Investigation of motor adaptation to movement versus object parameters.

Felix Huang, R. Brent Gillespie, Arthur D. Kuo

***Abstract*— In this study healthy human subjects (n=10) manually controlled a rotary handle to track a sinusoidally moving target as displayed on a computer screen. During movement, either the apparent handle inertia or tracking frequency changed to a higher or lower value. We analyzed the initial performance recovery following task perturbation using a linear fit of the velocity tracking error trends. For both types of task perturbations, we found significant increases in the intercept of the line fit (paired t-tests, two-tailed: $p<.05$) compared to trials with no change. We also found that adaptation rates indicated by the slope of the line fit of the tracking velocity error were larger for frequency changes than for apparent changes of the inertia for parameter increases ($p=0.029$, paired t-tests, one-tailed) and parameter decreases ($p=0.055$, paired t-tests, one-tailed). Our results provide evidence that humans use low impedance control that is task-specific to object parameters such as inertia. In addition, the results provide evidence that the adaptation to motion parameter changes and object parameter changes are different control processes.**

***Index Terms*— internal model, upper extremity, manual control, motor control, motor adaptation.**

I. INTRODUCTION

Successful control of arm movement during the manipulation of external objects requires not only kinematic planning of joint and object trajectories but also a means for coping with interaction forces that arise during motion[1]. The use of high impedance may be required to accommodate unexpected or random force interactions while attempting to perform the desired motion[2]. However, in predictable environments, low impedance control with the appropriate muscle activation might allow the motor system to achieve performance comparable to high impedance control but with less energetic costs.

Low impedance control could imply the presence of a control strategy specifically adapted to a task. Research on planar arm movements using a motorized manipulator has demonstrated learned task-specific adaptation to destabilizing force fields [3]. Other studies have uncovered evidence that humans use task-specific strategies in the positioning of external objects such as a virtual spring-mass or an inverted pendulum [4],[5]. Internal representations within the motor control system have been proposed for how humans control movement in predictable environments[6]. Such low impedance control would achieve performance goals efficiently by applying only the necessary muscle activation.

When the human motor system is required to cope with changing conditions, one possible adaptation scheme is to incorporate only the necessary component changes to control. If the desired motion remains fixed while the object properties changes, the motor system may transfer the associated arm and object kinematics to the new conditions. Similarly, if the object properties remain fixed while the desired motion changes, task-specific strategies associated with the object may still be useful for control. However, changes to the properties of the arm or manipulated object might require the human to perform interactive probing in order to develop an internal representation appropriate for control.

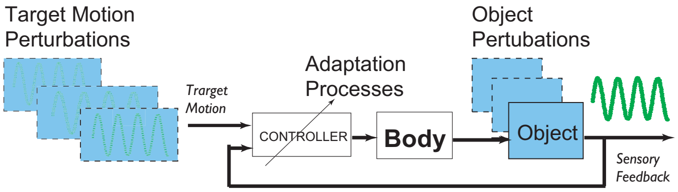

Fig. 1. We examine motor adaptation responses to perturbations in either the target motion or in the object properties. Updating the controller to cope with changes an the object could require a different adaptive mechanism than changes in the motion plan.

The current study examines differences in motor responses to changes in movement parameters versus changes in the object parameters, as shown in Figure 1). We chose a manual task in which interaction with an external inertia gives rise to forces between the arm and an environment. Study of how humans response to changes in conditions for this task may reveal behavior typical of human interaction with everyday objects. We hypothesize that the motor system will adapt to changes in object properties in a process distinct from changes in motion planning.

II. METHODS

In this study we investigate motor adaptation during control of a virtual object presented through a programmable manual interface. The goal of the motor task in this experiment was to control the motion of a rotary handle in order to follow a sinusoidally moving target as viewed on a computer screen. Our experiment compared the adaptation response to sudden changes in conditions during a manual tracking task. We explain in the following sections the development of a virtual environment that allowed for the perception of changing apparent inertia of the handle. We also describe the experiment protocol and metrics used to gauge the success in the tracking task.

A. Development of virtual inertia interaction environment

1) Analysis of Virtual Object Dynamics: Consider the linear system in Figure 2 consisting of an inertia whose

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displacement $\theta_I(t)$ is driven by the displacement $\theta_h(t)$ of a handle, driven in turn by the user's hand. We use I, B and k as the parameters of the inertia, damper, and spring system and consider the handle massless. Proper selection of spring stiffness and damping properties allows a close approximation of a direct interaction with an inertia operating at sufficiently low driving frequencies. The equations governing $\theta_I(t)$ and the interaction torque $\tau(t)$ are:

$$\ddot{\theta}_I(t) + 2\zeta\omega_n(\dot{\theta}_I(t) - \dot{\theta}_h(t)) + \omega_n^2(\theta_I(t) - \theta_h(t)) = 0 \quad (1)$$

$$\tau(t) = -B(\dot{\theta}_h(t) - \dot{\theta}_I(t)) - k(\theta_I(t) - \theta_h(t)) \quad (2)$$

where $\zeta = 2B/I$ and $\omega_n = \sqrt{k/I}$. Using the Laplace variable $s = \sigma + j\omega$ and $j = \sqrt{-1}$, it can be shown that the transfer function G(s) describing the handle motion in response to force interaction is:

$$G(s) = \frac{s^2 + 2\zeta\omega_n s + \omega_n^2}{2\zeta\omega_n(s + \omega_n/2\zeta)} \cdot \frac{1}{Is^2} \approx \frac{1}{Is^2}, \omega \ll \omega_n \quad (3)$$

Note from Equation (3) that if the driving frequency ω is much less than the natural frequency of the spring and inertia system, the effective dynamics of Equation (2) then describes the behavior of a simple rotary inertia, where $\theta_h(t) \approx \theta_I(t)$. The spring constant and damping constant are fixed (k=0.24 N-m/rad, B=0.015) for all conditions for the current study.

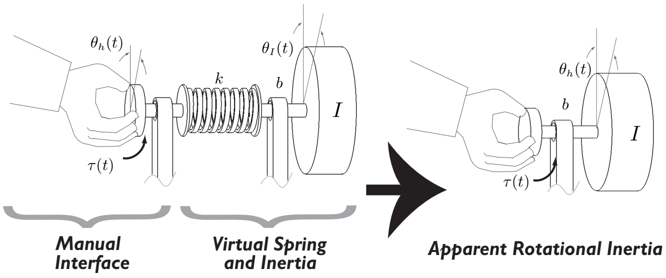

Fig. 2. A virtual mass stiffly coupled to a handle is used to simulate the effects of an interaction with a simple rotational inertia.

2) Selection of Task Parameter Changes: We chose changes in the inertia parameter and the tracking frequency that resulted in the same change in steady state RMS power during sinusoidal motion. Assuming $\theta_I(t) \approx \theta_h(t)$, and perfect tracking of sinusoidal motion, with amplitude A, frequency ω, and inertia I, then $\tau(t) = I\ddot{\theta}_h(t) = -IA\omega^2 sin(\omega t)$ and the mechanical power is:

$$P(t) = \tau(t)\dot{\theta}_h(t) = (-IA\omega^2 sin(\omega t)) \cdot (A\omega cos(\omega t)) \quad (4)$$

The power input expressed as $P(t)_{rms} \propto I\omega^3$, exhibits a proportional relationship to the inertia I or the cube of driving frequency ω. The equations above can then be used as a guide to set the parameter values of either inertia or frequency change. For example, a 50% power reduction implies either a 50% drop in I, or a $0.5^{1/3}$ change in the driving frequency ω. Note these results dictate the mechanical work required as opposed to the actual metabolic cost incurred. Other methods to balance the perturbations may be possible, such as equal change in terms of JND (just noticeable difference) in parameters or equal changes in peak interaction torque. This method of choosing the parameter magnitudes, however, addresses the null hypothesis that any differences in performance between tasks perturbation type are due to differences in required work.

3) Description of Apparatus: We designed and constructed a manual interface with a motorized handle that rotates about a horizontal axis. Using one hand, a human operator can grasp and turn a T-shaped handle comfortably with pronation/supination movements of the forearm. Using our apparatus, we created a virtual representation of a spring-inertia system that could be manipulated by an operator. We implemented a real-time simulation of the dynamic behavior including haptic display as expressed in our model of the system in Equation (2). Data were logged at 100 Hz.

B. Experiment Protocol

1) Human Subjects: Ten participants (9 male, 1 female) volunteered for the study. All reported having normal/corrected-to-normal vision. Each provided informed consent in accordance with University of Michigan human subject protection policies. Individuals were not paid for their participation. Participants were asked to use their dominant hand (all reported being right-handed) to operate the apparatus.

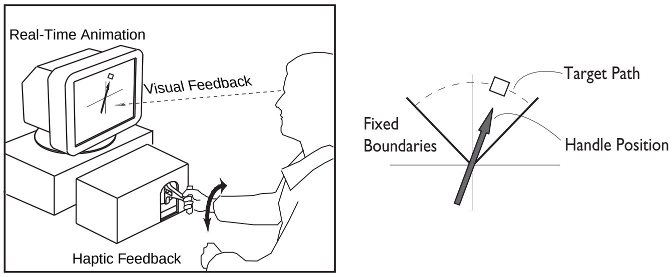

Fig. 3. Experiment participants use a rotary handle to track the motion of a square target moving between two markers (fixed at ± 45 degrees) as displayed on a screen. Haptic feedback presented through the handle simulated interaction with a rotary inertia.

2) Description of Manual Task: As depicted in Figure 3, subjects grasped a motorized handle and performed arm pronation and supination. Participants were instructed to control the handle in order to follow a sinusoidally moving target as accurately and smoothly as possible. Visual feedback was provided of the handle, pictured as an arrow pivoted about its center, and moving target, pictured as a square moving on an arc outside the radius (3.5 cm) of the arrow. Subjects performed the task while seated (50 cm from the screen) and were given instructions on arm and hand posture.

The interface provided haptic feedback appropriate to the manipulation of a specified inertia. During each 30 second trial, the target oscillated between fixed markers 45 degrees apart (centered about the vertical) at either a low frequency

(ω_1 =4.50 rad/s) or a high frequency (ω_2 =5.l5 rad/s). Also during each trial, the apparent inertia of the handle was either set at a low value I_1=0.012 $\mathrm{kg} \cdot \mathrm{m}^2$ or a high value I_2 =0.0179 $\mathrm{kg} \cdot \mathrm{m}^2$. In the experiment, the four unique parameter combinations of target frequency and apparent handle inertia were given according to a random schedule so that all 16 transitions were represented. There were a total of 34 trials (2 replicates of 17). The computer determined the appropriate parameter changes, and controlled the precise starting time of each trial so that they occurred at velocity or torque zero-crossings. Trials were presented without breaks for the total session duration (8.5 min). Subjects reported no physical fatigue from this protocol. In this report we discuss only the transitions to two conditions: a low parameter setting (I_1, ω_1), and a high setting (I_2, ω_2).

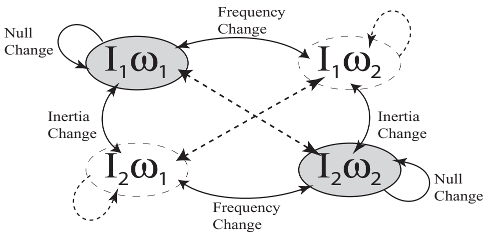

Fig. 4. Each trial presented conditions with particular parameters: a tracking frequency (ω_1 or ω_2) and an apparent inertia (I_1 or I_2). We compare the effects of either tracking frequency or inertia changes, by examining performance for trials with the same parameter settings (solid grey ellipses) but from different prior conditions (dashed ellipses).

C. Tracking Error Performance Analysis

In order to compare performance in tracking for the various experiment conditions, we examined the velocity error between the handle and the target velocities. In our analysis of the recorded movement data we found more gradual changes in RMS of velocity error compared to position error. We make the assumption that these gradual changes are a better reflection of any changes requiring learning or motor adaptation. We calculated the RMS velocity error, using a 1 second moving window for each 30 second trial, and then normalized the results by the mean trial value. We characterized the adaptation in response to a change of trial conditions by performing a linear fit of the first five seconds of the RMS velocity error trends. We present the results of linear fit parameters for: $E_{RMS}(t) = mt + b$, where m is the line slope, b is the line intercept, and t is the trial time in seconds. The subject averaged trends, grouped by transition type, were then analyzed.

We first perform an analysis of variance, considering p<.05 a the threshold level for significance. Using the line fit values as the outcome variables, we consider main effects and two-way interactions for transition types: (*Null Change*, *Inertia-Change*, *Frequency Change*); directionality: (*Parameter Increase*, *Parameter Decrease*), and trial replicate (1/2). In order to show that the initial responses to actual changes of task parameters (frequency or apparent inertia) were significant as compared to null transitions, we compare line fit value b between transition types, using a paired t-test (p<.05 significance level). In order to determine if the subsequent recovery behavior differs between the perturbation types we perform a paired t-test on the slope values m.

III. RESULTS

We found significant results from only the effects of transition type factor, from both the line intercept (p=0.026, and the line slope (p=0.040) two-way ANOVA results.

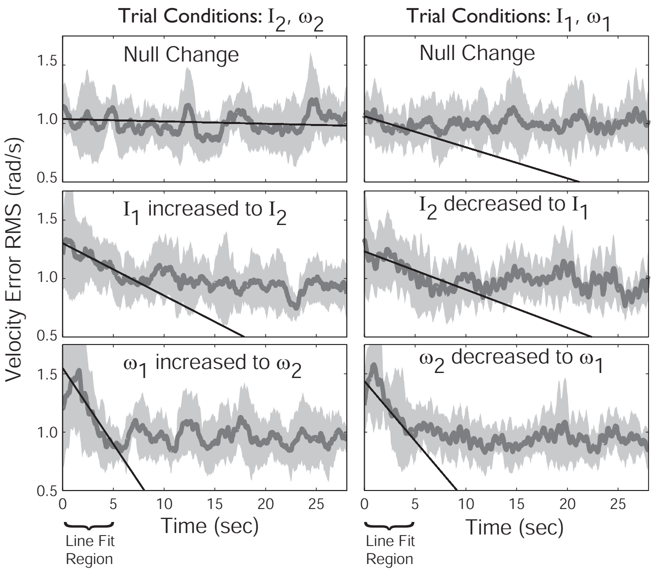

Fig. 5. Mean velocity error trends (1 sec moving RMS, normalized to trial mean), averaged across subjects (with ±1 SD) indicate increases in response to changes of both target frequency and apparent inertia. Initial performance (represented with linear fits for t=0-5 sec) indicates slower rates of adaptation for changes of apparent inertia.

As shown in Figure 5, the RMS of velocity error plots demonstrate initially larger error and gradual decrease over the 30 second trial for all cases with a change of condition. For increases in task parameters, velocity error linear fits indicate significantly larger values for the line intercept b for changes of both target frequency (49.3%, p=.0117, paired t-tests, two-tailed) and apparent inertia (25.5%, p=.0415, paired t-tests, two-tailed) compared to the null change. For decreases in task parameters, linear fits also indicate significantly larger values of b for changes of target frequency (16.0%, p=.0385, paired t-tests, two-tailed) and apparent inertia (35.4%, p=.0904, paired t-tests, two-tailed).

The rates of velocity error change indicated by the linear fit value m were typically negative, indicating reduction of error over time. As summarized in Table-I, for increases in task parameters, the rate value m was on average 65.6% smaller for changes of apparent inertia (p=0.029, paired t-tests, one-tailed) compared to target frequency. For decreases in the task parameters, m was on average 68.1% smaller for changes of apparent inertia (p=0.055, paired t-tests, one-tailed).

Pooling the results for both decreases and increases in task parameters, as shown in Figure 6 with first and second subject wide quartiles, line intercepts *b* for both target frequency (p=.007, paired t-test, two-tailed) and apparent inertia (p=.0362, paired t-test, two-tailed) are significantly larger than for the null change. We also find 9.1% smaller values of *b* for changes in apparent inertia versus target frequency (p=0.021, paired t-tests, one-tailed). Changes of inertia show 91.5% smaller values of *m* compared to change of target frequency (p=0.032, paired t-tests, one-tailed).

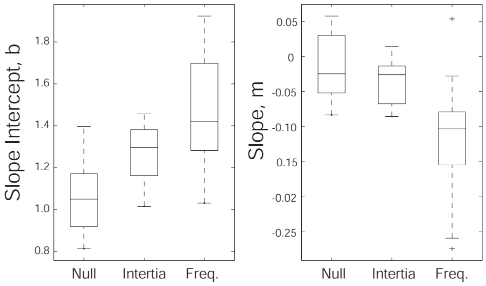

Fig. 6. Mean line fit parameters of initial adaptation velocity error RMS (t=0-5 sec) averaged across subjects are shown with median and upper and lower quartiles. Line intercepts, *b* for both target frequency (p=.007, paired t-test, two-tailed) and apparent inertia (p=.0362, paired t-test, two-tailed) are significantly larger than for the null change. Line slopes, *m* indicate fastest recovery rate for changes of target frequency compared to apparent inertia (p=.032, paired t-test, one-tailed).

IV. DISCUSSION

Analysis of the initial error responses to parameter changes provided evidence that humans employed task-specific control in the sinusoidal tracking task presented in this experiment. The trends of RMS error between the target and handle velocities indicated significant perturbations occurring for changes of both the tracking frequency or apparent inertia. Discrepancies between the perceived and actual target frequencies would expectedly result in movement error. However, for cases where the target movement has not changed, the resulting increased error must have been the result of muscle activation inappropriate to the task. A high impedance control strategy would be able reject disturbances for a range of force magnitudes. Such a scheme, however, would not explain the greater error in response to both increases and decreases in inertia. We infer that the initial error responses observed were due to a low impedance control strategy that was incompatible with changes of the inertia.

The rate of recovery following a parameter change could indicate the difficulty of adjustment. Rapid performance recovery in response to a change of tracking frequency could indicate that the operator needed a shorter time to load a motor program. Alternatively, this may show that the existing motor program is readily adaptable to the new conditions. One possibility is that an internal representation of the inertia is in use. Such a dynamic model of inertia could explain intrinsic flexibility to quickly adapt to different kinematics.

Transition Type	Parameter Increase	Parameter Decrease
Null	b=1.00 ± 0.27 m=-0.002 ± 0.075	b=1.06 ± 0.25 m=-0.027 ± 0.081
Inertia	b=1.30 ± 0.21* m=-0.045 ± 0.087**	b=1.23 ± 0.21 m=-0.033 ± 0.072**
Frequency	b=1.50 ± 0.37* m=-0.13 ± 0.11**	b=1.44 ± 0.40* m=-0.10 ± 0.11**

TABLE I. Linear fit parameters (paired t-tests: *two-tailed significant differences compared to null, **one-tailed significant differences between frequency and inertia.

The reason for a longer period of adjustment in reaction to a change of inertia may be that the appropriate low impedance strategy is not yet available. A system identification process may be necessary to obtain the new inertia model before good performance can be achieved. Perceptual-motor coordination may be necessary for adjusting to the novel object conditions. Note from Figure 5 (right), the slope for the null change is comparable to the case for a decrease inertia, suggesting possible continued adaptation even through constant task conditions. Probing the object and observing its responses in an interactive manner over an extended period may be the way that the motor system obtains information about the actual properties.

The results from this study suggest that the human motor system uses task-specific strategies during the manipulation of inertia in a simple sinusoidal tracking task. Given such a motor task with predictable force interactions, the human motor system may employ a simple control strategy to take advantage of lower energetic costs. A low impedance control scheme adapted specifically to object properties such as inertia could account for the trends observed in this study. These results also support the conclusion that different motor adaptation processes take place in response to changes in movement versus changes in object parameters.

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