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Short communication

## Moment arms of the human digital flexors

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## ABSTRACT

For the extrinsic hand flexors (flexor digitorum profundus, FDP; flexor digitorum superficialis, FDS; flexor pollicis longus, FPL), moment arm corresponds to the tendon's distance from the center of the metacarpalphalangeal (MP), proximal interphalangeal (PIP), or distal interphalangeal (DIP) joint. The clinical value of establishing accurate moment arms has been highlighted for biomechanical modeling, the development of robotic hands, designing rehabilitation protocols, and repairing flexor tendon pulleys (Brand et al., 1975; An et al., 1983; Thompson and Giurintano, 1989; Deshpande et al., 2010; Wu et al., 2010). In this study, we define the moment arms for all of the extrinsic flexor tendons of the hand across all digital joints for all digits in cadaveric hands.

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## 1. Introduction

Muscle moment arm is the shortest distance between the force across a joint and its center of rotation (Zajac, 1992). For the hand flexors (flexor digitorum profundus, FDP; flexor digitorum superficialis, FDS; flexor pollicis longus, FPL), moment arm corresponds to the tendon's distance from the center of the metacarpalphalangeal (MP), proximal interphalangeal (PIP), or distal interphalangeal (DIP) joint due to tethering by the annular pulleys (Strickland, 1995). Thus, loss of flexion at a joint after a pulley injury occurs secondary to mechanical changes resulting from the increased moment arm (Lin et al., 1989; Tomaino et al., 1998; Mitsionis et al., 1999). The clinical value for establishing accurate moment arms has been highlighted for biomechanical modeling, the development of robotic hands, designing rehabilitation protocols, and repairing flexor tendon pulleys (Brand et al., 1975; An et al., 1983; Thompson and Giurintano, 1989; Deshpande et al., 2010; Wu et al., 2010). However, no study has reported the normal moment arms for finger flexors across all digits and joints (Brand et al., 1975; An et al., 1983; Brook et al., 1995; Smutz et al., 1998; Fowler et al., 2001; Buford et al., 2005; Wu et al., 2009; Deshpande et al., 2010; Wu et al., 2010).

Derivation of the instantaneous moment arm across a joint has been modeled by Landsmeer (1961) and has been used to calculate moment arms in a variety of studies with the following equation:  $M = dE/d\theta$ , where  $E$  is the tendon excursion and  $\theta$  is the

joint angle (An et al., 1983). This study provides experimentally derived values for moment arms of the digital flexors across all joints for all five digits.

## 2. Methods

## 2.1. Sample preparation

This experiment utilized fresh-frozen upper limbs amputated at the distal humerus ( $n=6$ ) with all distal structures intact. Longitudinal forearm and palmar incisions were made proximal to the cardinal line (Vella et al., 2006) to avoid disturbing tendon architecture at the level of PA or A1 pulleys. The carpal tunnel was incised longitudinally and the flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP), and flexor pollicis longus (FPL) tendons were released in the forearm and pulled through the palmar incision. FDP tendons were identified by flexion of the DIP joint. The median nerve was also identified and severed to avoid mechanical interference during testing. Hands or digits were excluded if any anatomical abnormality was observed.

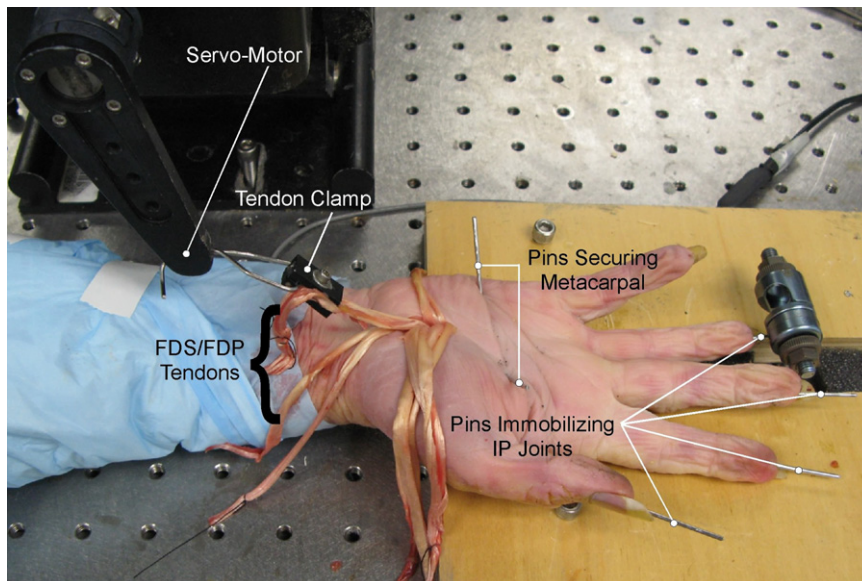
Steinmann pins (1.6 mm diameter, 85 mm length) were drilled proximally from the distal phalanx tip down the phalangeal medullary canals until they were distal to the MP joint for all five digits, securing the PIP and DIP joints (IP joint for the thumb) in extension. A 40 g weight was secured at the end of each pin to provide a physiologic counter-force during tendon excursion, with a moment distance of 85 mm (Fig. 1).

## 2.2. Mechanical testing

Hands were mounted palmar side up on a grooved platform that allowed placement of a single axis goniometer sensor (Biometrics Limited, Ladysmith, VA; accuracy  $\pm 2^\circ$  over  $90^\circ$  from neutral position). The two sensors of the goniometer were placed over the dorsal aspect of the bone just proximal and just distal to the tested joint with the assistance of benzoin tincture (James Alexander Corp., Blairstown, VA) and double-stick tape. Each tested digit was aligned longitudinally with the device, and the bone immediately proximal to the tested joint was secured with two Steinmann pins that penetrated two cortices and was then

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**Fig. 1.** Photograph of the biomechanical testing setup. The digit being tested is aligned with the motor, and the flexor tendon is securely clamped to the motor arm. In this image, the MP joint of the ring finger is being tested. Thus, the metacarpal is fixed to the base with two Steinmann pins, and an additional Steinmann pin passes down the phalangeal medullary canal to maintain the PIP and DIP joints in extension.

**Table 1**  
Moment arms calculated from first-order fits.

	Digit				
	Small	Ring	Long	Index	Thumb
MP					
FDP	12.91 ± 1.22	15.13 ± 1.25	13.06 ± 0.89	15.48 ± 1.52	16.63 ± 2.05 (FPL across MP)
FDS	12.45 ± 0.99	16.52 ± 1.73	13.28 ± 1.12	16.78 ± 1.65	
PIP					
FDP	8.61 ± 0.47	9.49 ± 0.55	11.81 ± 0.93	10.71 ± 0.34	11.74 ± 0.63 (FPL across IP)
FDS	6.77 ± 0.50	8.48 ± 0.41	8.69 ± 0.44	9.07 ± 0.45	
DIP					
FDP	8.69 ± 1.05	7.00 ± 0.99	7.77 ± 0.62	7.71 ± 0.78	

Shown as mean ± SEM in mm.

drilled into the wood platform. The tendon being tested was then attached to a dual-mode servo-motor (Aurora Scientific, Inc., Model 310, Aurora, Ontario, Canada; length signal linearity 0.5%).

Tendons were pulled by the servo-motor at a rate of 10 mm per second while simultaneously recording the tendon excursion distance and joint angle at 100 Hz (Supplementary Video 1). Excursions were manually set to obtain joint angles that mimicked the physiological ranges of motion from approximately 0–80°. After each experimental condition, the setup was examined for tendon slippage, goniometer transducer slippage, or pin displacement, and all tests were repeated three times and results averaged to ensure reproducibility of the experimental data. The procedure was performed for each tendon (FDS, FDP, FPL) across each joint (MP, DIP, PIP, IP) for each digit.

Supplementary material related to this article can be found online at doi:10.1016/j.jbiomech.2011.04.025.

During testing, adjacent fingers were not immobilized and were allowed to flex as normal. Hands were maintained at room temperature during all testing, and tendons were kept moist with Ringer's solution. All hands were defrosted only once for testing, and testing on each hand was completed within 8 h.

### 2.3. Moment arm calculation

Examination of the excursion–joint angle relationship revealed a general scheme of an initial nonlinear region followed by a qualitatively linear region until a maximal range of motion was obtained. At the maximal joint angle, a nonlinear plateau was apparent. Care was taken not to flex the finger beyond physiologic limits to avoid potential ruptures of flexor pulleys or permanent changes in the anatomy that might affect subsequent testing trials. Data were continuously sampled and collected, and a custom-written Matlab script was used to select the entire arc of motion, including toe regions, for each trial and generate

first, second, and third-order fits. All fits maintained an  $r^2 > 0.96$ . The first-order slopes for the three tests for a given experimental condition were averaged and reported as single values. Derivatives of the third-order fits were calculated, and equations representing the mean change in moment arm as a function of joint angle were calculated and reported.

### 2.4. Statistical analysis

Two-way ANOVA (SPSS, Chicago, IL) was used to examine main effects and interactions between digits and tendons at each joint (MP and PIP). Tukey's Post-Hoc tests were used to detect differences between tendons. Significance was set to  $p < 0.05$ , and all data are displayed as mean ± SEM.

## 3. Results

The six specimens included 4 females and had a mean age of 80.6 years (range: 61–91 years). One hand did not have an identifiable FDS tendon to the 5th digit, and the IP joint of one thumb could not be tested, resulting in a total of 129 unique testing conditions, each repeated three times.

The measured linear moment arms are reported in Table 1 and plotted in Fig. 2. In summary, linear moment arms across MP joints ranged from 12.9 to 15.5 mm for FDP and 12.5–16.8 mm for FDS, with FDS demonstrating a moment arm approximately 0.6 mm longer than FDP. At the PIP joints, moment arms ranged

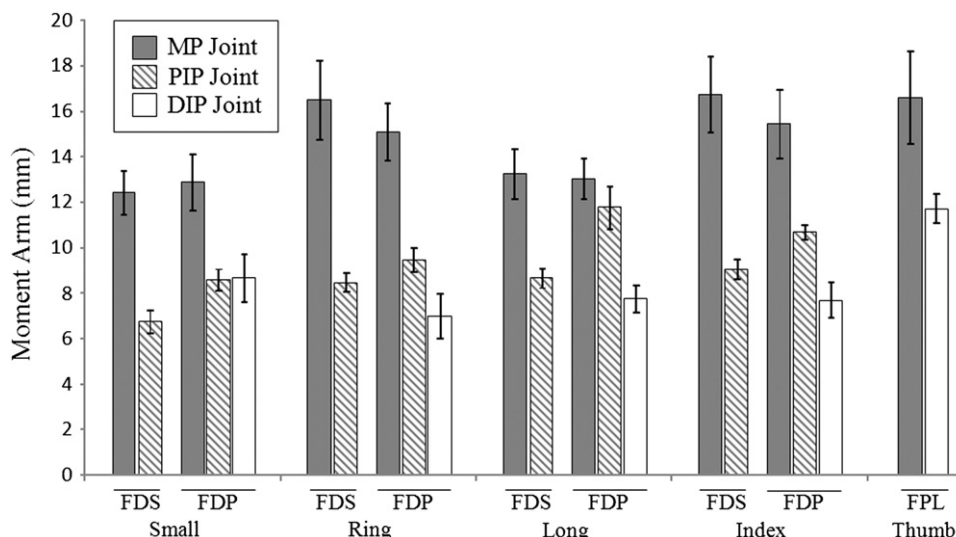


Fig. 2. Graphical representation of the linear moment arms obtained from six cadaver hands. Values shown are means  $\pm$  SEM (mm).

Table 2  
Moment arms (derivatives) calculated from third-order fits.

	Digit				
	Small	Ring	Long	Index	Thumb
MP					
FDP	$14.8x^2 - 12.7x + 14.4$ (0.05–0.79)	$2.8x^2 - 2.5x + 15.6$ (0.05–1.01)	$18.2x^2 - 14.9x + 14.6$ (0.05–0.87)	$-7.1x^2 + 11.2 + 11.6$ (0.05–1.08)	$83.1x^2 - 60.2x + 25.2$ (0.02–0.59)
FDS	$16.5x^2 - 18.1x + 17.0$ (0.05–0.77)	$10.6x^2 - 12.6 + 19.9$ (0.06–0.95)	$12.6x^2 - 9.3x + 13.8$ (0.05–0.84)	$-6.6x^2 + 8.0x + 14.5$ (0.06–1.06)	(FPL across MP)
FDP	$16.4x^2 - 21.8x + 14.2$ (0.05–1.32)	$15.7x^2 - 18.6x + 14.1$ (0.06–0.96)	$10.4x^2 - 12.9x + 13.8$ (0.05–1.10)	$15.3x^2 - 18.0x + 14.5$ (0.07–1.20)	$39.4x^2 - 33.7x + 17.9$ (0.03–0.64)
FDS	$15.4x^2 - 20.8 + 12.1$ (0.06–1.26)	$13.5x^2 - 16.4 + 12.4$ (0.06–0.97)	$10.3x^2 - 13x + 11.8$ (0.06–0.98)	$17.9x^2 - 21.6x + 13.9$ (0.06–1.20)	(FPL across IP)
DIP					
FDP	$15.0x^2 - 8.3x + 8.7$ (0.05–0.61)	$13.7x^2 - 11.2 + 8.1$ (0.06–1.02)	$21.0x^2 - 13.3x + 8.6$ (0.06–0.62)	$41.2x^2 - 34.2x + 13.3$ (0.05–0.71)	

$x$ =joint angle in radians (range). Moment arms are reported in mm.

from 8.6 to 11.8 mm for FDP and 6.8–9.1 mm for FDS, with FDS moment arms approximately 1.9 mm shorter than FDP. Moment arms at the DIP joint ranged from 7.0 to 8.7 mm.

Despite qualitatively larger moment arms for FDS compared to FDP, two-way ANOVA at the MP joint revealed no main effects and no tendon  $\times$  digit interactions. However, a significant main effect of both tendon and digit was observed at the PIP joint with no interaction between tendon and digit. Furthermore, at the PIP joint, digit 5 was significantly different from digits 2, 3, and 4.

The third-order analyses are reported in Table 2 and are shown grouped for all fingers in Fig. 3. For all but one joint (Index, MP), moment arms demonstrated a slight decrease in values from 0° to about 45° of joint angle, after which moments arms increased.

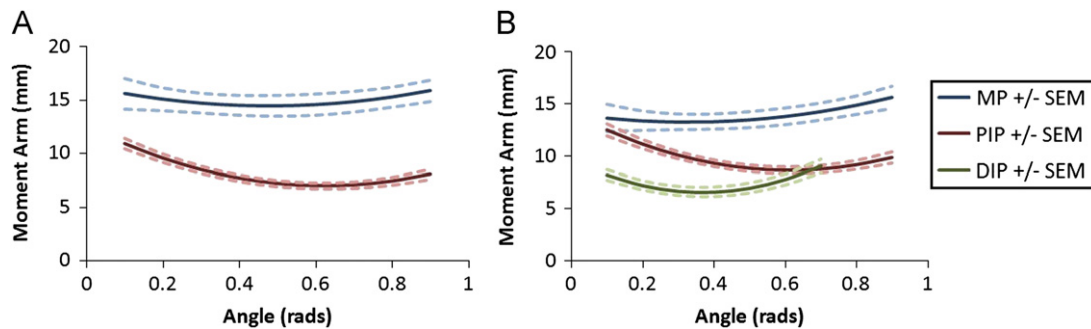
#### 4. Discussion

These results are the first to report moment arms for all extrinsic flexor tendons of the hand across all digital joints in cadaveric hands. Our study demonstrated that moment arms were nearly identical for a given joint (MCP, PIP, and DIP) across digits, but differed significantly between joints with the MP joint having the largest moment arm. In addition, although the FDS tendon moment arm was qualitatively larger than the FDP

moment arm at the MP joint, the difference was not significant for any digit. However, for a majority of fingers, the FDP moment arm was significantly larger than the FDS moment arm at the PIP joint. Finally, digit 5 was found to be significantly different from the other digits (statistics not shown). This result can be explained by a smaller bone size, which decreases its moment arm compared to the other digits.

Our results correlate closely with the previous classic reports by Brand et al. (1975), Armstrong and Chaffin (1978), and Ketchum et al. (1978). Importantly, two authors that had previously investigated both the MP and PIP joints reported results with a similar trend as our own and consistent with described anatomy (Armstrong and Chaffin, 1978; Ketchum et al., 1978). At the MP joint, where the FDS tendon runs superficial to the FDP tendon, one would expect the FDS moment arm to be longer than the FDP moment arm due to their anatomic relationship (our results: FDS 0.6 mm longer). In contrast, at the PIP joint, the FDS tendon attaches to the lateral aspect of the second phalanx while the FDP tendon continues distally over the volar aspect of the joint and middle phalanx, resulting in a shorter moment arm for the FDS relative to the FDP (in our study: FDS 1.9 mm shorter) (Armstrong and Chaffin, 1978; Ketchum et al., 1978).

One limitation of this study is the potential  $\pm 2^\circ$  of error introduced by goniometer inaccuracy. However, due to the fact



**Fig. 3.** Graphical representation of the third-order moment arms obtained from six cadaver hands with all fingers combined (excluding the thumb). (A) FDS averaged for all fingers. (B) FDP averaged for all fingers.

that range of motions varied from about 50–90°, and due to the fact that systematic error of joint angle would not influence the moment arm calculation (slope of the curve), we do not believe this changes our results or conclusions. A second limitation of this study is that moment arms for each joint were calculated with the other two joints (MCP, PIP, or DIP) in extension. Because moment arm values for a given joint (i.e., MCP) may be influenced by the position of an adjacent joint (i.e., PIP), these values reflect only a slice of overall behavior. In addition, the angle of pull of each tendon could potentially affect the moment arms calculated for the most proximal joints (i.e., MCP) as a result of A1 pulley deformation. However, we made every effort to approximate the physiologic angle of tendon excursion. A final limitation of this study was that anthropometric data and hand size was not recorded. Thus, no analysis can be performed to retrospectively determine how moment arm changes as a function of hand size.

These data reflect known anatomical relationships and provide reference values and equations for future studies that may address biomechanical modeling or clinical implications for the flexor tendons.

#### Conflict of interest statement

This material has not and will not be submitted for publication elsewhere until you make your final decision. None of the authors have any conflict of interest to declare for this work.

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