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Journal of Biomechanics 38 (2005) 2288–2293

JOURNAL OF BIOMECHANICS

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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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Accepted 16 July 2004

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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0021-9290/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2004.07.035

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

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