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Finger flexor motor control patterns during active flexion: An *in vivo* tendon force study

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Abstract

An *in vivo* tendon force measurement system was used to evaluate index finger flexor motor control patterns during active finger flexion. During open carpal tunnel release surgery ($N = 12$) the flexor digitorum profundus (FDP) and flexor digitorum superficilias (FDS) tendons were instrumented with buckle force transducers and participants performed finger flexion at two different wrist angles (0° or 30°). During finger flexion, there was concurrent change of metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joint angles, but the FDP and FDS tendon force changes were not concurrent. For the FDS tendon, no consistent changes in force were observed across participants at either wrist angle. For the FDP tendon, there were two force patterns. With the wrist in a neutral posture, the movement was initiated without force from the finger flexors, and further flexion (after the first 0.5 s) was carried out with force from the FDP. With the wrist in a flexed posture, the motion was generally both initiated and continued using FDP force. At some wrist postures, finger flexion was initiated by passive forces which were replaced by FDP force to complete the motion.

PsycINFO classification: 2540

Keywords: Flexor digitorum; *In vivo* force; Tendon; Flexion; Phalangeal joint

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1. Introduction

Index finger flexion is a complex process requiring the coordination of three intrinsic hand muscles: palmar interossei, dorsal interossei, and lumbricals, and four extrinsic hand muscles: flexor digitorum profundus (FDP), flexor digitorum superficilias (FDS), extensor digitorum communis, and extensor digitorum indicis. The intrinsic hand muscles each span one to two finger joints and the extrinsic muscles each span two to three finger joints plus the wrist. Therefore, flexion of the index finger involves the composite motions of the three finger joints: metacarpophalangeal (MP), proximal interphalangeal (PIP), and distal interphalangeal (DIP), and requires complex motor control.

Motor control patterns for extrinsic hand muscles, such as the FDP and the FDS, during finger motion have been studied using a variety of techniques. The kinematics of finger flexion have been examined in some detail (Arbuckle & McGrouther, 1995; Braido & Zhang, 2004; Gupta et al., 1998; Hahn, Krimmer, Hradetzky, & Lanz, 1995; Somia, Rash, Wachowiak, & Gupta, 1998), but kinematic studies provide no direct information on the actions of the involved muscles. Electromyography can investigate muscle activation patterns (Bendz, 1980; Boivin, Wadsworth, Landsmeer, & Long, 1969; Close & Kidd, 1969; Darling & Cole, 1990; Darling, Cole, & Miller, 1994; Dennerlein, Diao, Mote, & Rempel, 1998; Long & Brown, 1964; Vallbo & Wessberg, 1993), but this method yields only an estimate of muscle activation, as many motor units may be active, and motor unit action potentials are sampled in EMG according to many factors, including distance from the electrodes and motor unit size (Basmajian & Luca, 1985). Tendon forces from extrinsic muscles of the hand have been measured directly by instrumenting the tendon (An, Berglund, Cooney, Chao, & Kovacevic, 1990; Dennerlein et al., 1998, Dennerlein, Diao, Mote, & Rempel, 1999, 1997; Kursa, Lattanza, Diao, & Rempel, 2006; Powell & Trail, 2004a, 2004b; Schuind, Garcia-Elias, Cooney, & An, 1992; Urbaniak, Cahill, & Mortenson, 1975). However no simultaneous comparison of kinematic data with tendon forces exists in the literature.

This study combines tendon force data from buckle transducers in the extrinsic flexor tendons (FDP and FDS) with kinematic data (finger joint angles) in order to investigate motor control patterns during finger flexion. The goal of this study is to describe the roles of the finger flexors (FDP and FDS) and their relationships to joint angles (MP, PIP, and DIP) during finger flexion.

2. Materials and methods

Twelve participants (8 females and 4 males, age 42 ± 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 of the University of California, San Francisco approved the procedures. Participants were between 18 and 65 years of age, had no previous index finger tendon injuries, and were free of arthritis. Several days prior to surgery, the participants 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 in order to preserve motor control. A forearm tourniquet was inflated at the start of surgery to prevent excessive blood flow. The participants were supine with the shoulder abducted to 90°. After the flexor retinaculum ligament was

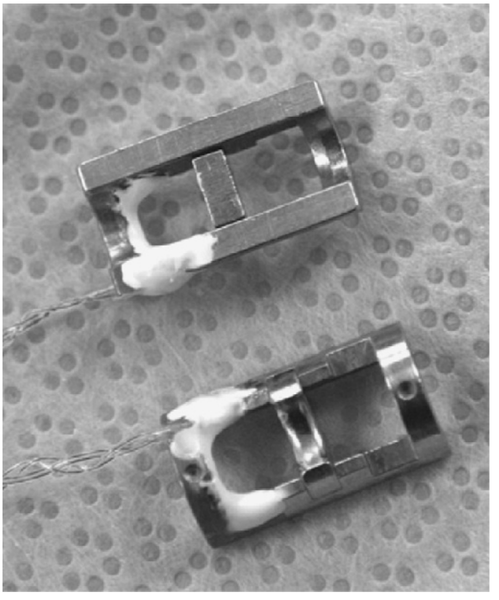

Fig. 1. Buckle transducers for measuring tendon force *in vivo*: the transducers consist of a 9 × 16 × 4.5 mm stainless steel frame and a removable stainless steel fulcrum. The tendon lies in semi-circular arches between the frame and fulcrum. Four uni-axial strain gauges were mounted to the frame to create a full bridge circuit.

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 (Kursa et al., 2006). The transducers consisted of a 9 × 16 × 4.5 mm stainless steel frame and a removable stainless steel fulcrum (Fig. 1). The tendon lies in semi-circular arches in the frame and fulcrum. Four uni-axial strain gauges were used to create a full bridge circuit. The transducers were tested using human cadaver flexor tendons of varying thicknesses in a Materials Testing System and a calibration factor was calculated for each transducer to adjust for tendon thickness and relate transducer output to tendon force as previously described by this group (Dennerlein, Miller, Mote, & Rempel, 1997). The estimated mean errors ranged from 3.8% to 7.3%. The sensitivity of the force transducers was 0.1 N.

After the transducers were inserted, the participant flexed the index finger against a load 20 times in order to seat the transducers onto the tendons. The tendon thickness in the transducer was measured using a digital micrometer with a resolution of 0.01 mm (Series 575 Digimatic Indicator, Mitutoyo, Kanagawa, Japan). The forearm tourniquet was released to allow tissue reperfusion (mean tourniquet time was 30 ± 13 min).

Data were collected during active finger flexion approximately 20 min after the tourniquet was deflated to allow time for reperfusion. The hand was positioned by the surgeon with the palm perpendicular to the surface of the operating room table, and the little finger resting on the surface of the table. The wrist was placed in either 0° or 30° of flexion using two sterilized angle brackets. The centers of rotation of the MP, PIP, DIP, and wrist joints of the index finger were marked with a black marker for use in later video analysis. The patients were instructed verbally to bend all the fingers until the fingertips lightly touched the palm as "tip contact" and then to straighten the fingers out. An example of the flexion

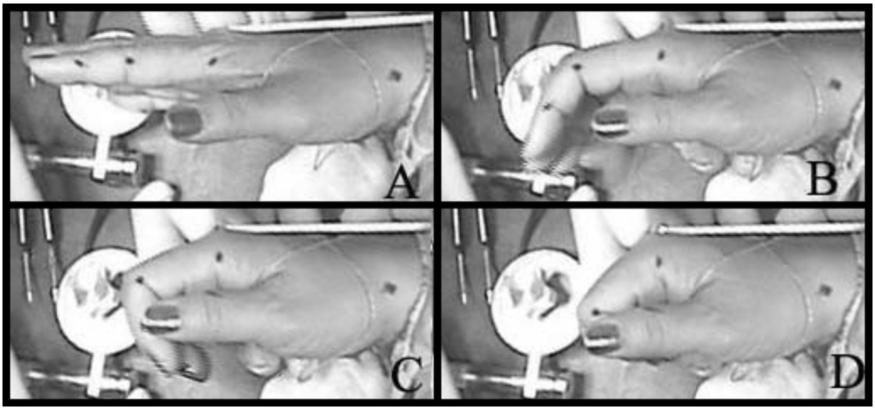

Fig. 2. Example of four postures during active finger flexion while tendon forces were measured. Participants were instructed and observed to slowly move all fingers in flexion to a loose fist and not to press their fingertips into the palms. The hand moves through flexion from the start of flexion (A) to the end of flexion (D). Images were captured from the video tape of the experiment. Black marks at the joints were used to measure MP, PIP, and DIP joint angles.

motion sequence with the wrist at 0° is shown in Fig. 2. Most participants completed two trials of flexion at each wrist angle. After the finger flexion measurements the carpal tunnel surgery was completed.

Video tapes of finger motion were collected during the experiment using a video camera (Sony Digital Handycam DCR-TRV10) which recorded 30 frames per second. The camera was mounted above the operating field with a view perpendicular to the finger flexion plane. Simultaneously, force data were collected from the tendons at 100 Hz using a personal computer with an analog to digital board (DAQCard-AI-16E-4 National Instruments). The data were filtered (4 Hz) and amplified using a National Instruments SCXI Data Acquisition System (SCXI 1121 module). The voltage output from the buckle force transducers was converted to tendon force using the calibration equations calculated from *in vitro* testing and the thickness measurement collected *in vivo*.

The two trials for each participant were evaluated using video data to determine which trial had the smoothest motion, the least pauses, and the largest range of motion for flexion, and this trial was used for analysis. The videotapes were then viewed to determine the start and stop times of flexion. The start and end of flexion were defined as the times of the first and last frame in which motion could be observed. The marked joint centers of rotation were used to measure joint angles for each frame of motion using the protractor tool in Adobe Photoshop. The DIP joint was obscured by the participant's thumb throughout the majority of the motion and as such the joint angle was impossible to determine. The DIP joint angle was thus not used in analysis. The video and force data were synchronized using the image of the surgeon's finger tapping on a load cell before the start of each trial (accuracy of synchronization: $\pm$ 1/30 s).

Joint angles and tendon forces were plotted as functions of time for each participant (e.g., Fig. 3). To investigate the relationships between joint angles during each movement, the MP and PIP joint angles during the course of each flexion movement were plotted against each other, and the plot was inspected to assess linearity. The statistical test was a Pearson product-moment correlation coefficient, R. Correlation coefficients were converted

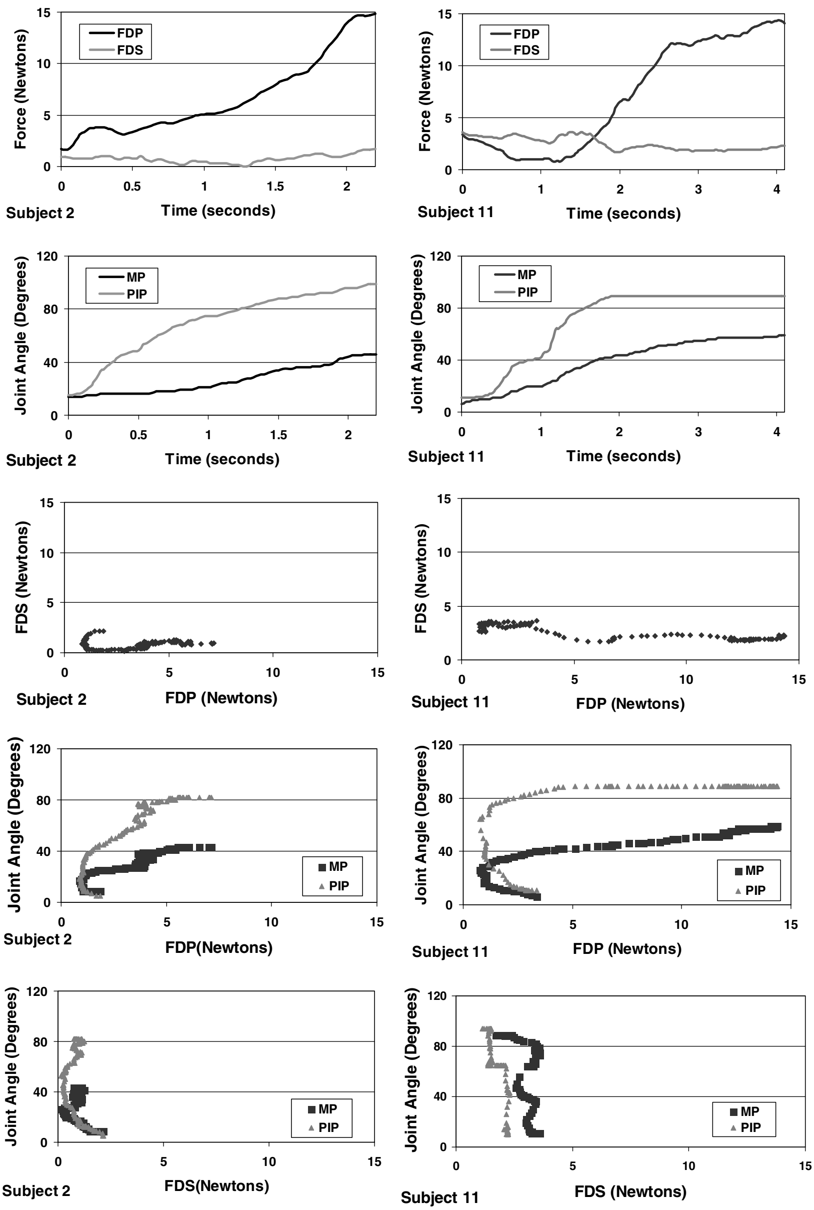

Fig. 3. Forces and joint angles as functions of time for finger flexions of two representative participants. In both participants, FDP force increased during flexion, but FDS force remained approximately constant and small (top row); FDS and FDP forces did not correlate (third row); MP and PIP joints both flexed (row 2), and their movements were correlated (not shown); joint angles correlated with FDP force (row 4), but not with FDS force (row 5). The two participants exhibited the two common patterns of FDP force: Participant 2 (left column, wrist 30° flexion) increased FDP force throughout the movement, but Participant 11 (right column, wrist at 0° flexion) initiated movement without large changes in FDP force, but increased FDP force to continue motion.

to z-scores and then two one-sample t-tests, one for each wrist angle, were used to determine if the correlation coefficients for the twelve participants were significantly different from zero. P-values less than .05 were considered significant. Likewise, to investigate the relationship between the deep and superficial tendon forces, FDP and FDS tendon forces during each movement were plotted against each other, and inspected for linearity. The statistical test was again a Pearson correlation coefficient. To investigate the relationship between joint angles and tendon forces, each joint angle (MP and PIP) was plotted as a function of each tendon force (FDP and FDS), and the correlation coefficients were calculated, converted to z-scores, and t-tested for significance. P-values less than .05 were considered significant.

3. Results

Examples of representative finger joint angle and tendon force patterns during finger flexions of two participants are presented in Fig. 3. Typically, both MP and PIP joint angles gradually increased throughout motion with the two joint angles changing concurrently (Fig. 3, row 2). FDP force generally increased during flexion while FDS force remained small and approximately constant (Fig. 3, row 1). FDP and FDS forces did not appear to be well correlated (Fig. 3, row 3). Joint angles appeared to correlate well with FDP force (Fig. 3, row 4), but not with FDS force (Fig. 3, row 5). Two types of FDP force patterns were observed. Participant 2 (Fig. 3, left column) increased FDP force throughout the movement, while Participant 11 (Fig. 3, right column) initiated movement with a decline in FDP force followed by increased FDP force to continue motion.

No instruction was given regarding the duration of the flexion motion, and movements were generally slow. Movement durations ranged from 0.9 to 5.3 s and averaged 2.6 ± 1.1 s. The speed of the motion was not related to the type of tendon force pattern. The longer-lasting motions generally included pauses in the middle of motion or very slow changes in joint angles near the end of motion. For both faster and slower motions, the first 0.5 s of motion was observed to be smooth and free of these pauses. We therefore analyzed the early and late portions of the movements separately. *Early motion* was defined as the first 0.5 s of motion, and *late motion* was defined as motion after the first 0.5 s.

Mean changes in joint angles and tendon forces, for the early and late portions of motion are presented in Table 1. The PIP joint angle changed more than the MP joint angle. Average changes in tendon forces were positive, with the exception of the FDP forces during early motion at 0° wrist flexion. FDP force changed most late in the movements. FDS force changed little, either early or late.

Correlation coefficients between the MP and the PIP joint angles and between the FDP and the FDS tendon forces during flexion are presented in Table 2. MP and PIP joint angles were highly correlated during movements (mean correlation coefficients .89–.95),

Table 1
Mean change in joint angles and tendon forces by time period and wrist posture (Mean ± SD (Range))

	Early motion (<0.5 s)		Late motion (>0.5 s)	
	Wrist = 0°	Wrist = 30°	Wrist = 0°	Wrist = 30°
ΔMP (°)	14 ± 11 (2–35)	11 ± 8 (1–30)	32 ± 11 (22–52)	23 ± 10 (9–45)
ΔPIP (°)	25 ± 20 (4–68)	26 ± 19 (3–64)	39 ± 25 (7–80)	40 ± 24 (0–70)
ΔFDP (N)	−0.2 ± 1.0 (−1.5–1.6)	0.9 ± 1.2 (−1.6–3.0)	3.2 ± 4.0 (−0.2–12.4)	2.5 ± 3.6 (−2.3–11.4)
ΔFDS (N)	0.0 ± 1.5 (−0.8–4.0)	1.9 ± 6.2 (−1.6–21.4)	0.4 ± 1.9 (−0.8–1.6)	1.7 ± 4.5 (−2.0–12.4)

PIP joint angles exhibited the largest changes during motion. Tendon force changes were generally positive except for the FDP when the wrist was at 0° during early motion.

Table 2
Summary statistics for correlation coefficients (R) between MP and PIP joint angles (PIP vs. MP) and between for FDP and FDS tendon forces (FDP vs. FDS) from one trial for each participant for each wrist angle

	PIP vs.MP				FDP vs.FDS			
	Early motion		Late motion		Early motion		Late motion	
	0°	30°	0°	30°	0°	30°	0°	30°
# Positive correlation	10	12	10	11	7	8	6	9
# Negative correlation	0	0	0	0	3	4	4	3
Mean correlation	.89	.94	.94	.95	.30	.08	.08	.21
Mean z-score	.74	.87	.83	.86	.22	.04	.02	.09
p-value	<.001*	<.001*	<.001*	<.001*	.24	.78	.85	.45

*indicates that correlation coefficients were significantly different from zero (paired t-test).

and all four sets of joint angle correlation coefficients were significantly different from zero. Mean correlations between FDP and FDS tendon forces were low for all conditions (range: .08–.40, Table 2), with 3–5 participants having negative correlations under each condition. None of the four sets of correlation coefficients for tendon force were significantly different from zero.

Correlation coefficients between joint angles and FDP force are shown in Table 3A. Both joint angles correlated with FDP force late in motion at either wrist angle, and also early in motion for the 30° wrist angle (range: .48–.63) and all were significantly different from zero. Correlations between joint angles and tendon forces were sometimes negative for the early motion when the wrist was at 0° (coefficients −.24 and −.22 for MP vs. FDP and PIP vs. FDP respectively). Of the ten participants, seven showed negative correlations between PIP angle and FDP force, and six showed negative correlations between MP angle and FDP force.

Table 3
Summary statistics for correlation coefficients (R) between the PIP joint angle and the FDP tendon force (PIP vs. FDP), MP joint angle and FDP tendon force (MP vs. FDP), PIP joint angle and the FDS tendon force (PIP vs. FDS), and MP joint angle and FDP tendon force (MP vs. FDS) from one trial for each participant for each wrist angle

A	Early motion				Late motion			
	PIP vs. FDP		MP vs. FDP		PIP vs. FDP		MP vs. FDP	
	0°	30°	0°	30°	0°	30°	0°	30°
# Positive correlation	3	10	4	10	10	10	9	11
# Negative correlation	7	2	6	2	0	1	1	1
Mean correlation	−.24	.48	−.22	.54	.56	.56	.63	.54
Mean z-score	−.17	.38	−.19	.41	.36	.33	.45	.33
p-value	.29	.03*	.31	.01*	<.001*	.02*	<.001*	.03*
B	**Early motion**				**Late motion**			
	PIP vs. FDP		MP vs. FDP		PIP vs. FDP		MP vs. FDP	
	0°	30°	0°	30°	0°	30°	0°	30°
# Positive correlation	3	6	2	6	5	8	5	9
# Negative correlation	7	6	8	6	5	3	5	3
Mean correlation	−.41	−.01	−.41	.03	.04	.34	.08	.39
Mean z-score	−.28	−.01	−.32	.03	.03	.24	.10	.29
p-value	.18	.97	.12	.86	.79	.10	.56	.08

*indicates that correlation coefficients were significantly different from zero (paired t-test).

Correlation coefficients between joint angles and FDS tendon force are shown in Fig. 3. The correlation coefficients were not significantly different from zero for any of the comparisons.

4. Discussion

The PIP and MP joint angles changed concurrently throughout finger flexion. Force from the deep finger flexors (FDP tendon force) generally increased during flexion, while the superficial flexors (FDS) played little role in the control of the movements with the FDS tendon force remaining small and approximately constant throughout. Joint angles were generally well correlated with FDP tendon force, but not with FDS force.

Our results regarding the roles of deep and superficial finger flexors generally agree with results of electromyographic studies of slow movements. Boivin et al. (1969) used fine wire electromyography to investigate FDP and FDS activation during flexion of the index finger. They observed that the FDP was "the most consistently active and highest graded muscle in flexion." The FDS was seen to "participate erratically" in flexion, as it was "a definite participant in this motion in most participants, but not used at all in two persons." Our joint angle vs. tendon force data indicate that the FDP was consistently the main muscle producing force to carry out flexion. We also found the FDS activity to be erratic, as there was no relationship between FDS force change and finger motion. Darling et al. (1994) observed consistent coactivation of the FDP and FDS during finger flexion. However, they studied much faster movements (durations 0.1–0.4 s) than those observed in our study. Darling also observed a coupling between MP and PIP joint motion, which is supported by our results. Long and Brown (1964) used fine-wire electromyography to investigate the relationship between activity in the extrinsic finger muscles and finger flexion for the long finger. They also found the FDP to be the major finger flexor. In their study, FDS activation varied depending on the wrist angle and was greater when the wrist was in flexion than in a neutral position. In early motion, we found significant correlations between FDP force and joint angles at 30° of wrist flexion, but no significant correlations at the 0° wrist angle. Indeed, for many participants at the 0° wrist angle, forces in FDP (and FDS) tendons declined during the early motion.

Lack of increase in FDP force, or even decline in FDP force, early in flexion movements is consistent with initiation of flexion by relaxation of extensors, aided by passive forces. The initial position of the finger joints (0°) probably required extensor activity, even in the absence of flexor activity. Our finding of negative correlations when the wrist was positioned at 0° but not at 30° flexion, supports this interpretation. This finding is further supported by a fine wire EMG study of flexor muscle activity (Bendz, 1980). During the initiation of grasp, in a neutral wrist posture, the FDP was not activated immediately at the start of flexion; rather the start of activity was delayed. A similar finding was reported by Dennerlein, Mote, and Rempel (1998) in a study using fine-wire EMG to evaluate extrinsic finger flexor and extensor muscle activity during touch typing. The downward or flexion motion of the finger during the keystrike was initiated before the onset of the FDS electrical burst. The typing movements were, however, aided by gravity, whereas the flexions of our participants were orthogonal to gravity. Control patterns differed between participants – some participants contracted the FDP during initiation of motion while others did not. Inter-individual differences were a result of variations in muscle activation patterns between participants and could not be explained by differences in motion as participants with similar joint angle vs. time plots exhibited distinct tendon force patterns.

Several limitations of *in vivo* measurements must be considered when interpreting this study. 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 and although they may affect the absolute force values, they will not influence the direction of the findings. Collection of data during carpal tunnel release surgery is another limitation. The recorded motion and associated muscle forces may not accurately represent movements executed during daily activities since participants have lost sensory feedback when the entire median nerve was anesthetized. The lack of proprioception may have modified motor control and may have limited the range of motion in some participants. However, relatively smooth composite finger flexion motion was observed on the video recordings suggesting that the motor control patterns are preserved. All of the movements we recorded were slow. Our findings may not generalize to rapid movements, for which forces to accelerate the fingers may be much more significant. Joint angles late in motion were at times obscured by the thumb of the participant. While the DIP was removed from analysis, errors in the PIP must be considered, as this joint was also obscured at the very end of motion and had to be estimated in some cases. Neither extensor muscles nor intrinsic hand muscle activity were measured, and may have contributed to the motion. We believe initiation of flexion by relaxation of extensors was a common pattern when the wrist was at 0°. Involvement of intrinsic hand muscles during flexion seems unlikely as previous EMG studies have reported that the interossei and lumbricals are inactive during finger flexion (Bendz, 1980; Long & Brown, 1964).

5. Conclusions

MP and PIP joint angles generally changed together throughout finger flexion movements. FDP force generally increased during flexion, but FDS force generally remained small and approximately constant. Deep and superficial tendon forces did not correlate. For the FDP, two patterns of force change were observed. With the wrist in a neutral posture, flexion movements were mainly initiated without FDP involvement, and likely using relaxation of extensors and passive forces, then continued using increases in FDP force. When the wrist was flexed, the motion was generally both initiated and continued with FDP force. Concurrent use of the FDP and FDS in finger flexion appears to be rare in slow finger flexions. Simultaneous measurement of tendon forces and kinematics generally validates the electromyographic findings, and also highlights the importance of relaxation of antagonist muscles and passive forces in initiation of slow movements.

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