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Short communication

Dynamic interaction between a fingerpad and a flat surface: experiments and analysis

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Abstract

Many neural and vascular diseases in hands and fingers have been related to the degenerative responses of local neural and vascular systems in fingers to excessive dynamic loading. Since fingerpads serve as a coupling element between the hand and the objects, the investigation of the dynamic coupling between fingertip and subjects could provide important information for the understanding of the pathomechanics of these neural and vascular diseases. In the present study, the nonlinear and time-dependent force responses of fingertips during dynamic contact have been investigated experimentally and theoretically. Four subjects (2 male and 2 female) with an average age of 24 years participated in the study. The index fingers of right and left hands of each subject were compressed using a flat platen via a micro testing machine. A physical model was proposed to simulate the nonlinear and time-dependent force responses of fingertips during dynamic contact. Using a force relaxation test and a fast loading test at constant loading speed, the material/structural parameters underlying the proposed physical model could be identified. The predicted rate-dependent force/displacement curves and time-histories of force responses of fingertips were compared with those measured in the corresponding experiments. Our results suggest that the force responses of fingertips during the dynamic contacts are nonlinear and time-dependent. The physical model was verified to characterize the nonlinear, rate-dependent force-displacement behaviors, force relaxations, and time-histories of force responses of fingertips during dynamic contact.
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Keywords: Nonlinear; Viscoelastic; Force/deflection responses; Fingertip; Compression tests

1. Introduction

Extended exposure of the human fingertips to repeated loading has been associated with many vascular, sensorineural, and musculoskeletal disorders, such as carpal tunnel syndrome, hand–arm vibration syndrome, and flexor tenosynovitis [1,2]. Since fingerpads serve as a coupling element between the hand and objects, investigation of the dynamic coupling between fingertip and objects could provide important information for the understanding of the pathomechanics of these diseases.

From a biomechanical point-of-view, a fingertip has a complex anatomical structure, composed of skin layers (epidermis and dermis), subcutaneous tissue, bone, and nail [3,4]. The material properties of the subcutaneous and skin tissues are known to be nonlinear and time-dependent [5–7]; consequently, the response of fingertips to mechanical loading are expected to be nonlinear and time-dependent. Rempel et al. [8] measured the force response of fingertip during keyboard strokes, and found that the peak forces on the fingertip ranged from 1.6–5.3 N. Serina et al. [9] studied the force-deformation behavior of the fingerpad during key tapping at frequencies of 0.5, 1, 2, and 3 Hz and at different inclinations; they found that force/deformation responses of the fingerpad are highly nonlinear and time-dependent. Pawluk and Howe [10,11] further investigated the dynamic contact pressure distributions between a fingerpad and a flat surface. The time-dependent force response and force relaxation behavior of the fingertips under physiological loading conditions, however, have not been explored systematically in a quantitative manner in these previous studies.

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From the modelling point of view, two types of models of fingertips have been proposed in the literature: structural models and physical models. The structural models consider simplified anatomical structures of the fingertip and can predict the stress/strain in the tissues. These models have been applied to predict the static force-deflection characteristics [12] and fingertip surface deflection under a static, line load [13]. These structural fingertip models are static in nature and cannot be applied to cases involving dynamic loading. Pawluk and Howe [10,11] used the physical (lumped element) model to simulate dynamic contact of fingerpads with a flat surface. However, the force response and force relaxation behavior of fingertips under physiologic loading conditions (e.g. low loading rates) were not investigated. Although the physical model did not consider anatomical structures of the fingertip and could not simulate the stress/strain properties within the soft tissues of fingertips, it is mathematically simple and can be readily used to estimate time-dependent force responses for many industrial and ergonomic applications.

The studies of the dynamic force response and force relaxation of finger-tips during grasping may provide important information to the understanding of the pathomechanics of work-related musculoskeletal disorders, and may help industrial ergonomic designers in their efforts to prevent musculoskeletal injuries. The purposes of the present study are: (a) to analyze, experimentally and theoretically, the time-dependent force responses and viscous relaxation of human fingertips during dynamic contacts with a flat surface, and (b) to develop a simple physical model which describes the nonlinear and time-dependent force response of fingertips.

2. Physical model

In classical viscoelastic theory, the constitutive equations are typically expressed in terms of stress, $\sigma(t)$, and strain, $\epsilon(t)$, using Bolzmann's principle of superposition, as shown by Fung [14]. The dependence of the instantaneous stress on the deformation history of a linearly viscoelastic material is expressed by a hereditary integral:

$$\sigma(t) = \int_{-\infty}^{t} E(t-\tau)\dot{\varepsilon}(\tau)d\tau \tag{1}$$

where $E(t)$ is a time-dependent relaxation modulus that characterizes the material's time-dependent response.

For many practical problems, it is convenient to write the hereditary integral (1) in terms of stress, σ:

$$\sigma(t) = \int_{-\infty}^{t} \frac{E(t-\tau)}{E_0}[E_0\dot{\varepsilon}(\tau)]d\tau = \int_{-\infty}^{t} \xi(t-\tau)\dot{\sigma}_0(\tau)d\tau \tag{2}$$

where $\xi(t) = E(t)/E_0$, with E_0 being the instantaneous modulus [$E_0 = E(0)$], is the normalized relaxation modulus and $\dot{\sigma}_0(= \dot{\varepsilon}E_0)$ is the time derivative of the instantaneous stress.

Considering the force (F) and displacement (Δ) as directly measurable quantities, Bolzmann's superposition principle can be reformulated in terms of $F(\Delta)$ and $\Delta(t)$. Assuming negligible contributions of pre-history loading for $t < 0$, Eq. (2) is rewritten as

$$F(t) = \int_{0}^{t} g(t-\tau)\frac{dF_0(\Delta)}{d\Delta}\dot{\Delta}d\tau \tag{3}$$

which can be reformulated using a mathematical conversion into:

$$F(t) = F_0[\Delta(t)] + \int_{0}^{t} F_0[\Delta(t-\tau)]\dot{g}(\tau)d\tau \tag{4}$$

where $g(t)$ is the dimensionless relaxation modulus or the relaxation function, and $F_0(\Delta)$ represents the instantaneous force/displacement relationship. Eq. (4) implies that the force response of the fingertip can be decomposed into two components. The first term describes the instantaneous force response, while the latter term characterizes the delayed force response that takes into account the effects of loading histories on the current deformation state.

For many practical problems (e.g. the force responses and viscous relaxations of a fingertip subjected to a sudden step displacement), the time-delivery of the prescribed displacement, $\dot{\Delta}$, is noncontinuous. Consequently, the time-delivery of the instantaneous force response, $dF_0[\Delta(t)]/dt = \frac{dF_0(\Delta)}{d\Delta}\dot{\Delta}$ also becomes noncontinuous. The numerical singularities associated with differentiations of the instantaneous force responses in Eq. (3) can be overcome by computing the differentiations of the relaxation modulus, $\dot{g}(t)$ in Eq. (4), which is continuous in the time domain. Therefore, in the present study, Eq. (4) is used to compute the force response of the fingertips.

The application of the proposed model requires the determination of two material/structural functionals, $g(t)$ and $F_0(\Delta)$. A series of experiments were performed on human fingertips to identify these parameters, which are further described in the following section. In order to determine $g(t)$, a step displacement, Δ_0, was applied to the fingerpad at $t = 0$, and the displacement was then kept constant for $t > 0$. The time-history of the response force of fingerpad, $F(t)$, was measured. Using Eq. (3), the relaxation function, $g(t)$, is then derived from the measured force response, in the following manner:

$$g(t) = \frac{F(t)}{F_0(\Delta_0)},\ F_0(\Delta_0) = F(0) \tag{5}$$

In the present study, a Prony series expansion for the dimensionless relaxation modulus [15] was employed to characterize the normalized relaxation modulus, such that:

$$g(t) = 1 - \sum_{i=1}^{N} g_i(1 - e^{-t/\tau_i}) \tag{6}$$

where g_i and τ_i ($i = 1,2,3,...$) are the material/structural constants of the fingertip; and N is a sufficiently large number to achieve a good fit of Eq. (6) to the experimental data.

The mechanical stability restrictions require that the instantaneous force response function satisfies

$$F_0(0) = 0 \ \text{ and } \ \frac{dF_0(\Delta)}{d\Delta} d\Delta > 0 \tag{7}$$

which implies that $F_0(\Delta)$ is an increasing function of Δ.

The instantaneous force response can be considered to follow a power law of the form:

$$F_0(\Delta) = A \cdot \left(\frac{\Delta}{\hat{\Delta}}\right)^b \tag{8}$$

where A (N) and b ($-$) are positive material/structural constants; $\hat{\Delta}$ (=1.00 mm) is the reference displacement, a characteristic displacement of fingerpad; and the displacement, Δ, is in mm. This formulation satisfies the mechanical stability restrictions, as described in Eq. (7).

3. Experimental methods

3.1. Experimental setup

An experimental setup was designed to study the mechanical response of a fingertip to dynamic loading. The setup comprises a 25 mm × 25 mm flat steel platen and a finger hold, as schematically shown in Fig. 1. A universal micromechanical testing machine (Type: Mach-I, Biosyntech, Montreal, Canada) was used to generate the platen motion using a displacement-controlled protocol. The testing machine was equipped with a displacement sensor with a resolution of 0.5 μm and a 9.8 N (1 kg) load cell with a resolution of 0.49 mN (500 mg). During the experiments, each subject was seated assuming a relaxed posture with forearm supported on an arm rest. Subjects were advised to place their index fingers in the finger hold that was designed to produce approximately a 20° angle of the dorsum of the distal part with respect to the horizontal table top (or the compression platen).

The steel compression platen was covered by a smooth plexiglass sheet (3 mm thick) in order to minimize the effects of temperature difference between the platen and the fingertip on the mechanical response of the fingerpad. In order to keep contact between the finger and the support surface during the test, a double-sided adhesive tape was applied on the nail of the subject's index finger before placing it on the finger rest. Since the thickness of the tape (0.10 mm) is small compared to the dimensions of the finger, the error associated with the deformation of the double-sided tape (i.e. the variation in tape thickness under compression) was negligible. We have calibrated the system to evaluate the error that may be introduced by the adhesive tape. A rubber block was compressed on the testing machine, once with the adhesive tape between the rubber block and compression platen and once without the adhesive tape. No measurable difference was found between the force responses obtained from these two measurements.

3.2. Test procedures

The experiments were performed by displacing the platen against the subject's fingertip by a specified magnitude using the displacement-controlled protocol. The resulting force response and platen displacement were recorded at a sampling frequency of 33 Hz. Four adult

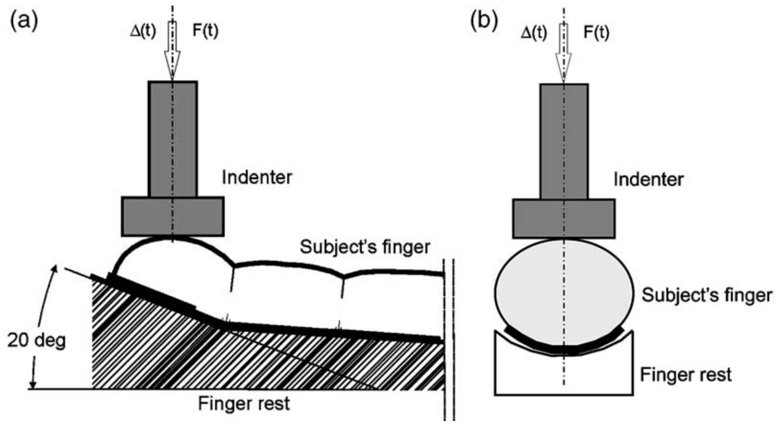

Fig. 1. Experimental setup for the finger compression tests. (a): Side view. The subject's finger was rested on a plastic finger rest, which kept the angle between the dorsum of the distal part of the index finger and the table top to be 20 degrees for all tests. (b): Cross section view. The nail was fixed onto the finger rest using a thin double-sided adhesive tape. The tests were conducted using a displacement-controlled protocol.

subjects (2 males and 2 females) participated in the study. The subjects had an average age of 24 years (21–30 years). The experiments were conducted on the index fingers of the right and left hand of each subject. Each subject gave written consent to the tests that had been approved by the NIOSH Human Subject Review Board. Each subject was permitted a few practice runs before data collection. The average width and height of the distal phalanx of the subject fingers were 16.5 ± 1.5 mm and 12.0 ± 2.0 mm, respectively.

Two series of experiments involving different magnitudes of fingertip compression were conducted. In test series A, the fingerpad was compressed to a displacement of 2.00 mm using six different rates of loading (0.1, 0.2, 0.4, 0.9, 1.5, and 5.7 mm/s), as demonstrated in Fig. 2a. The maximum displacement of the fingertip (2.00 mm) was held constant for approximately 30 s, allowing the response forces of the fingertip to stabilize. The platen displacement was then reduced to 1.00 mm at a speed of 1.00 mm/s, and the displacement (1.00 mm) was held constant for another 30 s.

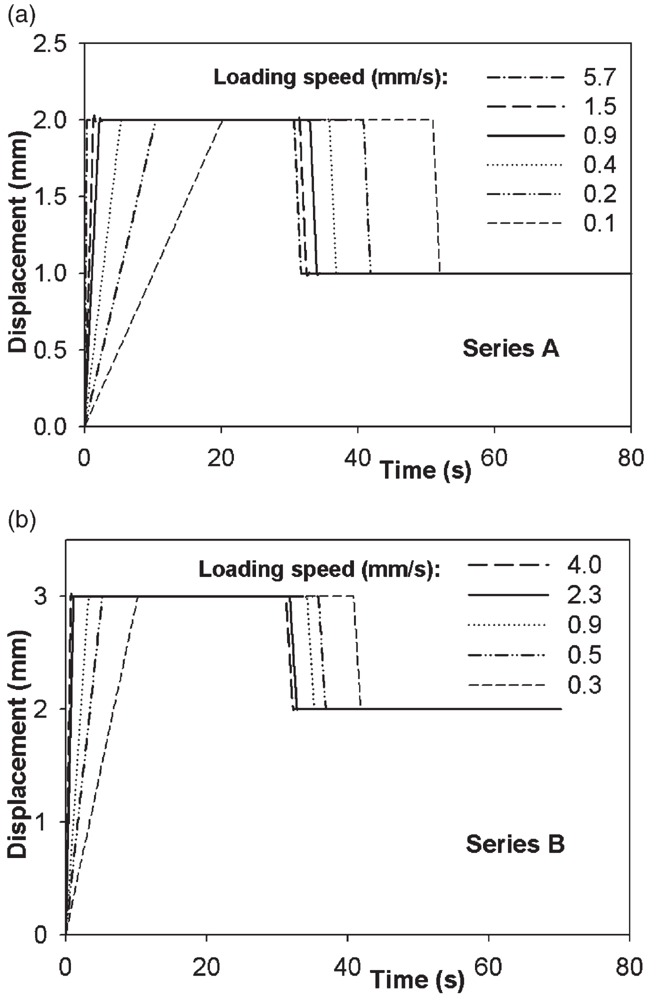

Fig. 2. The prescribed displacement histories of the compression platen. (a) Test series A. (b) Test series B.

Test series B involved a controlled displacement to 3.00 mm (Fig. 2b). The fingertip was loaded to the peak deformation (3.00 mm) using five different loading speeds (0.3, 0.5, 0.9, 2.3, and 4.0 mm/s), and the displacement was held constant at 3.00 mm for approximately 30 s. The platen displacement was then reduced from 3.00 mm to 2.00 mm at a speed of 1.00 mm/s, and held at 2.00 mm for another 30 s.

Force relaxation measurements were conducted prior to test series A and B in order to calibrate the proposed dimensionless relaxation modulus, $g(t)$, described in Eqs. (5) and (6). Fingertips were subjected to step displacements of 2.00 and 3.00 mm (at a loading speed of 5.00 mm/s), corresponding to test series A and B, respectively, that were kept constant for 30 s to permit the force response of the fingertip to approach steady-state values.

All subjects underwent the two force relaxation tests and two series of tests (A and B), with a break of 20 s between two successive runs within each series of tests, allowing for a recovery of the viscous deformation of the soft tissues. Each subject was permitted a 15 min rest period between the two series of tests to enable the subjects to recover from any musculoskeletal fatigue in fingers and hands. The experimental study involved eight tests, i.e. the index fingers of right and left hands of four subjects. Two of the tests were considered unsuccessful because the subjects were unable to keep the index finger stable during compression; the corresponding data were excluded from subsequent analysis. In the test results reported below, the mean values are calculated using the remaining six tests. The force relaxation tests were conducted only on the right index finger of each subject.

4. Results

Fig. 3a and b shows the time histories of the normalized force responses obtained from the force relaxation tests corresponding to test series A and B, respectively, together with the fitting curves, $g(t)$, as described in Eq. (6). Four sets of test data acquired from four subjects for each series (A and B) were used to obtain the dimensionless relaxation modulus functions. The results show relatively small variations among the data acquired from the four subjects. The averaged values of the test data for all subjects were used for the curve fitting. The standard lease square method was used and a criteria of 2% error tolerance was applied for the curve fitting. The results further revealed that satisfactory fitting can be achieved using two terms ($N = 2$) for the Prony series expansion [Eq. (6)]. The parameters defining $g(t)$ were determined from the measured data, as: $g_i = (i = 1{,}2)$ 0.2359 and 0.1541, and $\tau_i = (i = 1{,}2)$ 0.1182 and 5.45 s, for series A (Fig. 3a); $g_i = (i = 1{,}2)$ 0.3866 and 0.1560, and $\tau_i = (i = 1{,}2)$ 0.1802 and 5.45 s, for series B (Fig. 3b).

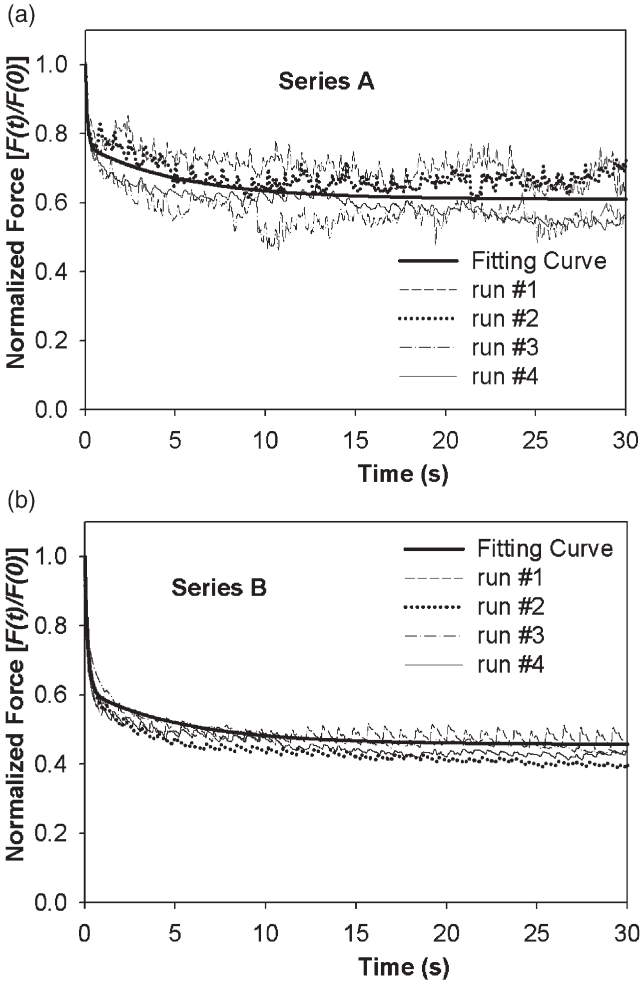

Fig. 3. The dimensionless relaxation modulus of the proposed model [$g(t)$] compared to the time histories of the normalized contact force responses of fingertips obtained under a step displacement during four trials. (a) Test series A. (b) Test series B.

Fig. 4 depicts comparisons between the rate-dependent force/displacement data obtained from experiments and those predicted using the proposed physical model for test series A and B. These results were obtained for the loading parts of test series A and B, and were the averaged values for all six available test data. The rate-dependent force/displacement curves were predicted using Eq. (4), which was based on two previously determined material/structural parameters underlying functions, $g(t)$ and $F_0(\Delta)$.

The instantaneous force/displacement relations, $F_0(\Delta)$, should, theoretically, be determined at an extremely high loading speed at which the viscous deformation is negligible. In the present study, the compression tests were performed using a conventional micro testing machine with limited loading and data acquisition speeds. Therefore, $F_0(\Delta)$ was obtained using an iterative scheme: (a) An initial instantaneous force/ displacement relationship, $F_0(\Delta)$ is assumed by multiplying the force/displacement curves corresponding to the tests at the highest loading speed in each test series (i.e. $v = 1.5$ and 4.0 mm/s for test series A and B, respectively) by a factor of p ($p \approx 1.2$ for the first trial). It is to be noted that the highest loading speed in series A (5.7 mm/s) could not be used because of insufficient data points; the test data acquired at the next highest speed (1.5 mm/s) were used. (b) The force/displacement curves corresponding to the highest loading speed were then derived using the force relaxation parameters (g_i and τ_i) obtained previously (Fig. 3) together with the initial estimate of $F_0(\Delta)$. (c) The magnification factor p was modified until an optimal fit of the model predictions with the experimental data were achieved. The optimized magnification factors, p, were 1.29 and 1.20, respectively, for test series A and B. (d) Finally, the instantaneous force/displacement relation [Eq. (8)] was fitted to the optimized force/displacement relationships, and the constants A and b were found to be 0.2368 (N) and 2.0696 for series A; and 0.1727 (N) and 2.8694 for series B, respectively.

The time-dependent force/displacement curves obtained from the experimental data, together with the optimized instantaneous force/displacement curves (labelled v_{max}, in the figures), are depicted in Figs. 4a and c, corresponding to test series A and B, respectively. The predicted rate-dependent force/displacement curves for test series A and B are shown in Figs. 4b and d, respectively. The results suggest that fingertips' stiffness and force magnitudes increase with increasing loading speeds. The results show good agreements between the experimental data and the model predictions in the entire range of loading speeds and deflections considered in this study.

The time-histories of the averaged values of the measured force responses for all subjects in test series A and B are depicted in Figs. 5a and c, respectively. The corresponding model predictions for the test series A and B are shown in Figs. 5b and d, respectively. Our results show that the predicted time-histories of the force responses are consistent with those obtained experimentally.

Fig. 6 illustrates the mean, minimum, and maximum values of the force responses as a function of time, corresponding to three different loading speeds in test series A and B. The mean values of the test data were calculated from six independent measurements; these test data are scattered within the region enclosed by the upper and lower bound curves. The predicted time-histories of the force responses corresponding to these test conditions are also shown in the figures. It is seen that the predicted force responses agree well with the mean experimental data over the entire range of loading speeds and time histories.

The instantaneous stiffness of the fingerpad used in the present study were compared with those measured

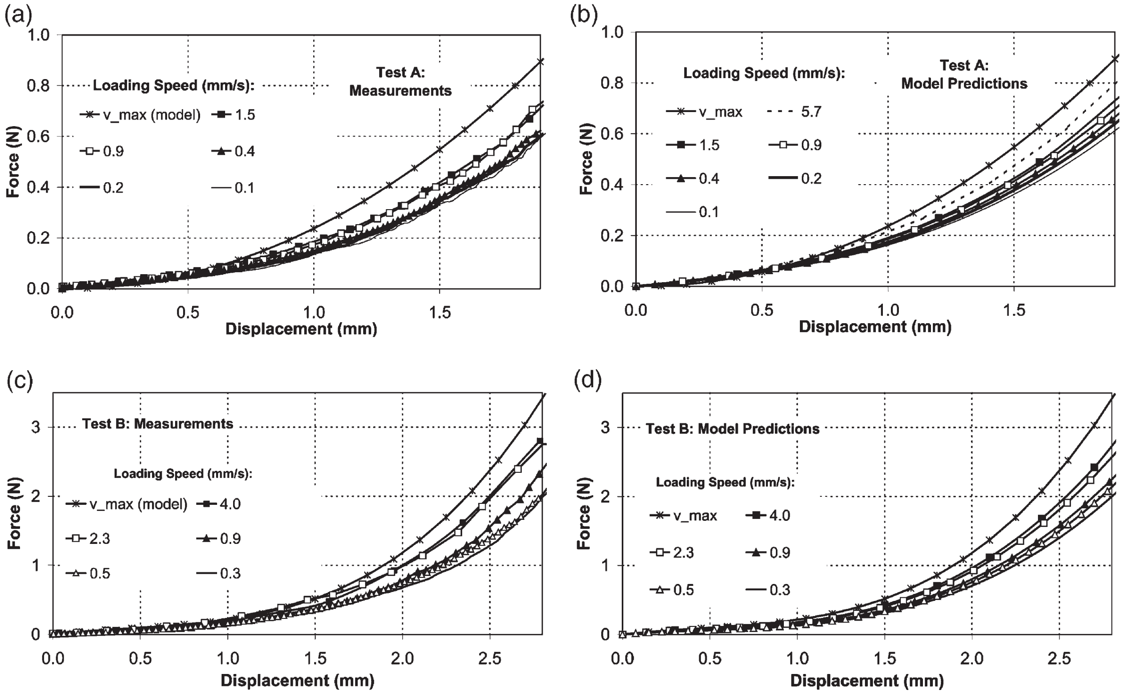

Fig. 4. The rate-dependent force-displacement curves of fingertips: experimental data vs. model predictions. (a) Series A—measurements; (b): Series A—model predictions; (c) Series B—measurements; (d) Series B—model predictions. The experimental data were the averaged values for all six available tests data.

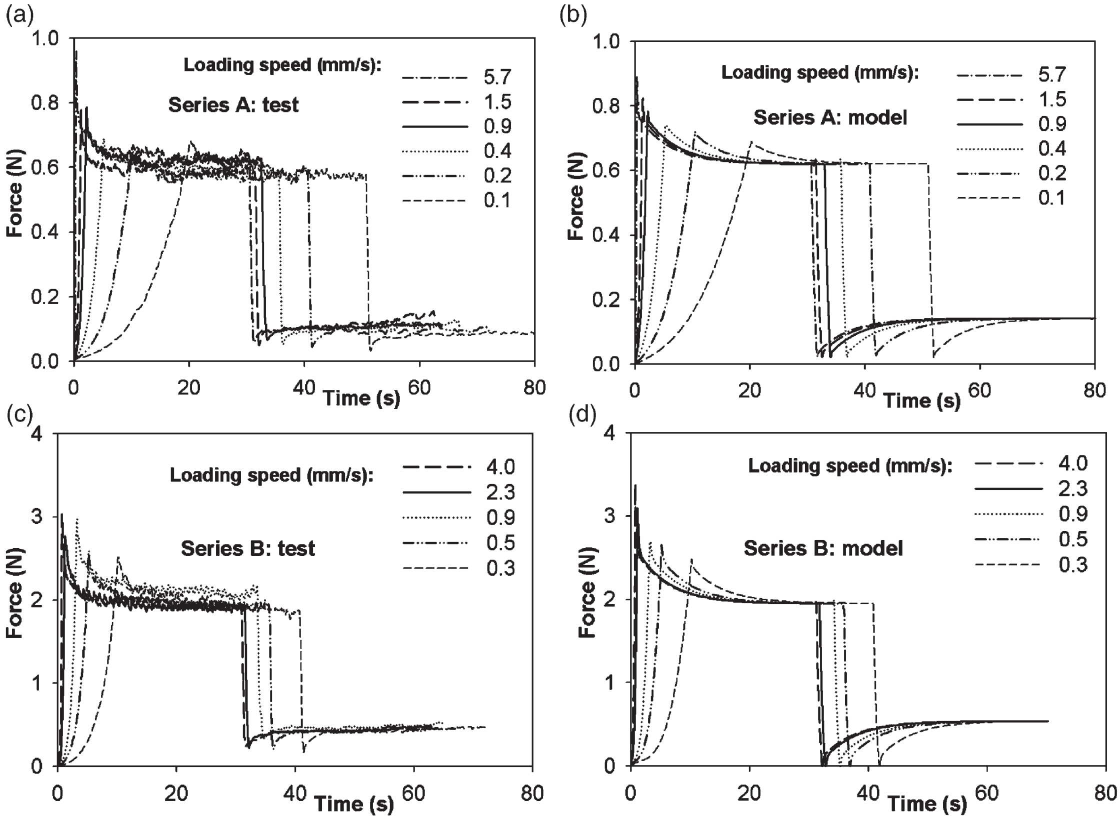

Fig. 5. The force responses as a function of time for fingertips subjected to the prescribed displacement histories as shown in Fig. 2. (a) Series A—measurements; (b): Series A—model predictions; (c) Series B—measurements; (d) Series B—model predictions. The experimental data were the averaged values for all six available tests data.

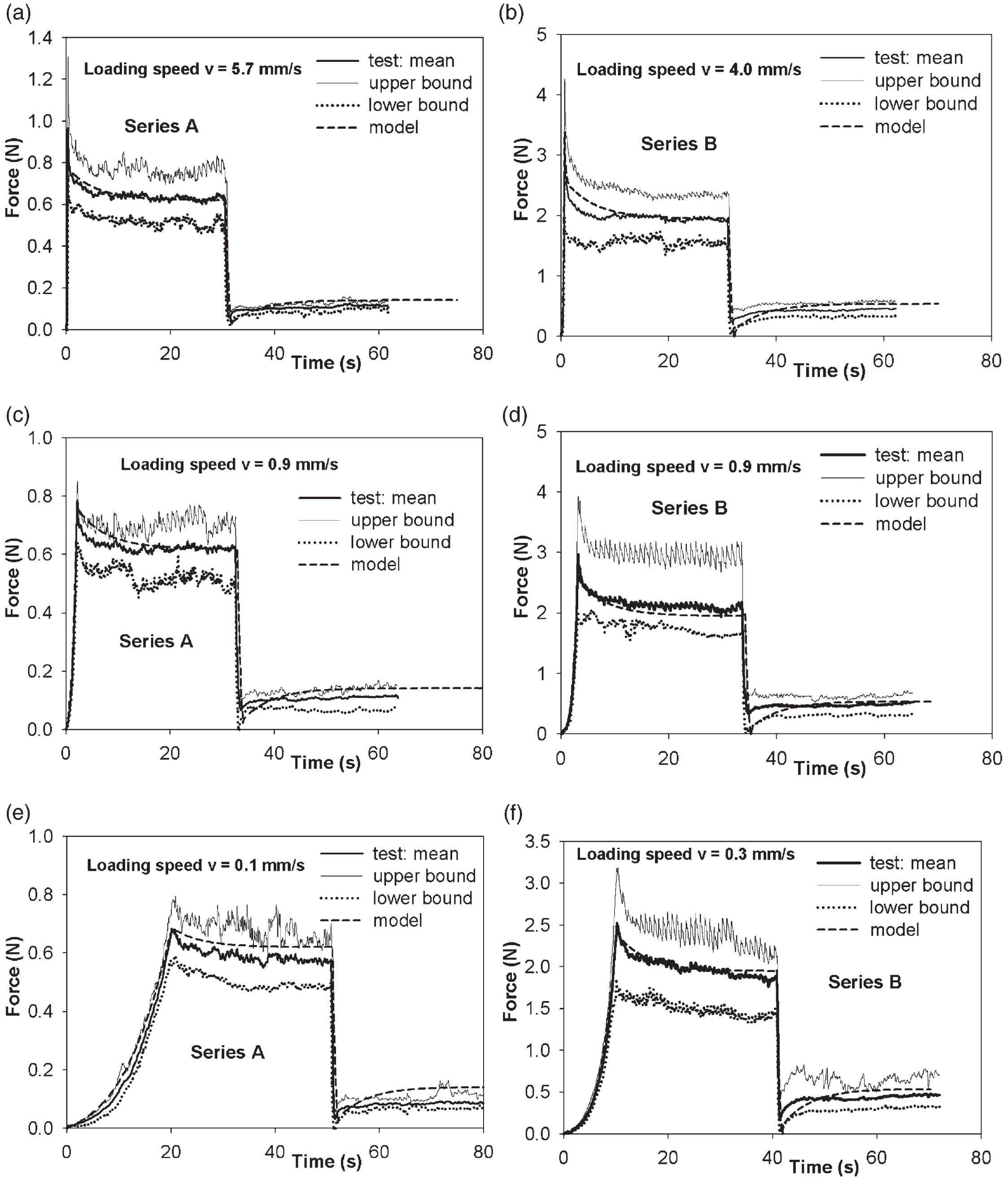

Fig. 6. The comparison of the force responses predicted using the proposed model to those obtained from the experiments. (a),(c), and (e): Series A. (b),(d), and (f): Series B. The mean values of the experimental data were calculated from six independent measurements which are scattered within the upper and lower bounds.

by Pawluk and Howe [10], as shown in Fig. 7. Pawluk and Howe's data were obtained using a similar test procedure as proposed in this study; however, the angle of the dorsum of the distal part with respect to the contact platen was not fixed in their tests, and the subject was allowed to take a comfortable posture during the measurements. Tests #1–#4 from Pawluk and Howe's [10] data were obtained using four different subjects under the same test procedure. The comparison shows good agreement in view of the trends, while the magnitudes differ, especially for high forces. The differences in magnitudes are attributed to the differences in subjects and test conditions (e.g. ambient temperature and contact angle between fingerpad and platen).

No significant difference between the force response behaviors between right and left index fingers was observed in the test. However, due to the small sampling number we cannot get a conclusive result from this observation.

The repeatability of the experiments has been tested

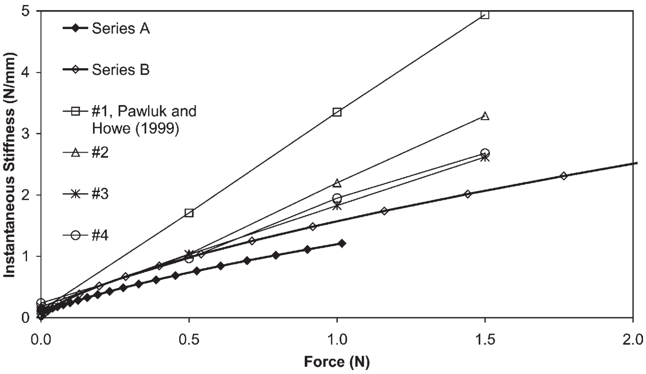

Fig. 7. The instantaneous stiffness of fingertips obtained in the present study compared to those reported by Pawluk and Howe [11]. Tests #1–#4 from Pawluk and Howe's data were obtained using four different subjects under the same test procedure.

on one subject by repeating the same loading procedure for three times. The subject was allowed to have a break of ten minutes after each run. The measured force values varied within a range of 15% (results not shown).

5. Discussion and conclusion

Hand–arm vibration syndrome (HAVS) has been associated with the degenerations of the local neural and vascular systems in the fingers during extensive exposure to vibration [16–18]. These hypotheses have been supported by numerous diagnostic tests of HAVS performed on the fingers or fingertips [19,20]. Several investigators [21,22] suggested that vibration energy absorption (VEA) may be a significant factor leading to the vibration injuries. These hypotheses obtained support from the epidemiological investigations [23] which indicated that HAVS might be correlated to VEA. Some studies have been conducted to characterize the total VEA in the hand–arm system [24,25]. A fundamental deficiency of these previous methods is that they could not determine the location of the energy dissipation in hand and arm. The local energy dissipation in fingertips might be an essential factor leading to the development of the vibration-induced disorders, since the most severe HAVS symptoms have been observed to be localized on fingers or fingertips. The study of the local VEA in the fingertips may, therefore, provide essential information to elucidate the mechanisms of HAVS. It is technically extremely difficult to experimentally separate the local VEA in the fingertips from the total energy absorption in the hand-arm system at low vibration frequency ($<$100 Hz). The most critical step to determine the local VEA is to obtain the dynamic force response of fingertips. In the present study, a physical model was proposed to simulate the nonlinear and time-dependent force response of fingertips during dynamic contact with a flat object. The proposed approach can be used to calculate force response and estimate the energy dissipation in fingertips during vibration and dynamic loading. Our approach could, therefore, be used to provide insight into the pathomechanics of occupational-related musculoskeletal disorders, and help in the design of hand tools and office equipment to prevent occupational injuries.

The predicted rate-dependent force/displacement curves and time-histories of force responses under different loading speeds agreed well with the corresponding experimental measurements. The results thus suggest that coupling of the nonlinear force/displacement relations and time-dependent force responses of fingertips under dynamic contact conditions can be adequately characterized using the proposed model. Both experimental results and the model predictions reveal general features of the force response of fingertips when contacting a flat surface: (a) the force/displacement relationship of fingertips is nonlinear—the stiffness of the fingertips under compression increases dramatically with increasing deformation and follows a power law; (b) the force/displacement curves are rate- or time-dependent—a higher loading speed yields higher fingerpad stiffness; (c) the loading or deformation histories influence the transient force responses of the fingertips; and (d) the response forces of the fingertips, which are compressed and then held constant for a relatively long period, tend to reach a steady-state value that depends on the imposed displacement.

The present study represents an extension of the investigations conducted by Pawluk and Howe [10,11]. In our proposed model, the relaxation modulus is expanded using a general Prony series, which describes the force relaxation curves accurately with two terms. The analysis of the force response using Bolzmann's superposition principle directly, however, would pose difficulties because of the numerical singularities associated with the discontinuous nature of the force time-history (Eq. (3)). Alternatively, we propose another form to derive the force responses (Eq. (4)). The solution of Eq. (4) requires knowledge of the relaxation modulus, $g(t)$, and the instantaneous force-displacement relationship, $F_0(\Delta)$, which can be determined using two sets of experiments: (a) a force relaxation test, and (b) a fast loading test at a constant loading speed ($v > 1.0$ mm/s). These tests can be conducted using commercially available testing machines.

Theoretically, the instantaneous force/displacement relationship should be obtained by loading the fingertip at a very high speed, so that the viscous effects during the loading process can be neglected. However, in real tests, it is technically difficult to avoid the measurement errors produced by the inertial effects of the loading equipment and soft tissues during high speed loading. Consequently, it would be a technical challenge to obtain repeatable data of the instantaneous force/displacement relationships using "direct" measurements. Using the proposed "indirect", iterative approach, reliable instantaneous force/displacement relationships can be obtained by performing tests at "slow" loading speeds.

In order to restrict the movement of fingers during the tests, the subjects' fingers had to be kept in place. Because the lateral restriction on deformation of soft tissues of the fingerpads will affect the force response characteristics, previous researchers have usually glued the nails on the testing table using commercial super glue [10,26]. In the present experiments, a thin double-sided tape was used to fix the nail on the testing table. While the fixation strength of the doubled-sided tape is relatively poor compared to that using super glue, this method was considered to be more convenient, as it allowed subjects to relax between successive tests.

The time histories of the measured force response shows force fluctuations when the displacement was kept constant, and the posture of the subjects was not changed (Figs. 3, 5a and c and 6). Although the subjects maintained a fixed posture during the tests, involuntary muscle activation and pulsing blood flow in the fingers are believed to cause these force fluctuations. The use of a low-pass filter would eliminate these "high" frequency fluctuations. In our physical model, the anatomical micro-structures were not considered, therefore, these force fluctuations would not be simulated.

The proposed model simulates the force response of the soft tissues for dynamic loading, while the inertial effects of the tissues were neglected. The proposed model is quasi-static in nature, and the force response was considered to depend on the deformation histories of the soft tissues exclusively. Therefore, the proposed model is not suitable for predicting impact forces, where inertial effects would become important.

The model predictions agree well with the experimental results. They indicate that the force-displacement curves at high loading speeds (e.g. >1.0 mm/s, as in Fig. 4) differ distinctively, while those for low loading speeds (e.g. <0.5mm/s) are similar and tend to converge to a steady-state. Experimental and theoretical results suggest that the peak resultant contact force at the fingertip increases by 50% to 75% at high (>1.0 mm/s) compared to slow (<0.2 mm/s) speeds of loading.

The measured time-histories of the force response exhibit high transient forces near the end of the displacement ramps (Fig. 5). These "singularities" in the time-histories of the force response may be caused by the sudden transition of the loading speed to zero, thereby inducing large decelerates. Such transient effects were smaller for the low compared to the high loading speeds. Consequently, the measured rate-dependent force-displacement curves are presented in the deformation ranges of 0.0–1.9 mm (Fig. 4a,b) and 0.0–2.9 mm (Fig. 4c,d) for test series A and B, respectively.

Many factors may affect the stiffness and force response of the soft tissues in the fingerpads. Preliminary evidence indicates that the ambient temperature and finger posture during the test may have great effects on the force response. In order to reduce temperature effects, we conducted all tests at a strictly controlled room temperature (approximately 22 °C), and all subjects were climatized while staying in the room for at least 30 min prior to testing. All components of the test equipment that contact with the hand and fingers of the subjects were covered with plexiglass. All compression tests were performed using a contact angle of 20° between the fingertip and the flat contact surface, so that the results can be compared across tests and subjects.

The fingertip is complex in anatomical structure and contains biological materials of totally different characteristics. One way to model such complicated problems is using finite element, such as [27]. However, in many cases bioengineers are mainly interested in the global force responses of fingertips, not the detailed stress/strain distributions in tissue level. The proposed model was intended for these practical applications. One-dimensional quasi-linear viscoelastic models have been previously used for other soft tissues, such as cartilage [28], soft tissues [29], and skeletal muscles [30]. Since the major interest for such phenomenological models is the total force responses of the system, the biological substructures of the fingertip are not considered, while the effects of the different material properties in fingerpad are included in the global force/deformation response measures. The limitation of such phenomenological models, in general, is that the local stress/strain distributions in the soft tissues cannot be predicted.

In summary, the force response of fingertips during dynamic contact with a flat surface was investigated experimentally and theoretically in the present study. Our results suggest that the force response of fingertips during dynamic contacts is nonlinear and time-dependent. The physical model is able to characterize the nonlinear, rate-dependent force-displacement, force relaxation, and force time-histories of fingertips during dynamic contacts.

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