HAPTIC FEEDBACK IMPROVES UPPER EXTREMITY CONTROL OF RESONANCE

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INTRODUCTION

Humans experience reaction forces in common motor tasks such as bouncing a ball (Schaal et al., 1996) or swinging a leg. These reaction forces may be useful feedback when resonance detection and maintenance are important. Our goal was to test whether haptic feedback complements visual feedback in the continuous manual control of a resonant sprung mass (Dingwell et al. 2002). We hypothesized that subjects would perform better in this when given combined visual and haptic feedback than with either feedback channel alone. We designed an apparatus with a motorized handle that would simulate the dynamics of a sprung mass. Comparing errors in the power spectrum of the input motion, subjects demonstrated better performance with visual and haptic feedback than with visual feedback alone (paired t-test: $p<0.002$) and haptic feedback alone ($p<0.04$).

METHODS

Ten healthy adults (7 male, 3 female) participated in this study after providing informed consent. The task was to repeatedly turn a handle connected to one end of a virtual torsional spring, with a virtual torsional mass at the other end, so that the mass was actuated to resonance. Using the dominant hand, each subject grasped a motorized handle and operated the handle using wrist pronation and supination (See Figure 1). Three feedback conditions were presented: Vision-Only, Haptic-Only, and Vision-Haptic. For each condition, four undamped resonant systems were presented: (7, 9, 11, and 13 rad/s), each with a spring stiffness of 0.0125 N-m/rad. Three trials of each combination were presented in random order for a total of 36 trials, each lasting 30 sec. In each trial, the computer released the sprung mass from an initial stretch, and the subject attempted to find and maintain a resonant motion of the mass, relying on available feedback to do so. Visual feedback consisted of a computer animation of the motion of the handle and sprung mass. Haptic feedback consisted of a torque produced by the motor and felt through the handle, simulating the reaction of the sprung mass.

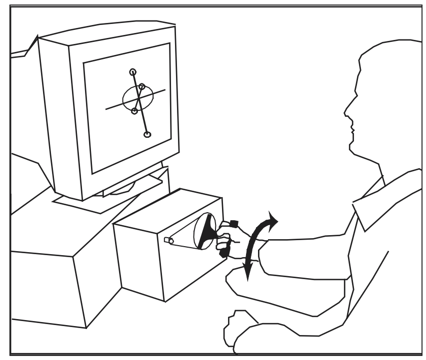

Figure 1. Operation of virtual sprung mass resonance task may include visual and haptic feedback.

Using collected handle input data (100 Hz sample rate) from each trial, we determined the power spectrum of the input motion. As a metric for the input error, we calculated the sum of squared differences (SSD) be-

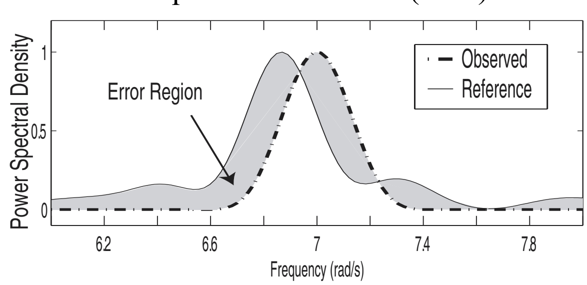

Figure 2. These frequency distributions of handle input motion show an error between the observed and a reference spectra at a target 7 rad/s. Data are sample from one subject.

tween the observed and reference frequency distributions in a band of 2 rad/s centered about the target frequency (See Figure 2). The reference distributions were determined from simulated handle input data (also sampled at 100 Hz) operating at the target natural frequencies.

RESULTS AND DISCUSSION

Our metric SSD demonstrated significantly better performance when both feedback channels were available. See Figure 3 for mean results of frequency distribution sum-squared errors for each condition. Vision-Only trials produced significantly more error than Vision-Haptic trials for all frequencies tested (paired t-test, $p < 0.002$). Haptic-Only trials produced significantly more error than Vision-Haptic trials in only the highest and lowest frequencies tested (paired t-test, $p < 0.04$ for 7 and 13 rad/s).

For this experiment design, haptic feedback was the dominant channel of sensory information. However, vision contributed to significant gains in performance, suggesting that both feedback channels aid control. Visual inspection of the handle input phase portraits showed that most subjects had faster convergence to resonance when haptic feedback was provided. The scatter in the phase portraits typically occured earlier in the trial (see sample plot in Figure 4, left). With haptic feedback, discontinuities in the

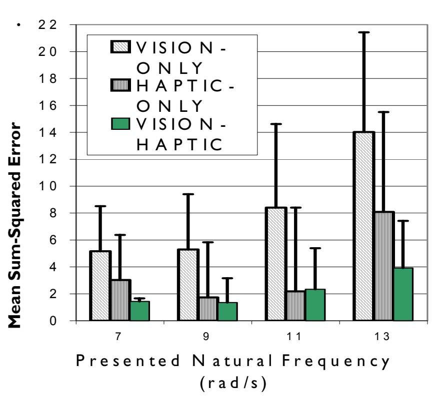

Fig. 3. Sum-squared errors (n=10, +1 s.d.) for each feedback condition and natural frequency.

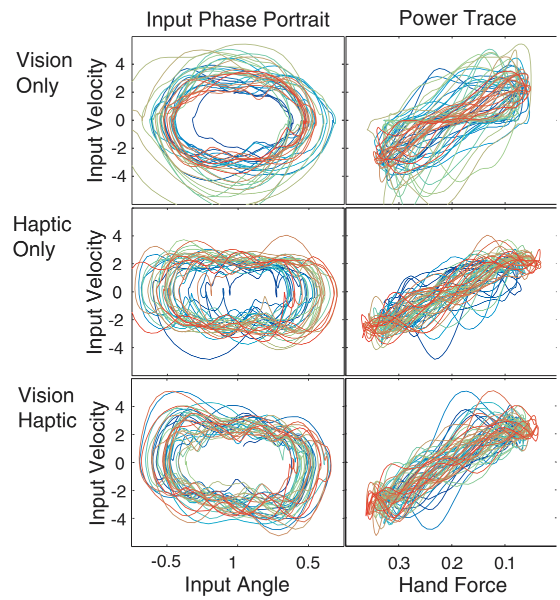

Fig. 4. Sample phase portraits (left) and power traces (right) for each feedback condition.

phase typically occur, due possibly to force coupling between the hand and the virtual sprung mass. A plot of the input velocity versus the spring torque shows that, with haptic feedback, more positive work is done to the system, as evidenced by more consistency in the first and third quadrants of the sample power traces (Figure 4, right).

In the manual control of resonant systems such as a sprung mass, haptic feedback costs mechanical work and may affect input motion. Yet it may improve performance by providing information to complement vision for control or identification purposes. Haptic feedback may aid resonant tasks since it is energetically advantageous for a human to be aware of effort and thus minimize negative work while achieving the task goals.

ACKNOWLEDGEMENTS

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