Human Control of Dynamically Complex Objects

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Abstract— **Humans interact with a variety of objects, many of which have dynamically complex properties, such as a cup of coffee. An efficient way to manipulate such objects is to drive them at a resonant frequency. This requires less effort due to dynamic amplification of control inputs. However, errors in control may also be amplified, increasing variability and making it difficult to achieve a kinematic goal. How humans control dynamically complex objects near a resonant frequency, while at the same time achieving kinematic goals, is unknown. To address this question, ten healthy subjects were asked to practice oscillating a cart and pendulum (simulated using a haptic display). Subjects had to move the cart between two spatial targets at the pendulum's resonant frequency. A visual display showed the pendulum bob moving in a semicircular cup (the cart was hidden), mimicking a ball rolling in a cup. Results showed that in early practice subjects moved below the resonant frequency and used an in-phase strategy − the cup and ball moved in the same direction. This was associated with large applied forces and high variability. With practice subjects moved above the resonant frequency and switched to an anti-phase strategy − the cart and pendulum moved in opposite directions. Concurrently, subjects' applied force decreased by half and the interaction force of the ball on the cup increased, which moved the cup to the spatial targets. Using this strategy, subjects became less variable and more accurate. Although the switch in phasing was in part dictated by the task dynamics, the direction of the shift is best explained by a controller that seeks to exploit the dynamics of an object to achieve task goals with small outlays of energy and low variability.**

I. Introduction

In daily life humans interact with a wide array of different objects in the environment. These include objects that may be considered rigid, but also those with more complicated internal dynamics − a cup of coffee provides an instructive example. A key property of objects with internal degrees of freedom is their resonant frequencies, which can be identified by humans through manipulation [1, 2]. An advantage of exciting an object at its resonant frequency is that only small driving forces or torques are required because control inputs are dynamically amplified.

However, an undesired side-effect of operating near or at a resonant frequency is that the dynamic amplification may lead to large undesired outputs or at the very least, to high variability in task performance. Two prior studies examined humans manipulating mass-spring systems: one required subjects to achieve and maintain a steady state oscillation [1], the second required subjects to regulate the force that was applied to a mass-spring system [2]. In neither study was the position of the end-effector explicitly specified, which in many daily life tasks is of primary importance. For example, if you want to take a sip of coffee, you must position the cup accurately at your mouth. Such kinematic constraints pose a problem that the central nervous system must solve: how to control a dynamically complex object while at the same time achieve kinematic goals?

This study addressed this question by asking subjects to oscillate an object with pendular dynamics at one of the object's resonant frequencies. The object was simulated in a virtual environment with visual and haptic interfaces. The object's dynamics were based on a cart and pendulum model, but subjects saw the object as a semicircular cup with a ball inside, simulating a cup of coffee. Subjects were asked to rhythmically move the cup and ball between two spatial targets in synchrony with a metronome that sounded at the resonant frequency of the ball and cup. Subjects were not informed that the metronome frequency was the resonant frequency, and they received no specific instructions about the kinematic trajectory or the phasing between the ball and cup. Therefore, in principle, subjects could choose from many different strategies to satisfy the task goals.

We expected that when humans first performed the task, they would choose a strategy where they force the object to the spatial targets with large control efforts. However, these larger forces would not only lead to large undesired ball movements, but would also be associated with much higher variability due to the effects of signal-dependent noise in the nervous system [3]. With practice, we expected that subjects would discover an easier "guiding" strategy that required less force by exploiting the intrinsic dynamics of the object. The smaller forces would also reduce variability and improve accuracy.

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II. METHOD

A. Mechanical System

The mechanical system was a high-fidelity haptic simulation of a pendulum suspended from a cart (Fig. 1). The cart was restricted to one-dimensional motion along a frictionless surface.

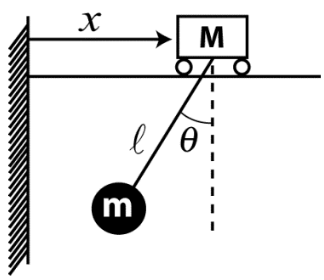

Fig. 1. Model of cart and pendulum system.

This cart and pendulum system has two degrees of freedom. The equations of motion were derived using the Lagrange method of mechanics; the first equation is

$$\left(m+M\right)\ddot{x}=F_A+F_B \quad (1)$$

and the second is

$$\ddot{\theta}=\frac{\ddot{x}}{\ell}\cos\theta-\frac{g}{\ell}\sin\theta \quad (2)$$

where M is the cart mass, m is the ball mass, $\theta,\dot{\theta}$, and $\ddot{\theta}$ are the ball angle, angular velocity, and angular acceleration, respectively, $\ddot{x}$ is the cart's horizontal acceleration, ℓ is the pendulum length, g is gravitational acceleration, F_A is an external horizontal force applied to the cart (by a human), and F_B is the reaction force of the ball on the cart, defined as

$$F_B=m\ell\ddot{\theta}\cos\theta-m\ell\dot{\theta}^2\sin\theta . \quad (3)$$

The parameters of the system were: ℓ = 0.25 m, M = 3.0 kg, m = 0.6 kg, g = 9.81 m/s^2. Under a small-angle approximation the natural frequency f_0 of the pendulum is

$$f_0=\left(2\pi\sqrt{\frac{\ell}{g}}\right)^{-1} \quad (4)$$

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Based on ℓ = 0.25 m and g = 9.81 m/s^2, the natural frequency is $f_0\approx 1.00Hz$. For larger pendulum angles (>10°) f_0 decreases with increasing amplitude of oscillation. To understand the input-output behavior of the system, the frequency response properties were determined using a linearized model of the cart and pendulum and a simplified biomechanical model of a human arm [4].

B. Participants

Ten young (21-35 yrs) healthy male and female adults participated in the study. Prior to participating, subjects were informed of all experimental procedures and read and signed an informed consent document approved by the Institutional Review Board at Northeastern University.

C. Experimental Configuration

Subjects manipulated the cart by applying forces to a robotic manipulandum (HapticMaster, Moog, The Netherlands; [5]). The manipulandum had a spherical knob, which was attached to the robotic arm by a thin aluminum shaft. Subjects grasped the spherical knob, with the connecting shaft positioned between the index and middle fingers. Subjects used their dominant arm; all subjects were right handed except for one who used the left arm.

D. Instrumentation

The HapticMaster has three controllable translational degrees of freedom; however, for the experiment it was constrained to medial-lateral motion in the horizontal plane. The robot used admittance control with dedicated haptic and graphic servers operating at 2500 Hz and 120 Hz, respectively. All graphic programming and computations related to the pendulum were performed on the graphic server via a custom C++ program. At each iteration, the graphic server queried the haptic server for the current robot arm kinematics and determined $\ddot{\theta}$ using Equation 2. The pendulum θ and $\dot{\theta}$ were computed using a fourth-order Runge-Kutta integrator, and the force of the pendulum bob on the cup F_B was computed by solving Equation 3. This force was sent to the haptic server, which computed the resulting medial-lateral acceleration of a virtual mass (m+M), such that

$$\ddot{x}=\frac{F_B+F_A}{m+M} . \quad (5)$$

The visual display was then updated and the robot motors moved the manipulandum according to $\ddot{x}$.

E. Visual Feedback

The visual interface was provided on a rear-projection screen positioned 2.4 m away from subjects. The cart and pendulum rod were hidden, but the pendulum bob (the ball) was visible (Fig. 2). A semicircular arc with an arc length of 180° and radius equal to L was drawn below the ball so the ball appeared to roll in the cup. The cup served as a visual reference to help in gauging the angle of the ball. The ball could not escape from the cup; if θ exceeded 180° the ball would continue swinging above the cup.

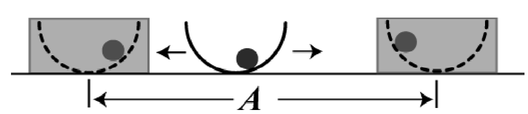

Fig. 2. Schematic of the visual display. The amplitude of cup oscillation A was specified by the distance between two green target boxes (A = 0.1 m)

Two target boxes were shown that specified the oscillation amplitude A, which was set to 0.1 m. This distance corresponded to the actual physical distance moved using the manipulandum; however, the distance on the rear-projection screen appeared 2.5 times larger, such that the on-screen distance between the targets was 0.25 m.

F. Instructions

Subjects were instructed to move the cup back and forth between the target boxes, reversing the direction of cup movement in synchrony with the beats of a metronome. The metronome frequency was set to 2 Hz so that two beats were provided for each cycle at the reversal points, providing an effective full-cycle frequency of 1 Hz. Together, these instructions specified the amplitude and frequency of the cup movement; no instructions were given as to the phasing between the ball and cup.

G. Protocol

Subjects practiced oscillating the cup and ball for 40 trials in one experimental session. Each trial lasted 45 s. A three minute-break was given after every 10 trials. At the start of each trial the cup was positioned in the center of the left target box and the ball was in the bottom of the cup with zero potential and kinetic energy. Once subjects moved the cup from the target box, the trial and metronome started.

H. Data Processing and Analysis

Only the last 30 s of each 45 s trial was analyzed to eliminate transients. All data processing, analysis, and statistical tests were performed in MATLAB®. The raw data were filtered with a zero-lag fourth-order low-pass Butterworth filter. Filter cut-off frequencies were determined by visual inspection of the frequency spectra obtained by fast Fourier transform. Position, velocity, and force/acceleration data were filtered with cut-off frequencies of 6, 8, and 10 Hz, respectively.

Subject performance was characterized by three parameters: 1) the frequency of cup oscillation f, 2) the amplitude of cup oscillation A, and 3) the relative phase between ball and cup φ. These variables are illustrated in Fig. 3. The amplitude A was defined as the distance between the minima and maxima of the cup's position. The cup's oscillation period T was defined as the time between two successive maxima of the cup position, with oscillation frequency $f = 1/T$. The relative phase φ between the ball and cup was computed as $360 \cdot t_B/T$, where t_B is the time from each cup position maximum and the subsequent ball position maximum, where $x_B = -L \sin(\theta)$. If the ball and cup moved in the same horizontal direction, their relative phase φ was defined as in-phase $\varphi = 0$ or 360°; movement in opposite directions was defined as anti-phase $\varphi = 180°$.

Criteria for inclusion in subsequent data analysis were that for at least three of the last five trials, subjects' had to fulfill the task goal, *i.e.* the mean f and A had to be within two standard deviations of the target f (1.0 Hz) and A (0.1 m). Two subjects failed to meet these criteria, and were therefore excluded from subsequent analysis.

One sample t-tests were used to determine if f and A were different from the goal at the end of practice, and to test whether φ was different from perfect anti-phase (φ =180°). For the latter test, circular statistics were used [6].

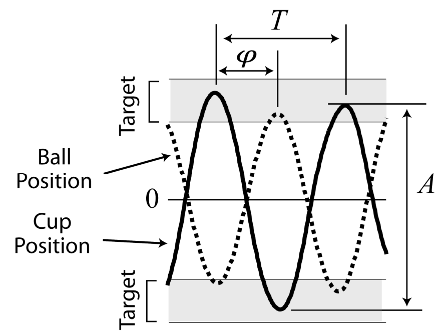

Fig. 3. Definition of the three performance variables: 1) period of oscillation T, 2) amplitude of oscillation A, and 3) relative phase φ between ball and cup. The ball position is defined relative to the cup.

III. Results

The continuous cup and ball kinematics are shown for a representative subject in Fig. 4. The subject began practice by oscillating the cup and ball close to in-phase ($\varphi \approx 0°$). Later in practice, the subject switched to an anti-phase ($\varphi \approx 180°$) pattern, upon which both ball and cup oscillation amplitude decreased and became more consistent. At the end of practice the average maximum angle of the ball across subjects was 56°± 3°.

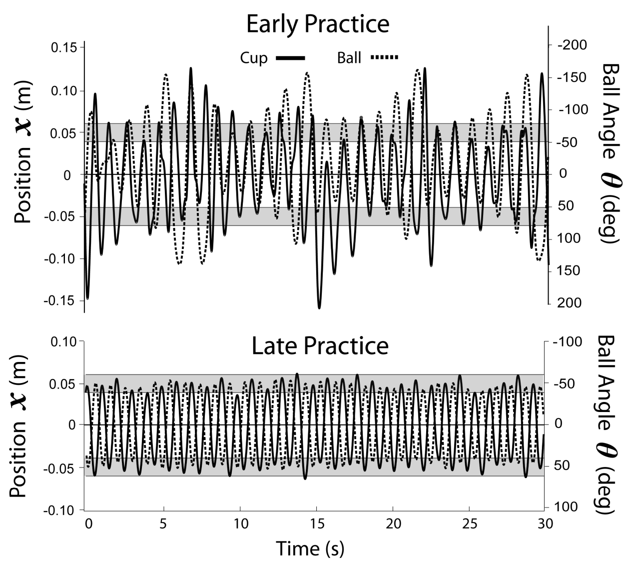

Fig. 4. Exemplary cup and ball kinematics for one subject.

Fig 5 shows the average cup oscillation frequency f and amplitude A, and relative phase φ for all subjects for the first and last trials. The standard deviations represent cycle-to-cycle variability. With practice subjects improved their task performance, indicated by f and A moving closer to their target values; the variability also decreased substantially. At the end of practice the average f was 1.02 ± 0.02 Hz, which was close to the target frequency, although slightly but significantly higher (p = .006). The average amplitude A was 0.11 ± 0.01 m, which was slightly but significantly larger than the target A (p=.006). The average relative phase φ was 175°, which was slightly but significantly below a perfect anti-phase relation (p = .043).

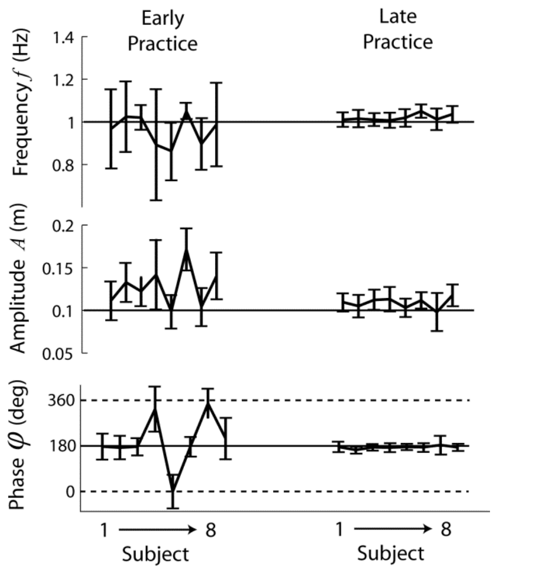

Fig. 5. Average cup oscillation frequency f and amplitude A and ball and cup relative phase φ for the first and last trials for all subjects (φ = 180° = anti-phase; φ = 0° or 360° = in-phase). Error bars show cycle-to-cycle variability (± one standard deviation).

Fig. 6 illustrates the change of the three performance variables across trials (averaged across all subjects). The standard deviations express between-individual variability.

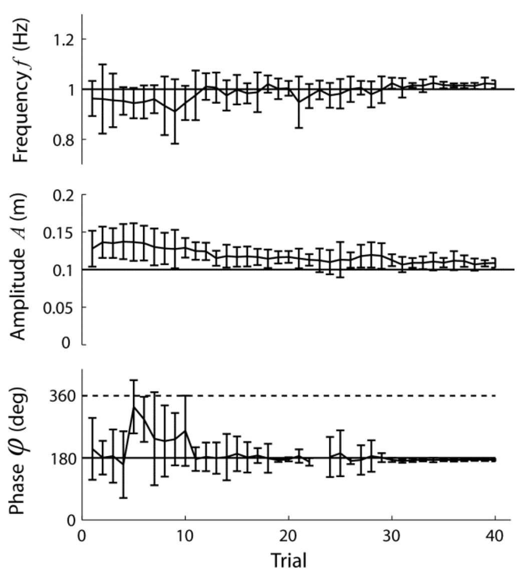

Fig. 6. Average frequency f, amplitude A and relative phase φ of cup oscillation for all trials and all subjects. Error bars represent variability across subjects (± one standard deviation).

As evident in Fig. 5 and Fig. 6, the variability of relative phase φ was relatively large during early practice – both within and between-subjects. Therefore, φ in early practice was examined in more detail. Fig. 7 shows how φ changed from cycle to cycle for all subjects from the first to the fifth trial. While some subjects maintained an anti-phase relation throughout early practice (e.g. subject 3), some used an in-phase relation (e.g. subject 7), and others had a more variable phasing, which alternated between in-phase and anti-phase (e.g. subject 2).

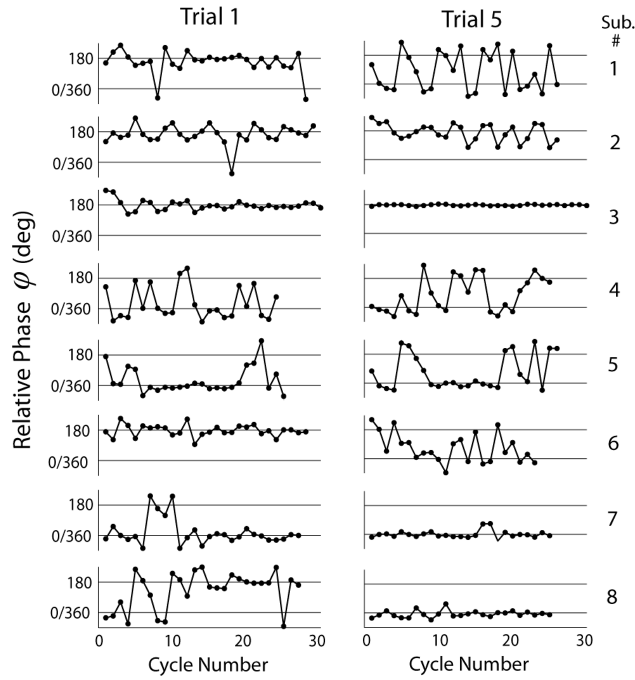

Fig. 7. Relative phase φ between the cup and ball oscillations for the first and fifth trials for all subjects. Note that since φ is an angular measure the data are wrapped, i.e. 0° is the same as 360°.

Fig. 8 shows how the subjects' profiles of cup velocity $\dot{x}$ (solid line), acceleration $\ddot{x}$ (dashed line), applied force F_A (solid line), and the ball force F_B (dashed line) changed over practice. The shaded bands indicate one standard deviation across subjects.

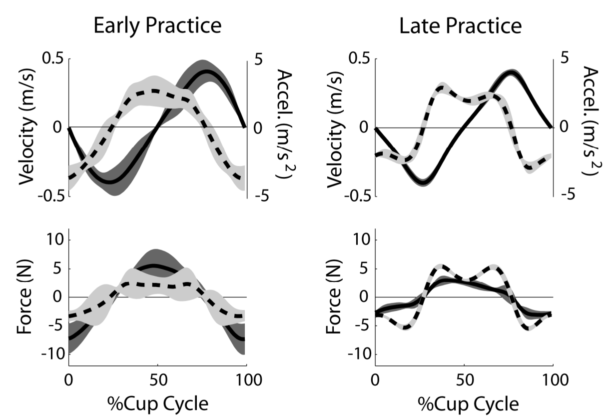

Fig. 8. Average kinematics and kinetics of the cup plotted as a function of the cup's oscillation cycle. Top row: cup velocity $\dot{x}$ (solid line) and acceleration $\ddot{x}$ (dashed line). Bottom row: applied subject force F_A (solid line) and the ball force F_B (dashed line). Shown are the average and standard deviation (shading) across subjects.

To further understand subjects' control strategies, the data were analyzed in the frequency domain. Fig. 9 shows the normalized power spectrums of subjects' applied force F_A in early and late practice. Here, the most prominent difference is that in late practice there is a more pronounced peak around 3 Hz, and another smaller one near 5 Hz.

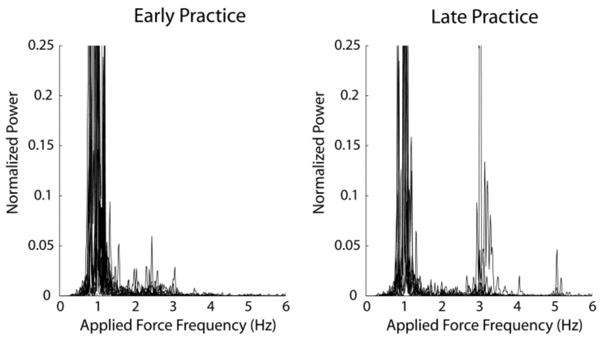

Fig. 9. Power spectrum for the force that subjects applied to the cup F_A in early (first trial) and late (last trial) practice. The data from all subjects is overlaid. For each subject the power is normalized to the peak power, which always occurred close to 1.0 Hz. Note that in late practice one subject had exceptionally large powers near 3 and 5 Hz.

In order to gain insight into possible reasons for subjects' change in strategy we examined the frequency response of the system, which coupled the ball and cup system to a simple model of a human arm. The relation between the applied external force and the ball displacement is shown in Fig. 10, while the relation between the applied external force and the cup displacement is shown in Fig. 11. The vertical dashed line shows the mean frequency that subjects adopted in late practice. For these simulations the human neuro-mechanical output impedance was modeled as 2^{nd}-order with a bandwidth of 2.0 Hz and a damping ratio of 0.6. Qualitative features of the simulations are insensitive to these specific parameter values.

In the magnitude plot for the ball (Fig. 10) the resonant frequency is at 0.966 Hz. This is slightly below 1.0 Hz due to the interaction between the two modes of ball and cup motion (in-phase and anti-phase). The phase plot shows that the relative phase changes rapidly near resonance: below the resonant frequency the phase is approximately in-phase (0° or 360°); above the resonance frequency it changes to approximately anti-phase (180°).

For the cup magnitude plot (Fig. 11), it is interesting to note the presence of a *dynamic zero* at the resonant frequency of the pendulum. A perfectly sinusoidal force applied at this frequency would be opposed by a precisely equal and opposite reaction force due to ball motion. As a result, the cup would not move. However, in the task subjects were not confined to perfectly sinusoidal forcing but could choose any "good-enough" strategy. In fact, it is clear from Fig. 9 that subjects learned to shape their actions to include higher harmonics of the fundamental task frequency.

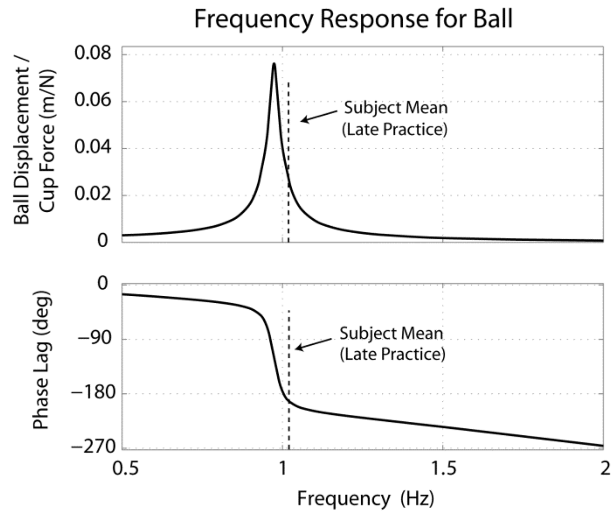

Fig. 10. Bode magnitude and phase plots for the balls; response showing the frequency response between the frequency of the applied external force and the ball displacement, based on a linearized model of the ball and cup dynamics and human end-effector. The resonant peak is at 0.966 Hz.

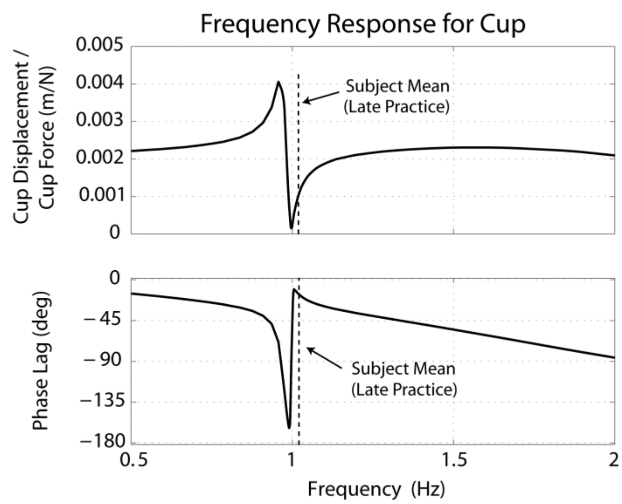

Fig. 11. Bode magnitude and phase plots for the cup's response showing the frequency response between the applied external force the cup displacement, based on a linearized model of the ball and cup dynamics and human end-effector.

IV. Discussion

This study sought to determine how humans control a dynamically complex object near its resonant frequency while at the same time achieving kinematic goals. An experiment was performed in which subjects were required to oscillate a cup containing a ball between two spatial targets at the ball's resonant frequency. No restrictions were placed on the relative phase between the ball and cup or the specific form of subjects control inputs.

The main results were that: 1) Subjects switched from a strategy where they forced the cup between the two spatial targets (resembling motion control), to a permissive strategy of "guiding", where they learned to let the ball reaction force do the work to move the cup to the targets. 2) Subjects avoided the resonant frequency by a small margin. Interestingly, in early practice subjects were below the resonant frequency, but subsequently shifted above. This may be interpreted as "cheating" to avoid large undesired ball displacements and forces. However, this may also be due to the fact that, in this nonlinear system, larger-amplitude motions are associated with lower resonant frequencies. Further study is needed to test this hypothesis.

The nature of subjects' transition between movement strategies can be understood by examining the frequency response of the coupled ball/cup/human system. In early practice, subjects oscillated the ball and cup below the resonant frequency, i.e. to the left of the resonant peak in Fig. 10, which is associated with an in-phase ball and cup oscillation ($\varphi \approx 0°$). With practice, subjects increased the oscillation frequency, moving to the right of the resonant peak, causing a shift to an anti-phase pattern ($\varphi \approx 180°$). Thus, the relatively abrupt switch in relative phase is predicted by the dynamics of the system. Of course, it should be noted that the frequency response analysis of Figs. 10 and 11 assumes sinusoidal behavior based on a linearization of the actual system, and therefore is a crude approximation of the physical system.

A question remains: why did subjects choose to move from below to above the resonant frequency, and not vice-versa. One reason is that the initial in-phase strategy was energetically expensive, as it required subjects to exert about twice as much force on the cup (Fig. 8). The anti-phase strategy required much less force from the subjects, as the reaction force from the ball performed most of the work in moving the cup. Thus, it is likely that once subjects find the energetically easier anti-phase strategy, they prefer to stick with this solution. These observations are also consistent with several findings in the motor control and learning literature: with practice humans learn to exploit the natural dynamics of an object [7], and humans initially use "model-free" control, but once the dynamics are learned switch to "model-based" feedback/feedforward control [8].

Another interpretation of subjects' change in strategy is that the guiding strategy is associated with lower variability. This was observed at the group level, where the variability decreased with practice (Fig. 7), and within each subject, where the variation from cycle to cycle became smaller with practice (Fig. 6). This decrease in variability is likely to result from the decreased applied force, which in turn would require reduced muscle activations. Since noise increases with muscle activation [9], less activation should result in a more consistent movement pattern. Therefore, not only is the anti-phase strategy energetically favorable, but it is also less variable, making it attractive to subjects.

Finally, the results show that subjects "cheated" since in early practice the cup oscillation frequency was slightly below the instructed frequency, and in late practice it was above the target resonant frequency. It is likely that subjects were sensitive to the resonance properties of the ball and cup system, but also felt that they could afford to deviate from the temporal requirement in order to improve their performance in the spatial requirement.

Acknowledgment

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