Respecting the Coupled Dynamics: Haptic Feedback Carries both Power and Information

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Abstract— **Haptic feedback provided in the axis of a motor task cannot be removed without changing the motor task itself. Haptic feedback couples the biomechanics of the backdrivable body to the dynamics of the environment and establishes a conduit for both power and information exchanges. To isolate the roles of haptic feedback in information exchange and power exchange, we devised a task without haptic feedback that preserved the motor challenge of controlling the coupled dynamics. We placed an identified model of a participant's biomechanics in the virtual environment and coupled it to the original task dynamics. Visual feedback was provided to substitute for the missing haptic feedback. We compared the performance of N=5 participants in the same motor task with and without haptic feedback and in the new task without haptic feedback. The presence of the coupled dynamics in the task predicted the match across conditions rather than the feedback modality. Our results provide support to the idea that rather than controlling their environment, humans control the coupled dynamics of their body and environment.**

I. INTRODUCTION

Certain haptic sensations, especially those that arise through contact with the environment, are accompanied by significant power exchanges compared to visual and auditory sensations. Portions of the body are backdriven by contact forces and the dynamics of body and artifact in the environment become coupled. Here we speak of instances in which haptic feedback is provided in the axis of control and instances in which the impedance of artifact and body are approximately matched. Such haptic feedback would perhaps more appropriately be called force or kinesthetic feedback. Note that *haptic rendering* aimed at making virtual objects seem real is almost always concerned with synthesizing haptic feedback in the axis of control. For example, haptic feedback from a virtual ball that one juggles would be presented in the axis used to maintain the juggle [1] and click-feel from a button is presented in the axis of the button press. Because the transfer of mechanical power gives rise to coupling between the dynamics of the body and artifact, one can say that the dynamics under control by the user are not those of the artifact, but the coupled dynamics of the body and artifact.

Paradoxically, the brain is faced with a greater challenge when controlling the coupled dynamical system that includes the combined body and artifact. There are new degrees of freedom to be managed—dynamic modes that involve exchanges of potential and kinetic energy between body and artifact. But something magical takes place when the body and artifact dynamics are coupled. A feedback loop is closed and the artifact becomes an extension of the body. The tool handle or machine interface disappears and the user gains a new means to effect change in their environment. This kind of magic is certainly at play when a skilled carpenter wields a hand-tool, a tennis player hits a ball with a racket, or a musician plays an acoustic instrument. The notion of a tool as an extension of the body has been explored in philosophical (phenomenological) studies of experience and consciousness [2] and through sensorimotor experimentation [3], [4]. More recently, the ability of the sensorimotor system to utilize coupled dynamics in sensing tasks has been explored [5], [6].

Dynamic coupling between body and environment carries significant implications when attempting to isolate the contributions of haptic feedback to motor performance. In light of dynamic coupling, it becomes apparent that haptic feedback is not strictly an information signal. Many authors have noted that to turn off haptic feedback changes the motor task [7]–[9]. And a user will notice that the task dynamics change quite noticeably when haptic feedback is removed. Thus comparing performance in a visuomotor task with and without haptic feedback is comparing apples and oranges.

Further evidence for the importance of the coupled dynamics in the analysis of haptic rendering systems is available from the literature on coupled stability. The stability properties of a virtual environment change markedly once a user grasps the haptic device, even when the user applies no control action [10], [11]. The passive biomechanics of the user evidently contribute damping to the coupled dynamics. Thus a virtual environment whose model analysis would predict instability due to sampled data effects or other destabilizing processes is observed to be stable when a user grasps the haptic device. Evidently a flow of power toward the human user contributes to the stability margin. Higher grip forces are associated with even greater margins of stability, because higher grip forces are associated with higher impedance and greater dissapative effects [12].

The question then arises, how could a task without haptic feedback be modified so that it may be compared to a task with haptic feedback? Can two different motor tasks be devised whose performance can be compared in the sense of apples to apples, one with and the other without haptic feedback? If haptic feedback couples the dynamics of body

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and environment, and the motor task comprises control of the coupled dynamics, then perhaps when haptic feedback is replaced by visual feedback the coupled dynamics could somehow be preserved in the motor challenge. For this paper we devised a motor task without haptic feedback that retained the coupled dynamics. We augmented (coupled) the virtual environment with a model of the user's biomechanics. System identification of the passive biomechanics informed the design of the new motor task.

The remainder of the paper presents models of the virtual environment and biomechanics both in coupled and uncoupled configurations that form the basis of our analysis and experiment design. We present the methods and results of an experiment designed to separate the contribution of haptic feedback in its information relay and dynamic coupling roles. We conclude the paper with a discussion of results and future work.

II. Model Development

The motor challenge we set for our participants was to excite and maintain oscillations in a virtual oscillator for 30 seconds and subsequently to relax for 30 seconds. Fig. 1 shows our single-axis haptic device (a motorized wheel) and a schematic of the virtual oscillator (spring-inertia) rendered at the handle of the haptic device. We devised three conditions under which participants would drive oscillations, which we describe in a sequence of three models below. The conditions differ not only by whether haptic or visual feedback was provided, but also by the dynamics of the virtual environment being driven. In addition to the virtual oscillator, these models encompass the passive biomechanics and means by which a participant acts on the haptic device handle and through the handle on the virtual environment.

A. Hand Model

To model the finite impedance through which a human user acts on their environment, we adopt a simple mass-spring-damper model with parameters m_1 (mass), k_1 (stiffness), and b_1 (damping) driven by a motion source $r(t)$. This model has roots in the literature on human motor behavior, where it was at one time known as the equilibrium point hypothesis [13] or virtual trajectory model [14]. The second order mass-spring-damper model has also been shown to fit system identification data describing the driving point impedance collected under conditions in which the hand is mechanically backdriven [12], [15]. By virtue of the mass-spring-damper dynamics, the motion of the hand $z(t)$ will bend under load. In addition to the hand bio-mechanics the mechanics of the haptic device also have to be considered; mass m_1 and damping b_1 are representative of the combined mass and damping of the hand and device.

B. Coupled Hand-Oscillator Model

Let us consider the case in which a user is asked to drive sinusoidal motion in an undamped oscillator. Figure 2 shows a schematic of the user with motion source $r(t)$ modeling a neural signal (not measurable directly) along with the hand and handle position $z(t)$ in black. The hand drives motion $w(t)$ of a virtual mass m_2 through a virtual spring k_2. The physical apparatus and virtual environment is shown in Figure 1.

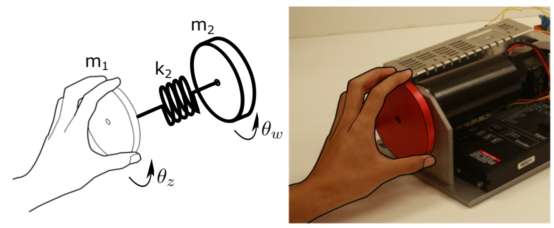

Fig. 1. Experimental Apparatus and Virtual Environment. A single-axis haptic device was used to render a virtual spring-inertia comprising stiffness k_2 and inertia m_2.

The oscillator (undamped spring-mass) (in blue outline) is rendered through a haptic device. The variable $z(t)$ describes both the hand and the grasped handle of the haptic device. Haptic feedback F_m is provided in the axis of control and the dynamics of the hand/arm are coupled to the dynamics of the oscillator.

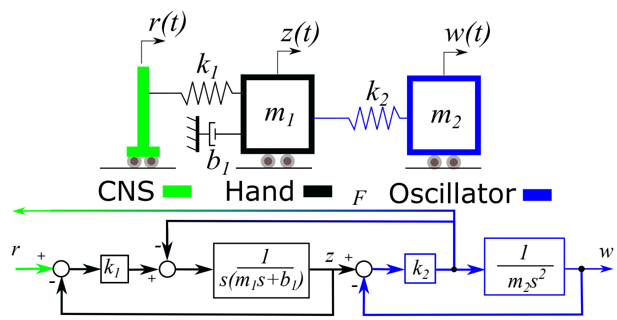

Fig. 2. Coupled Hand-Oscillator Model. The spring k_1, damper b_1, and mass m_1 that together describe the backdrive impedance of the body are driven by a motion source $r(t)$ to produce displacements $z(t)$ at the hand. The oscillator is comprised of a stiffness k_2 and mass m_2. This translational schematic is standing in for a rotational system such as Fig 1. The corresponding block diagram is shown. Importantly, the diagram features a feedback signal F that represents the torque rendered through the haptic device to the dynamics of the body.

At this point we can already make an important observation. An undamped oscillator will produce sustained oscillations if excited and then held still ($z(t)$ = 0, holding the handwheel stationary). If the user relaxes (CNS command $r(t)$ = constant), then energy stored in the oscillator will backdrive the biomechanics including the damper b_1 and the entire system will come to a standstill. The forces acting on z(t) must be balanced in order to do this if m_1,b_1, and k_1 are finite. By linearity, a persistent sinusoidal excitation $r(t)$ at frequency $\omega_0 = \sqrt{k_2/m_2}$ will produce, at steady-state, a sinusoid at $\omega_0 = \sqrt{k_2/m_2}$ in $w(t)$. Thus if the user applies an open-loop drive to the system with sinusoidal motion at frequency $\sqrt{k_2/m_2}$ in $r(t)$, the hand and handle $z(t)$ will eventually cease motion while $w(t)$ will exhibit sinusoidal motion 180 degrees out of phase. If the user relaxes these forces are no longer balanced and k_2 will backdrive $z(t)$ untill the damping in the human hand dampens out the oscillations in the undamped oscillator.

C. Decoupled Hand-Oscillator Model

In a second model we would like to describe the effect of turning off or removing haptic feedback. Thus we sever the haptic feedback channel F_m as pictured in Figure 3. In doing so we have severed not only the information in haptic feedback but also the force feedback that was previously backdriving the the human hand. The signal $z(t)$ with which the motion source in the virtual environment drive the virtual oscillator (in blue) is drawn from the hand $z(t)$, as might be sensed using an encoder (ENC) on the haptic device handle. It is clear from the resulting block diagram that this is not mechanically equivalent to the Coupled Hand-Oscillator system because the coupled dynamics have not been preserved.

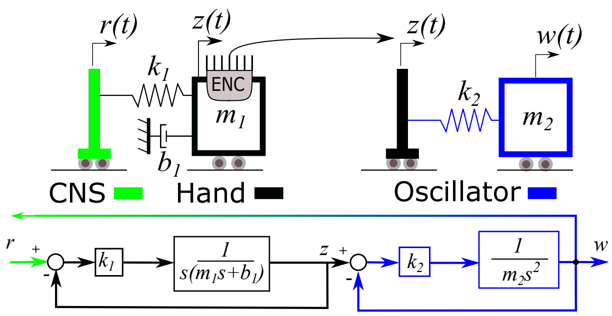

Fig. 3. Decoupled Hand-Oscillator Model. Without coupling, or if the haptic device motor is disabled, the dynamics of the virtual spring-mass system is driven by the motion source $z(t)$, the displacement of the haptic device handle. Importantly, the diagram no longer features the feedback signal containing F as in Fig 2.

The behavior of this Decoupled Hand-Oscillator system under an (open-loop) sinusoidal excitation $r(t)$ at frequency $\omega_0 = \sqrt{k_2/m_2}$ will be very different than the behavior of the Coupled Hand-Oscillator. The hand is not loaded by the oscillator (no haptic feedback) and thus $z(t)$ will oscillate at frequency ω_0 in steady-state. When the virtual oscillator is then driven at its resonant frequency (the virtual motion source derives its motion $z(t)$ from the encoder on the haptic wheel), the amplitude of oscillation will grow. Then if driving motion in $r(t)$ ceases (the user relaxes), $z(t)$ will come to a standstill but the oscillator will continue to oscillate.

D. Coupled Virtual Hand-Oscillator Model

To create a motor task for the user that lacks haptic feedback but which is arguably equivalent to driving an oscillator with haptic feedback, we develop a model in which the coupled dynamics are preserved. But these coupled dynamics exist fully in the virtual environment and visual feedback is used in place of the missing haptic feedback. Thus in Figure 4, we have generated a model of the human hand bio-mechanics ("Virtual Hand", in red) and coupled it to the virtual oscillator (in blue). The actual human hand, now unable to feel torque feedback, drives the haptic device handle (whose inertia is already lumped in m_1). An encoder on the handle $z(t)$ is used to derive the signal $z^*(t)$ with which the virtual environment is driven. The "Virtual Hand" is now backdriven by the force F from the virtual oscillator.

The behavior of the Coupled Virtual Hand-Oscillator system can be expected to mimic that of the Coupled Hand-Oscillator system. When a sinusoid at the resonant frequency ω_0 is applied at $r(t)$, the steady-state sinusoid $z(t)$ will drive a virtual environment (virtual hand, virtual oscillator) that is modeled after what was previously a coupled physical (hand) and virtual (oscillator) system. And when $r(t)$ = constant, energy stored in the oscillator will dissipate through the damper b_1.

E. System Identification for Hand Model

We hypothesize that due to the smaller rotation angle of the task in [11], we could utilize the previously identified mass m_1 and stiffness k_1 but would need to recalculate the damping coefficient b to obtain an appropriate model for our task. In this work, we will adopt the second order model $\tau = J\ddot{\theta} + b\dot{\theta} + k\theta$. Since m and k are known we can solve for b: $b = (\tau - k\theta - J\ddot{\theta})/\dot{\theta}$. To obtain data to generate our estimate of b we asked a single participant to grasp the haptic wheel handle without actively driving it. We then generated a sinusoidal motor command at an intensity that produced approximately 90 degree $(+/-)$ motion and recorded the encoder angle and input current i_c using a Hall Effect sensor (Tamura L01Z050S05). The motor constant for our Maxon Motor is $k_t = 60.3$ N-mm/A as identified by the datasheet. We then calculated output torque using $\tau_{out} = k_t i_c$.

Since, m_1 and k_1 have been selected, the observed phase difference between the motor command and hand wheel motion can be resolved by fitting b_1. The final bio-mechanical model of the hand is then given by $m = 0.180$ Nm/(rad/sec^2), $k = 2.558$ N-m/rad, and $b = 0.508$ Nm/(rad/sec).

F. Control Strategies

In order to successfully accomplish the motor task outlined at the start of section II differing strategies are employed depending on the feedback available in each of three models outlined. In the case where haptic feedback was available; only in the Coupled Hand-Oscillator condition, in order to maintain the oscillations the participant simply has to oppose the haptic feedback to keep the handle still. This is because an excited spring-mass system with the link $z(t)$ held still will resonate with the same magnitude indefinitely (because there is no damping). The oscillations felt and opposed will be sinusoidal at the natural frequency of the virtual spring mass.

In the other two conditions, Coupled Virtual Hand Oscillator and Decoupled Hand-Oscillator, no haptic feedback was available and either an open loop or visual feedback based strategy had to be used. This corresponds to the same strategy as the Coupled Hand-Oscillator condition but without haptic feedback; the participant is attempting to oppose oscillations they can no longer feel. The correct action in this case is to move the handwheel in a sinusoidal motion at the natural frequency of the virtual spring mass. Visual feedback was provided to allow the participants to estimate whether they were causing the spring-mass system to resonate at its natural frequency. Alternatively, in the Coupled Virtual

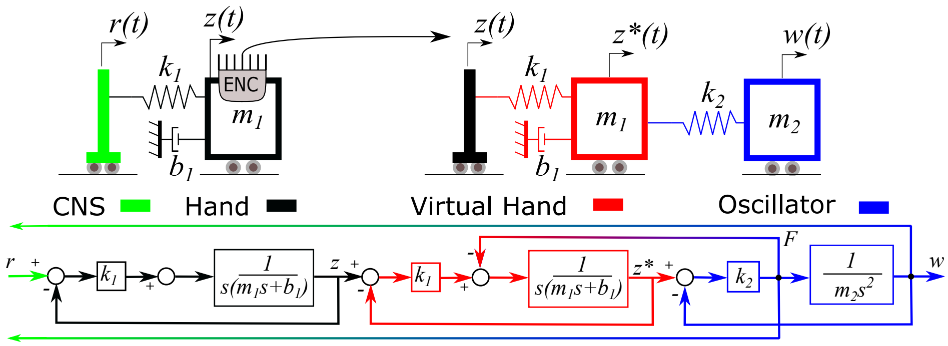

Fig. 4. Coupled Virtual Hand-Oscillator Model. Haptic feedback has been removed and thus the mass-spring-damper biomechanics (in red) are no longer loaded by a reaction force from the oscillator. However, the double-mass task dynamics have been preserved by inserting a model of the hand (virtual hand, in black) into the virtual environment.

Hand-Oscillator condition this strategy can be interpreted as using visual feedback to keep the virtual hand still, effectively commanding the virtual hand to oppose haptic feedback.

G. Model Simulation

Given the damping estiamtion and the models presented in the previous section we can conduct a simulation comparing Decoupled Hand-Oscillator and the Coupled Virtual Hand-Oscillator conditions. The simulation results in Figure 5 were generated using the same Simulink models used for the human subject experiment in the following section but with the encoder signal $z(t)$ replaced by a sinusoid generator at the natural frequency of the spring mass oscillator. Figure 6 shows the results of the experimental measures on the simulation results.

The virtual oscillator had a mass of $0.18\ Nm/(rad/sec^2)$, a spring constant k of $2.5578\ Nm/rad$, and just enough damping b to remove Euler integration error. The amount of damping b was $T_s k = 0.0026\ Nm/(rad/sec)$ (where T_s was the sample time of $0.001s$). The natural frequency of this oscillator was $0.6Hz$.

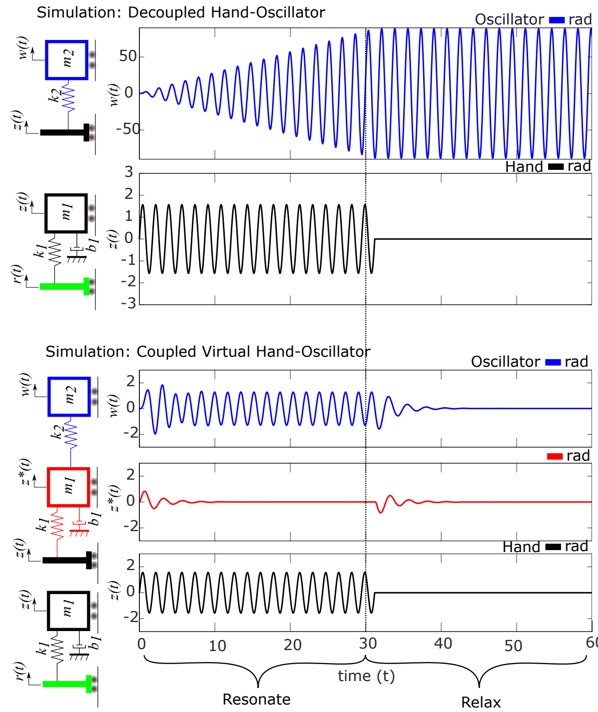

Fig. 5. Simulation Results: The Decoupled Hand-Oscillator and Coupled Virtual Hand-Oscillator systems are simulated using a sinusoid generator. The first thirty seconds the system is excited at the natural frequency of the virtual spring mass and then the generator is shut off for thirty seconds.

III. Methods

A. Participants and Apparatus

Experiments were conducted with 5 male participants from the University of Michigan. All participants signed an informed consent according to an IRB approved protocol (HUM00148462). The angular position $z(t)$ of the haptic wheel (Encoder US Digital E6S-2048-157), the angular position $w(t)$ of the virtual oscillator, an amplified, rectified measure EMG of surface electromyographic signal (Otto-bock 13E200=60) from the medial aspect of the forearm, and the current commanded to the motor (Maxon RE-40-148877) were all recorded at 1KHz. The EMG signal was low pass filtered at 5Hz. All signals were collected using a Sensoray 626 with Simulink real-time at 1KHz. The haptic wheel is pictured in Fig. 1.

B. Experiment Conditions

In this experiment we compared the participant's ability to maintain resonance in a coupled spring mass with only one channel of information present; either visual information or haptic information. Visual information was substituted in the conditions where haptic feedback was unavailable and was displayed on a screen. However, in order for the conditions to be comparable, preservation of the coupled dynamics is needed but removal of haptic information is necessary; we now make use of the Coupled Virtual Hand-Oscillator model we developed earlier and pictured in Fig 4. Each participant was asked to resonate three different systems: 1) Coupled Hand-Oscillator 2) Decoupled Hand-Oscillator and 3) Coupled Virtual Hand-Oscillator. Each system was demonstrated and explained to the participant prior to a trial with demonstration and training time as appropriate. All participants were informed that the natural frequency f_n of the spring mass oscillator was 0.6Hz prior to the trials. The trial order was randomized.

The task given to each participant was to excite and

Simulation Resonate: RMS of Signals	Hand	Virtual Hand	Oscillator
Decoupled Hand-Oscillator	1.110	x	36.26
Coupled Virtual Hand-Oscillator	1.110	0.147	0.941

Simulation Relax: τ_C of Oscillator Signal	Oscillator
Decoupled Hand-Oscillator	∞
Coupled Virtual Hand-Oscillator	1.952

Fig. 6. Simulation: Average RMS value of metrics (in rad) across all three conditions.

maintain oscillations in a spring mass ('resonate' portion 30 seconds) followed by performing no motor action and relaxing ('relax' portion 30 seconds). Participants were instructed to induce an excitation by quickly turning the handle by about 90 degrees to the right and then back to center. For the remainder of the 'resonate' portion participants were then asked to maintain the oscillations by relying on either haptic feedback or visual feedback depending on which was available in the given condition. In these cases without haptic feedback the participants were instructed to move the handwheel in a sinusoidal motion (alternating from 90 to -90 degrees) at the natural frequency of the virtual spring mass using the visual feedback to adjust their magnitude and phase as needed. The visual feedback provided to the participants was in the form of laterally moving blocks similar to the right side of Fig 4).

C. *Experimental Measures*

Two separate measures were used to evaluate the perform under each instruction. For the first half of each trial, the resonate portion, the root mean square value (RMS) calculated. For the second half, the relax portion, the time constant τ_c was calculated.

IV. Results

A. *Sample Data*

Representative data for a single participant is shown in Fig 7. The icons on the left side of the figure indicate which element of the spring-mass-damper is generating the signals shown to the immediate right.

B. *Summary Data*

1) Root Mean Square (RMS): In figure 8 the average (across all 5 participants) RMS value of the resonate signals is shown. The virtual hand was present only in the Coupled Virtual Hand-Oscillator condition and therefore the corresponding RMS value is absent from the other two conditions in the graph. The symbol ∞ indicates that the oscillations in the virtual oscillator did not stabilize; they continued to grow so an RMS value was not determined.

2) Time Constant (τ_c): To calculate τ_c the maximum value for the second half of the resonate phase was used (period of trial between 15 and 30 seconds). Figure 8 shows the results for all trials. The symbol ∞ indicates that a value could not be determined as oscillations did not decay.

V. Discussion and Conclusion

In this paper we explored the idea that, rather than controlling object dynamics, the central nervous system controls the coupled dynamics of body and object. Force feedback synthesized by a haptic device, along with motion of the device handle, make up the two variables that couple

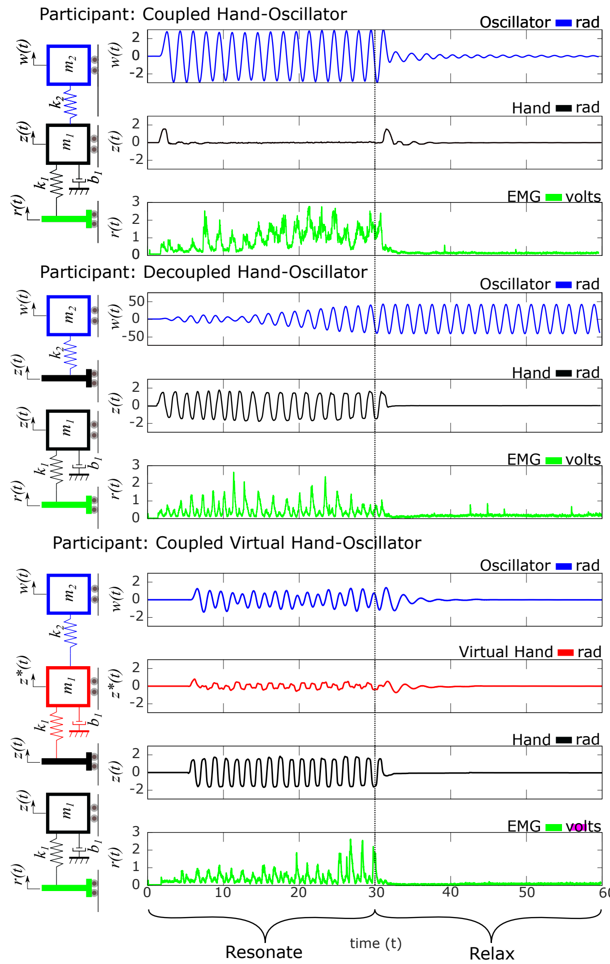

Fig. 7. Single Representative Participant Results: This figure shows representative data from the human subject experiment. The participant attempts to resonate the system at the oscillator's natural frequency for the first 30 seconds and then relaxes for the next 30.

user biomechanics and object dynamics. If haptic feedback is removed then the dynamic coupling is broken, even if the user retains an ability to drive the object dynamics. We devised an experimental condition that preserved the coupled dynamics yet removed force feedback by placing and coupling a model of the arm/hand (with parameters set by system identification) into the virtual environment. We asked our participants to first drive and maintain oscillations for 30 seconds ('resonate') and then to grasp the wheel but behave passively ('relax') for another 30 seconds. As expected, the performance of our participants driving the all-virtual coupled dynamic system (Coupled Virtual Hand-Oscillator) better matched the condition with haptic feedback (Coupled Hand-Oscillator) than the condition without haptic feedback (Uncoupled Hand-Oscillator). Coupled participant-virtual environment behavior (Fig. 7) matched predictions set up by simulation (Figure 5). In particular, the same

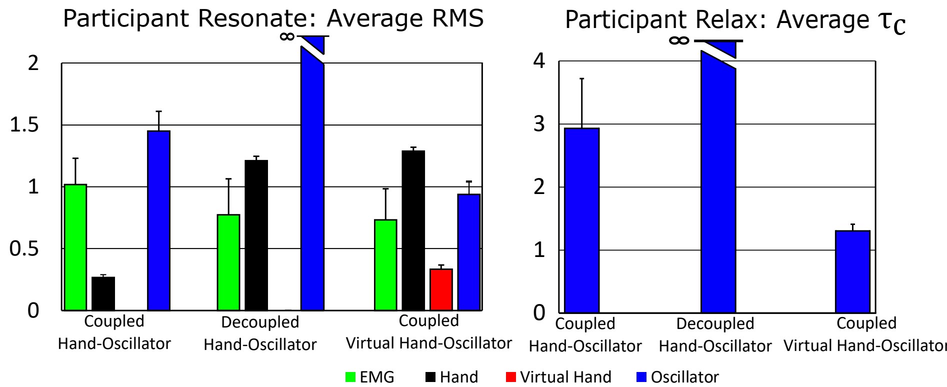

Fig. 8. All Participants: means of metrics across all three conditions. Errors bars associated with each bar indicate variance. The amplitudes associated with the RMS values are in volts (EMG) and rad (hand, virtual hand, and oscillator).

model describes the behavior of the coupled physical hand and oscillator as the coupled virtual hand and oscillator. In response to the oscillatory input generated by the participant in the first 30 seconds, the coupled system (whether coupled through the haptic device with haptic feedback or strictly in the virtual environment) responds with steady oscillations. The uncoupled system responds with growing amplitude. When a participant relaxed, energy stored in the oscillator quickly dissipated, but only in the coupled-dynamics cases (see Figure 7). The EMG signals (green traces) indicated that our participants were following instructions, though when haptic feedback was present a greater muscle action was necessary to oppose the haptic feedback to keep the handle still once oscillations were initiated. In our future work we plan to assess task performance more closely and quantify the learning rate. It appears that our participants were adopting primarily open-loop strategies when visual feedback was substituted for haptic feedback. Anecdotally, the tasks involving visual rather than haptic feedback were more difficult to perform. Haptic feedback was easily incorporated in the sense of anticipatory control, in that our participants held the handle stationary simply by opposing the torque that they felt. By participant report, it was not as easy to quell oscillations in the virtual handle as it was in the physical handle. The fourth-order (double-mass) coupled dynamics were certainly more challenging to handle than the essentially second-order dynamics of the uncoupled system. Also, we did not set parameters in the virtual hand model according to data from individual system identification experiments. It would be interesting to assess whether our participants were adapting to changes in dynamics having to do with differences between the dynamics of their own hand and that of the virtual hand adopted for our experiments.

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