CONTROL STRATEGIES FOR MANIPULATING MASS-SPRING OBJECTS

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INTRODUCTION

When planning and executing reaching movements, the CNS must account for the mechanical properties of the arm. It is believed that this is accomplished through the use of an internal model of arm dynamics that adapts when the physical properties of the arm are consistently altered, such as when making reaching movements in external force fields (Lackner and Dizio 1994; Shadmehr and Mussa-Ivaldi 1994) or when lifting rigid objects (Bock 1990). However, it is not known if model-based strategies are used to control dynamical systems outside the body; i.e. those that add new degrees-of-freedom (DOF) to the mechanical system being controlled (i.e. the arm). Examples of such tasks include carrying a cup of coffee, or controlling an external prosthesis.

To perform such tasks, humans could use knowledge of the object dynamics learned through their interactions. Alternatively, they might employ a less model-dependent strategy, such as slowing down or globally increasing arm stiffness to enforce a specific kinematic trajectory for the hand. We tested for evidence of these alternative hypotheses.

METHODS

Six young healthy subjects (3M & 3F; age = 30.7 ± 4.6 yrs) held the handle of a robotic manipulandum (Fig. 1A). Subjects made reaching movements (Fig. 1B) with their dominant arm while the robot produced forces that simulated a mass-on-a-spring (Fig. 1C) defined by the equation of motion:

$$\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -K/M & 0 \end{bmatrix} \cdot \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} + \begin{bmatrix} 0 \\ K/M \end{bmatrix} \cdot u \qquad (1)$$

where M = mass, K = stiffness, q_1 and q_2, were the y-position and y-velocity of the mass, respectively. The control input u was the y-position of the handle (Fig. 1C). Subjects performed 600 trials and were instructed to bring both their hand and the mass to rest ($dy/dt \leq 0.02$ m/s) within the target zone within 0.8 ± 0.2s. Trials exceeding 2.5s were terminated automatically.

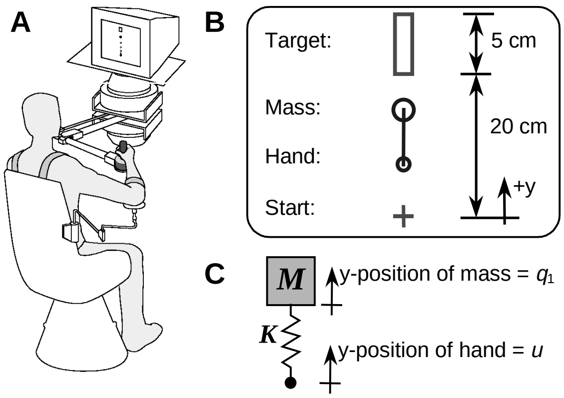

Fig. 1: A: 2-DOF robotic manipulandum. B: 1D reaching task. C: Mass-spring object.

Subjects learned to perform the task with an object of M = 3 kg and K = 120 Nm^{-1}. Exponential fits to movement time data were used to quantify learning rates ($T = a \cdot e^{bN} + c$ where T = Movement time & N = Trial #). If subjects simply slowed down until the mass-spring object effectively behaved like a simple mass, no learning would be observed.

The object's dynamics depended only on K/M (Eq. 1). Thus, all objects with the same K/M will exhibit the same output ([q_1, q_2]) for the same input (u). If subjects enforced a pre-defined u, by implementing a high-stiffness position controller, unexpectedly replacing the learned object with an object having the same K/M should not significantly affect task performance.

The last 120 trials included 12 "catch trials" where the K/M = (120 Nm^{-1} / 3 kg) object was unexpectedly replaced with either a K/M

= (40 Nm^{-1} / 1 kg) object (n = 6) or a K/M = (200 Nm^{-1} / 5 kg) object (n = 6). Deviations in catch trial kinematics from post-learning trials were evaluated to estimate the impedance at the hand-object interface. Movement times for all conditions were also analyzed using a one-way repeated measures ANOVA with Tukey's 95% confidence intervals.

RESULTS

All subjects significantly improved their movement times with practice (Fig. 2A/B). Thus, subjects acquired the capacity to predictively control object dynamics. They did not simply slow down to avoid perturbations imposed by the object. Subjects also showed dramatic improvements in movement kinematics between initial exposure ("IE3") and post-adaptation ("PA3") trials (Fig. 2C/D).

All subjects exhibited substantial kinematic deviations when exposed to both the 1 kg (CT1) and 5 kg (CT5) catch trial objects, compared to 95% confidence intervals (CI) of post-adaptation (PA3) kinematics (Fig. 2E). Differences in total movement times between all conditions (Fig. 2B) were highly significant ($p \leq 0.001$), except that the 1kg catch trials (CT1) did not differ from the initial exposure (IE3) trials ($p = 0.207$).

DISCUSSION

Subjects in the present study adopted neither of the model-independent control strategies hypothesized. Increasing hand stiffness would increase resistance to larger perturbations. The 5 kg object generated larger interface forces relative to the learned 3 kg object, whereas the 1 kg object generated smaller interface forces. The large deviations exhibited, particularly in the CT1 trials, are inconsistent with high hand stiffness. Hand stiffnesses of the order of 1000N/m (within the known physiological range) would have been sufficient to suppress all but minimal perturbations to hand movements during the catch trials. Rather, these catch trial deviations (Fig. 2E) suggest a control strategy where subjects attempted to apply forces matched to those required for the 3 kg learned object (Fig. 2D). Thus, subjects exhibited behavior that was consistent with computing the force applied to the object based on a planned object movement (i.e. with the formation of an inverse model of object dynamics). These results have implications for motor learning and rehabilitation.

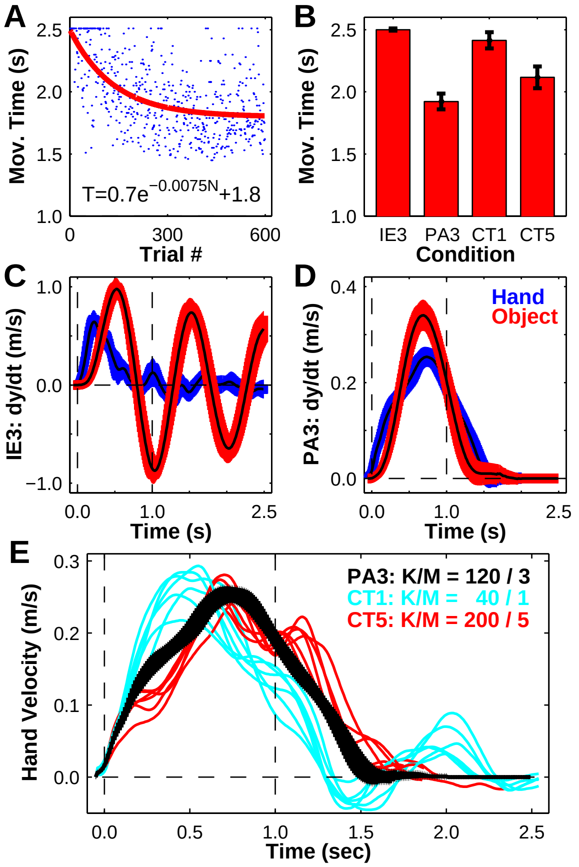

Fig. 2: Total movement times for (A) a typical subject and (B) all subjects and conditions. Velocity profiles for subject in A during initial exposure (IE3) trials (C) and post-adaptation (PA3) trials (D). Individual catch trial kinematics for subject in A for 1kg (CT1) and 5kg (CT5) objects vs. 95% CI for PA3 trials (E).

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REFERENCES

Bock O (1990). *Behav. Brain Res.* **41**: 167-177.
Lackner JR and Dizio P (1994). *J. Neurophysiol.* **72**(1): 299-313.
Shadmehr R and Mussa-Ivaldi FA (1994). *J. Neurosci.* **14**(5): 3208-3224.