Non-linear viscoelastic models predict fingertip pulp force-displacement characteristics during voluntary tapping

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Abstract

We evaluated whether lumped-parameter non-linear viscoelastic models of human fingertip tissue can describe fingertip force-displacement characteristics during a range of rapid, dynamic tapping tasks. Eight human subjects tapped with their index finger on the surface of a rigid load cell while an optical system tracked fingertip position using an infra-red LED attached to the fingernail. Four different tapping conditions were tested: normal and high-speed taps with a relaxed hand, and normal and high-speed taps with the other fingers co-contracted. A non-linear viscoelastic model comprised of an instantaneous stiffness function and viscous relaxation function was capable of predicting fingertip tissue force response due to measured pulp compression under these four different loading conditions. The model could successfully reconstruct very rapid (less than 5 ms) force transients, and forces occurring over time periods greater than 100 ms, with errors of 10%. Model parameters varied by less than 20% over the four conditions, despite almost 3-fold differences in average forces and 38% differences in fingertip velocities. Energy dissipation by the fingertip averaged 81%, and varied little ($<3\%$) across conditions, despite a 1. 5-fold range of energy input. The ability of a lumped-parameter model to describe fingertip force-displacement characteristics during a range of conditions contributes both to understanding the transmission of force through the fingertip to the musculoskeletal system and to predicting the stimulation of mechano-receptors located within the fingertip.

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1. Introduction

The fingertip pulp or pad is at the forefront of the human's tactile and mechanical linkage to the physical environment. Within the fingertip lie mechano-receptors of the peripheral sensory nervous system, which provide critical tactile information about objects important for dexterous manipulation (Birznieks et al., 2001; Johansson et al., 1982). The pulp can also attenuate peak forces encountered during dynamic finger activity, similar to the heel pad during running (Alexander et al., 1986; Hajian and Howe, 1997). These peak forces may be a risk factor for the development of musculoskeletal disorders of the upper extremity associated with computer keyboard work (Armstrong et al., 1987; Feuerstein et al., 1997; Rempel et al., 1999; Serina et al., 1998). Hence, understanding the force-displacement properties of the fingertip is an important component of understanding how mechanical energy from the impact forces is absorbed by tissue and what sensory information may be available during rapid finger activities.

Studies of the mechanical properties of the fingertip have demonstrated that dynamic loading properties affect the mechanical response of the fingertip (Gulati and Srinivasan, 1995; Lundström, 1984; Nakazawa et al., 2000; Pawluk and Howe, 1999; Serina et al., 1997; Srinivasan, 1989). Lunström (1984), for example, found that the energy absorption characteristics of the skin associated with vibrating the tissues depended on stimulus frequency. In Serina et al. (1997) data from subjects who slowly (approximately $7 \, \mathrm{mm \, s^{-1}}$) pressed the fingertip against a hard surface with the fingertip indicated mechanical stiffness depended upon

displacement history, velocity and magnitude, as well as fingertip angle. Using ramp and hold displacement profiles with pulp compression speeds up to $80\,\mathrm{mm\,s^{-1}}$, Pawluk and Howe (1999) found that there was not a unique relationship between force and fingertip pulp displacement. They found that a nonlinear viscoelastic model of soft tissue (Fung, 1993) could describe pulp force-displacement. Although the fingertip has a complex structure, these studies illustrated that its behavior could be captured by structural models with few parameters. However, the ramp force trajectories employed by these studies did not contain the rapid impact forces and velocities observed during many dynamic tasks such as touch typing (Dennerlein et al., 1998, Rempel, 1994).

We seek to characterize the mechanical loads and pulp displacement experienced by the fingertip pads during tapping tasks that are more similar to the motion of typing. We evaluated the ability of a nonlinear viscoelastic model with a force-relaxation function to describe fingertip force-displacement characteristics during tapping by measuring vertical force and fingertip pulp compression while subjects voluntarily tapped on a stiff substratum. Both Serina et al. (1998) and Pawluck and Howe (1999) examined the pulp characteristics over a range of pulp compression velocities. Similarly, we examined the force-displacement characteristics over four impact conditions, emulating different types of motor control conditions expected or encountered within touch-typing.

We first hypothesize that during dynamic tasks such as tapping, there is not a unique relationship between force and fingertip displacement alone, causing differences in the force-displacement relationship across the four rapid impact tapping conditions. Second, given that our first hypothesis is satisfied, we hypothesize that a non-linear viscoelastic model with a relaxation function developed for non-impact loading also describes pulp force-displacement characteristics during tapping (Pawluk and Howe, 1999). This second hypothesis will be further supported if the model parameters and the relative energy absorbed did not vary across the four conditions tested.

2. Methods

To evaluate our hypotheses, we collected experimental data during dynamic tapping that included impact forces, and used the modeling methods proposed by Pawluk and Howe (1999) to determine the non-linear stiffness and relaxation parameters for the fingertip across several different motor control tapping conditions. Eight subjects (4 females, 4 males), ages 27 to 38 (mean $= 33 \pm 4$ S.D.) participated in the study. Subjects gave informed consent prior to experiments, and all

experimental procedures were approved by the Human Subjects Committee at the Harvard School of Public Health.

Subjects sat beside the experimental apparatus, and rested their right forearm on a table which was adjusted to position their elbow at $90°$ of flexion with the shoulder relaxed. We attempted to keep finger postures the same for all subjects by instructing the subjects to curl their fingers comfortably, and rest the dorsal side of the middle phalanges of all fingers but the thumb on the platform. The index finger was then extended over the surface of the force transducer while the other fingers curled under the palm. The proximal pad of the palm also rested on the support surface to maintain the wrist in neutral to very slightly extended posture.

Subjects were instructed to tap 30 times, once per second, minimizing contact time on the force transducer for each of four conditions: relaxed tapping, relaxed high-speed tapping, "co-contracted" tapping, and "co-contracted" high-speed tapping. The one tap per second frequency simulated a synchronous tapping rate of the index finger slightly faster than would be expected in touch-typing. During relaxed tapping, subjects were instructed to tap on the force transducer in the most comfortable manner possible. During high-speed tapping, subjects were instructed to tap using the highest downward velocity of the finger possible. During normal and high-speed co-contracted tapping, subjects were instructed to squeeze all of the fingers except the index finger against the palm of their hands. The final 15 taps for each condition were selected for analysis. The order of the four conditions was randomized.

We measured fingertip forces using a stiff strain-gauge force transducer (Fig. 1) securely anchored to the table. The transducer had a resolution of $2.5\,\mathrm{mN}$ and a dynamic resonant frequency of $1000\,\mathrm{Hz}$. The position of the finger in the vertical direction relative to the surface of the transducer was measured using an infrared light emitting diode (IRLED) glued to the fingernail, and a custom camera system containing a CCD transducer. The CCD system's resolution was $0.01\,\mathrm{mm}$. The LED provided a measure of the pulp compression, assuming no rotation of the distal phalanx during the contact portion of the tap (Birznieks et al., 2001). Transducer outputs were acquired at $10\,\mathrm{kHz}$, using computer data-acquisition hardware and software (NB-MIO16E and LabVIEW, National Instruments, Austin Texas). Data were filtered using a 20th-order Hamming filter at a cut-off frequency of $500\,\mathrm{Hz}$. Fingertip velocity and acceleration was calculated by differentiating position data using a fourth-order difference equation.

Following Pawluk (1999), the force response as a function of time and tissue compression was modeled as:

$$F_o(t) = \int_{-\infty}^{t} G(t-\tau)\frac{\partial T^e[x(\tau)]\partial x(\tau)}{\partial x \quad \partial \tau}\,\mathrm{d}\tau, \qquad (1)$$
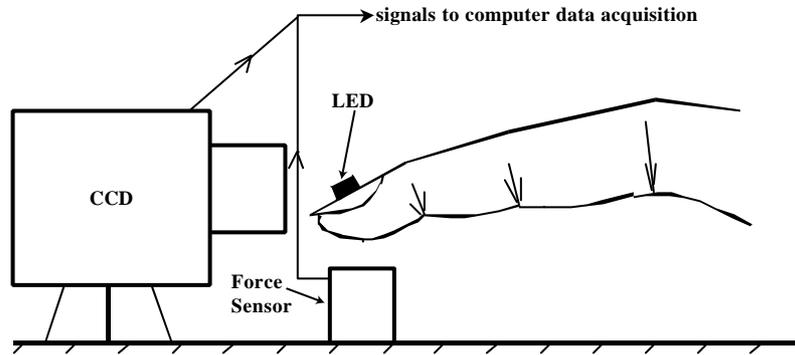
Fig. 1. Apparatus for measuring fingertip position and finger tip force during tapping task. Subjects tapped on stiff force sensor at a frequency of 1 Hz. An infra-red LED glued to the fingernail allowed measurement of fingertip position by a CCD position-measurement system.

where T^e is the instantaneous force response due to compression of the tissue, x, and $G(t)$ is the relaxation response of the tissue over time, t. We modeled $T^e(x)$ as an exponential function.

$$T^e(x) = \frac{b}{m}[e^{m \cdot x} - 1], \qquad (2)$$

where m is the non-linear stiffness coefficient and b is the non-linear scaling coefficient.

Pawluk and Howe's (1999) experimental procedure used a compression ramp to estimate $T^e(x)$, and a subsequent hold to estimate the time-dependent effects $G(t)$. For holds of less than approximately one second, the relaxation function reduces to a simple exponential decay given by

$$G(t) = c_0 + c_1 e^{-vt}, \qquad (3)$$

where v is the relaxation time constant and c_0 and c_1 are coefficients.

During a voluntarily controlled tap, position and force do not follow a ramp and hold. First, an impact force phase causes rapid (<5 ms) compression of the fingertip, and local maxima in both compression and force. For the remaining period of the tap, small changes in pulp compression occur and at times, force increases to a second local maximum, then decreases back to zero (Rempel et al., 1994). To determine the model parameters, we first divided the tap into two portions, and made an initial fit of the model parameters to the data. Starting with the initial model parameters, we then conducted an iterative search for parameters that minimized the error between the measured and predicted force trajectories.

To make an initial estimate of $T^e(x)$, we used position and force measurements from the beginning of the tap to estimate the parameters m and b of the equation:

$$\frac{dT^e(x)}{dx} = mT^e(x) + b. \qquad (4)$$

We calculated the stiffness, $dT^e(x)/dx$, for the entire tap using a fourth-order difference equation. The first local maximum of stiffness before the time of maximum force
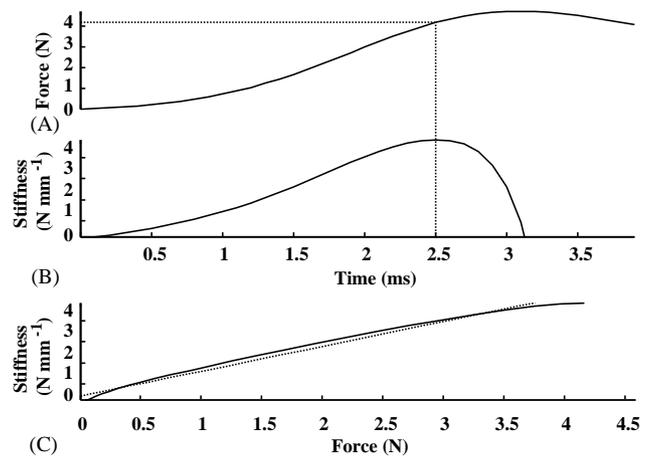
Fig. 2. Procedure used to make first estimate of elastic response, $T^e(x)$. (A) Measured force for 4 ms following contact at the beginning of the tap. $T^e(x)$ was assumed to equal force over this time interval. (B). Stiffness ($dT^e(x)/dx$) over time for the first 4 ms of tap. Vertical dotted line indicates time at which maximum stiffness was reached. (C) Stiffness with respect to force, from the beginning of the tap until the time at which maximum stiffness was reached. Solid line represents measured force and stiffness, dotted line represents least-squares fit of Eq. (4) to data.

development was identified (Fig. 2). The parameters m and b in Eq. (4) were then fitted to the force and stiffness data from the beginning of the tap to the point of maximum stiffness using a least-squares method. The point of maximum stiffness was chosen because it is likely to represent the period of loading before substantial relaxation began to occur.

Unlike a ramp and hold, voluntary tapping creates conditions where position changes caused the force to increase above the first local maximum to reach a second maximum of greater magnitude. In these conditions, estimating $G(t)$ from force changes relative to the first local maximum would result in negative values for v. Consequently, to generate an initial estimate of $G(t)$, we normalized the relaxed force to the estimated value of the instantaneous stiffness at each time t, given by $T^e[x(t)]$ resulting in a normalized
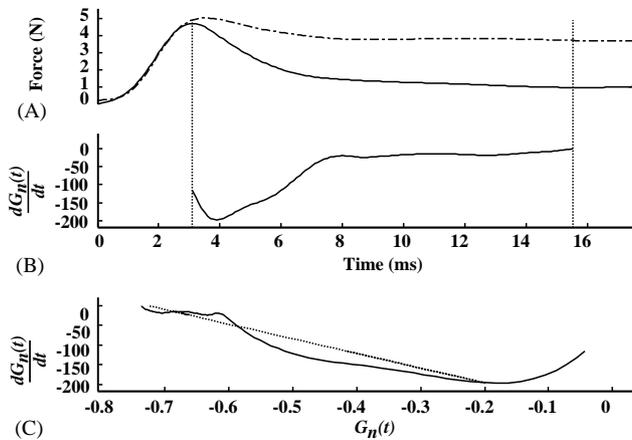
Fig. 3. Procedure used to make first estimate of relaxation response, $G_n(t)$. (A) Measured force (solid line) and force estimated from instantaneous elasticity, $T^e(x)$ (dash-dotted line), for 17 ms following contact at the beginning of the tap. Dotted vertical line between 2 and 4 ms represents time where maximum force was reached. Dotted vertical line between 14 and 16 ms represents time when maxima of $|F(t_i) - T^e[x(t_i)]|$ was reached. (B) Derivative of normalized relaxation function ($dG_n(t)/dt$), during time interval used to calculate relaxation function. (C) $dG_n(t)/dt$ as a function of $G_n(t)$ (solid line), and least-squares fit used to calculate parameters of Eq. (6) (dotted line).

relaxation function $G_n(t)$:

$$G_n(t) = \frac{F(t) - T^e[x(t)]}{T^e[x(t)]}. \tag{5}$$

We differentiated $G_n(t)$ with respect to time (Fig. 3B) from the time of the maximum force to the time, t_i corresponding to a maximum value of $|F(t_i) - T^e[x(t_i)]|$ (Fig. 3A), and fitted the data to the differential equation,

$$\frac{dG_n(t)}{dt} = pG_n(t) + q. \tag{6}$$

The estimated parameters p and q of the normalized relaxation function then provided the v, c_0 and c_1 of Eq. (3) for each tap. We used the functions $T^e(x)$ and $G_n(t)$, with the parameters calculated for each tap, to reconstruct a predicted force $F_p(t)$ as a function of time. Since there were periods where $\partial x = 0$, causing equation (1) to be undefined, we approximated Eq. (1) to reconstruct $F_p(t)$ using the equation

$$F_o(t) = \int_{-\infty}^{t} G(t - \tau) \frac{\partial T^e[x(\tau)]}{\partial \tau} d\tau. \tag{7}$$

We defined the percentage error by

$$Error = 100 * \frac{\sqrt{\sum_{t=0}^{t=\tau} \left[F(t) - F_p(t) \right]^2}}{\sqrt{\sum_{t=0}^{t=\tau} F(t)^2}} \tag{8}$$

from the beginning of the tap ($t = 0$) until the force dropped to zero, indicating the end of the tap. We evaluated the error for each tap individually to facilitate

the parameter search (see below), providing a lower bound for errors.

The predicted force $F_p(t)$ underestimated the peak forces during taps. Relaxation could cause the calculated value of $T^e(x)$ to be underestimated when it is assumed that no relaxation occurs during the period during which $T^e(x)$ is calculated. Moreover, the initial estimate $G_n(t)$ may differ from $G(t)$. For these reasons, we implemented a search over the parameters of $T^e(x)$ and $G(t)$, with the objective of minimizing the error of Eq. (8), using a multidimensional unconstrained non-linear minimization (*fminsearch* in MATLAB, Mathworks, Natick, MA, USA). Model fits improved, on average, by 34%.

Energy input to the fingertip pulp (E_{in}) was calculated by integrating force with respect to position for positive increments of position change (i.e. fingertip loading), and energy output (E_{out}) by integrating for negative increments of position change (i.e. fingertip unloading).

Differences between parameter estimates over the conditions were tested using a repeated-measures analysis of variance (JMP, the SAS Institute, Cary, NC, USA). Independent variables were subject, condition, and tap, with subject identified as a random effect.

3. Results

The force-displacement characteristics of the fingertip pulp varied across the four conditions (Fig. 4, Table 1). High-speed and co-contracted conditions had higher average fingertip force, F_{ave}, during a tap ($p < 0.001$); whereas both high-speed conditions had higher peak forces, F_{peak}, relative to normal-speed conditions during the impact phase ($p < 0.001$). High-speed taps also had larger pulp displacement, ds_{mf}; at maximum force relative to normal-speed taps ($p < 0.0001$).

Displacement did not have a unique relationship with force production during the latter half of the tap. Whereas the force generated during co-contracted taps exceeded the force generated by relaxed taps, the maximal pulp displacement for relaxed, high-speed taps exceeded that of co-contracted, normal-speed taps (compare Fig. 4B to A; Table 1). The magnitude of the maximum peak forces appeared to influence pulp displacement to a greater extent than average force production.

The proposed non-linear viscoelastic model of the fingertip pulp was able to characterize force response as a function of pulp displacement and time during the impact and contact phases of dynamic taps. Reconstruction errors of 9–10% were observed for all conditions (Table 2; Fig. 5).
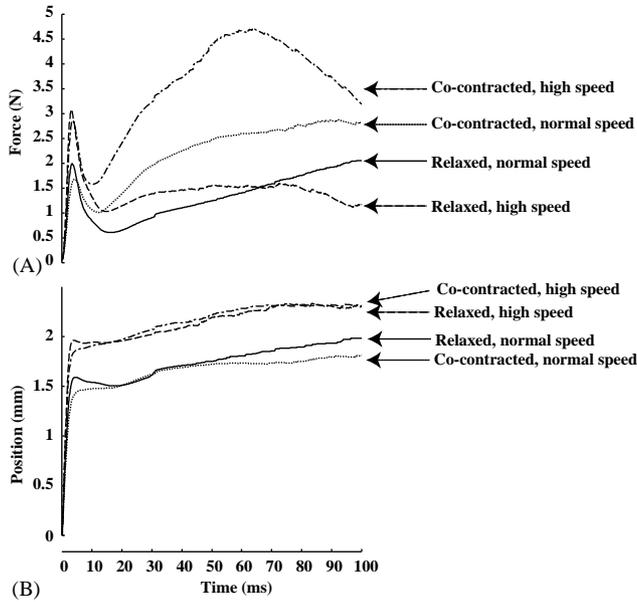
Fig. 4. Averaged force and displacement for the first 100 ms of taps during four experimental conditions. Each curve represents an average of 120 taps. (A) Average force production for tapping under four different conditions. (B) Average displacement of the fingertip pulp during tapping under different conditions. For both (A) and (B), solid line represents relaxed, normal-speed tapping, dashed line represents relaxed, high-speed tapping, dotted line represents co-contracted, normal-speed tapping, and dashed-dotted line represents co-contracted, high-speed tapping.

Model parameters varied among different experimental conditions, but the relative variance was smaller than the variance of forces, displacements, and velocities of the fingertip. The non-linear stiffness, m, was 16% greater during co-contracted conditions relative to relaxed conditions ($p < 0.001$). For normal-speed taps, the force scaling coefficient b was 19% lower during the co-contracted condition ($p < 0.01$), resulting in the model predicting lower forces during periods of small displacement for co-contracted taps. The greatest average difference between the maximum and minimum average values of m was only 17% and for b only 20% (Table 2), despite 1.8-fold differences in peak forces, almost 3-fold differences in average forces, 38% differences in V_i and 20% differences in ds (Table 1). For relaxed, normal-speed taps, the relaxation time constant, v was significantly shorter than v for normal and high-speed co-contracted taps, by 328 and 325 s^{-1} respectively ($p < 0.0001$). The coefficients c_0 and c_1 showed no significant differences across conditions.

The energy dissipated by the fingertip pulp ranged only from 80% to 85% of energy introduced into the finger during the tap, E_{in} (Table 1), despite the 1.5-fold range of E_{in}. The hysteresis and proportion of energy dissipated by the fingertip pulp was greater during relaxed high-speed taps ($p < 0.0001$) than the other conditions.

Table 1
Tap dynamics for four experimental conditions

Condition	Relaxed normal-speed	Relaxed high-speed	Co-contracted normal-speed	Co-contracted high-speed
Tap duration, D_t (ms)	168.7 ± 109.6	80.6 ± 33.0	147.7 ± 66.6	107.0 ± 50.5
Initial velocity, V_i (m s^{-1})	0.75 ± 0.27	0.91 ± 0.28	0.66 ± 0.25	0.80 ± 0.25
Peak force, F_{peak} (N)	2.32 ± 1.14	3.25 ± 1.31	1.90 ± 0.81	2.99 ± 1.80
Time to peak force, T_{pf} (ms)	3.7 ± 0.7	3.4 ± 0.6	4.2 ± 1.6	3.8 ± 0.6
Time to peak stiffness, T_{pk} (ms)	2.6 ± 6.6	2.2 ± 6.6	2.9 ± 14.7	2.2 ± 8.0
Fingertip displacement, ds (mm)	1.74 ± 0.58	2.00 ± 0.62	1.75 ± 0.56	2.05 ± 0.62
Average force, F_{ave} (N)	0.72 ± 0.41	0.99 ± 0.56	1.54 ± 1.29	2.04 ± 2.03
Maximum force, F_{max} (N)	2.35 ± 1.13	3.25 ± 1.31	2.86 ± 1.81	4.27 ± 3.80
Time to maximum force, T_{mf} (ms)	6.4 ± 18	3.4 ± 0.5	32 ± 32	25 ± 25
Displacement at maximum force, ds_{mf} (mm)	1.67 ± 0.54	1.9 ± 0.56	1.75 ± 0.59	2.04 ± 0.65
Initial kinetic energy, KE_i (N mm)	2.7 ± 2.0	4.1 ± 3.0	2.1 ± 1.7	3.4 ± 2.8
Energy input, E_{in} (N mm)	1.79 ± 1.12	2.56 ± 1.65	1.89 ± 1.20	3.13 ± 2.86
Hysteresis (N mm)	1.44 ± 0.93	2.20 ± 1.43	1.51 ± 0.99	2.44 ± 2.09
Energy dissipation (%)	81 ± 5.2	86 ± 4.3	80 ± 7.5	80 ± 8.2

Table 2
Viscoelastic model parameters (Eqs. (2) and (3))

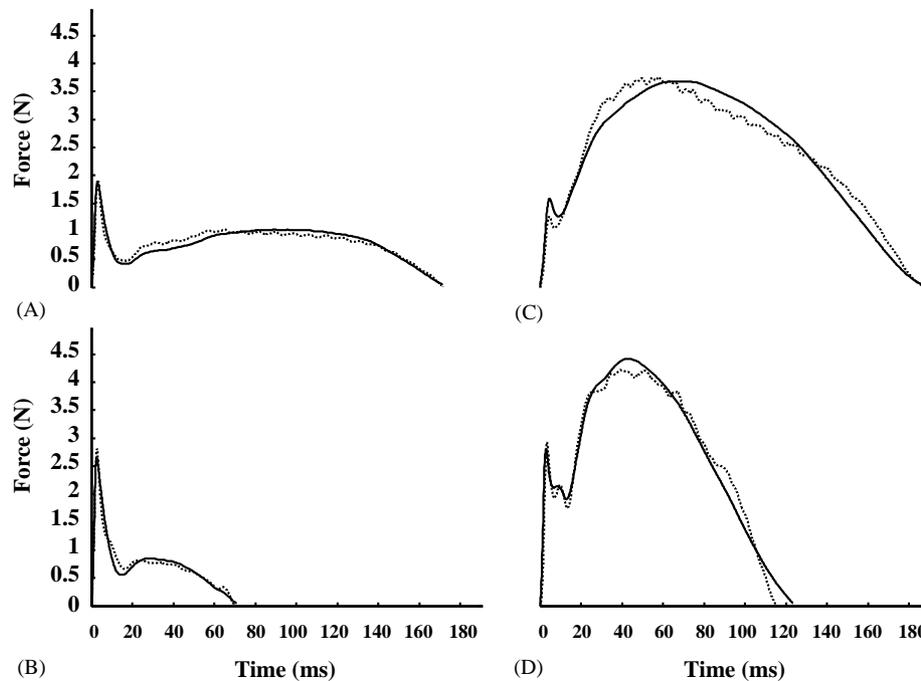| Condition	Relaxed normal-speed	Relaxed high-speed	Co-contracted normal-speed	Co-contracted high-speed
m (mm^{-1})	2.48 ± 1.01	2.46 ± 1.11	2.85 ± 0.95	2.89 ± 1.21
b (N mm^{-1})	0.25 ± 0.24	0.24 ± 0.20	0.20 ± 0.20	0.20 ± 0.20
v (s^{-1})	243 ± 179	413 ± 460	420 ± 774	569 ± 629
c_0	0.82 ± 0.23	0.82 ± 0.06	0.81 ± 0.41	0.83 ± 0.31
c_1	0.18 ± 0.23	0.18 ± 0.06	0.22 ± 0.24	0.19 ± 0.14
Error (%)	10 ± 4	10 ± 3	9 ± 6	9 ± 4

Fig. 5. Representative forces (solid lines) and nonlinear viscoelastic model fits (dotted lines) to tapping forces under four experimental conditions. (A) Relaxed, normal-speed tap. (B) Relaxed, high-speed tap. (C) Co-contracted, normal-speed tap. (D) Co-contracted, high-speed tap.

4. Discussion

Previous models of the fingertip pulp, specifically the non-linear viscoelastic model of Pawluk and Howe (1999) have been verified only under controlled experimental conditions. We sought to test the hypothesized model using dynamic loading regimes beyond those previously tested, such as those observed during touch typing. Our data support the hypothesis that a viscoelastic model with force relaxation is capable of predicting fingertip force from fingertip pulp compression during the dynamic impact of tapping, through a range of different impact conditions, with only minor modifications.

Several limitations of this study should be taken into account. First, we measured pulp compression when tapping on a stiff substratum. Although this avoids potential confounding effects of surface stiffness, it is not representative of many tapping tasks such as using computer keyboards. Second, we did not measure fingertip angle. Although we instructed subjects to adopt a consistent hand position when tapping, differences in fingertip angle could influence the measured model parameters and energy dissipation (Serina et al., 1997). Third, we measured fingertip position using a LED mounted on the fingernail, which is not a direct measurement of pulp displacement. However, Birznieks et al.(2001) illustrated that the fingernail is an adequate surrogate measure of the distal phalange (Birznieks et al., 2001).

The various motor control conditions resulted in differences in the force and displacement trajectories. Initial peak forces, within the first 5 ms of contact, increased with an increase in fingertip velocity V_i, suggesting a causal relationship to finger momentum. Subsequent to the initial force peak, the co-contracted taps had higher forces than relaxed taps, resulting in higher average forces (Figs. 4, 5; Table 1). For relaxed taps, forces may be the result of gravity and passive tension in the muscles, requiring little flexor force to initiate the movements (Dennerlein et al., 1998). However, when the subjects were instructed to co-contract other finger muscles, the activity of the other muscles may have influenced the index finger flexor activity.

The parameters of the non-linear viscoelastic model of the fingertip pulp during the rapid, dynamic loading regime experienced by the fingertip during tapping were similar to those observed during ramp-and-hold or sinusoidal position inputs involving velocities approximately one-tenth the velocities observed during tapping (Pawluk and Howe, 1999; Serina et al., 1997). The nonlinear stiffness term m ranged across subjects from 1.8 to 3.4 mm^{-1}, compared to the 1.6 to 3.2 mm^{-1} range reported by Pawluk and Howe (1999). The mean value measured during tapping was 2.7 mm^{-1}, 25% higher than 2.1 mm^{-1} calculated by Pawluk and Howe (1999). This increase may be due to the effect of immediate relaxation on the calculation of instantaneous stiffness. The rate dependence of stiffness found by Pawluk and

Howe (1999) could result from relaxation during the ramp portion of the experiments. Considering the mean time constant of $231 \, \text{s}^{-1}$ reported by Pawluk and Howe (1999), some relaxation would be expected to occur during the 15 ms necessary to displace the fingertip pulp 1.2 mm at the maximum measured indentation velocity of $0.08 \, \text{m s}^{-1}$, which could result in underestimates of m.

Calculated values for the relaxation time constant, v for the non-relaxed conditions were almost twice the average value of $231 \, \text{s}^{-1}$ reported by Pawluk and Howe (1999), indicating a more rapid relaxation of the fingertip pulp from sudden loading during a tap (Table 2). Some of this disparity may be due to technical limitations involved with generating a pure ramp-and-hold trajectory, which may have caused Pawluk and Howe (1999) to underestimate the time constant of the relaxation function. If the probe continues to move during the initial portion of a hold period, then forces caused by stiffness could attenuate the force decrease due to relaxation, and cause an underestimate of v. Changes in fingertip position and conditioning of the fingertip pulp tissue could also account for some of the discrepancy between relaxation during experiments with more controlled position inputs (Serina et al., 1997).

The fingertip pulp showed substantial hysteresis (Table 1) causing a majority of the work done on the fingertip pulp to be dissipated. The average energy absorbed during tapping (1.90 N mm) was within the range of values observed by Serina et al. (1.27–2.67 N mm at $0°$; (Serina et al., 1997)). Using the initial velocities observed during tapping (average $0.78 \, \text{m s}^{-1}$; Table 1) and the estimates of finger moment of inertia (I) scaled to the masses of the fingers used in the present study (assuming geometric similarity, $I \sim m^{5/3}$, assuming $I = 7.07 \times 10^{-5} \, \text{kg m}^2$ for a finger mass of 32 g) and effective length (r_2) from (Dennerlein et al., 1998b) ($r_2 = 0.070 \, \text{m}$), the initial kinetic energy (KE_i; Table 1) of a finger during tapping is approximately 3 N-mm. The fingertip pulp consequently absorbed 60% of the KE of a finger during tapping. The remaining KE must be transmitted to the hand or arm and stored or dissipated by proximal musculo-skeletal elements.

In conclusion, the lumped-parameter non-linear viscoelastic model of the human fingertip pulp was capable of predicting fingertip force from fingertip pulp compression during the dynamic impact of tapping. The model was successful through a range of different impact conditions resulting from different motor outputs. Fingertip pulp model parameters, including the energy absorbed, did not substantially vary across the four conditions tested. These results contribute both to understanding the transmission of force through the fingertip to the musculoskeletal system and to predicting the stimulation of mechano-receptors located within the fingertip.

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