D. T. V. Pawluk
Johns Hopkins University,
Zanvyl Krieger Mind/Brain Institute,
338 Krieger Hall,
3400 N. Charles Street,
Baltimore, MD 21218
e-mail: dpawluk@bme.jhu.edu

R. D. Howe
Harvard University,
Division of Engineering and Applied Sciences,
Pierce Hall,
29 Oxford Street,
Cambridge, MA 02138
e-mail: howe@deas.harvard.edu

Dynamic Contact of the Human Fingerpad Against a Flat Surface

This paper investigates the dynamic, distributed pressure response of the human fingerpad in vivo when it first makes contact with an object. A flat probe was indented against the fingerpad at a 20 to 40 degree angle. Ramp-and-hold and sinusoidal displacement trajectories were applied to the fingerpad within a force range of 0–2 N. The dynamic spatial distribution of the pressure response was measured using a tactile array sensor. Both the local pressure variation and the total force exhibited nonlinear stiffness (exponential with displacement) and significant temporal relaxation. The shape of the contact pressure distribution could plausibly be described by an inverted paraboloid. A model based on the contact of a rigid plane (the object) and a linear viscoelastic sphere (the fingerpad), modified to include a nonlinear modulus of elasticity, can account for the principal features of the distributed pressure response.

1 Introduction

As a finger touches a rigid object, the skin contact area begins as a small spot, then expands to subtend much of the fleshy pad of the fingertip. The changing pressure distribution across the skin is an important determinant of the mechanical behavior of the hand–object system in manipulation (Howe and Cutkosky, 1996). It also provides information about the local mechanical conditions at the surface of the skin to which the tactile receptors respond (Johansson and Vallbo, 1983). Both this mechanical interaction and the tactile sensory response are important for the understanding of human dexterity (Johansson and Westling, 1984). In addition, in order to display tactile feedback to a user's fingers realistically in teleoperation and virtual reality (Cohn et al., 1993; Wellman et al., 1997), as well as minimally invasive surgery (Howe et al., 1995), we must understand how the fingers would have interacted with remote objects if they were in direct contact.

There have been several previous studies examining the dynamic force response of the fingerpad to indentors of various shapes and sizes (Gulati and Srinivasan, 1995; Serina et al., 1997; Pawluk and Howe, 1999), finding both a nonlinear stiffness and significant relaxation across time. For the aforementioned applications, we further need to understand how this force is spatially distributed on the fingerpad and how this distribution varies with the time history of indentation. A few related studies have examined other contact parameters during indentation of the fingerpad. Srinivasan (1989) investigated the deformation profile of the fingerpad to a static line load, modeling it as a fluid-filled membrane under plane strain conditions. Similarly, Pubols (1987) measured the deformation profile to a dynamic point probe. Both Westling and Johansson (1987) and Serina (1996; Serina et al., 1998) have examined the growing contact area during quasi-static indentations, for which Serina further proposed an ellipsoidal fluid-filled membrane model. Lee and Rim (1991) used pressure-sensitive film to determine the net peak force and pressure centroid on a fingerpad during grasping for forces within the range 10–200 N. However, none of these studies have experimentally examined the pressure distribution.

There have also been several distributed, linear, mechanical models proposed to relate mechanical stimuli on the surface of the skin to the tactile sensory response (Phillips and Johnson, 1981; Van Doren, 1987; 1989; Srinivasan and Dandekar, 1996; Dandekar, 1995; Maeno et al., 1997). None of these models agree with the nonlinear variation of pressure with indentation observed in the experimental data presented below. In addition, models based on finite element techniques (Srinivasan and Dandekar, 1996; Dandekar, 1995; Maeno et al., 1997) are computationally expensive and thus inappropriate for tactile display applications.

The main objectives of this paper are twofold. The first is to measure the distributed pressure response of the fingerpad when a flat surface is applied with various *dynamic* displacements within the force range of 0 and 2 N. The second is to develop a model that is compatible with the observed measurements and has a closed-form solution. A closed-form solution is essential for providing real-time tactile feedback in teleoperational and virtual environments, as well as providing an efficient analysis tool for examining more complex systems in which the fingerpad is a part.

2 Methods

2.1 Experimental Apparatus. A flat-tipped, motorized indentor (Fig. 1) applied controlled displacements vertically (with reference to the tabletop) to the fingerpad of the index finger of the right hand (Pawluk and Howe, 1999). The subject's hand was supported in a plastic mold closely fitted to the dorsum of the hand with the index finger raised at a 20 to 40 degree angle with respect to the axis of the distal phalange. The hand and forearm were constrained using athletic tape, and the fingernail was glued to the mold to preclude fingerpad movement.

A two-axis strain gage based force sensor (rms noise ≈ 3 mN) measured the forces in the vertical and in the proximal–distal horizontal direction. A 4.5 g, low-impedance piezoelectric accelerometer (Model 8636B500, Kistler Instrument Corporation, Amherst, NY) measured the acceleration of the indentor tip (rms noise ≈ 90 mm/s^2, resonant frequency = 22 kHz). A magnetoresistive position sensor (Rotary Blue Pot Model CP-2UT, Midori America Corporation, Fullerton, CA) located on the motor shaft measured the position of the indentor (rms noise ≈ 3 μm). A flat 8 element × 8 element capacitive tactile array sensor (Pawluk et al., 1998), mounted in front of the tip, measured the pressure distribution. The total force, position, and acceleration were sampled at 13 kHz. The tactile array elements were sequentially sampled at the same 13 kHz rate, corresponding to a sampling rate of 200 Hz for the individual elements.

The elements of the tactile array sensor were spaced 2 mm apart,

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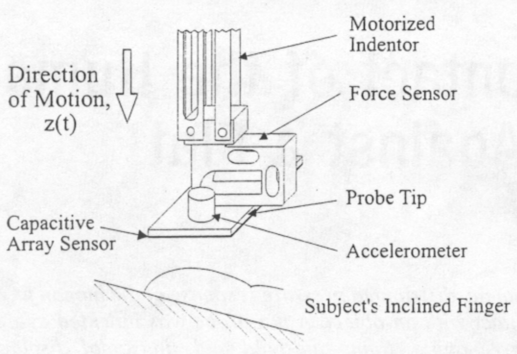

Fig. 1 Side view of the tip of the experimental apparatus

giving a total sensor area of 256 mm^2; this spacing is smaller than the mean width of the receptive fields of tactile receptors (Johansson and Vallbo, 1983) and typical of the pin spacing in a tactile display (Cohn et al., 1993; Howe et al., 1995). The noise of the sensor was Gaussian with a standard deviation of 0.5 kPa. The modulus of elasticity of the sensor was 1 MPa; the resulting error introduced into the measured pressures had a mean of approximately 4 percent and a standard deviation of 4 percent. Temporally, the responses of the array elements typically reached within 85 percent of their final value in less than 5 ms. Spatially, summation occurred across an element and to a lesser extent between adjacent elements; the coupling between adjacent elements was less than 8 percent. The spatial impulse function was similar for all elements and can be closely approximated by

$$f_{\text{spatial}}(r) = \frac{1}{2\pi\sigma^2}\, e^{(-1/2)[(r^2/\sigma^2)]} \qquad (1)$$

where $\sigma = 0.96$ mm and r is the radial distance from the center of the element. Details of the calibration and verification procedures can be found in Pawluk et al. (1998).

2.2 Experimental Design

Protocol. Forces of 0–2 N were used as this range is the most relevant for grasping and precision manipulation and for the mechanoreceptors' response (Westling and Johansson, 1987). Two different input trajectories were used to identify the system. First, the static elastic response was examined using a quasi-static indentation trajectory. A 0.2 mm/s (quasi-static) position ramp was applied to the fingerpad to approximately 2–3 N; 0.2 mm/s was chosen because the force response did not differ appreciably from that at slower speeds (Pawluk and Howe, 1999). Second, a fast ramp at 60 mm/s was applied to approximately 2–3 N, followed by a 5–7 s hold phase at the end point position. The objective of this component of the analysis was to examine time-independent effects (the instantaneous elastic response) with the fast ramp, and time-dependent effects (the relaxation function) with the hold phase (Fung, 1993). Sixty mm/s was chosen because the force response did not differ appreciably for higher speeds (Pawluk and Howe, 1999).

The system response to more general, but easily interpretable inputs, was also investigated using sinusoidal trajectories. These trajectories were a smooth position ramp to a set operating point, followed by five cycles of either a 2, 4, 8, or 16 Hz position sinusoid, which spanned a force range from close to 0 N to approximately 2 N.

The protocol applied four trials of the quasi-static ramp, followed by four trials of the fast ramp and hold, then a pseudo-random presentation of four trials each of the four different types of sinusoidal trajectories (16 trials) and, finally, four trials, again, of the fast ramp and hold. The latter four trials were to verify repeatability. Five healthy subjects (one female, four male; ages 20–28) voluntarily participated.

Additional Considerations. The center of contact with the fingerpad, determined by the pressure centroid at a force level of 2–3 N, was aligned with the center of the tactile array before the protocol was executed. This allowed at least most, if not all, of the contact area to be measured by the tactile array sensor. In addition, because of its importance in modeling the contact distribution, the pressure centroid was recorded both before and after the experiment to verify minimum movement.

During the experiment, the fingerpad was allowed to recover from viscoelastic effects for a minimum of 14 seconds between each trial; the adequacy of this interval was previously verified (Pawluk and Howe, 1999). In the case of the fast ramp and hold, it was necessary to adjust the force response to compensate for inertial effects due to deceleration of the probe tip in front of the force sensor. This was performed by measuring the acceleration of the probe tip and using it to calculate a correction for the measured force due to the inertial forces (Pawluk and Howe, 1999). To minimize the effect of any drift in the sensors, the data just before contact in each trial were used as a baseline for the force, acceleration, and distributed pressure measurements. For all experiments, the measured force in the longitudinal horizontal direction was below 4 percent of the vertical force at the same instant in time. Friction was minimized by using a thin layer of petroleum jelly on the surface of the sensor.

3 Experimental Results

Quasi-Static Ramp. The total force response to the quasi-static ramp (Fig. 2) showed an exponential response, as did the pressure response of the individual elements with decreasing magnitudes from the center of contact. During the indentation, the contact area grew significantly during the initial contact and then more slowly at higher force levels. Although the distribution was symmetric in the latitudinal (medial–lateral) direction of the finger, there was a clear asymmetry in the longitudinal (proximal–distal) direction of the fingerpad (Fig. 3). This asymmetry grew slightly with increasing indentation (from 0 to 3 N) as the pressure centroid was found to move 0.6 mm, on average across subjects, away from the distal tip. The pressure profiles as a function of radial distance from the center of contact were similar at all force levels (Fig. 4), appearing parabolic in shape. The small nonzero values of pressure at large values of radial displacement (i.e., the "tails"), which all profiles exhibited, can be attributed to the spatial response of the tactile array sensor used to measure the pressure distribution (Pawluk et al., 1998).

Fast Ramp-and-Hold. The total force response of the fingerpad for all subjects showed an exponentially increasing response to the fast position ramp and an exponentially decaying force response to the position hold phase (Fig. 5). The pressure responses of all of the individual array elements also roughly showed similar characteristics (as shown for the hold phase in Fig. 5). However, the sampling limitation for an individual element (i.e., 200 Hz) made it difficult to determine the details of the form as it precluded capture of the fast transients.

Sinusoids. In order to determine whether the characteristics of the pressure responses observed during the system identification held for more general inputs, we examined the responses to sinusoidal trajectories. The measured responses exhibited the same general characteristics of the previous data (Fig. 6).

4 Analysis

Our goal was to devise an initial model that captured the primary features of the data, particularly: (1) the inverted parabolic shape of the pressure distribution (the central concentration of pressure with a smooth decrease to the edges) and (2) the viscoelastic biomaterial response (the nonlinear variation of the local pressure with normal displacement and the temporal pressure relaxation). For simplicity, in this initial analysis, we assumed

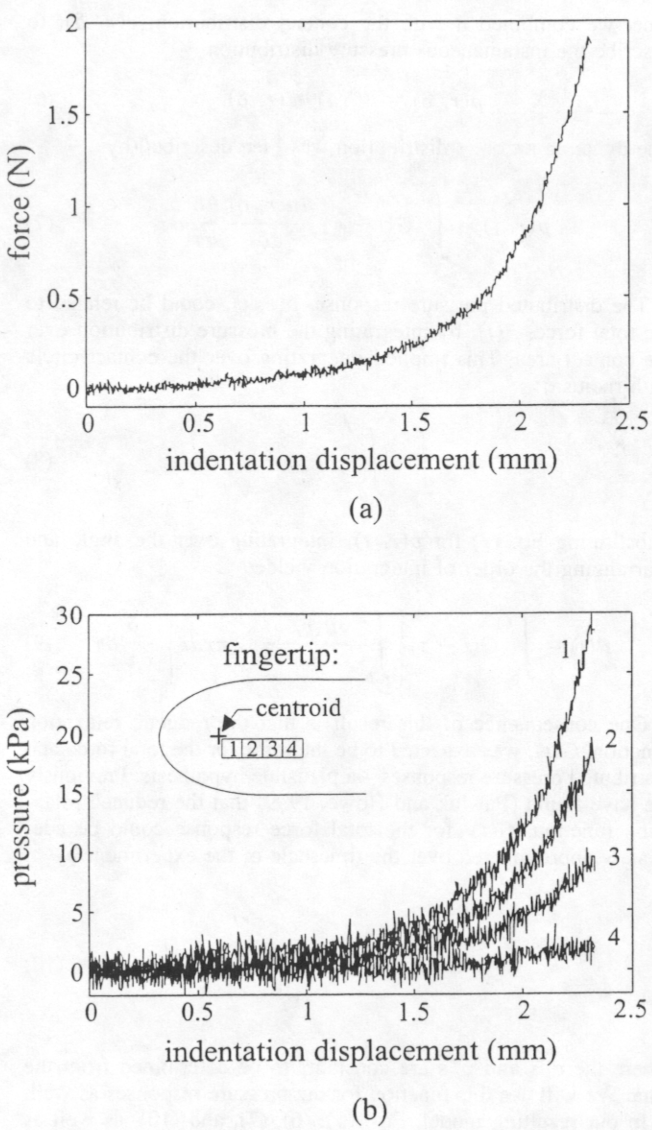

Fig. 2 Quasi-static indentation: one experimental trial of a typical subject: (*a*) total force; (*b*) pressures measured by four individual tactile array elements along the line indicated in the inset. Responses decrease for elements farther from the center of contact (indicated by the cross).

radial symmetry and ignored the distal–proximal asymmetry evident in Fig. 3.

4.1 Model. The simplest physical configuration to model the indentation of the fingerpad by a flat surface is a rigid plane (the surface) in contact with a compliant incompressible sphere (the distal segment of the finger). Assuming a linear, isotropic, homogeneous elastic medium, this situation is described by Hertz contact (Johnson, 1985). For a rigid body motion of the plate upon contact, $\delta(t)$, along the axis of indentation, z, the resulting pressure, $p(r, \delta)$, on the fingerpad at a distance r from the center of contact is given by

$$p(r, \delta) = \frac{4}{\pi R} 2\mathcal{G}[a^2(\delta) - r^2]^{1/2} \qquad (2)$$

$$= 2\mathcal{G} \cdot c(r, \delta) \qquad (3)$$

where $\mathcal{G}$ is the shear modulus of the material, $(1/R)$ is the relative curvature of the two surfaces $(1/R_1 + 1/R_2)$, $a(\delta)$ is the contact radius, given by $a^2(\delta) = R\delta(t)$, and $\delta(t) = (z(t) - z_0)$, the position trajectory of the indentor from the contact point. For our experiments the probe was flat, and therefore the relative curvature is defined by the curvature of the fingerpad, $R = R_{\text{fingerpad}}$.

We modified the Hertz solution to include linear viscoelasticity by replacing two times the shear modulus, $2\mathcal{G}$, by an integral operator, expressed in terms of the relaxation function (Johnson, 1985). The resulting pressure distribution, $p(r, t)$, at time t and a distance r from the center of contact can be described in terms of the relaxation function for the material, $\Psi(t)$, and the contact distribution, $c(r, \delta)$, by

$$p(r, t) = \int_0^t \Psi(t - \tau) \frac{\partial c(r, \delta)}{\partial \delta} \frac{\partial \delta}{\partial \tau} d\tau. \qquad (4)$$

We further modified the Hertz model to capture the nonlinear increase in the pressure and force with indentation. This discrepancy was unlikely due to contact geometry as Hertz contact appeared to capture the distribution of the pressure adequately. We

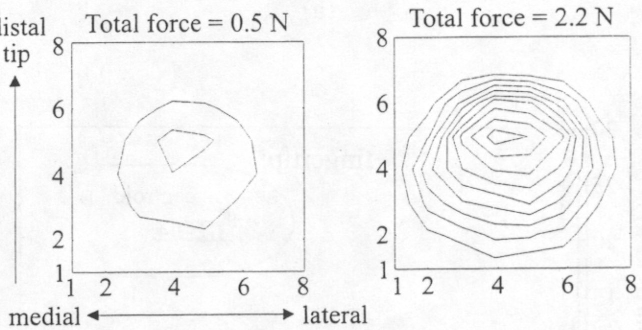

Fig. 3 Contour plots of the distributed pressure responses to a quasi-static indentation: one experimental trial of a typical subject. Contours indicate increasing pressure levels of 4 kPa. Orientation of the array sensor with respect to the fingerpad is indicated in the left of the figure. The axes indicate the row and column number of the array elements, which were spaced 2 mm apart. Contours are interpolated between data points using the MATLAB software package.

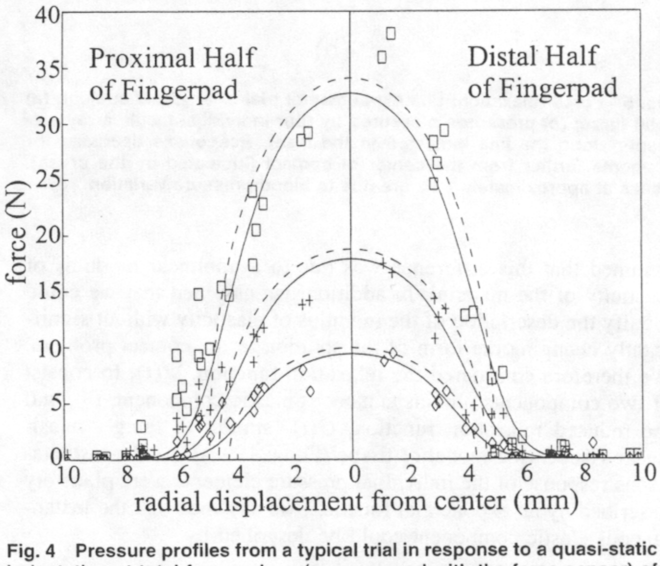

Fig. 4 Pressure profiles from a typical trial in response to a quasi-static indentation at total force values (as measured with the force sensor) of 0.54 N, 1.1 N, and 2.3 N. Measured pressures are indicated by symbols, the width and height of which indicate the standard deviation of the measurement error. The data points on the left-hand side of the graph show the pressure measurements (of individual array elements) proximal to the body with respect to the perpendicular line crossing the length of the fingers. The data points on the right-hand side show the pressure measurements (of individual array elements) distal to this line. Solid lines are the model fit, which also accounts for the spatial response of the distributed pressure sensor. Dashed lines are the estimated behavior at the surface of the fingerpad.

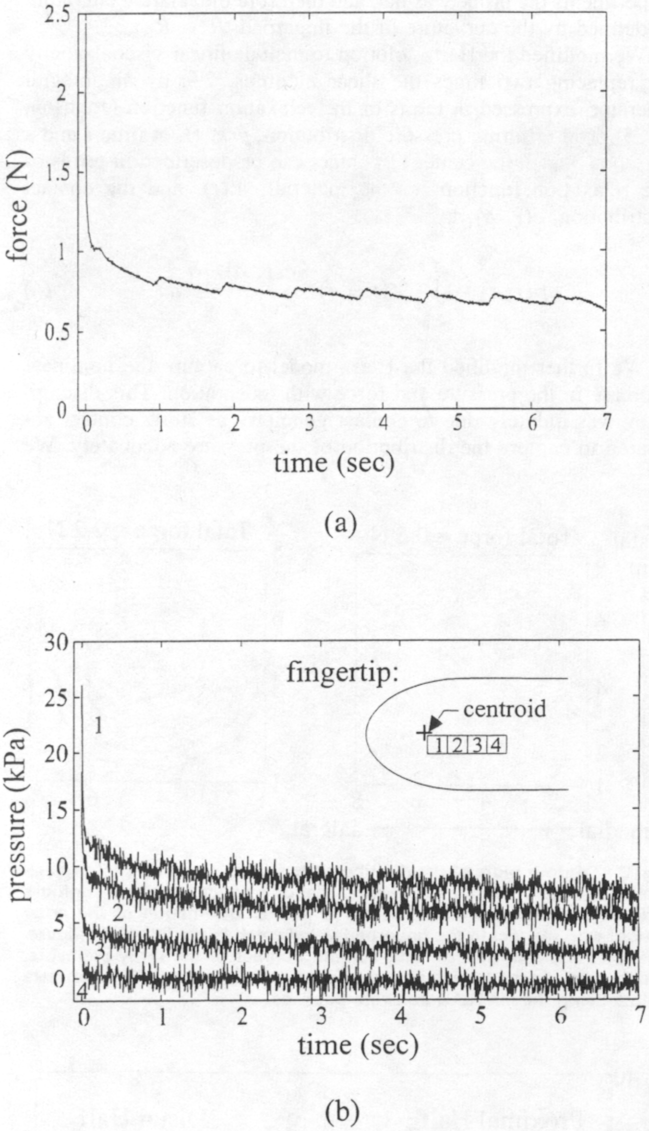

Fig. 5 Force relaxation: one experimental trial of a typical subject: (*a*) total force; (*b*) pressures measured by four individual tactile array elements along the line indicated in the inset. Responses decrease for elements farther from the center of contact (indicated by the cross). Peaks at approximately 1 Hz are due to blood pressure variation.

assumed that this difference was due to a nonlinear modulus of elasticity of the material. In addition, we assumed that we could modify the description of the modulus of elasticity without significantly changing the form of the solution to the contact problem. We therefore considered the relaxation function, $\Psi(t)$, to consist of two components: the instantaneous elastic component, $t^{(e)}$, and the reduced relaxation function, $G(t)$ [similar to Fung's quasi-linear viscoelastic model of tissue (Fung, 1993)]. As the instantaneous response of the individual pressure elements were plausibly described by an exponential function, we assumed that the instantaneous elastic component could be described by

$$t^{(e)}(u) = \frac{b}{m}\left[e^{m*u(t)} - 1\right]. \tag{5}$$

Here $u(t)$ is the deformation at the point of maximum indentation on the fingerpad, and b and m are constants to be determined by the data. For contact with rigid objects, such as in our experiment, $u(t)$ is equal to the rigid body motion of the object upon contact, $\delta(t)$.

As the instantaneous elastic component was independent of time, we combined it with the contact distribution, $c(r, \delta)$, to describe the instantaneous pressure distribution

$$p(r, \delta) = t^{(e)}(u)\cdot c(r, \delta). \tag{6}$$

The dynamic pressure distribution was then described by

$$p(r, t) = \int_0^t G(t-\tau)\,\frac{\partial p(r, \delta)}{\partial \delta}\,\frac{\partial \delta}{\partial \tau}\,d\tau. \tag{7}$$

The distributed pressure response, $p(r, t)$, could be related to the total force, $P(t)$, by integrating the pressure distribution over the contact area. This implied integrating over the contact circle with radius a:

$$P(t) = \int_0^{2\pi}\int_0^a p(r, t)\cdot r\,dr\,d\theta. \tag{8}$$

Substituting Eq. (7) for $p(r, t)$, integrating over the angle and rearranging the order of integration yielded

$$P(t) = \int_0^t G(t-\tau)\left\{\int_0^a \frac{\partial p(r, \delta)}{\partial \delta}\cdot 2\pi r\,dr\right\}\frac{\partial \delta}{\partial \tau}\,d\tau. \tag{9}$$

One consequence of this result is that the reduced relaxation function, $G(t)$, was expected to be the same for the total force and distributed pressure responses—a plausible hypothesis. Previously we have found (Pawluk and Howe, 1999) that the reduced relaxation function, $G(t)$, for the total force response could be adequately approximated over the timescale of the experiment by

$$G(t) = \frac{c_0 + \sum_{i=1}^{3} c_i e^{-v_i t}}{\sum_{i=0}^{3} c_i} \tag{10}$$

where the c_i's and v_i's are constants to be determined from the data. We will use this function for the pressure responses as well.

In our resulting model, Eqs. (5), (6), (7), and (10), as well as Eqs. (2) and (3) describing $c(r, \delta)$, predict the pressure at each point on the fingerpad as a function of the indentation history $\delta(t)$ of the plate, the radius of curvature of the fingerpad $R_{\text{fingerpad}}$, the nonlinear stiffness parameters m and b, and the force relaxation parameters c_i and v_i for $i = 0$ to 3.

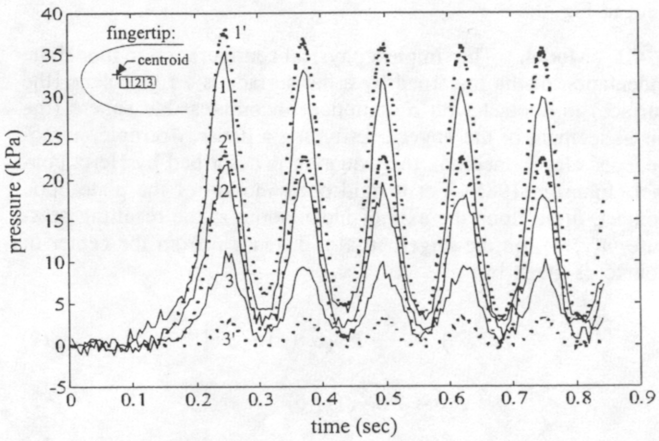

Fig. 6 Distributed pressure response to an 8 Hz sinusoidal displacement input: one trial for a typical subject. Pressures measured by three individual tactile array elements along the line indicated in the inset. Solid lines show the experimental data. Dotted lines show the model fit.

le 1 Model parameters of the normalized force relaxation for indi-
ial subjects

bject	c_0	c_1	c_2	c_3	v_1 (sec^{-1})	v_2 (sec^{-1})	v_3 (sec^{-1})	$r^2_{G(t)}$
l.p.	0.33	0.44	0.13	0.10	163	2.8	0.31	0.89
d.s.	0.33	0.42	0.16	0.08	256	9.7	0.91	0.83
a.h.	0.29	0.47	0.13	0.10	226	8.6	0.61	0.89
ɔ.w.	0.33	0.42	0.16	0.08	238	20.5	0.79	0.67
f.c.	0.29	0.49	0.11	0.10	175	8.2	0.59	0.87
ıeans	0.31	0.45	0.14	0.09	212	10.0	0.64	0.83

4.2 Parameter Fit. The reduced relaxation function, $G(t)$, s determined by fitting Eq. (10) to the force sensor data (which s sampled at a much higher temporal rate than the distributed essure data) for the hold phase of the fast-ramp-and-hold trajec-y. Four trials were fit by a simplex method using MATLAB to termine the parameters c_0, and c_i and v_i, $i = 1$ to 3 (Table 1). ıe variation of the force relaxation accounted for by the model, $_{G(t)}$), was, on average, 83 percent. Most of the error in the fit uld be attributed to the intertrial variability in the data them-lves.

Due to limitations in the sampling rate of the tactile array (200 z/element), the instantaneous pressure response, $p(r, \delta)$, was ost accurately determined from the quasi-static pressure re-ionse, $p_{ss}(r, \delta)$, where

$$p_{ss}(r, \delta) = \frac{c_0}{\sum_{i=0}^{3} c_i} \cdot p(r, \delta). \tag{11}$$

he spatial impulse response of the array sensor elements (Eq. (1)) 'as taken into account through the convolution (Fearing, 1987)

$$p_{\text{predicted}}(r, \delta) = p_{ss}(r, \delta) * f_{\text{spatial}}(r) \tag{12}$$

'here * indicates the convolution operator. Four trials were fit by simplex search on $R, b' (= c_0 b / \sum_{i=0}^{3} c_i)$, and m over the entire isplacement contact trajectory (Table 2, Fig. 4). The contact oint, z_0, was determined by examining each trial in reverse rder to obtain the first zero crossing and averaging across rials. The center of the pressure distribution was taken to be the ressure centroid (which usually did not coincide with the ocation of the peak pressure). The value used was that mea-ured before initiation of the experimental protocol (as de-cribed in Section 2.2). The mean squared error of the fit for all ubjects was, on average, 9.6 percent. Most of the error in the it was due to the asymmetry of the distribution.

4.3 Model Confirmation. The model was verified using the distributed pressure responses to the sinusoidal position trajecto-ries. The predicted distributed pressure response, $p(r, t)$, was calculated from the measured position input, $z(t)$, using the model with the parameters determined from the system identification (Tables 1 and 2). The experimental displacement input, sub-sampled at 3250 Hz, was used as the input to the model. The contact point, z_0, was assumed to be the same as in the quasi-static trials, as was the center of the pressure distribution. The resulting pressure distribution was spatially filtered using Eq. (1) for com-parison with the tactile array data (e.g., Fig. 6). The variance accounted for was, on average, 75 percent across all sensor loca-tions and sinusoidal frequencies.

5 Discussion

In this study, we examined the distributed pressure response of the fingerpad to displacement indentations of various trajectories within the force range of 0–2 N. Both the individual tactile sensor element measurements, and the total force exhibited nonlinear stiffness that appeared exponential with indentation. In addition, significant time relaxation was apparent. The contact area of the pressure distribution grew rapidly during initial contact, and then more slowly at higher force levels. The shape of the contact pressure distribution was similar in form at all total force levels, approximating an inverted parabola skewed away from the distal tip.

The model presented here succeeded in predicting the dominant functional form of the distributed pressure response of the finger-pad: It successfully captured the approximately parabolic shape of the pressure distribution, as well as the nonlinear variation of the local pressure with indentation and the exhibition of time relax-ation. It was also effective (average $r^2 = 75$ percent) in quanti-tatively predicting the response of the fingerpads to trajectories not used for model parameterization, i.e., the sinusoidal displacement inputs. However, it tended to underestimate the pressure responses in the proximal direction from the center of contact and overesti-mate the responses in the distal direction. This was particularly noticeable at the most proximal and distal edges of the contact area. In addition, some differences in the time decay envelope existed between the model responses and the experimental data for the sinusoidal indentations. These limitations are discussed in more detail below.

Experimental Limitations. The primary experimental limita-tion was the tactile array sensor measurements, which were limited by sensor compliance, and spatial and temporal resolution. The most significant effect was that of spatial resolution. Preliminary results (at 1 mm resolution) by Johansson and his colleagues (1997) suggest that the contact distribution is flatter in the center with a sharper fall-off in the distal direction. Our sensor was not able to resolve these details. However, the resolution of our sensor is comparable to the receptive fields of the tactile receptors (Jo-hansson and Vallbo, 1983) and the pin spacing in tactile displays (Howe et al., 1995), the motivating factors for our experiment.

The faster trajectories (i.e., the fast ramp-and-hold) were also expected to be limited in accuracy by the finite time response of the motorized indentor and the compliant rubber coating of the tactile array sensor. This probably resulted in a small underesti-mation in the measurement of the force relaxation function.

Model Limitations. The assumption of radial symmetry pro-duced most of the resulting error in the predicted pressure distri-butions, as was apparent by the trends in the error. In the distal direction, because of this assumption, we would expect to overes-timate the width of the distribution and underestimate the rate of pressure decrease with distance from the center of contact. In the proximal direction we would expect the converse to be true: The width would be underestimated and the rate of pressure decrease, as a function of distance away from the center of contact, would be overestimated. This was indeed what happened (e.g., Fig. 6). In

Table 2 Model parameters of the quasi-static indentation for individual subjects

Subject	R (mm)	m (mm^{-1})	b' (kPa/mm)	m.s.e.
d.p.	15	2.1	2.3	8.0 %
d.s.	12	1.1	6.1	9.6 %
a.h.	14	1.9	1.9	14 %
p.w.	17	1.1	3.6	9.0 %
f.c.	15	1.7	3.8	7.6 %
means	14	1.6	3.5	9.6 %

addition, the pressure centroid was found to move slightly away from the distal tip with indentation (0.6 mm, on average across subjects, for the quasi-static indentations) implying that the asymmetry increased with increasing indentation. This asymmetry in the pressure distribution was likely due to structural differences within the fingertip (i.e., the bone of the distal phalange is modified significantly and the curvature of the finger becomes greater toward the distal tip), although it may possibly be due to variations in the tissue properties themselves.

In addition, some of the error could be attributed to differences between the decay envelopes of the model responses and the experimental data. We believe that this inaccuracy was due to small errors in fitting the time relaxation function. To calculate the resulting pressure responses in our simulations, we took the instantaneous response (a large quantity) and decreased it by an amount depending on the past history (also a large quantity), producing a relatively small result. In doing so, small errors in the time relaxation function would get magnified in the final result.

Model Assumptions. Several assumptions were made in the development of the model, largely devolving from using Hertz contact theory as its basis: (1) The curvature of the contact region can be approximated as a quadratic and that any other terms (i.e., any asymmetry) can be neglected; (2) although Hertz theory only applies for contact radii much less than the radius of curvature of the surface and the depth of the object, it would still be a good approximation for contact radii comparable to these two dimensions; (3) the tissue could be considered homogeneous and isotropic; and (4) the Hertz solution could be modified to include an exponential modulus of elasticity without significantly affecting the shape of the pressure distribution.

The first of these assumptions (i.e., that of symmetry) was the most significant limitation of the model. Unfortunately, there are no precedents in the literature for handling additional terms in a closed-form solution. Other possibilities for the asymmetry, such as nonhomogenous material properties of the fingerpad, are similarly problematic. Nevertheless, by assuming symmetry, we believe that we have captured most of the response behavior while providing a tractable, closed-form model.

The remaining three assumptions are interrelated in that they address nongeometric Hertz contact conditions (i.e., the contact radii are much smaller than the surface curvature and depth of the fingerpad, and the tissue is linear, homogeneous, and isotropic). Although these conditions were all violated in the experiment, our interest was whether empirically such a solution was a sufficient approximation. Unfortunately, the exponential pressure and force responses as a function of indentation depth indicated it clearly was not. Modifying all of these contact conditions to approximate the experimental conditions better could potentially produce a better match to the experimental results. However, we assumed that the nonlinear material properties of the tissue were the dominant factor and only incorporated a nonlinear modulus of elasticity into the model. Extending the Hertz solution to include an exponential modulus of elasticity without changing the shape of the pressure distribution appeared plausible considering the solution for a power law stress–strain relationship (Johnson, 1985), although the validity of this approximation remains to be justified from first principles. Alternatively, it is possible that large displacements, the nonhomogeneity and structure of the fingerpad, or a combination of these properties are more important.

We also made an additional assumption based on linear viscoelastic theory: Namely that, although the solution applies only for growing contact areas (Johnson, 1985), it would be a good approximation for loading histories that included decreasing contact areas as well. We found that it did work well for conditions during which the contact area decreased, although we were limited to trajectories that remained in contact with the fingerpad.

Comparison With Previous Results and Models. In the absence of previously published distributed pressure data for comparison, we note that the total force response is comparable to that obtained by Gulati (1995), Serina (1996), and Pawluk and Howe (1999). In addition, the pressure distribution model is consistent with a model of the total force response we have previously proposed (Pawluk and Howe, 1999).

In contrast to the limited amount of data, there have been several previous models of the fingerpad. Although half-space models (i.e., Phillips and Johnson, 1981; Van Doren, 1987) have worked well in explaining the tactile sensory response, they predict the opposite trend in the pressure distribution to that measured here. In our case, the nonplanarity of the fingerpad is a key parameter. Fluid-filled membrane models (Srinivasan, 1989; Serina, 1996) would also predict very different (i.e., uniform) pressure distributions than those measured here. They are also inconsistent with the known response of the tactile receptors, which respond differentially to the spatial location of an indentor, since they predict a uniform membrane tension and fluid pressure. We expect that previous finite element models using curved surfaces (Srinivasan and Dandekar, 1996; Dandekar, 1995; Maeno et al., 1997) would show reasonable agreement with our static data. However, these models have not incorporated a time-dependent component and have the disadvantage of the inability to be computed in real time.

Extension of the Model. For linear viscoelastic contact theory, one can extend the solution to include the effects of both the object's curvature and viscoelasticity, in addition to that of the fingerpad. These object properties are important for understanding the human tactile system and dexterity, as well as for display purposes in minimally invasive surgery. Inclusion of the first property is addressed by using the relative curvature of the two surfaces as the effective curvature: $(1/R) = (1/R_{\text{fingerpad}} + 1/R_{\text{object}})$. The second is addressed by using a series combination of the two separate materials for the relaxation function, $\Psi(t)$ (Johnson, 1985). If we hypothesize that these relationships hold for our model, we can make an interesting prediction: The curvature of the object and its compliance affect the distributed pressure response in different manners when the object is indented as a function of displacement. A change in curvature will affect both the magnitude of the pressures and the width of the contact area, whereas a change in compliance will only change the magnitude of the pressure, albeit in a complicated manner.

It would also be useful in the future to extend the model to account for the asymmetry in the pressure distribution. Informal experiments suggest that this asymmetry varies with the contact angle between the distal phalange axis and the indentor surface. Quantification and modeling of this effect may be useful in grasp analysis, where issues like the size and location of the centroid of the contact area are important considerations for contact stability (Howe and Cutkosky, 1996). However, these issues are beyond the scope of the present paper. Nonetheless, we expect the fundamental form of the pressure response to be the same despite variations in angle.

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