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In vivo forces generated by finger flexor muscles do not depend on the rate of fingertip loading during an isometric task

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Abstract

Risk factors for activity-related tendon disorders of the hand include applied force, duration, and rate of loading. Understanding the relationship between external loading conditions and internal tendon forces can elucidate their role in injury and rehabilitation. The goal of this investigation is to determine whether the rate of force applied at the fingertip affects in vivo forces in the flexor digitorum profundus (FDP) tendon and the flexor digitorum superficialis (FDS) tendon during an isometric task. Tendon forces, recorded with buckle force transducers, and fingertip forces were simultaneously measured during open carpal tunnel surgery as subjects ($N = 15$) increased their fingertip force from 0 to 15 N in 1, 3, and 10 s. The rates of 1.5, 5, and 15 N/s did not significantly affect FDP or FDS tendon to fingertip force ratios. For the same applied fingertip force, the FDP tendon generated more force than the FDS. The mean FDP to fingertip ratio was 2.4 ± 0.7 while the FDS to tip ratio averaged 1.5 ± 1.0 ($p < 0.01$). The fine motor control needed to generate isometric force ramps at these specific loading rates probably required similar high activation levels of multiple finger muscles in order to stabilize the finger and control joint torques at the force rates studied. Therefore, for this task, no additional increase in muscle force was observed at higher rates. These findings suggest that for high precision, isometric pinch maneuvers under static finger conditions, tendon forces are independent of loading rate.
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Keywords: Hand; Tendon; In vivo; Force; Rate

1. Introduction

Tendon disorders of the distal upper extremity are a well recognized problem in the workplace (National Research Council and Institute of Medicine, 2001). Risk factors for tendon disorders of the hand and wrist include the applied force, duration and rate of repeated motions, and sustained non-neutral hand posture. These injuries are associated with jobs that require high force and/or high repetition (Silverstein et al., 1986; Moore and Garg, 1994).In addition, several studies have demonstrated a relationship between the velocity of wrist motion during repetitive occupational tasks and a higher rate of upper extremity disorders (Marras and Schoenmarklin, 1993; Malchaire et al., 1997).

External forces applied by the fingers have been measured during different dynamic and static work activities to assess and quantify exposure in order to improve hand tool design. Fingertip forces vary widely between occupational tasks. During typing, peak loads at the fingertips reach 3 N (Martin et al., 1996) while during power tool use the finger forces can be as high as 190 N (Oh and Radwin, 1993). To understand injury mechanisms better and to develop effective prevention strategies, it is important to understand how these external loads are related to internal tendon forces and how factors such as movement rate and hand posture affect the relationship.

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The effect of rate of external force application on muscle forces has been estimated with electromyography (EMG) during static and dynamic activities. During power tool use, average flexor muscle activity was greater when the external force acting on the hand was applied in a shorter time (faster rate) (Radwin et al., 1989; Oh and Radwin, 1998). Another study also showed that peak EMGs of wrist flexors and extensors increased with decreasing time of force application (Armstrong et al., 1999). During dynamic finger flexion, finger flexor and extensor muscles are also co-activated and their activity increases with increasing movement rate and frequency. The activity of both the flexor and extensor muscles increases at higher fingertip tapping frequencies (Schnoz et al., 2000). When index finger joints are flexed, the flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) muscles remain active throughout the motion and their activity levels increased with speed (Darling et al., 1994). These EMG studies suggest that higher flexor and extensor muscle forces may be generated at higher loading rates during static and dynamic activities. The additional agonist and antagonist muscle forces may be required to provide additional stability and control of finger joint positions and torques at faster loading rates. However, EMG data only provides information about the relative activity of each muscle and may be influenced by motion artifact, cross-talk, and electrode placement. The most reliable assessment of the effects of external loading conditions on tendon forces is obtained by directly measuring tendon forces in vivo.

The relationship between force at the fingertip and in vivo tendon force in one or both flexor tendons has been measured experimentally during static loading. The ratio of tendon to fingertip force was 7.9 ± 6.3 for the FDP tendon and 1.7 ± 1.5 for the FDS tendon during tip pinch (Schuind et al., 1992). Another study reported FDS to fingertip force ratios ranging from 1.7 to 5.8 (Dennerlein et al., 1998). These ratios exceed model predictions and contain large variability between subjects. Finger position and loading force rate may influence these ratios, the associated motor control strategies, and distribution of forces among the muscles of the finger. The first study did not record finger joint positions, while the second study measured force in only one tendon. Neither study controlled the rate of force application.

The goal of this investigation is to determine whether the rate of force applied at the fingertip affects in vivo forces in the FDP tendon and the FDS tendon during an isometric task. We hypothesize that the ratio of flexor tendon to fingertip force will increase as the rate of force application increases during static loading. We also hypothesize that the FDP tendon will generate a greater force than the FDS tendon per unit fingertip force in a moderately flexed finger posture.

2. Methods

Fifteen subjects (10 females and 5 males, average age 41 ± 10 years) who were scheduled for open carpal tunnel release surgery participated in the study after reading and signing a consent form. The Committee on Human Research from the University of California, San Francisco approved the procedures. Subjects had no previous index finger tendon injuries. Several days prior to surgery, the subjects practiced the experimental tasks in a setting that simulated the procedure during surgery.

The experiment was conducted during open carpal tunnel release surgery with local anesthesia injected at the incision site and a forearm tourniquet. After the flexor retinaculum ligament was released with a longitudinal incision, the FDP and FDS tendons of the index finger were isolated and buckle force transducers were placed around each. The transducers were a modified version of the device previously described by this group (Dennerlein et al., 1997). The transducers were tested and calibrated prior to the experiment (Dennerlein et al., 1997). A calibration factor was calculated for each transducer to adjust for tendon thickness and relate transducer output to tendon force. The estimated mean errors ranged from 3.8% to 7.3%.

After the transducers were inserted, the subject flexed the index finger against a load 20 times in order to seat the transducers onto the tendons. Then the tendon thickness was measured and the tourniquet was released to allow tissue reperfusion. The subjects were supine with the shoulder abducted to 90°. A custom-designed apparatus supported the load cell at the end of the index finger in a predetermined location to achieve the desired hand position. The hand was placed in the device with the thumb up, the palm facing the feet, and the wrist in 15° extension (Fig. 1). The MP joint of the index finger was positioned by the surgeon in 45° flexion using an angle bracket while the PIP and DIP finger joints assumed a natural pinching position with the fingertip on the load cell. The other fingers remained relaxed in a slightly flexed position. The centers of rotation of the joints of the index finger and wrist were marked with a surgical pen on the radial side of the hand and this side was recorded with a digital video camera (Sony, DCR-TRV10) mounted above the operating field and set perpendicular to the plane of finger flexion. Data were collected from the tendon transducers and fingertip load cell (ATI Industrial Automation, Apex, NC, USA; resolution of 0.1 N) simultaneously at 100 Hz using a laptop computer with an A/D board.

Subjects were instructed to steadily increase the force on the load cell at three different rates until the fingertip force reached 15 N. To help achieve the target force and force rates, subjects observed a computer monitor mounted above their heads that provided real-time feedback of fingertip force. Subjects were able to

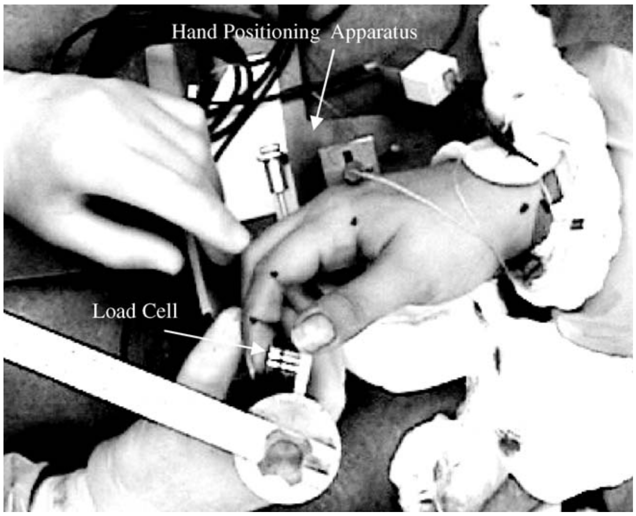

Fig. 1. View of experimental setup from above. The subject's hand is stabilized in a thumb up posture using the hand positioning apparatus and the joint postures are recorded with a video camera. The fingertip force is measured with a six-axis load cell as the FDP and FDS tendon forces are recorded with two buckle force transducers (not visible). Estimated joint centers of rotation are marked.

compare the force that they exerted with the desired force profile and adjust their fingertip force to match the desired pattern. They were instructed to attain the maximum force in 1, 3, or 10 s, corresponding to fingertip force rates equal to 15, 5 and 1.5 N/s (fast, medium, and slow). Three to 33 trials were collected for each subject at each rate. After the tasks were completed, the tendon thickness was measured again, the transducers were removed, and the carpal tunnel surgery completed.

The voltage output from the buckle force transducers was converted to tendon force using the calibration factor adjusted for tendon thickness. Due to transducer problems, FDP tendon force for one subject during the trial at the slow force rate was omitted from analysis. The forces measured with the load cell and buckle transducers were filtered using a sixth-order, low-pass Butterworth filter at a cutoff frequency of 25 Hz. The total force at the fingertip was computed as the vectorial sum of the acquired three orthogonal force components. On average, 96% of total fingertip force was directed perpendicular to the load cell surface. The start of each loading task was defined as the time when the fingertip force first exceeded 1 N (2.5 N for subjects 3 and 8) and the end occurred when the force reached its maximum value. Tendon and fingertip forces corresponding to these times were extracted. For all the trials, the relationship between force in each tendon and force at the fingertip was defined as the slope of the line of tendon versus tip force, calculated with a linear regression. The fingertip force rate at each time point was defined as the slope of a linear fit of tip force and time over 0.1 s (10 points). Based on the mean fingertip force rate and its standard deviation, the trial closest to the target loading rate was selected for each subject at each rate for further analysis. For each trial, the MP, PIP and DIP joint angles, as well as the angle between the fingertip and external force applied on the load cell (EF angle), were measured from a video frame corresponding to the midpoint time of each selected trial (Adobe Photoshop).

A two-factor repeated-measures analysis of variance was used to determine whether the rate of force application (fast, medium, and slow) and tendon (FDP and FDS) affected the ratio of tendon to fingertip force ($p = 0.05$).

3. Results

An example of typical tendon and fingertip forces produced at the fast, medium, and slow loading rates is displayed in Fig. 2. The average maximum tip forces and mean tip force rates that the subjects attained during the trials are summarized in Table 1. Most people were able to produce the desired maximum force of 15 N at their fingertips, but two subjects were only able to generate maximum forces of 8.9 and 11.6 N. One person was unable to press at the fast rate in any of the trials. Subjects maintained a similar finger joint posture and external force angle throughout all the trials (Table 1).

Small differences in tendon versus tip force slopes at different rates are demonstrated by typical force data from one subject (Fig. 3). Similar data across all subjects (Fig. 4) shows high linearity for the FDP and tip force and for the FDS and tip force relationships ($R^2 = 0.98$ and 0.95, Table 1). The average ratios of the tendon to tip forces for all subjects and rates are listed in Table 1 and the individual values are displayed in Fig. 5.

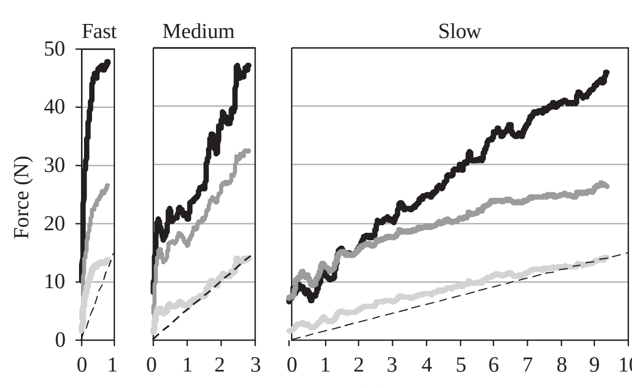

Fig. 2. Example from one subject of FDP tendon, FDS tendon, and fingertip forces during a typical loading trial at the fast, medium and slow fingertip force rates. ▬ Force in the FDP tendon ▬ Force in the FDS tendon ▬ Force at the fingertip — – Target fingertip force ramp.

Table 1
Parameters related to tendon and fingertip forces during loading at three different fingertip force rates. Data reported as mean ± standard deviation ($N = 15$). P-values were calculated with a repeated measures ANOVA

	Fingertip loading force rate			
	Fast	Medium	Slow	p-values
Maximum tip force (N)	16.3 ± 2.7	14.6 ± 2.6	13.9 ± 2.9	0.04
Mean tip force rate (N/s)	15.0 ± 2.9	4.7 ± 1.0	1.4 ± 0.3	< 0.01
MP angle (deg)	33 ± 12	34 ± 11	37 ± 12	0.06
PIP angle (deg)	51 ± 21	54 ± 21	49 ± 24	0.31
DIP angle (deg)	24 ± 28	20 ± 23	18 ± 24	0.24
EF angle (deg)	60 ± 17	61 ± 13	65 ± 11	0.13
FDP vs. tip force R^2	0.99 ± 0.02	0.98 ± 0.03	0.97 ± 0.04	0.29
FDS vs. tip force R^2	0.95 ± 0.09	0.96 ± 0.04	0.94 ± 0.08	0.84
FDP vs. tip force slope	2.7 ± 0.6	2.4 ± 0.7	2.2 ± 0.8	0.29
FDS vs. tip force slope	1.6 ± 1.2	1.4 ± 0.8	1.5 ± 1.0	0.29

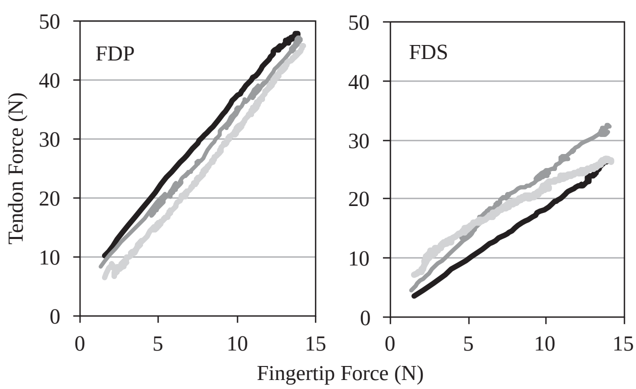

Fig. 3. Example from the same subject of the relationship between force applied at the fingertip and force in the FDP (left) and FDS (right) tendons during a typical loading trial at the fast, medium, and slow fingertip loading force rates. Fast Medium Slow.

RMANOVA indicates that the interaction term between tendon and rate is not significant. The rate of force application does not have a significant effect on the ratio of tendon to fingertip force for either tendon ($p = 0.29$). The FDP tendon generates more force than the FDS tendon for the same amount of applied fingertip force ($p < 0.0001$). The mean FDP to fingertip force ratio across all the trials was 2.4 ± 0.7 while the FDS to tip ratio averaged 1.5 ± 1.0; the coefficients of variation were 0.3 and 0.7, respectively. Adding peak fingertip force and MP angle as additional factors to the repeated measures ANOVA does not change the conclusion that force rate does not have a significant effect on the tendon to fingertip force ratio ($p = 0.46$).

4. Discussion

Ratios between forces generated by the two flexor tendons of the index finger and the force applied at the

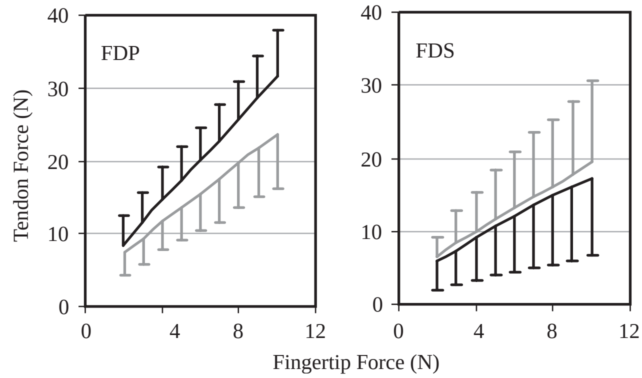

Fig. 4. Relationship between force applied at the fingertip and force in the FDP and FDS tendons during a loading trial at the fast and slow fingertip force rates. Data are reported as mean ± standard deviation for all subjects who attained fingertip forces of 2 to 10 N during trials at both rates ($n = 13$ for FDP and $n = 14$ for FDS). Fast Slow.

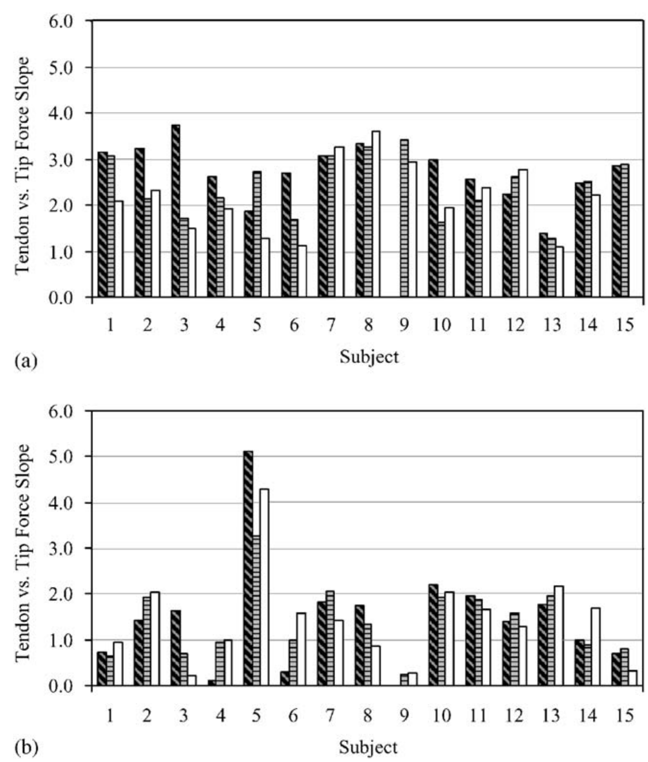

Fig. 5. Relationship between force in the FDP tendon (a) and at the fingertip and between force in the FDS tendon (b) and at the fingertip during loading at three different fingertip force rates for each subject. Fast Medium Slow.

fingertip were investigated during a task involving increasing fingertip force linearly from 0 to 15 N at rates of 1.5, 5, and 15 N/s while maintaining a static hand posture. These three different fingertip loading force rates do not significantly affect the FDP to fingertip or the FDS to fingertip force ratios. This finding does not support the hypothesis that increasing fingertip loading rates will increase flexor tendon to fingertip force ratios. Forces in the FDP tendon are significantly higher than forces in the FDS tendon for the same externally applied fingertip force. The force ratios and relative force contributions of each muscle exhibit large inter-subject variability, but the FDP to fingertip force ratio is less variable among subjects than the FDS to fingertip ratio, as indicated by the lower coefficients of variation.

Ratios between flexor tendon and fingertip force during isometric loading have been measured previously. The FDP to fingertip ratio of 7.9 ± 6.3 observed by Schuind et al. (1992) is much larger than the mean value of 2.4 ± 0.7 from our study. The lower variability in our study may be due to a consistent finger posture between subjects. The FDS ratio of 1.7 ± 1.5, from the same study, is similar to our results of 1.5 ± 1.0. Both these FDS to fingertip ratios are smaller than 3.3 ± 1.4, the ratio measured in another study (Dennerlein et al., 1998). The smaller values of tendon to fingertip ratios presented in our study are in closer agreement with model predictions (Weightman and Amis, 1982; Chao et al., 1989; Harding et al., 1993). Differences in finger positions may account in part for the difference between the values found in the literature and those from the current study.

Surprisingly, the rate of fingertip force application did not affect the amount of force generated by the extrinsic finger flexor muscles per unit fingertip force during the experimental task. It was originally hypothesized that increased antagonist co-contraction would be required to provide additional stability and control of finger joint position and torque during faster loading and that flexor forces would also rise to balance this extensor activity. In contrast to the findings of this study, an increase in flexor activity was measured with increasing movement speeds during dynamic finger flexion (Darling et al., 1994; Weiss et al., 1996; Schnoz et al., 2000) suggesting that muscles may respond differently to static and dynamic conditions. Therefore, the impact of different motion parameters on muscle loads should be evaluated in the context of a particular task. The difference between the results of the two studies may also be explained by the difference in experimental techniques. EMG measurements may be influenced by motion artifacts during dynamic motions, limiting their reliability. On the other hand, a study that investigated different rates of force development (ranging from 5% to 20% MVC/s) during an isometric contraction of the biceps Brachii muscle supports our findings (Sbriccoli et al., 2003). The overall muscle activity as measured by electromyography did not depend on the rate of isometric force generation even though the motor unit recruitment strategy did change.

This study measured forces in two of seven muscles that control the index finger. The FDP and FDS muscles span multiple joints and act over multiple finger segments to produce the desired flexion force at the fingertip. To control external force output and finger position, other muscles must be activated to maintain postural stability and provide the appropriate torques at all index finger joints. The activity of the three intrinsic muscles and two extrinsic extensors will influence flexor force and must be considered for a complete understanding of the system. Co-contraction of all seven finger muscles has been reported during a low force, precision grip task and during the production of static MVC forces (Maier and Hepp-Reymond, 1995; Valero-Cuevas et al., 1998). These studies indicate that all finger muscles are involved in isometric fingertip force generation, but their individual contributions and roles may vary with force, finger posture, and force direction. It is possible, that for this task, similar levels of co-contraction were occurring in the other muscles even at the different loading rates. In our study, it is likely that the fine motor control needed to generate the precise force ramps required high activation levels of intrinsic and extrinsic finger muscles in order to stabilize the finger and control joint torques. Therefore, we observed no additional increase in FDP and FDS forces at the higher rates. Perhaps, less co-contraction at slow rates and lower tendon to tip force ratios would occur during a less constrained loading task. Unfortunately, the activity of the other five muscles and their response to changes in loading force rate cannot be directly estimated. However, the presented results have important implications since the extrinsic flexors are responsible for generating the majority of flexion force and are the most likely candidates for injury or delay in healing. Specifically, our findings suggest that adjusting fingertip loading rate over the range evaluated here during isometric force application may not be important for reducing tissue forces when designing hand tools. This contradicts the impression in the occupational health literature that loading rate has an effect on internal muscle forces and can be adjusted to limit them (Radwin et al., 1989; Oh and Radwin, 1998; Armstrong et al., 1999).

Several limitations of in vivo measurements must be considered when interpreting and applying the presented data. First, measurement errors are introduced by the use of buckle force transducers and during the conversion of their output to force. However, these errors are small relative to the forces measured (see Methods section) and although they may affect the absolute force values, they should not influence the conclusions regarding the effect of loading rate on tendon to fingertip force ratios. Collection of data during carpal tunnel surgery is another limitation. The muscle forces may not accurately represent control strategies and movements executed during daily activities since subjects have lost finger sensory and proprioceptive feedback due to local anesthesia of the median nerve. In addition, the upper extremity is constrained for the surgical procedure and subjects do not have visual feedback of finger motion. However, the performance during surgery appeared similar to the practice trials, indicating that the limitations were related to the task itself and not the surgery.

The findings of this study indicate that changes in fingertip loading force rates between 1.5 and 15 N/s during a static fingertip loading task do not alter internal flexor tendon forces. The implications are that the motor control for the isometric loading tasks investigated in this experiment will involve similar recruitment of antagonists. Thus, modifying loading rate does not alter the tendon to tip force ratio. The results of this study demonstrate the importance of in vivo measurements in understanding how external factors impact internal forces in tendons and the motor control mechanisms.

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