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CHARACTERIZING THE HUMAN WRIST FOR IMPROVED HAPTIC INTERACTION

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ABSTRACT

Haptic displays provide the user with a sense of touch in both simulation of virtual environments and teleoperation of remote robots. The instantaneous impedance of the user's hand affects this force interaction, changing the transients experienced during activities such as exploratory tapping. This research characterizes the behavior of the human wrist joint while holding a stylus in a three-fingered grasp. Nonparametric identification methods, evaluating frequency- and time-responses, support a second-order system model. Further analysis shows a positive linear correlation between grip force and wrist impedance for all subjects, though each individual's trend is unique. These findings suggest that a quick calibration procedure and a real-time grip force measurement could enable a haptic display to predict user response characteristics throughout an interaction. Such knowledge would enable haptic control algorithms to adapt continuously to the user's instantaneous state for improved performance.

1 INTRODUCTION

Haptic displays are becoming increasingly popular in virtual reality and simulated environments because they allow users to touch as well as see artificial objects. Telerobotics also makes wide use of such systems because force feedback from the remote environment can significantly improve the operator's sense of presence and ability to perform complex tasks. In both situations, the device presents force information to the user in order to create the sensation of touching another environment.

Though the haptic controller specifies the forces to be displayed, the signals perceived by the user are a result of a complex interaction between their hand, the haptic mechanism, and the control algorithm. Because most haptic devices are lightweight and stiff with high speed digital controllers, designers often assume that the haptic interaction will be entirely determined by their software. However, the display of high-frequency force signals, such as impacts and transients, also depends on the user's grasp and effective endpoint impedance. For example, a light hold is often detrimental to haptic displays because it provides little system damping, causing limit cycles, buzzing, and other undesired behaviors. On the other hand, a firm grip can overpower a haptic display that has been tuned for softer operation, making rigid surfaces feel spongy and overshadowing subtle nuances of the interface. Haptic displays would be more robust if they accounted for this variation.

Tapping on various real surfaces with a pen elicits a contact response that varies with material and impact velocity, as well as grasp style and force. Traditional haptic systems ignore the varying impedance of the user's hand and thus cannot re-create the complexity of these interactions. Other researchers have proposed using vibration feedback to increase the realism of haptic tapping, but these algorithms do not account for changes in the user's hand [1]. This paper proposes an alternate method based on knowledge of the mechanical impedance of the operator's wrist. In particular, impacts with the environment could be rendered with higher fidelity if the haptic display could predict the response of the operator's hand to forces being displayed.

Haptic displays employ a wide variety of mechanisms for user interaction, including joysticks, thimbles, finger loops, and styli. A pen-like stylus is often used for single-point exploration of virtual and remote environments. For example, the PHANToM has a stylus attached to the end of its grounded three degree-of-freedom robotic arm [2]. As the user holds the stylus and moves it around, the haptic display continuously measures end-point position and applies corresponding reactionary forces to the user.

When interacting with such a system, the operator uses large arm motions to position his or her hand at a desired location in three-dimensional space. He or she then often employs extension and flexion of the wrist to move the stylus up and down, making contact with objects in the virtual or remote environment. The forces generated by this exploratory tapping interaction strongly depend on the mechanical impedance of the user's wrist, which is modified in tandem with grip force. This paper develops a characterization of the behavior of the human wrist in this configuration using traditional system identification techniques. It develops a linear second-order system model and details the governing relationship between grip force and wrist stiffness and damping.

2 WRIST MODEL BACKGROUND

The hand's dominant mode of movement during exploratory tapping is extension and flexion of the wrist joint, which creates motion along the axis of the stylus. In a standard three-finger pen grasp, the hand can be approximated as a rigid body that pivots around a one-degree-of-freedom revolute joint in the wrist, as shown in Figure 1. The index finger, middle finger, and thumb act as a near-rigid structure, transmitting forces applied along the axis of the stylus to the wrist joint at the base of the hand; these torques cause the joint to rotate. A full understanding of the dynamics of this interaction requires characterization of the transfer function between force input and displacement output.

Prior work indicates that human joints in the upper extremity are well modeled as linear time-invariant (LTI) systems. Hogan found that the human arm behaves like a passive object when interacting with a machine, despite active control by the central nervous system [3]. That work also demonstrated that humans increase the impedance of their arm by tensing their arm muscles, adapting to various stimulii. Dolan et al. tested several dynamic models of the arm and found that the linear second-order system was most similar to observed force-displacement data about an equilibrium point [4]. Tsuji et al. also estimated hand impedance with a linear second-order model, finding that the subject's grip force on a manipulandum increased both stiffness and damping in the system [5]. Recently, Milner examined the impedance of the human wrist when empty-handed and found agreement with a second order model, again observing changes in impedance through muscle cocontraction [6]. These previous findings indicate that a second-order LTI system would provide useful information about the behavior of the human wrist when grasping a stylus.

The model's assumption of time invariance only holds when activation levels in the muscles surrounding the joint stay constant. This research uses a measurement of stylus grip force to track muscle activation around the wrist joint, and all tests are performed while the subject maintains a constant grip force. Results presented in Section 3 demonstrate that a second-order LTI model adequately characterizes the dynamics of passive wrist movement seen in exploratory tapping. Section 4 presents the effect of grip force variation on these model parameters, and Section 5 contains conclusions and suggestions for future work.

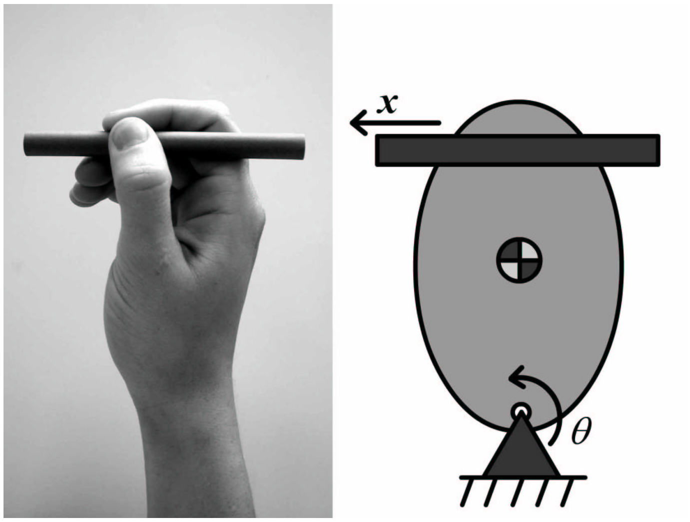

Figure 1. ONE-DEGREE-OF-FREEDOM WRIST MODEL: In a standard three-finger pen grasp, the fingers form a rigid structure and the hand rotates about the wrist joint, causing translation of the stylus.

3 MODEL IDENTIFICATION

Standard system identification techniques provide a framework for the characterization of linear time-invariant systems; such approaches are often used to characterize human joint dynamics [7, 8]. This study uses two different system identification methods to investigate the dynamic behavior of the wrist joint: frequency response, also known as spectral analysis, and time response. The model parameters for a given grip force were extracted directly from each subject's frequency response data. The results of these two non-parametric investigations were compared in order to elucidate the order and coefficients of the model as well as validate the experimental method.

3.1 EXPERIMENTAL SETUP

System identification requires the ability to apply a variety of force signals to the system and observe the resulting displacement of the joint. A custom one-degree-of-freedom testbed was developed for these experiments, as shown in Figure 2. Extension and flexion of the wrist joint are isolated through a stylus

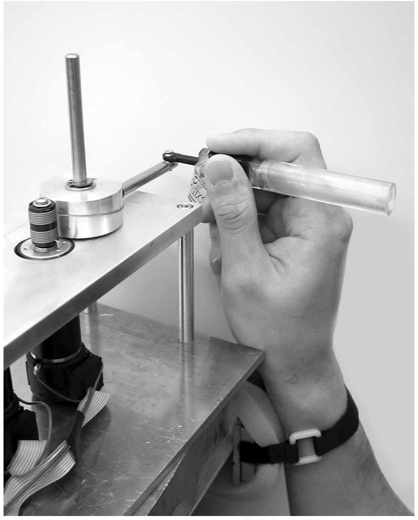

Figure 2. EXPERIMENTAL SETUP: The stylus attaches to an electric motor, providing force display and position measurement. A force sensor under the thumb measures grip force.

interface, modeled after exploratory tapping procedures.

The experimental setup centers around a lightweight, pen-sized stylus. Subjects grasp the stylus between their thumb and first two fingers with their forearm immobilized against the edge of the table by a padded strap. A small force-sensing resistor, located on a flat area under the user's thumb, measures grip force. The tip of the stylus is attached to a perpendicular lever arm by a small ball and socket joint to allow the user to assume a comfortable hand posture throughout the experiment. A high fidelity DC motor drives the lever arm through a simple torque-amplifying cable drive. The optical encoder on the motor is used to measure the position of the tip of the stylus. Data from the grip force sensor and encoder are recorded at a rate of 1 kHz, and the applied force signal is updated at the same frequency. Assuming a small range of motion, the motor data maps linearly to the stylus tip, enabling characterization of the wrist's effective transfer function. This simple setup isolates the motion of the user's wrist to resemble the act of tapping on a surface with a stylus.

Six subjects participated in this study, five men and one woman. They ranged in age from twenty-two to thirty-six and had various levels of experience with haptic devices. All subjects completed the experiment with their right hand, including the one left-handed male. The position of the experimental setup was adjusted for the comfort of each subject, so that their initial wrist position corresponded to the center of the testbed's workspace. Once their hand was so positioned in the device, subjects were shown a graphical display of grip force on a computer monitor in front of them. They then performed several practice tests, maintaining their grip force at a constant pre-specified level without consciously resisting the forces applied to the stylus.

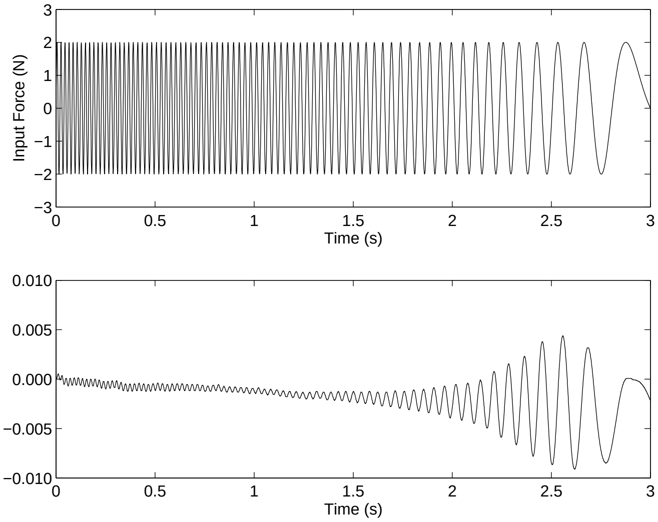

Figure 3. INPUT AND SAMPLE OUTPUT SIGNALS: The system responds to a swept sine wave input with equivalent frequency content and variable magnitude and phase, which is typical of an LTI system.

The experiment itself was broken into three sets of six frequency response trials at three seconds per trial. Each set included one trial at each of six grip force levels between 5 N and 25 N, randomized to eliminate order effects. A short pause of about ten seconds occurred between trials, and a longer break was given between sets to prevent fatigue. Three subjects also participated in time response trials, performing three short pulse response tests at a single grip force level after completing the frequency response sets.

3.2 FREQUENCY RESPONSE

Spectral analysis was conducted in order to identify the frequency response characteristics of the human wrist. Such a strategy is commonly used to characterize the behavior of unknown mechanical systems, and other researchers have used it successfully to develop a one-degree-of-freedom model of the human arm [9]. This technique compares the frequency content of an input signal with that of the system's corresponding output using discrete Fourier transforms (DFTs). The ratio of output to input DFTs yields an empirical transfer function estimate (ETFE), or experimental Bode plot [10]. A swept sine wave force input, which has a linearly varying frequency, is commonly used because it achieves uniform stimulation of the system's governing dynamics.

This work uses a three-second-long swept-sine-wave input signal, starting at 50 Hz and ending at 1 Hz, as shown in the top half of Figure 3. Shorter tests do not provide enough excitation at the low frequencies of interest, and longer tests require the subject to remain passive for longer than most can manage. The frequency range was chosen to bracket the anticipated resonant frequency near 5.5 Hz reported for a relaxed wrist in [6]. The system responds minimally above 50 Hz, and the subject's active response begins to interfere with the test near 1 Hz, so these values were chosen as extrema. Beginning the signal at its maximum frequency creates a smaller start-up transient and lowers the subject's propensity to actively respond to the stimulus. During each trial, subjects were asked to maintain a constant grip force at one of six levels between 5 N and 25 N. Initial analysis and model validation focused on the tests at 9 N, a moderate level. Analysis of the effect of grip force variation appears in Section 4.

A sample trial with input and output signals for one subject at 9 N grip force is shown in Figure 3. The system's response is seen to be a sine wave of the same frequency as the input signal across the length of the test. The magnitude and phase of the response vary with frequency, supporting our assumptions of linearity and time invariance. A small start-up transient and low magnitude drift can be observed, but the system generally conforms to our model. The wrist acts to attenuate the input at high frequencies, but its strong response near 2.5 seconds indicates the presence of a resonant mode.

The ETFE of this system is formed by dividing the discrete Fourier transform of the output signal by that of the input. For each subject the ETFEs from all three trials at 9 N grip strength were averaged together, and the magnitude and phase of the resulting values were smoothed with a boxcar filter. The resulting diagram can be viewed as an experimentally determined Bode plot, as seen in the sample shown in Figure 4. The shape of the system's frequency response corresponds to that of a second-order system with a lightly damped resonance at 10 Hz.

Figure 4 also shows the frequency response of the linear second-order system that best fits these experimental results. The behavior of such a system is given in Equation (1), where x is the displacement of the end of the stylus, m, b, and k, are the effective endpoint mass, damping, and stiffness of the hand, and F is the applied force.

$$m\ddot{x} + b\dot{x} + kx = F \tag{1}$$

The experimentally determined response matches the model well at frequencies between 3 and 30 Hz. The two diverge at low frequency, where the subject actively compensates for the stimulus, and at high frequency, where encoder noise begins to dominate the signal. For a moderate range of frequencies, though, spectral analysis indicates that the human wrist holding a stylus behaves like a second-order LTI system.

3.3 TIME RESPONSE

An analysis of the wrist's response to signals in the time domain was conducted for comparison with the frequency domain results. A similar time response approach was used in [11] to identify the dynamics of the human hand grasping a haptic knob. As discussed in this reference, transient signals are difficult to use for identification of human joint dynamics because the subject reacts to the sudden stimulus as quickly as 20-30 ms after it begins. An input pulse of short duration and high magnitude can thus be used, and the response during the first tens of milliseconds can be analyzed.

The time response of three subject's wrists was tested by ad-

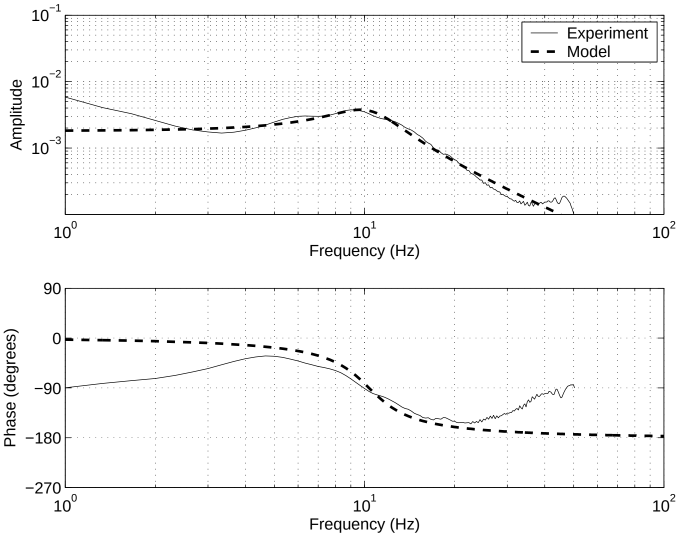

Figure 4. TYPICAL ETFE: An experimentally determined Bode plot, averaged from three trials by one subject, shows second-order behavior in the frequency range of interest.

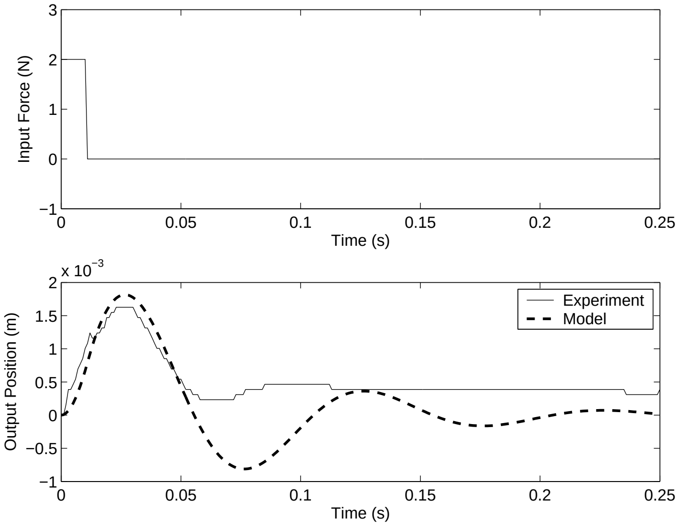

Figure 5. PULSE RESPONSE: The initial response to a pulse matches the second-order behavior indicated by frequency domain analysis.

ministering a 10 ms pulse and measuring the resulting movement of the stylus while they maintained a constant grip force of 9 N. A sample output for one trial is shown in Figure 5, along with the response predicted by the second-order wrist model identified for this subject using frequency domain analysis. The experimental response corresponds well to the predicted signal, matching initial slope and approximate peak amplitude. After 50 ms, the muscles in the subject's wrist and hand contract reflexively, and the small amplitude motion dissipates quickly. The initial time response of the system, however, confirms the second-order system model obtained through spectral analysis and validates the frequency domain approach to wrist joint characterization.

3.4 MODEL PARAMETERS

Frequency and time domain analyses yield the effective endpoint mass, damping, and stiffness of each subject's hand for a moderate grip force. These values characterize the translational second-order system fit to the experimental force and position data, and they serve to predict user behavior with this particular device. Generalizations require viewing the wrist as a rotational second-order system instead, as governed by Equation (2), where θ is the angular displacement of the wrist and τ is the torque applied to this joint. The wrist's rotational inertia J, damping coefficient β, and stiffness coefficient κ are related to the translational parameters by R^2, the square of the distance from the wrist joint to the stylus.

$$J\ddot{\theta}+\beta\dot{\theta}+\kappa\theta=\tau \qquad J=mR^2 \quad \beta=bR^2 \quad \kappa=kR^2 \tag{2}$$

Table 1 lists effective translational and derived rotational parameters for all six subjects at the same grip force level of 9 N. The rotational inertia values match well with those calculated for each subject using the mass and length approximations given in [12]. Furthermore, the rotational damping and stiffness parameters can be compared with values previously published for the relaxed wrist. The relaxed wrist's damping coefficient is given as 0.02 to 0.03 Nms/rad [13] and the relaxed wrist's stiffness coefficient is given as about 3 Nm/rad (De Serres and Milner 1991, as cited in [6]). Gripping a stylus contracts the muscles surrounding the wrist, so the values identified in this work are expectedly higher than those found for a relaxed wrist.

Table 1. MODEL PARAMETERS: Effective linear and rotational parameters for all subjects at 9 N grip force.

Subject	m (kg)	b (Ns/m)	k (N/m)	J (kgm^2)	β (Nms/rad)	κ (Nm/rad)
1	0.135	4.5	440	0.0021	0.070	6.82
2	0.150	6.0	520	0.0020	0.078	6.79
3	0.130	4.3	560	0.0014	0.048	6.22
4	0.160	6.0	500	0.0023	0.086	7.20
5	0.140	4.8	750	0.0015	0.052	8.12
6	0.140	4.6	460	0.0013	0.044	4.40

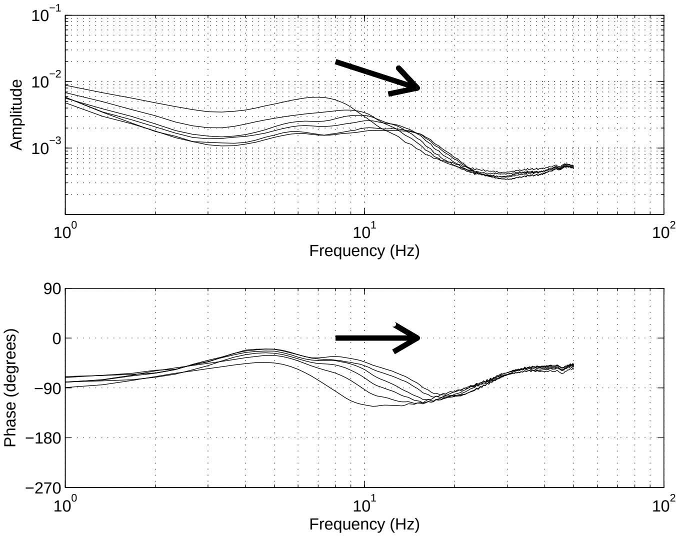

Figure 6. TYPICAL ETFES FOR VARYING GRIP FORCE: Stiffness and damping increase as grip force rises, as shown by the trend arrows, increasing the second-order system's resonant frequency and damping ratio.

Many sources support approximating human joint dynamics as a linear second-order system, including joints in the fingers, hands, and arms. Finding such a result for the wrist using traditional system identification techniques validates our methodology and suggests that it can be used for further study of the relationship between grip force and joint impedance.

4 GRIP FORCE VARIATION

Subsequent analysis investigated the relationship between grip force and wrist joint mechanical impedance. The increased muscle activation associated with higher grip force also changes the subject's effective stiffness and damping. The frequency response technique detailed in Section 3.2 was applied to the experimental data taken at six different grip force levels: 5, 9, 13, 17, 21, and 25 N. As discussed above in Section 3.1, each subject conducted three trials of a swept sine wave input at each grip force level. The trials were then analyzed to produce an average ETFE at each grip force level for each subject. This set of six ETFEs elucidates trends in wrist behavior, as shown in Figure 6 for one subject. Complete results for all subjects are appended in Figure 8.

The ETFE magnitude and phase plots change shape incrementally as grip force increases. Response magnitude and resonant peak height decrease, and resonant frequency increases. These trends correspond to increasing the stiffness and damping

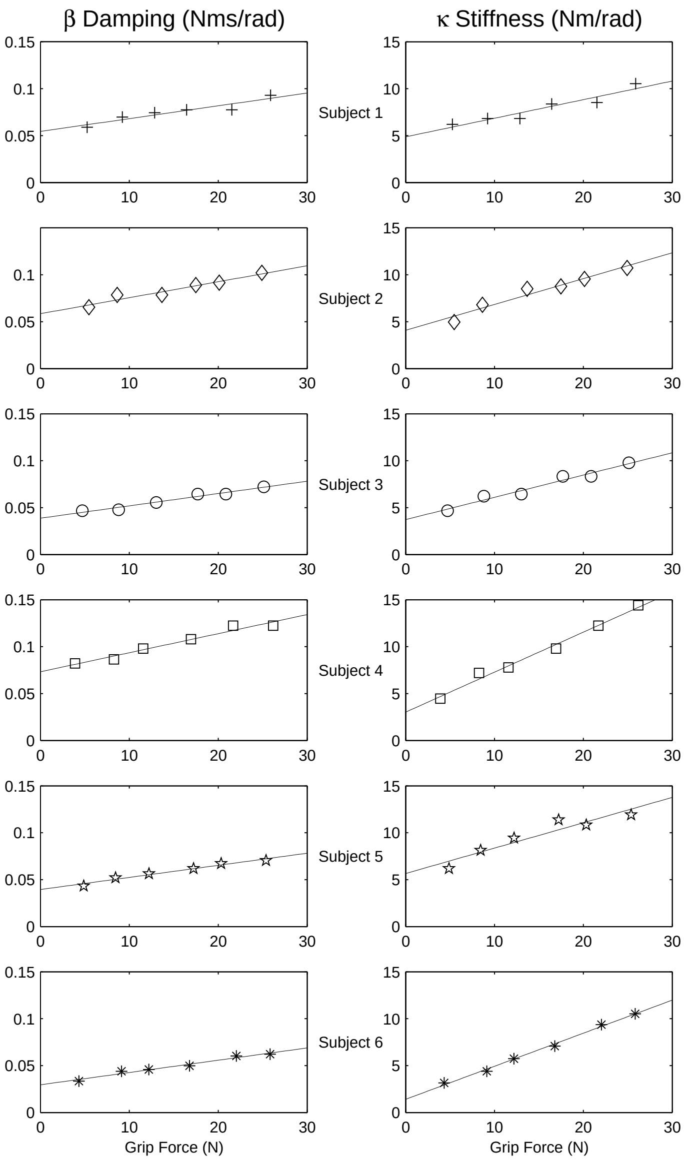

Figure 7. DAMPING AND STIFFNESS TRENDS: All subjects show an approximately linear increase with rising grip force.

of the second-order system as the subject's wrist muscles contract more strongly and grip force increases. Similar trends have been observed by researchers characterizing the human hand and arm [5, 11].

To examine the parametric changes, a second-order system was fit to each averaged ETFE. A single inertia value was obtained for each subject and used for all six test conditions. Damping and stiffness values were fit to each grip force plot, varying substantially over the range of conditions tested. The extracted rotational coefficients β and κ show a positive linear correlation to grip force, as shown for all subjects in Figure 7. The coefficient of determination r^2 for damping ranges from 0.885 to 0.970 and for stiffness ranges from 0.896 to 0.995 across subjects, with a mean value in both cases of 0.95. This value can be interpreted to mean that about 95% of the variability in damping and stiffness can be explained by their relationship to grip force. These findings indicate that there is a strong linear trend between grip force and wrist damping and stiffness.

The straight-line estimators shown in Figure 7 capture the tendency of each system to increase impedance as grip force increases. Fitting a single linear regression to the pooled subject data yields a much poorer fit, with a coefficient of determination r^2 of 0.25 for damping and 0.73 for stiffness. The slope and intercept that match each subject's trends are unique for both damping and stiffness; using a generalized model would inadequately characterize the variations observed. Such findings indicate that a linear model could be used to accurately predict changes in damping and stiffness when calibrated to each user of a haptic system.

5 CONCLUSIONS

The results of this study show that the human wrist grasping a stylus can be well modeled as a second-order linear system. Stiffness and damping were found to increase almost linearly with stylus grip force, though inter-subject variability for these parameters was significant. These findings indicate that a haptic display could use an initial calibration procedure and a simple grip force measurement to continuously estimate the impedance of the user.

General haptic design can be improved by incorporating such knowledge into new control schemes that adapt to sensed changes in grip force. For example, a system could be designed to automatically change the stiffness of virtual objects to correspond to the firmness of the user's grip. Such modifications may create a more effective haptic experience. A haptic controller could also use this information to compute the force profile needed to perfectly stop the user's hand in motion when it comes in contact with a virtual object, giving the user the illusion of contact with a very rigid surface.

Alternatively, a telerobotic system could change the impedance of the slave robot to match that of the human operator, a capability that could be useful in unpredictable remote environments. A telerobotic system could also use this operator model to estimate the user's response to high frequency force feedback from the slave. The controller could then subtract it from the commanded position to stave off closed loop instability. All of these applications are currently under investigation, building on this characterization of the user's effective impedance.

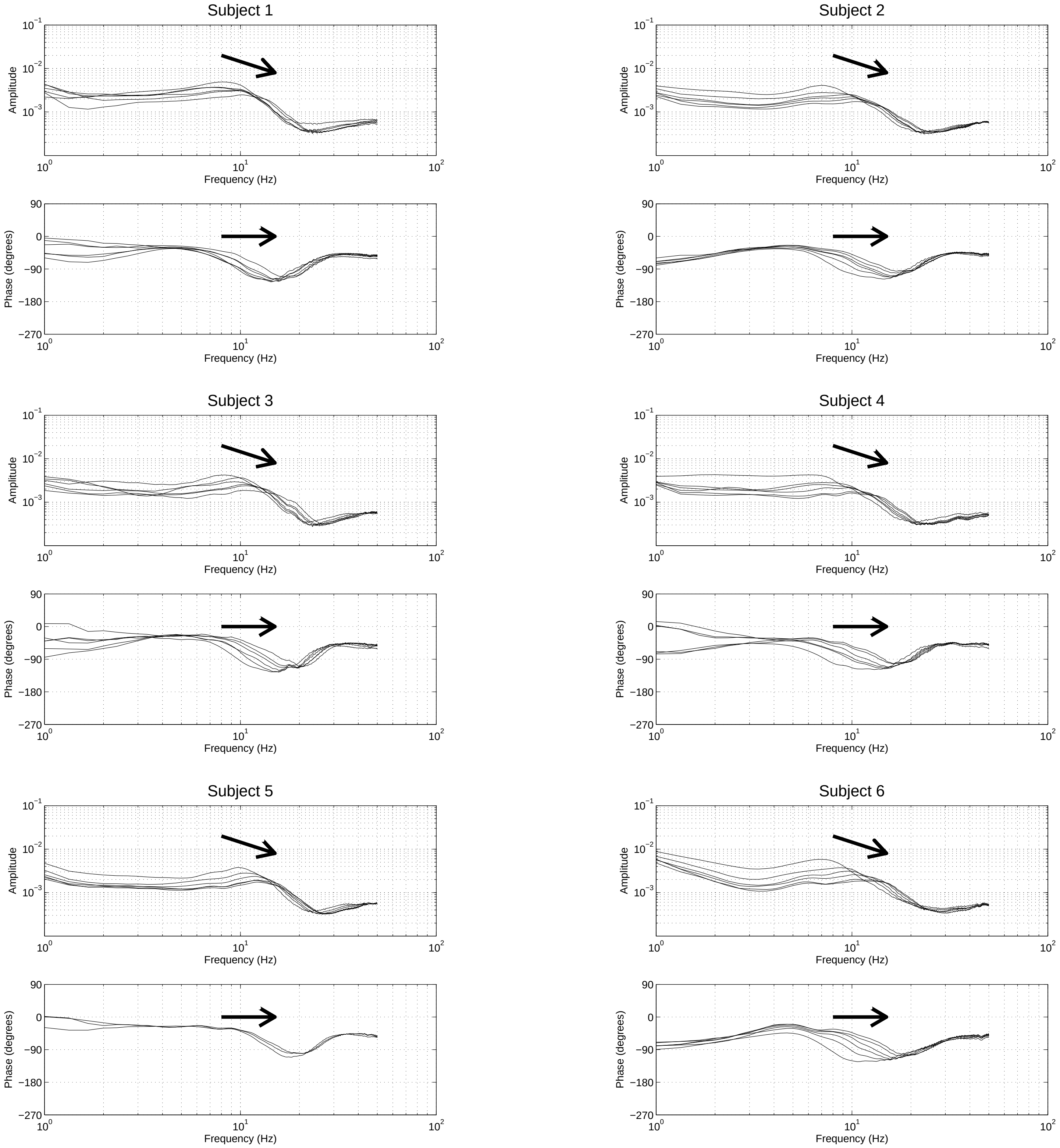

Figure 8. ETFES WITH VARYING GRIP FORCE: All subjects exhibit similar trends of increasing resonant frequency and damping ratio with grip force, as depicted by the trend arrows.

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