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FORCE RESPONSE OF THE FINGERTIP PULP TO REPEATED COMPRESSION—EFFECTS OF LOADING RATE, LOADING ANGLE AND ANTHROPOMETRY

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Abstract—Repeated loading of the fingertips has been postulated to contribute to tendon and nerve disorders at the wrist during activities associated with prolonged fingertip loading such as typing. To fully understand the pathomechanics of these soft tissue disorders, the role of the fingertip pulp in attenuating the applied dynamic forces must be known. An experiment was conducted to characterize the response of the *in vivo* fingertip pulp under repeated, dynamic, compressive loadings, to identify factors that influence pulp dynamics, and to better understand the force modulation by the pulp. Twenty subjects tapped repeatedly on a flat plate with their left index finger, while the contact force and pulp displacement were measured simultaneously. Tapping trials were conducted at three fingertip contact angles from the horizontal plane (0°, 45°, and 90°) and five tapping rates (0.25, 0.5, 1, 2, and 3 Hz). The fingertip pulp responds as a viscoelastic material, exhibiting rate-dependence, hysteresis, and a nonlinear force-displacement relationship. The pulp was relatively compliant at forces less than 1 N, but stiffened rapidly with displacement at higher forces for all loading conditions. This suggests that high-frequency forces of a small magnitude (< 1 N) are attenuated by the nonlinearly stiffening pulp while these forces of larger magnitude are transmitted to the bone. Pulp response was significantly influenced by the angle of loading. Fingertip dimensions, gender, and subject age had little to no influence on pulp parameters. © 1997 Elsevier Science Ltd

Keywords: Fingertip; Pulp; Compression; Tapping.

INTRODUCTION

Repeated, high forces applied at the fingertip are transmitted to flexor tendons and may contribute to the development of soft tissue injuries at the wrist and arm during prolonged repetitive hand activities, such as typing (Silverstein *et al.*, 1987; Bergqvist *et al.*, 1995). Injuries associated with repeated work of long duration, such as carpal tunnel syndrome and flexor tenosynovitis, account for more than fifty percent of all occupational illnesses (Bureau of Labor Statistics, 1993). While forces applied at the fingertips have been quantified (Armstrong *et al.*, 1992; Rempel *et al.*, 1994), determination of the resulting *in vivo* tendon forces and their significance are open issues. A full understanding of the pathomechanics of these soft tissue disorders requires a biomechanical model of the hand capable of predicting tissue forces under repeated, dynamic loading conditions. Current hand biomechanical models are inadequate because they are quasi-static and either assume a rigid interface model at the fingertips (e.g., An *et al.*, 1979; Thompson and Giurintano, 1989) or make overly simplifying assumptions about the soft tissue (Buchholz and Armstrong, 1992). The complete biomechanical model must represent the dynamic properties of the chain of soft tissues in the system (e.g. skin, fatty tissue, tendons, muscles).

An essential component of a dynamic hand biomechanical model is the fingertip pulp, the soft tissue interface that modulates the transmission of forces during contact of the finger with an object. The pulp is comprised of the skin around the palmar surface of the distal phalanx and the underlying fatty tissue (Glicenstein and Dardour, 1981; Thomine, 1981). Previous studies have determined the mechanical behavior of this tissue to be nonlinear under quasi-static (Peleg and Campanella, 1989; Srinivasan, 1989; Swyngedau and Peleg, 1992) and cyclic loadings (Thompson *et al.*, 1981). However, the response and force transmission of the pulp under loadings encountered during repetitive tasks, which involve dynamic compressive forces that return to zero during the loading cycle, remain unknown. Rate-dependence, repeated loading, and inclination of the load at the fingertip are other important parameters in hand function that have not been studied.

The objectives of this investigation were to resolve the following questions: (1) How does the fingertip pulp respond to repetitive, small forces? (2) How does the pulp response modulate the transmission of these forces to the underlying bone? (3) How do loading rate, loading angle, fingertip size, and individual factors (age and gender) influence the dynamic properties of the pulp? This study provides the information needed to develop a dynamic, biomechanical model of the hand and fingers in repetitive loading.

METHODS

Subjects tapped repeatedly on a flat plate with their left index finger at specified tapping rates and fingertip inclinations at contact while fingertip contact force and pulp displacement were measured simultaneously. In this

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study, a 'tap' was defined as a single, rapid contact and release of the fingertip onto the flat plate and was executed as a rapid pressing action. Previous researchers compressed the entire fingertip between two rigid plates and equated pulp displacement to the change in fingertip thickness (Peleg and Campanella, 1989; Swyngedau and Peleg, 1992; Thompson *et al.*, 1981). Our preliminary *in vitro* experiments determined that the soft tissue interface between the distal phalanx and the fingernail may contribute substantially to the total thickness change measured when the entire fingertip is compressed (Serina and Rempel, 1994). Loading the fingertip by tapping isolates the compression to the pulp and permits direct measurement of pulp displacements from relative changes of the fingertip position during contact.

A two-camera motion analysis system (Selspot, Selcom AB, Sweden) tracked index fingertip motion during tapping while a force transducer (Wilcoxon Research, Model L5; resolution: 0.001N) mounted underneath the plate recorded the applied force (Fig. 1). Fingertip position and inclination were determined by the location of two infra-red LEDs (diameter: 1.8 mm; mass: 2 g), whose three-dimensional motion was tracked by two cameras located at ± 45° from the plane of finger flexion and angled − 20° vertically (field-of-view: 5 cm^3; resolution: 20 μm). A fixture secured the left hand and restricted index finger motion to the vertical plane. The wrist and forearm were held in pronation. Contact of the fingertip with the plate was detected within 0.15 mm by three photoelectric sensors mounted on the plate surface (Keyence, Kensington, CA). Force, position, and sensor data were collected by two personal computers. A manual trigger linked to both computers initiated data acquisition.

Twenty subjects (12 male, 8 female; mean age: 35 ± 12 yr; age range: 22–58 yr) participated in this study. All subjects were without any known finger soft tissue disorders or visible calluses on the tested fingertip. The experimental protocol and consent procedures adhered to guidelines for the testing of human subjects prescribed by U.S. federal law and University of California policy.

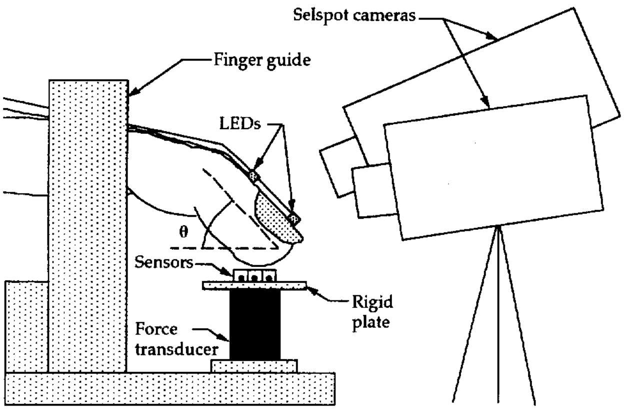

Fig. 1. A schematic of the experimental setup. The applied force and fingertip vertical displacement are simultaneously measured while the subject repeatedly taps on the contact plate. The fingertip angle (θ) is specified for different tapping conditions at 0°, 45°, and 90°. Photoelectric sensors mark the instant of contact and release of the fingertip from the plate.

Distal finger segment length (DIP palmar crease to tip), thickness (at fingertip swirl), and width (at DIP joint) were measured prior to experimentation with the finger fully extended. A lateral fingertip X-ray of one subject was taken and the thickness of the uncompressed pulp was measured.

Each subject completed 15 tapping trials, grouped into three randomly ordered sets by fingertip angle at contact: 0°, 45°, and 90° (relative to the horizontal). Fingertip angle was adjusted by varying the distance of the palm from the force transducer until the desired angle at contact was achieved, then securing the hand at that position. At each fingertip angle, subjects completed tapping trials at five randomly ordered rates: 0.25, 0.5, 1, 2, and 3 Hz. Subjects were instructed to maintain the specified fingertip angle during contact and to minimize the impact by matching closely the applied force history to the positive half of a sine wave with amplitude 5.0 ± 0.5 N. Auditory beats from a metronome and CRT displays of the contact force and a reference sine wave assisted subjects in attaining and maintaining the specified tapping rate and force history. Force, position and sensor data from thirty consecutive taps were captured simultaneously at sampling rates of 100, 200, 400, 800 and 1100 Hz during the 0.25, 0.5, 1, 2, and 3 Hz tapping rates, respectively. Different sampling rates were used to collect approximately 100 data points during the contact portion of each tap. In preliminary tests, tapping data was collected at various sampling rates within the tested range and compared. Analyses on the data verified that use of different sampling rates did not bias the results.

The pulp tissue was tested in a quasi-equilibrium state during each trial. Tissue preconditioning by continuous tapping at 1 Hz for 2.5 min preceded all trials at each fingertip angle. Preliminary experiments on three subjects showed that the measured tissue behavior no longer varied after about 2.5 min. Within a trial, the unchanging vertical position of the distal LED at the instant of contact confirmed that the quasi-equilibrium state was achieved. The tissue returned to its normal state within several minutes after the completion of the experiment.

Plots of the contact force vs pulp displacement were generated for each tap. Pulp displacement was defined as the vertical displacement of the fingertip following triggering of the sensor. Data were digitally filtered by a low-pass, sixth-order Butterworth filter with the cutoff frequency set at one-tenth the sampling frequency. Power spectral analyses validated this filtering technique. The range of sampling frequencies used did not permit adequate filtering if a fixed cutoff frequency was chosen. To reduce the variability associated with subject-controlled loading, only taps satisfying three criteria were accepted for analysis: (1) maximum force = 5.0 ± 0.5 N, (2) peak-to-peak fingertip angle variation during contact $\leqslant \sim 4.0°$, and (3) during contact horizontal fingertip displacement < vertical fingertip displacement. On average, 13 taps from each trial were accepted for analysis.

Pulp parameters were calculated from the force–displacement curves for each accepted tap. Energy input to the pulp during loading was calculated from the area under the loading curve. Hysteresis, energy dissipated by the pulp, equaled the area between the loading and unloading curves. Pulp displacement at the maximum load was obtained from the fingertip position data. Pulp displacements at 1 and 4 N were estimated by regressing separately the loading and unloading curves with third-order polynomials across 1.0 ± 0.5 N ($R^2 \geqslant 0.99$) and 4.0 ± 0.5 N ($R^2 \geqslant 0.87$) and calculating displacements from the resulting splines. Pulp stiffnesses at 1 and 4 N were the first derivative of the force–displacement spline at the specific force. The 1 and 4 N force magnitudes represent the average and maximum forces experienced during typing (Rempel *et al*., 1994).

Summary statistics were calculated for all subjects, tapping rates, and fingertip angles. Repeated measures analyses of variance with within-subject factors, tapping rate and fingertip angle, were conducted to examine differences in pulp displacement, stiffness, energy, and hysteresis. Findings with significant tapping rate-by-fingertip angle interaction were followed with Tukey studentized range tests at a procedure-wise error rate of $p < 0.05$ (Neter *et al*., 1990). Multiple regression techniques, including indicator variables for subjects, were employed to explore whether any significant within-subject relationships for tapping rate existed with maximum loading rate, defined as the maximum value of the force derivative with respect to time. Relationships of fingertip dimensions (length, thickness, and width) and subject age to the summarized pulp parameters (displacement, stiffness, energy input, and hysteresis) were evaluated using Pearson correlation coefficients and tested for statistical significance. Gender differences among all pulp parameters were assessed with a student *t*-test. Statistical significance was accepted when $p < 0.05$. All statistical analyses were conducted on JMP (SAS Institute Inc., Cary, NC).

RESULTS

Under all loading conditions, the fingertip pulp experienced large displacements initially at the low forces, but substantially less displacement after the force of contact exceeded 1 N (Fig. 2). Most of the maximum pulp compression occurred before the contact force reached 1 N: 62% at 0°, 74% at 45°, 63% at 90°. Mean ($\pm$s.d.) pulp displacement at 1N over all subjects, tapping rates, and fingertip angles was 1.53 ± 0.60 mm. As contact force increased, the pulp stiffened rapidly with displacement, from 3.5 ± 2.9 N mm^{-1} at 1 N to 20.4 ± 29.5 N mm^{-1} at 4 N. Mean pulp displacement at 4 N was 2.09 ± 0.84 mm and at 5.0 ± 0.5 N was 2.18 ± 0.90 mm. The mean energy required to compress the pulp to 5.0 ± 0.5 N over all taps was 2.05 ± 1.33 N mm. A large proportion of the energy imparted to the fingertip pulp during compression was dissipated by viscous elements, as indicated by the large amount of hysteresis present (1.33 ± 0.93 N mm): 59% at 0°; 66% at 45°; and 75% at 90°. Mean values of pulp parameters over all subjects, grouped by fingertip angle and by tapping rate, are presented in Table 1. Pulp displacement did not return to its initial, unloaded value between taps.

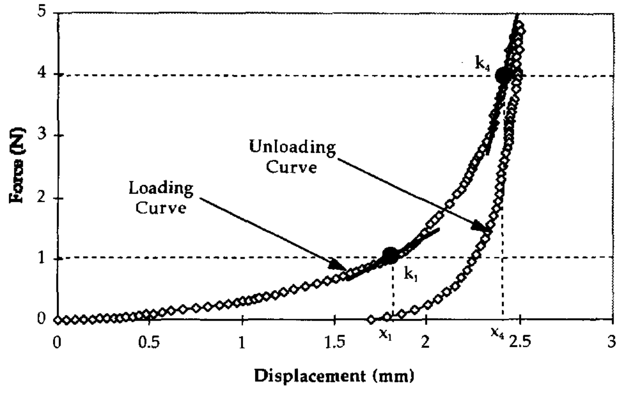

Fig. 2. A typical fingertip pulp force–displacement curve from one subject for a single tap at 0.5 Hz. Pulp displacement at 1 N (x_1) and 4 N (x_4) and pulp stiffness at 1 N (k_1) and 4 N (k_4) were calculated from the loading curve. Energy input was calculated as the area under the loading curve. Hysteresis equalled the area between the loading and unloading curves.

An increasing fingertip angle strongly influenced pulp parameters, decreasing significantly the pulp displacement, energy input, and hysteresis (Fig. 3; Table 1) while increasing pulp stiffness (Fig. 4). Displacements, energy inputs, and hystereses at each of the fingertip angles were significantly different ($p < 0.05$). Significant differences for stiffness between all fingertip angles were found at 1N only. At 4 N, significant differences in stiffness were found between 0° and 90° and between 45° and 90°. The thicknesses of the uncompressed pulp, measured from X-ray of one fingertip, were 5.9 mm at 0°, 4.9 mm at 45°, and 3.6 mm at 90°.

Tapping rate significantly affected all pulp parameters. All pulp displacement measures were significantly larger at the slowest tapping rate than at the two fastest rates for 0° and 45° (Fig. 3). At 90°, significant differences in displacement between tapping rates were found at 1 N only (Table 1). Energy input and hysteresis were larger at the slower tapping rates (0.25 and 1 Hz) than at the faster rates (2 and 3 Hz) with statistically significant differences at 0°. Pulp stiffness, however, increased with increasing tapping rate at all fingertip angles (Fig. 4). Significant differences between tapping rates were observed only at 45° and 90° for the stiffness at 1 N ($p < 0.05$). The mean value of the maximum loading rate, over all subjects, increased linearly ($p < 0.05$, $R^2 = 0.85$) from 11 to 164 mm s^{-1} as the tapping rate increased from 0.25 to 3 Hz. No significant differences in pulp parameters were found between 0.25 and 0.5 Hz or between 2 and 3 Hz for most cases where significant trends with tapping rate were observed.

Few statistically significant Pearson correlations were found among the relationships of pulp parameters with fingertip dimensions, gender, and subject age. Statistically significant correlations between fingertip dimensions and mean pulp parameters were present only at the 45° fingertip angle. Stiffness at 1 N was significantly correlated with length ($p = 0.047$, $r = 0.45$), thickness ($p = 0.020$, $r = 0.51$), and width ($p = 0.037$, $r = 0.47$). Both the energy input and hysteresis were significantly correlated with thickness ($p = 0.019$, $r = 0.52$; $p = 0.030$, $r = 0.49$) and width ($p = 0.026$, $r = 0.50$; $p = 0.035$, $r = 0.47$). Subject age and gender had no statistically significant effect on pulp parameters. However, mean fingertip dimensions were influenced by gender. Females

Table 1. Mean values of all pulp parameters grouped by fingertip angle and by tapping rate over all subjects ($N = 20$)

Pulp displacement at 1 N (mm)

	0°‡	45°§	90°¶
0.25*	2.08	1.67	1.19
0.5*†	1.83	1.62	1.16
1*†	1.87	1.67	1.12
2†	1.84	1.51	1.02
3†	1.79	1.52	1.04

Pulp stiffness at 1 N (N mm^{-1})

	0°	45°	90°
0.25	1.41*	2.40*†	3.79§
0.5	1.52*	2.79*†	4.30§¶
1	1.59*	3.03†	5.19¶
2	1.92*	3.68†‡	6.68‖
3	1.95*	4.47†	7.23‖

Pulp displacement at 4 N (mm)

	0°	45°	90°
0.25	3.23*	2.24§	1.47‖
0.5	2.91†	2.11§¶	1.43‖
1	2.91†	2.17§¶	1.38‖
2	2.62‡	1.94¶	1.24‖
3	2.59‡	1.92¶	1.24‖

Pulp stiffness at 4 N (N mm^{-1})

	0°†	45°†	90°‡
0.25*	5.72	15.1	39.8
0.5*	6.28	16.63	42.63
1*	5.43	13.53	42.48
2*	8.56	16.31	41.42
3*	6.81	18.87	54.83

Energy input (N mm)

	0°	45°	90°
0.25	4.09*	2.02‡	1.00§
0.5	3.70*	1.75‡	0.90§
1	3.85*	1.77‡	0.95§
2	2.89†	1.64‡	0.86§
3	3.07†	1.57‡	0.83§

Hysteresis (N mm)

	0°	45°	90°
0.25	2.67*	1.36§	0.71‖
0.5	2.26*‡	1.20§¶	0.62‖
1	2.44*	1.29§¶	0.67‖
2	1.27†	0.87†¶‖	0.49‖
3	1.96‡	1.12§¶	0.65‖

Note. Each table shows how the particular pulp parameter varies with fingertip angle and with tapping rate. Within a table, except for tables of pulp displacement at 1 N and stiffness at 4 N, values with the same superscripts are not significantly different ($p > 0.05$). For these two tables, the tapping rate-by-fingertip angle interaction terms were not significant and the values in rows or in columns having the same superscripts are not significantly different ($p > 0.05$)

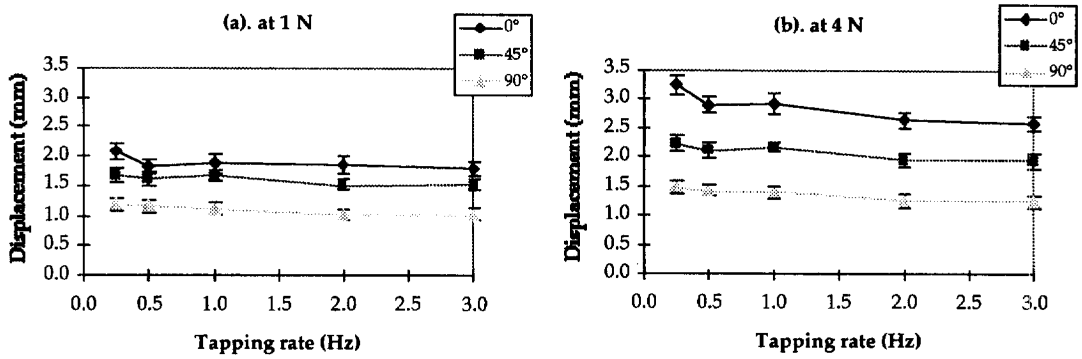

Fig. 3. Mean pulp displacements and standard errors at (a) 1 N and (b) 4 N vs tapping rate at each fingertip angle (0°, 45°, 90°) over all subjects ($N = 20$). Differences in displacements between all fingertip angles were significant at 1 N and at 4 N ($p < 0.05$). Differences between tapping rates were significant at all fingertip angles at the 1 N force level ($p < 0.05$). At 4 N, significant differences between tapping rates were observed only at the 0° and 45° angles.

possessed significantly smaller fingertip lengths, thicknesses, and widths (25 ± 1, 13 ± 1, 16 ± 2 mm, respectively) than males (28 ± 1, 15 ± 2, 18 ± 2 mm, respectively).

DISCUSSION

Subject-controlled loading of the pulp in this experiment generates a repeatable relationship between the contact force and the pulp displacement for each tapping condition. The linear relationship between maximum loading rate and prescribed tapping rate supports the use of visual and auditory cues for controlling fingertip compressive loading. The nonlinear force–displacement relationships obtained resemble those reported by others for quasi-static compression (Peleg and Campanella, 1989; Srinivasan, 1989; Swyngedau and Peleg, 1992).

Under the prescribed loading conditions, the pulp exhibits characteristics of a viscoelastic material:

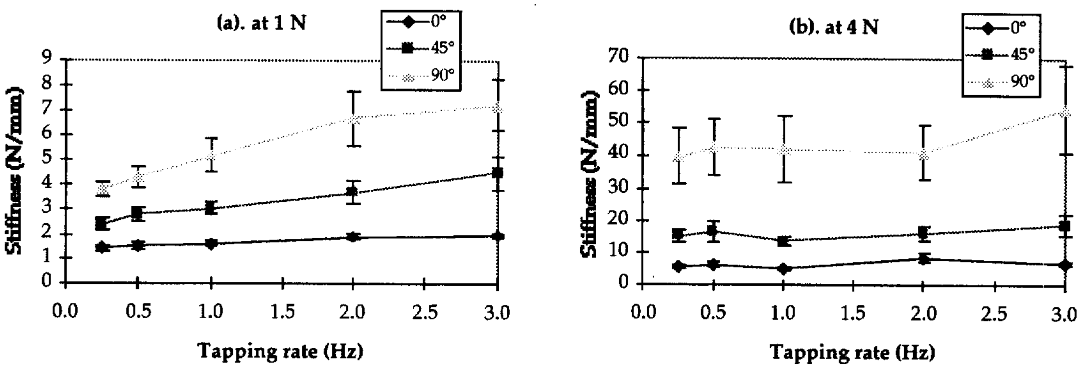

Fig. 4. Mean pulp stiffnesses and standard errors at (a) 1 N and (b) 4 N vs tapping rate at each fingertip angle (0°, 45°, 90°) over all subjects ($N = 20$). Differences in stiffness between 0° and 90° and between 45° and 90° fingertip angles were significant at 1 N and at 4 N ($p < 0.05$). Differences between tapping rates were significant at 45° and 90° at the 1 N force level ($p < 0.05$). No significant differences for stiffness at 4 N between tapping rates were found.

repeatability, rate-dependence, hysteresis, and nonlinearity of the force response to displacement (Christensen, 1982). The recovery of the pulp, during the unloaded period between taps, to a repeatable state by the initiation of the next tap indicates the presence of elastic components. The dependence of the pulp parameters on loading rate supports the presence of inertial and viscous elements in the pulp. Viscous behavior in the pulp response results in the large hysteresis observed in all force–displacement curves. There is no indication that plastic deformation is present.

Force transmission to the underlying bone is modulated by the nonlinear force–displacement response of the pulp. Below 1 N, inertial forces dominate and the relatively compliant pulp filters high-frequency forces. The pulp functions effectively as a tactile sensor by undergoing large displacements (62–74% of maximum displacement), skin stretching, and surface vibration to stimulate the mechanoreceptors embedded in the pulp (Hubbard, 1974). At higher forces, the stiffer pulp acts as a padding to mechanically protect the bone from direct impact. More high-frequency forces are transmitted to the underlying bone. Increasing the fingertip angle relative to the load or the rate of loading also stiffens the pulp and increases the amount of high-frequency force transmitted. The physical implication of this response is that in typing, where peak forces are impulsive and may be as small as 1.7 N (Rempel *et al.*, 1994), it is possible that the pulp behaves as a low-pass filter and dissipates the peak forces. The force–displacement relationship of the pulp during a keystroke is necessary to validate this hypothesis.

Fingertip geometry and composite material structure of the pulp may account for the measured viscoelastic response during loading and unloading. The curvature of the fingertip surface results in an increasing area of contact as compression increases. In the subcutaneous region, elastic adipose cells are loosely enmeshed in a fibrous-tissue network and are suspended in a fluid matrix (Kuhns, 1949). Under load, pressure gradients force adipose cells and extracellular fluid away from the loading point. This is evident by the lateral bulging of the pulp observed during compression. The pulp experiences large displacements under small changes in force. As force increases, the fibrous-tissue network and skin stiffen as they stretch and limit adipose cell movement (Lanir, 1987). Resistance to displacement increases rapidly as most of the pulp is under compression, requiring additional pulp displacement to occur by compressing the cells against the hard plane of the distal phalanx. When the load is removed, complete tissue recovery is not immediate because recovery, like compression, depends on reversed pressure gradients to return the fluid to the original state.

An analytical model of the pulp should include factors such as the fingertip shape, the skin elasticity, and the viscoelastic nature of the subcutaneous tissue components. A spring–mass–dashpot system with nonlinear elements will not provide a physical interpretation of the pulp response under load. A composite model would describe interactions between the various components. Such a model need not consider the proportions of tissue constituents and fingertip size. Because no effect of age on any pulp parameter was observed, proportions of collagen, elastic fibrous tissue, and water content in the pulp which change with age (Kuhns, 1949) probably do not affect pulp parameters. Although an association between fingertip angle and the uncompressed pulp thickness was apparent, weak correlations of pulp parameters with fingertip thickness suggest that the fingertip geometry and direction of loading, rather than tissue thickness, affect pulp material properties.

A limitation of the experimental design is that discrimination of the individual effects of loading rate and recovery time on the pulp properties is difficult. By nature of repeated tapping at a regular cadence, an increase in tapping rate increases the loading rate but also reduces the time between taps for the pulp to recover to its initial state. More pulp displacement remains between taps at the higher tapping rates, and a significant decrease in the vertical distal LED position at the instant of contact with increasing tapping rate results ($p < 0.001$). Less pulp displacement and greater pulp stiffness occur. Despite the coupling, loading rate effects can be isolated by plotting pulp stiffness at 1 N vs tapping rates. The significant differences found in this study reveal that the pulp response is indeed rate dependent.

Force transmission by the pulp to the bone is modulated by the nonlinear stiffening of the pulp with increasing force under repeated, dynamic compressive loading conditions. The pulp is compliant at forces less than 1 N and stiffens rapidly at higher forces. High-frequency forces less than 1 N may be filtered by the relatively compliant pulp, but higher forces are likely transmitted to the underlying bone by the stiffer pulp. This modulation of forces has implications for typing and keyswitch design, where peak, impulsive forces are repeatedly applied to the fingertips. Further experimentation is necessary to determine the force components that contribute to hand and wrist soft tissue injuries during repetitive hand activities, such as typing. Tapping rate and loading angle strongly influence pulp parameters while fingertip dimensions, gender, and subject age have little or no influence. This information forms the foundation for the development of a dynamic biomechanical model of the fingertip pulp.

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