Published in final edited form as:

J Orthop Res. 1999 March ; 17(2): 178–184. doi:10.1002/jor.1100170205.

In Vivo Finger Flexor Tendon Force while Tapping on a Keyswitch

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Summary

Force may be a risk factor for musculoskeletal disorders of the upper extremity associated with typing and keying. However, the internal finger flexor tendon forces and their relationship to fingertip forces during rapid tapping on a keyswitch have not yet been measured *in vivo*. During the open carpal tunnel release surgery of five human subjects, a tendon-force transducer was inserted on the flexor digitorum superficialis of the long finger. During surgery, subjects tapped with the long finger on a computer keyswitch, instrumented with a keycap load cell. The average tendon maximum forces during a keystroke ranged from 8.3 to 16.6 N (mean = 12.9 N, SD = 3.3 N) for the subjects, four to seven times larger than the maximum forces observed at the fingertip. Tendon forces estimated from an isometric tendon-force model were only one to two times larger than tip force, significantly less than the observed tendon forces ($p = 0.001$). The force histories of the tendon during a keystroke were not proportional to fingertip force. First, the tendon-force histories did not contain the high-frequency fingertip force components observed as the tip impacts with the end of key travel. Instead, tendon tension during a keystroke continued to increase throughout the impact. Second, following the maximum keycap force, tendon tension during a keystroke decreased more slowly than fingertip force, remaining elevated approximately twice as long as the fingertip force. The prolonged elevation of tendon forces may be the result of residual eccentric muscle contraction or passive muscle forces, or both, which are additive to increasing extensor activity during the release phase of the keystroke.

Although the rate of injury to the tendons at the wrist and adjacent tissues associated with repetitive work is reported to be high (55% of all work-related repetitive motion disorders [6]), the injury mechanisms are not well understood. Along with motion, posture, and vibration, the force exerted during a repetitive task is a risk factor for tendon-related disorders (4,19,23). Understanding how force is transmitted from the site of external application (fingertip) to the internal tissue (finger flexor tendons) is critical to understanding the mechanics of repetitive motion disorders. This understanding determines how the internal biological tissues support an externally applied force, and such knowledge identifies tendons that are exposed to higher forces. The knowledge of *in vivo* tendon tension also guides techniques of tendon repair, procedures for rehabilitation (15,22), and design of joint replacements (25).

Rempel et al. (21) and Martin et al. (18) have measured exposure to force during keyboard work. The fingertip force history during a keystroke contains three distinct phases: (I) the keyswitch compression, (II) the high frequency component during finger impact at the end of keycap motion, and (III) the compression and release of the fingertip (21). Currently, applied fingertip loads and finger postures are used as the input or independent variables in inverse biomechanic models to predict tendon force (7). Harding et al. (13) specifically assumed quasi-

static equilibrium—that is, a simple proportional relationship—during the dynamic activity of piano playing. These models, however, have not been validated for dynamic applications, and hence the internal tendon force (dosage) during a keystroke remains unknown.

The goal of this study was to evaluate the relationship between fingertip force and finger flexor tension by measuring the *in vivo* force in the finger flexor digitorum superficialis tendon during the rapid finger motion of a keystroke. During gait, the directly measured tendon forces of the Achilles tendon are not proportional to the forces measured at the foot (15). Similarly, it is unlikely that during a rapid keystroke the relationship between the tension of the finger flexor tendon and the force at the fingertip is simply proportional. Therefore, we investigated the following three hypotheses. First, existing isometric models based on quasi-static equilibrium do not accurately predict the observed ratios of tendon-to-tip force. Second, high-frequency fingertip forces, for example during fingertip impact, will not be observed in the tendon at the wrist. Third, the relationships between tendon and tip force, as defined by the slope of lines fitted to the data, are different during the loading and unloading portions of a keystroke.

MATERIALS AND METHODS

Five subjects (four female and one male; mean age: 38 years [SD = 8 years]), undergoing open carpal tunnel release surgery at the University of California, San Francisco, participated in the study. All subjects read and signed a consent form. The University of California, San Francisco, Committee on Human Research and the University of California, Berkeley, Committee for the Protection of Human Subjects approved the procedures and consent forms. Prior to surgery, the hand length and joint thicknesses of the metacarpal phalangeal, proximal interphalangeal, and distal interphalangeal joints were measured for each subject. Hand lengths ranged from 20 to 57 percentile, and the average joint thickness ranged from 76 to 98 percentile (11,12). The subjects practiced the tapping tasks before the procedure.

Surgery was performed, as usual, with the patient under local anesthesia at the incision site, and each subject retained motor control of the forearm musculature throughout the procedure. The subjects were prone with the shoulder abducted to 90° and the palm rotated upward resting on the operating table. The carpal tunnel contents were exposed through a 5-cm longitudinal carpal tunnel incision. The flexor digitorum superficialis tendon of the long finger was identified, and the synovium was removed. A gas-sterilized tendon force transducer (6% accuracy [8]) was then mounted onto the flexor digitorum superficialis tendon. *In vitro* dynamic tests of the tendon transducer, in which a tapping-like load (21) was applied to the tendon, indicated that the bandwidth of the system is greater than 50 Hz. After the subject flexed the long finger 10 times to seat the transducer onto the tendon, the tendon thickness was measured *in situ* for use in the transducer calibration facts (2,8). The subject's forearm was rotated 90° from full supination toward a neutral forearm posture with the thumb upward and the palm toward the feet. Finger movements were performed in the horizontal plane. The tourniquet was released prior to data collection, relieving any ischemia, and the forearm and wrist were manually stabilized during the tapping tasks with the wrist straight.

The first subject tapped on a rigid surface with a load cell measuring fingertip force (bandwidth of 1,000 Hz; GreenLeaf Medical Pinch Meter, Palo Alto, CA, U.S.A.). The remaining four subjects tapped on a keycap and keyswitch assembly. The keycap contained a custom-designed load cell with a 3% of full-scale accuracy and bandwidth of 1,000 Hz (24). Subjects were unable to view their hands; however, a buzzer connected to the switch in the keyswitch assembly provided audio feedback of contact. The subjects were asked to tap at one keystroke per second and minimize fingertip contact time with the keycap. Because the tendon force of subject 2 contained a peculiar pattern, described in the Discussion section and suspected to be passive force, the passive tendon force was measured for two subjects (subjects 4 and 5). The finger

was passively moved from flexion to extension and then back to neutral by the surgeon. For this data, tendon force was recorded at 50 Hz. Articulation occurred about the metacarpophalangeal, proximal interphalangeal, and distal interphalangeal joints, with the wrist fixed in a neutral position. The sum of the metacarpophalangeal and proximal interphalangeal joint angles indirectly represented the excursion of the flexor digitorum superficialis tendon. The surgeon removed all transducers once the tasks were completed, and surgery continued. The procedure extended the time of the surgery by approximately 20 minutes.

Data from the fingertip load cell and tendon-force transducers were recorded on a computer data acquisition system at 2,000 Hz. The data were digitally low-pass filtered with a cutoff frequency of 300 Hz. A video camera mounted above the surgical field recorded the sagittal view of the finger posture, fingertip position, and load cell alignment at 30 frames per second. The angles of intersection of lines aligned with the dorsal surface of the finger segments during contact with the keycap defined the approximate joint angle (approximate error = $\pm 1^\circ$), which was later used as input to the tendon-force models (17).

Data on 17-35 keystrokes were collected per subject. The relationship between tendon and tip forces was described by four different multiplier (tendon-to-tip gain) parameters: the ratio of tendon-to-tip maximum forces, the ratio of tendon-to-tip mean forces during contact, the slope of a line fitted to the force data during the loading region, and the slope of a line fitted to the data during the unloading region.

A two-dimensional force model of the finger predicted the tension of the flexor digitorum superficialis, flexor digitorum profundus, extensor digitorum communis, and the intrinsic muscles for each subject (predicted ratio I). The tendon tension model represents the finger as three rigid links for the distal, middle, and proximal phalanx connected by hinge joints. Spanning the joints are the tendons of the extrinsic and intrinsic finger muscles. The balance of static equilibrium for the j th joint is

$$\sum_i F_i r_{ij} + F_{tip} r_{j,tip} = 0 \quad (\text{Eq. 1})$$

where F_i is the force in the i^{th} tendon, r_{ij} is the moment arm for the i^{th} tendon at the j^{th} joint, and the product $F_{tip} r_{j,tip}$ is the moment created by the force applied at the fingertip. The joint thickness and posture measurements taken from the video determined the subject-specific tendon moment arms as described by Armstrong and Chaffin (3) and An et al. (1). Hand length measurements determine the distances between adjacent joint axes of rotation in the sagittal plane as described by Buchholz and Armstrong (5). To find a solution to the indeterminate set of equilibrium equations, we assumed muscle contraction balances the tension to minimize the sum of the squares of the muscle stress (7,20):

$$J = \sum_i (F_i^2 / PCSA_i^2) \quad (\text{Eq. 2})$$

where $PCSA_i$ is the physiological cross-sectional area of the muscle. Values of $PCSA$ were from Chao et al. (7). For the subjects that used a pulp-pinch posture (for all but subject 1, the distal interphalangeal joint was hyperextended), the assumption that the distal interphalangeal joint is a hinge joint was invalid. Therefore, a second tendon-force model, which adds a passive constraint torque at the distal interphalangeal joint simulating its end of the range of motion in the direction of extension (9), also predicted tendon tension for each subject (predicted ratio II). Quadratic programming techniques provided a solution for the six muscle-tendon forces

and the distal interphalangeal joint constraint moment (Matlab; Mathworks, Natick, MA, U.S.A.).

The three hypotheses were tested with parametric statistical methods and simple graphical methods. The *in vivo* force ratios were compared with predicted force ratios with use of paired *t* tests. The suspected nonproportional relationship and the dissipation of the high-frequency fingertip force components were observed by graphically plotting the two forces against each other. Furthermore, the dissipation of the high-frequency components was modeled as a second-order filter, where the low-pass cutoff frequency was calculated by linear regression techniques. The nonproportional relationship was evaluated by comparing slopes of lines fitted to the loading and unloading regions with use of paired *t* tests.

RESULTS

Summary measures for tendon force for each subject are presented in Table 1. When the fingertip was in contact with the keycap, the relationship between the tension of the flexor digitorum superficialis tendon and the fingertip force was not simply proportional (Figs. 1 and 2). First, although the fingertip force patterns (Fig. 1) contained the three phases observed by Rempel et al. (21), the tendon force did not include the impact force (Phase II). Once the fingertip contacted the keycap, tendon force increased continually during the keyswitch compression, through the fingertip impact, and up to the maximum force of the fingertip compression phase. It appears that the impact force is dissipated into structures, such as the fingertip pulp, finger joint ligaments, and other connective tissues distal to the wrist. A low-pass, second-order filter fitted to the fingertip force and tendon tension data with the fingertip force as the input had an average cutoff frequency of 13 Hz (SD = 7 Hz).

Second, the relationships between the tendon and fingertip force differed between the loading and unloading portions of the keystroke (Fig. 2). Tendon force increased with increasing fingertip force, but after peak fingertip force, tendon force decreased at a slower rate than tip force. The average half relaxation times (time following maximum force for a 50% reduction in force) were 0.071 seconds (SD = 0.013 seconds) for the tip and 0.151 seconds (SD = 0.023 seconds) for the tendon force, a significant difference (paired *t* test: $p = 0.006$). As a result, the average slope of the line fitted to the tendon and tip forces (Table 1) in the unloading region was less than during loading ($p = 0.0011$). Correlation coefficients for the linear regression ranged from 0.67 to 0.95.

Third, when the fingertip was not in contact with the keycap, the tendon force was often elevated (Figs. 1 and 2). Tendon force increased before contact of the fingertip with the keycap. The tendon was preloaded at the point of contact. The y intercepts of the lines fitted to the data approximate this preload (Table 1). For subject 2, there was a large increase and then decrease in tendon force before contact. As contact ended, the tendon force, as mentioned previously, was elevated, approximately 57% of the maximum value averaged across subjects. Here, the intercepts of the lines fitted to the unloading portion of the data provided a measure of the tendon tension when the tip force was removed.

Finally, the model estimates of the tendon-to-tip force ratio (predicted ratio I) were significantly ($p < 0.03$) less than the measured ratios (predicted ratio I in Table 1). When the distal interphalangeal joint constraint torque was added to the model, the estimates (predicted ratio II in Table 1) were still smaller than the measured maximum and mean ratios but not significantly so ($p = 0.16$). The estimates with the distal interphalangeal constraint were somewhat greater than the slopes during the loading portion of the histories (mean difference = 0.2) but also were not significant ($p = 0.75$).

DISCUSSION

The goals of this study were to examine the relationship between the fingertip force and the finger flexor tendon force during a keystroke and to determine whether the relationship was proportional. Figure 2 illustrates that the relationship was not proportional. Most inverse tendon-force models assume a causal relationship—that is, the applied load at the fingertip creates the tendon tension. For isometric models, this assumption is acceptable because the relationship is proportional (9) and causality is a moot issue. However, the true causality is reversed. The tendon force with the effects of dynamics and the forces of several muscles superimposed create the tip force. The result is that the force histories of the flexor digitorum superficialis tendon during a keystroke are a complicated function of fingertip loading and muscle mechanics associated with different contraction states.

Change in the muscle-contraction states coincides with abrupt transitions in the slope of the tendon force with respect to time at points A, B, and C in Fig. 1. Just prior to fingertip-keycap contact, the muscle shortens as the finger flexes—an unloaded concentric contraction. When the fingertip first contacts the keycap (point A), the inertia of the keycap and the force of the keyswitch spring are added to the fingertip, increasing the load of the concentric contraction. When the fingertip stops moving at the end of keyswitch travel (point B), an isometric contraction begins and the tendon force continues to increase. As the release motion begins (point C), the isometric contraction ends and the flexor muscle lengthens, initiating an eccentric contraction.

The properties of the muscle mechanics may contribute to the tendon force remaining elevated for some time after the tip force vanishes. The speed associated with the coordinated movement of a keystroke requires that the force applied by the fingertip be removed quickly. However, the decay of the flexor digitorum superficialis muscle force is set by muscle physiology and is relatively slow, on the order of 0.1 seconds (16). Electromyographic studies of typing indicate that the beginning of extensor activity overlaps with the end of the flexor activity (10,26). Because the flexor muscle contraction is near the maximum value as the release movement begins and because during the release motion the flexor muscle lengthens, its contraction is eccentric. This type of contraction produces higher forces than an isometric or shortening muscle (14). Superimposed on the residual eccentric contraction is the muscle's passive force. As the fingertip moves away from the keycap, the flexor muscle lengthens past its free length and the passive muscle force increases.

The passive muscle force may also explain the increase and decrease of flexor digitorum superficialis tendon force prior to contact with the keycap for subject 2. Figure 3 plots the position of the fingertip relative to the keycap as observed from the video system. The location of a dot of ink on the fingertip was digitized for each video frame (30 Hz) and calibrated to a known width in the field of view. Most of the motion was about the metacarpophalangeal joint. The tendon force followed a repeatable pattern with respect to fingertip position prior to contact (Fig. 4). The data displayed the same shape and magnitude of a muscle's passive muscle-force properties, which were measured for subjects 4 and 5 (Fig. 5). This elevated tendon force pattern prior to the keystroke was observed for only one subject, but the movement pattern was more typical of that observed during typing (10).

The data indicated that in predicting simple relationships, such as the ratio of maximum forces, inverse isometric-force models underestimate the measured ratios. The estimates from isometric tendon models were in the same range as those of Harding et al. (13)—0.8-2.7 for five postures emulating the hand during piano playing. Some of this discrepancy may be attributed to the distal interphalangeal hyperextension (pulp pinch) posture selected during a keystroke, as proposed by Dennerlein et al. (9). Adding a distal interphalangeal constraint

torque, which aids the flexor digitorum profundus tendon in counteracting the torque created by the tip force at the distal interphalangeal joint, appears to accommodate the different strategies related to distal interphalangeal pulp-pinch posture. Although the distal interphalangeal constraint provides some improvement in model prediction, none of the models include the important bias of muscle preload or co-contraction, and thus they underpredict the ratios of mean forces (mean error = 1.2). The model with the distal interphalangeal constraint torque better predicted the slopes from the lines fitted to the data because the linear regression provided a line with an intercept, which approximated the preload. The ratios of maximum and mean forces are slopes of lines that pass through zero and thus do not include the tendon force (preload) as the fingertip first contacts the keycap (Fig. 2).

This study has several limitations. First, only one of the six tendons of the long finger was measured, providing a limited view of all the internal forces. The forces in the other finger tendons, specifically the flexor digitorum profundus, remain unknown. Ideally, simultaneous measurement of both tendon forces would elucidate how the flexor digitorum superficialis and flexor digitorum profundus work passively and actively together during a keystroke. Second, tapping on a single keyswitch while prone on one's back in a surgical setting is a different task than touch-typing. The posture of the upper extremity and the slight sedation of the subjects during surgery may have compromised the motor performance during a keystroke. Indeed, the duration of the keystroke was longer, contact velocities were slower, and the motion patterns, except for one subject, were different than for touch-typing (10,21). Third, the subjects had carpal tunnel syndrome, and their associated sensory deficiencies may have also affected the motor control of the keystroke. These limitations suggest that the reported maximum and mean tendon forces and the observed fingertip forces may be different than those that occur during touch-typing. However, the conclusions about the four parameters relating fingertip force and tendon force rely on the mechanics of the musculoskeletal system rather than on the motor control and therefore remain valid.

In conclusion, the findings of this study provide a view inside the musculoskeletal system during a keystroke that to date has only been conjectured. The force histories of the flexor digitorum superficialis tendon are a complicated function of fingertip loading, fingertip motion, and muscle contraction state. The tendon force remained elevated after the force at the fingertip vanished. Furthermore, the maximum forces in the flexor digitorum superficialis tendon were four to seven times larger than the maximum forces during a keystroke. This is greater than the levels predicted with use of existing isometric models.

Acknowledgment

The authors would like to acknowledge the patients and staff of the University of California, San Francisco, Ambulatory Care Surgery Center. The authors also thank Joseph (Seppi) Lin, Pete Johnson, and Joel Bach of the University of California, San Francisco, Ergonomics Program for their support and cooperation. This research was funded partly by the University of California, San Francisco, School of Medicine Research Evaluation and Allocation Committee Cason Fund.

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FIG. 1.

Flexor digitorum superficialis tendon and fingertip force histories for five subjects during a keystroke. Subject 1 tapped on a rigid surface. Abrupt changes in tendon force slope are denoted at points A, B, and C and correspond to a change in muscle contraction state. The three phases of the fingertip force are denoted for subject 4. The fingertip impact force was not observed at the tendon for those who tapped on a keyswitch (subjects 2-5).

FIG. 2.

Comparison of the flexor digitorum superficialis tendon with the fingertip force for the keystrokes of Fig. 1. First contact with the keycap is A, impact is at B, and release of the keycap is at C. Tendon force is often elevated when the fingertip first contacts the keycap. It also remains elevated, decaying more slowly, as the fingertip force vanishes.

FIG. 3.

The force and motion histories for subject 2. Subject 2 used a four-stroke motion pattern consisting of a backswing, downswing, a release, and then a return to rest movement. Points 1, 2, and 3 mark the maximum backswing position, maximum tip force, and maximum release position, respectively.

FIG. 4.

The flexor digitorum superficialis tendon forces with respect to fingertip position during the backswing and downswing for five keystrokes of subject 2. Comparison of tendon force with fingertip position and the repeatable pattern suggest that the forces during the backswing and downswing are passive force-length properties of the flexor digitorum superficialis muscle.

FIG. 5.

The flexor digitorum superficialis tendon force while the finger was moved passively by the surgeon (subjects 4 and 5). Data for extension and flexion were averaged together every 30° between 165 and -15° (vertical error bars are SE). The ordinate is the sum of the relative metacarpophalangeal (MP) and proximal interphalangeal (PIP) joints and is positive for flexion.

TABLE 1
Flexor digitorum superficialis tendon tensions and parameters relating tendon-to-fingertip force during a keystroke

	Subject					Mean
	1 ^a	2	3	4	5	
Keystroke duration (ms)	136 (33)	277 (70)	158 (33)	210 (36)	224 (37)	219 (53)
Max. tendon tension (N)	11.2 (3.4)	14.0 (6.6)	14.6 (3.6)	8.3 (2.0)	16.6 (6.8)	12.9 (3.3)
Mean tendon tension (N)	6.5 (1.8)	8.0 (4.2)	7.9 (2.0)	5.0 (1.4)	8.6 (3.4)	7.2 (1.4)
Ratio of maximum forces ^b	3.5 (1.0)	4.4 (0.3)	6.6 (1.0)	5.5 (1.7)	6.8 (1.5)	5.4 (1.4)
Ratio of mean forces ^b	3.4 (1.2)	4.5 (1.2)	6.5 (1.0)	6.2 (1.8)	5.6 (1.3)	5.2 (1.3)
Slope loading ^b	1.9 (0.6)	3.7 (0.8)	5.0 (1.4)	3.0 (1.0)	5.5 (1.4)	3.8 (1.5)
Intercept loading (N)	4.7 (1.1)	1.7 (2.2)	2.8 (1.3)	3.1 (1.3)	2.0 (1.5)	2.9 (1.2)
Slope unloading ^b	0.6 (0.6)	2.1 (1.3)	3.2 (1.5)	1.5 (1.9)	4.7 (1.3)	2.4 (1.6)
Intercept unloading (N)	8.8 (2.7)	7.1 (4.1)	7.9 (4.0)	5.9 (2.4)	5.3 (3.4)	7.0 (1.4)
Predicted ratio I ^{b,c}	1.9 (0.6)	1.4 (0.1)	0.9 (0.3)	0.8 (0.1)	1.0 (0.2)	1.2 (0.5)
Predicted ratio II ^{b,c}	1.9 (0.6)	5.9 (0.2)	3.8 (0.9)	4.5 (0.7)	4.2 (0.4)	4.1 (1.5)
Isometric ratio ^{b,d}	2.7 (0.9)	4.8 (0.9)	5.8 (0.6)	4.5 (0.4)	2.8 (0.8)	4.1 (1.4)

Results are presented as mean (SD). ms = millisecond, and Max. = maximum.

^a Subject who tapped on a rigid surface and self-selected a tip-pinch posture. Other subjects tapped on a keyswitch and used a pulp-pinch posture.

^b The ratios are in terms of units of force at the fingertip.

^c Ratio of flexor digitorum superficialis tendon-to-tip force predicted from tendon force model (I [7]; II: distal interphalangeal passive torque added [9]).

^d Ratio of tendon-to-tip force measured during an isometric task reported in ref. 9.