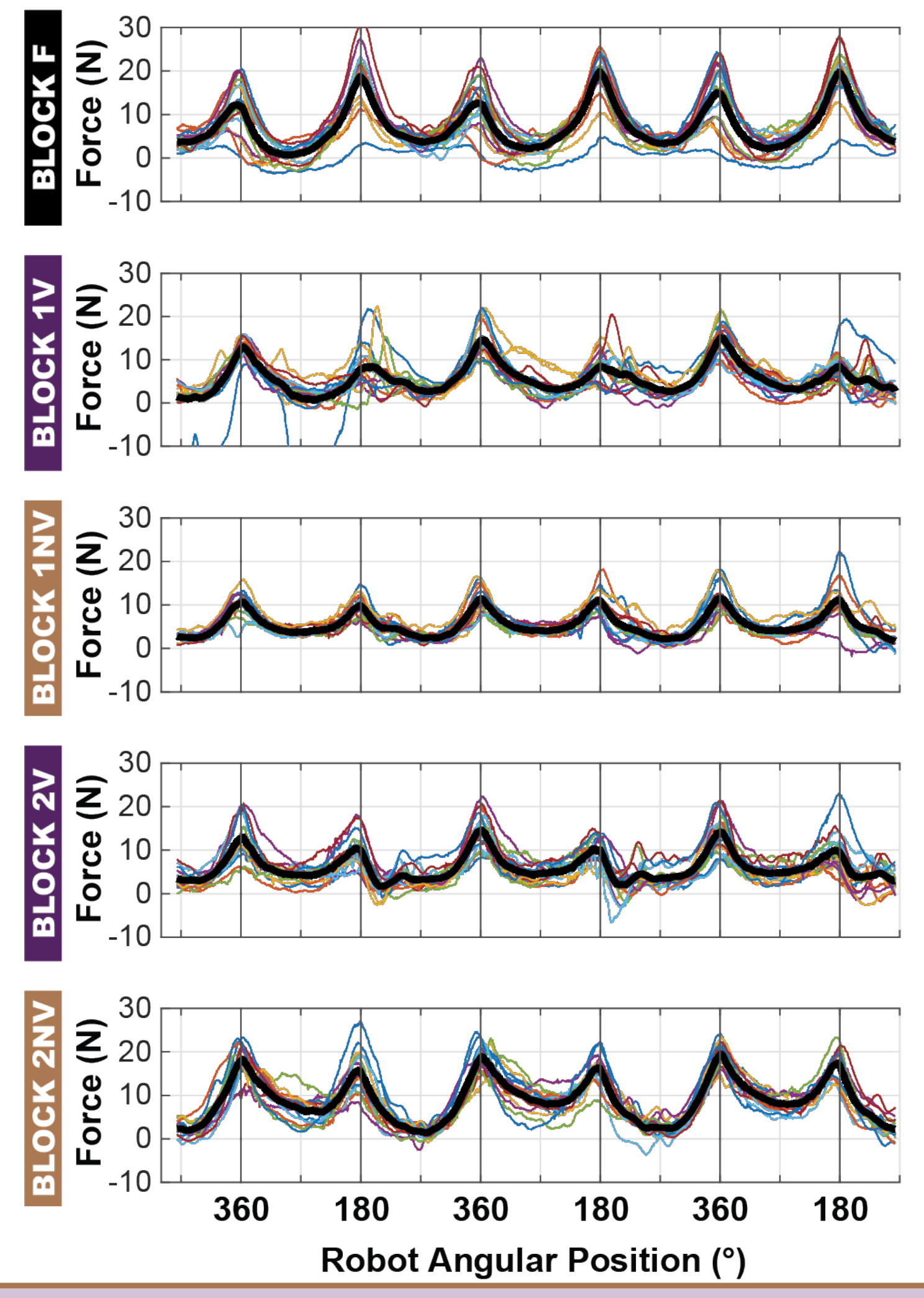


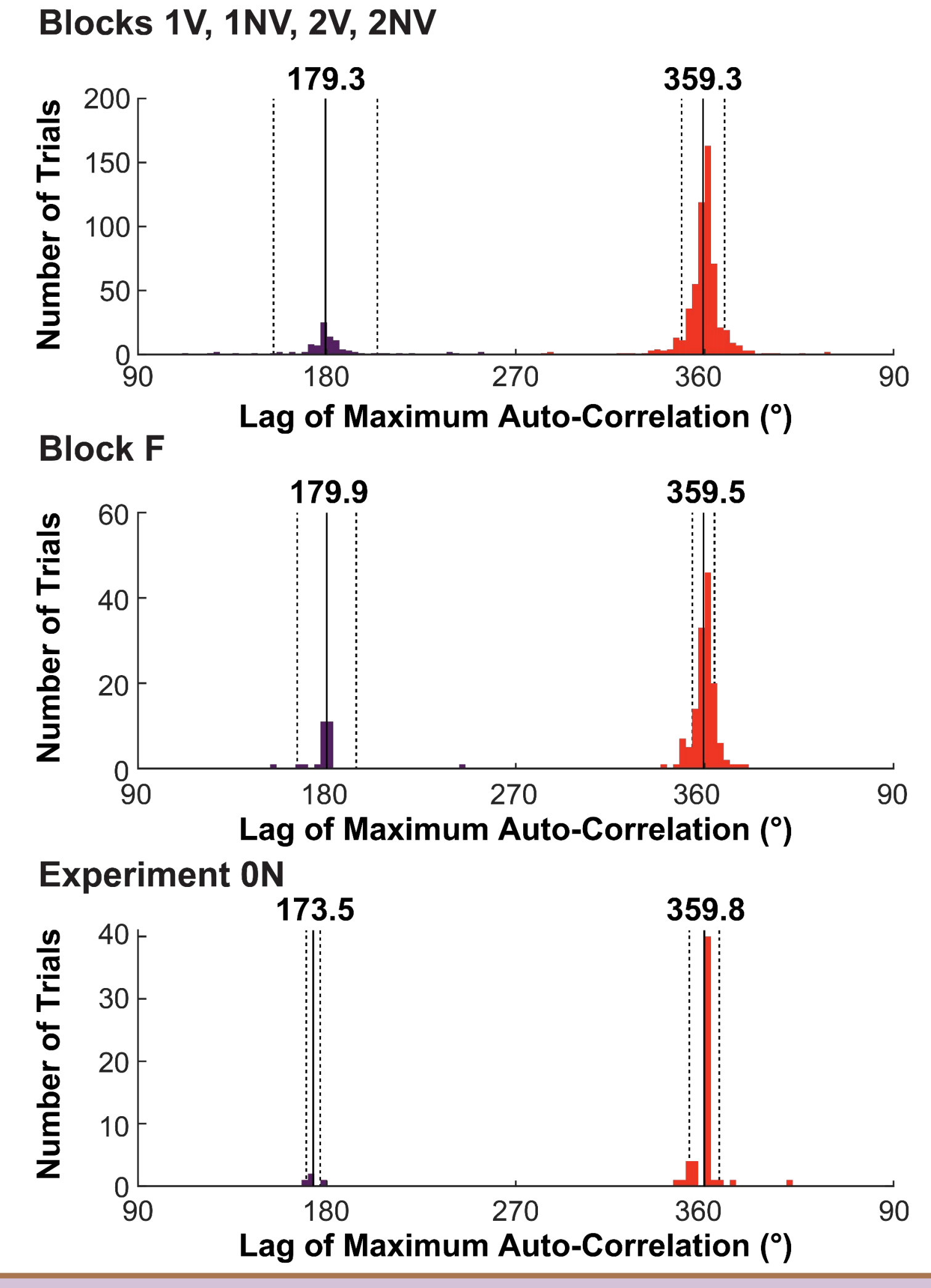
**Key Results:**

- Performance only improved in the first block. It remained constant in the remaining blocks, even with visual feedback.
- Performance was better in Experiment 0N compared to Experiment 5N.

## RESULTS

### *FORCE ERROR IS MOTION-DEPENDENT AND PERSISTENT*





**Key Results:**

- Peaks in the autocorrelation function around 180° and 360° lag indicate that force is motion-dependent.
- This observation was robust across both experiments and all subjects.
- Motion-dependent force presented spontaneously during task familiarization (Block F) and persisted during practice.

**Dynamic Primitives:**

- An internal model might be used to compute both $f_0(t)$ and $x_0(t)$.
- The periodic force errors seen here suggest that the controller appears to be content with "good-enough" performance, which can be obtained using a limited set of "primitive" oscillations and a sufficiently low mechanical impedance (Hogan 2012).

## CONCLUSIONS

- Despite extensive practice, both with and without visual feedback, subjects could not accurately apply a constant force during motion.
- Errors in force control were motion dependent. This suggests a coupling between motion and force, which is not described by direct force control. However, this coupling is accounted for in the indirect force controller, which contains an impedance term.
- The periodic pattern of motion-dependent force errors is consistent with planned motion composed of oscillatory primitives.
- These findings suggest that a simple mathematical model combining dynamic motion primitives with mechanical impedance, as an additional primitive, is competent to describe how humans control physical interaction.
- This work is of particular concern in (1) human quantification of performance and (2) estimation of human intent.

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