

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 indenter 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

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

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

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

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

