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Mechanical behavior of the fingertip in the range of frequencies and displacements relevant to touch

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ABSTRACT

It was previously suggested that the mechanical properties of the fingertip could be characterized by elasticity from DC to about 100 Hz and by viscosity above this frequency. Using a specifically designed high mobility probe, we accurately measured the impedance of the fingertips of seven participants under a variety of conditions relevant to purposeful touch. Direct measurements vindicated previous indirect observations. We also characterized the dependency of the fingertip impedance upon normal load, orientation, and time.

1. Introduction

There is an indirect evidence that a fingertip can be represented by a dominantly elastic load up to a frequency of about 100 Hz, beyond which the load presented by the fingertip, by and large, becomes entirely viscous. This evidence was obtained by Cohen et al. (1999, Fig. 6) using stroboscopic illumination to observe the movements of the glabrous skin when excited by a probe vibrating in the range 0.5–240 Hz, and with displacements up to 1 mm. They found that the probe had a tendency to decouple from the skin for increasingly smaller probe displacements past a frequency of 80 Hz, which is indicative of phase shift between force and displacement. Lamoré et al. (1986) stimulated mechanoreceptors through conventional sinusoidal excitation and through the amplitude modulation of a 2 kHz carrier. They found that the skin could be represented by a high-pass mechanical filter with a corner frequency at 80 Hz (Lamoré et al., 1986, Fig. 4). These findings are mutually consistent considering that the skin operates as a transmission medium in the latter experiment, whereas it acts as a load in the former. They are also are in accordance with earlier results obtained from vibrating the skin of the arm and the thigh (von Gierke et al., 1952), although the finger differs anatomically from these areas. A probe contact area of 2.17 cm^2, similar to a finger contact surface area, gives a cross-over frequency of 100 Hz (Moore, 1970, Fig. 2).

We hypothesized that the fingertip can be represented in the tangential direction by an elastic load up to about 100 Hz, by a viscous load above, and with negligible inertial contribution over the entire frequency range relevant to touch. To test this hypothesis, we developed a mechanical probe achieving very high mobility (stiffness ≤ 1.2 N/m, damping ≤ 0.5 N s/m, accelerance $\leq 10^{-3}$ N s^2/m) which could approximate a source of force when loaded by a fingertip (Wiertlewski and Hayward, 2012).

We found that the tangential elasticity of the index fingertip of seven participants ranged from 0.6×10^3 to 2.0×10^3 N/m, a result that is inline with previous studies. Moreover, we found that the viscosity of the fingertip load ranged from 0.75 to 2.38 N s/m and that the inertia of the tissues entrained by a light touch ranged from 110 to 230 mg. Viscous forces indeed far dominate the elastic and inertial forces above 100 Hz. We evaluated the effects of the normal load, orientation, and time course of stimulation. Contact mechanics considerations were used to evaluate the effective complex Young modulus of the fingertip tissues.

2. Previous approaches to the direct determination of fingertip mechanics

Hajian and Howe (1997) found that a finger could be represented by a mass–spring–damper system through impulsive testing delivered by a pneumatic piston acting against a finger that underwent significant rigid-body displacement. Since the excitation had little high-frequency energy, the identification was reliable only in the low frequencies. Kern and Werthschützky (2008) used the 'impedance head' approach where force and acceleration are simultaneously measured in the proximity of the interface between the probe and the finger. This approach,

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however, is known to provide unreliable results in the high frequencies, owing to a possible lack of truly co-located measurements (Brownjohn et al., 1980).

Several other studies were performed in quasi-static conditions (Serina et al., 1997; Pawluk and Howe, 1999b; Jindrich et al., 2003). With specific reference to loading through lateral traction, Nakazawa et al. (2000) found the values of 0.5 N/mm and 2 N s/m, for elasticity and viscosity, respectively. Pataky et al. (2005), using similar methods, modeled the elastic behavior of the fingertip and the relaxation effect and found values of 1 N/mm and 11 s, for stiffness and relaxation duration, respectively.

The computational modeling of the fingertip (Srinivasan, 1989; Serina et al., 1998; Dandekar et al., 2003; Tada and Pai, 2008; Wu et al., 2007) could predict the bulk response from material properties (Silver et al., 2001; Wang and Hayward, 2007; Pan et al., 1997; Gennisson et al., 2004). The results of these studies are dispersed because of the numerous assumptions required to construct and solve the models, not mentioning the lack of anatomical realism that they must contend with (Hauck et al., 2003).

3. Materials and methods

It is crucial to use an excitation probe that stores little energy compared to that dissipated by the sample. Thus, a probe should have a high mobility compared to that of the sample. The converse approach, to maximize the impedance of the probe so that all the energy is reflected in the sample – the impedance head approach – has the shortcomings alluded to earlier. Other approaches involving air pressure or ultrasonic waves would not do justice to the contact mechanics in effect during tactual behavior.

3.1. Apparatus

The apparatus, see Fig. 1, comprised a probing plate suspended by an eight-bar flexure that guided its movements in the tangential direction. It was stiff in the normal direction. The probe was driven by a voice-coil actuator. To reduce its impedance, position, velocity, and acceleration measurements were fed back, see Fig. 2, where $f_d(t)$ was the interaction force and $\dot{x}(t)$ the velocity. The feedback was tuned to reduced the effective impedance to a small value across the DC-500 Hz range. Let $Y_p = 1/Z_p$ represent the mobility of the probe and Z_c the impedance of the active feedback, the closed-loop impedance of probe was $Z_a = (1+Y_pZ_c)/Y_p$.

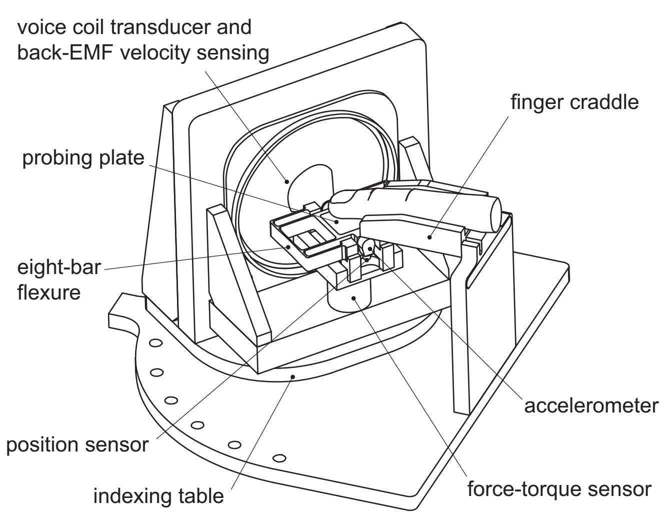

Fig. 1. Impedance measurement apparatus.

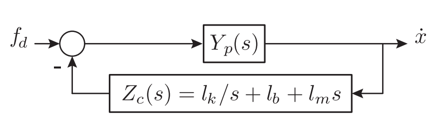

Fig. 2. Closed-loop control of the probe implemented with analog electronics feeding back sensed position, velocity and acceleration.

The instrument was supported by a conventional force–torque sensor (Nano 17, ATI Industrial Automation, Apex, NC, USA) to measure the average normal and tangential components of the interaction force. A full description is provided in Wiertlewski and Hayward (2012).

The finger was immobilized by a strap onto a hinged cradle permitting the participants to push freely on the probing plate that could be oriented by 15° steps using an indexing table that rotated about a vertical axis. The testing signal, f_d, was a logarithmic frequency sweep and the acceleration, $\ddot{x}$, was recorded. Using the Fourier transform of the two signals (Welch method), F and $\ddot{X}$, the impedance Z was computed from

$$Z(j\omega) = j\omega\frac{F(j\omega)}{\ddot{X}(j\omega)},$$

where $j=\sqrt{-1}$ and ω was the angular pulsation. The impedance of the sample was obtained by subtracting the probe unloaded impedance from the coupled impedance.

3.2. Contact condition

The contact surface was made from polycarbonate plastic. We first experimented with bonding the fingertip to the plate. This condition created a dependency of the force–displacement curves upon loading or unloading of the contact, owing to a modification of the micromechanics. Estimating that the coefficient friction was higher than 1.2, we restricted the measurement conditions to values where there should be no slip, thereby avoiding the introduction of foreign elements.

3.3. Participants

There were seven volunteer, four males and three females. They gave their informed consent. None of the participant reported any skin condition nor any injury to their fingers. The participants' ages ranged from 23 to 32 with a mean of 25 years.

3.4. Procedure

The participants washed and dried their hands. Their index finger was fastened to the cradle. Before each experimental protocol, the impedance of the unloaded probe was calibrated by measuring it 10 times. Standard deviation was never above 1% of the absolute value of the impedance and the mean value was used in the calculation of the fingertip impedance.

Small-signal linearity protocol. Participants regulated the normal force component to 0.5 N via a visual feedback available from a computer screen. Once they could stabilize the desired value, the finger impedance was recorded during a 20–500 Hz frequency sweep lasting 1 s. Proximal-distal and medial-lateral tests were performed. The tangential force applied to the fingertip was varied from 0.0625 N to 0.5 N by steps of 0.0625 N.

Normal force dependency protocol. The same frequency sweeps were used but with an amplitude of 0.25 N. Once the participant could remain longer than 10 s within a 10% tolerance range, the data were recorded. The normal force component reference values followed a loading cycle, 0.25, 0.4, 0.5, 0.6, 0.75, 1.0; 1.25, 1.5, 2.0, 1.5, 1.0, 0.5, and 0.25 N to detect, if any, the occurrence of hysteresis in the impedance values.

Directional dependency protocol. The angle between the stimulation direction and the finger proximal-distal axis was varied. The requested normal force component was 0.5 N and measurements were made each 15° in a 180° range. Impedances were recorded from both the left to right and right to left and then averaged to cancel drift in the mechanical properties.

Time dependency protocol. To achieve higher temporal resolution, the frequency sweep duration was reduced to 0.25 s and the range to 80–300 Hz. Participants stabilized the pushing force to remain within 10% of 0.5 N. Only medial-lateral stimulation was tested.

Young's modulus estimation. To estimate the contact surface area, participants pressed their inked right index finger on a sheet of paper set on a scale. They pressed until reaching a normal force component of 0.5 N. They repeated this procedure four times.

3.5. Data processing

3.5.1. Lumped parameters determination

The fingertip was modeled by a mass–spring–damper system, which gives,

$$Z(j\omega) = b + j\left(m\omega - \frac{k}{\omega}\right),$$