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MECHANICAL IMPEDANCE AND ENERGY DISSIPATION IN THE HUMAN FINGERPAD

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INTRODUCTION

The fleshy pad at the tip of the human finger mediates many of our mechanical interactions with the world. Because it acts as a coupling element between the hand and grasped objects, a complete explanation of precision manipulation must include the role of fingerpad deformation. Fingerpad mechanics are also important in tactile sensing, as the receptors respond to changes in skin curvature. In addition, a better understanding of fingerpad impedance is important in practical applications like the ergonomic design of vibrating tools [4,6] and in the analysis of repetitive tasks like keyboard typing [5].

A few researchers [4,6] have measured the linear impedance of the fingerpad as a function of frequency for a variety of preload forces. Both Gulati and Srinivsan [2,3], and Serina, Mote and Rempel [5] have examined the fingerpad response in similar force and frequency ranges to those presented here, proposing ad-hoc piecewise models. This paper presents experimental measurements and an experimentally-based model that relates the displacement and velocity applied to the fingerpad to the force response. We also use this model to analyze the energy dissipated by the fingerpad, which is important for ergonomic design.

EXPERIMENTAL METHODS

A flat-tipped, motorized indentor applied controlled displacements normal to the fingerpad of the index finger. The subject's hand was supported in a plastic mold with the index finger raised at a 20° to 40° angle to approximate contact angles in fingertip manipulation. The resulting force as well as the position, velocity and acceleration were recorded. To identify the system, a fast displacement ramp (60 mm/sec) was applied to approximately 2 to 3 N, followed by a 5 to 7 sec hold phase at the end point position. To verify the resulting model, the response to sinusoidal displacements (2, 4, 8 and 16 Hz) was measured. Four healthy subjects voluntarily participated.

EXPERIMENTAL RESULTS

The experimental data from all subjects for the system identification protocol showed an exponentially increasing force response to the fast position ramp (Figure 1). For the position hold phase, subjects showed an exponentially decaying force response which approached a non-zero steady state value within 5 to 7 seconds (Figure 2). The responses to the sinusoidal displacement trajectories of differing frequencies exhibited the same general characteristics of the previous data: nonlinear increasing stiffness and linear force relaxation.

ANALYSIS

Model. We propose a model of the fingerpad based on Fung's quasi-linear viscoelastic model of tissue [1]. It consists of two components: (1) an instantaneous elastic response, $T^{(e)}(x)$, which is the instantaneous force response of the fingerpad to a step change in position, x; and (2) the reduced relaxation function, $G(t)$, which is the normalized, time varying response of the fingerpad following the position step.

The elastic response, $T^{(e)}(x)$, can be determined by the fast ramp portion of the ramp and hold protocol. Examination of the force response as a function of position (Figure 1) suggested that it can be modeled as an exponential function of position, analogous to tissues of constant cross-sectional area

$$T^{(e)}(x)=\frac{b}{m}\left[e^{m(x-x_0)}-1\right]. \qquad (1)$$

The mean values of the constants b and m determined from the experimental data were 2.1 mm^{-1} and 0.19 N/mm, respectively. The variation of the force response accounted for was, on average, 97%.

The reduced relaxation function, $G(t)$, can be determined by the hold phase of the ramp and hold protocol (Figure 2). Examination of the data suggested that three time constants and a constant term were needed. $G(t)$ is then represented by

$$G(t)=\left(c_0+\sum_{i=1}^{3}c_i e^{-v_i t}\right)\Big/\sum_{i=0}^{3}c_i \qquad (2)$$

where c_i are the proportion each term contributes to the force relaxation response and v_i are the time constants. The mean values determined for c_i were 0.26, 0.41, 0.18 and

0.15, for i = 0 to 3 respectively, and the mean values of the time constants were 4 msec, 67 msec and 1.5 sec. The variation accounted for by Equation 2 was, on average, 87%. Most of the remaining variance is probably due to blood pressure variations at the pulse frequency.

The resulting force response, *F(t)*, to an arbitrary applied displacement trajectory, *x(t)*, is then described by the convolution

$$F(t)=\int_{-\infty}^{t} G(t-\tau)\frac{\partial T^{e}\left[x(\tau)\right]}{\partial x}\frac{\partial x(\tau)}{\partial \tau}d\tau \qquad (3)$$

The model was verified using the force responses to the sinusoidal position trajectories, and was accurate to within a few percent.

Energy Considerations. Energy dissipation is an important consideration during tasks as it is potentially detrimental to the tissues involved. The amount of energy dissipated by the fingerpad is affected by many variables. Significant differences occur based solely on the nature of the task: some tasks consist of transient inputs, such as a tap during typing, while others are a steady state repetitive input, such as the vibration of a power tool. Our impedance model can be used to quantitatively examine this issue. We applied sinusoidal inputs superposed on an offset of 1.5 mm to the model, examining the initial and steady state responses. An input duration of eight seconds allowed transient effects to relax to a steady state response.

We calculated the power dissipation

$$P=W/\Delta t \qquad (4)$$

where Δt is the time duration considered and W is the work done, calculated numerically from the applied displacement, x, and force response, F, as

$$W=\int F dx\,. \qquad (5)$$

F is calculated from Equation (3). The power dissipated, P, was calculated over the first half sinusoid as an estimate of the initial transient, and over the last full sinusoid to estimate the steady state results.

As shown in Figure 3, the power dissipation is about 1.5 to 3 times greater during the initial transient than in the steady state. The extreme case of a transitory input is perhaps a rapid tap, which is a simple approximation to typing. During the loading phase, more work is done due to the rapid change of the input. During the unloading phase, the finger may break contact with the object because of the finite time response of the tissue. (In these simulations, amplitudes were chosen to always maintain contact.) In the extreme case contact breaks immediately when the direction reverses and no work is done during the unloading phase; all the work done during contact is therefore dissipated.

DISCUSSION

The model presented here further forms the basis for an explanation of the distributed pressure response across the fingerpad, which we have experimentally measured. This provides localized information necessary for understanding the basis of manipulation and tactile sensing.

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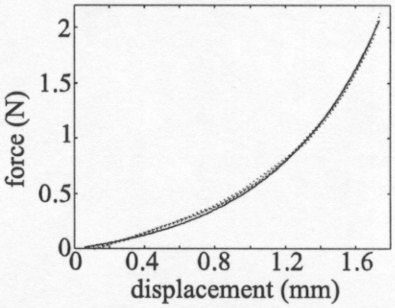

Figure 1. Typical elastic response. Dotted lines are four experimental trials; the solid line is the model fit.

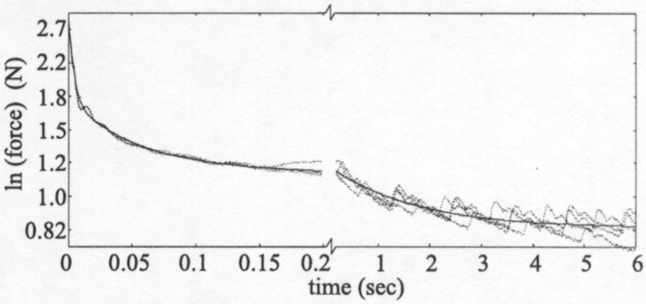

Figure 2. Typical force relaxation. Dotted lines are four experimental trials; the solid line is the model fit. Blood pressure variations at about 1 Hz are clearly visible.

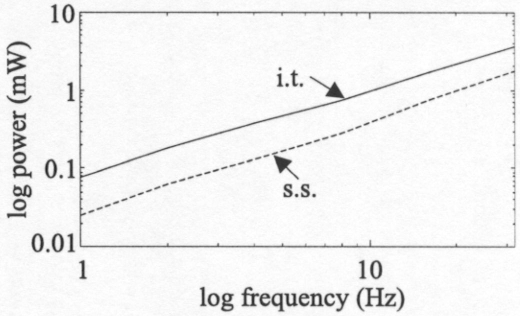

Figure 3. Estimated power dissipation. Comparison of initial transient (i.t.) and steady state (s.s.) responses for 0.28 mm peak-to-peak sinusoidal displacement inputs superposed on an offset of 1.5 mm.