

Anatomical variation of the musculotendinous junctions of the forearm flexor muscles relative to the carpal tunnel: A cross-sectional cadaveric study

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Abstract

Purpose: Anatomically, there is a relationship between the forearm flexor muscle bellies and the carpal tunnel that has possible biomechanical implications. The purpose of this study was to provide quantitative data on the distal termination of the FDS and FDP muscle bellies relative to the proximal carpal tunnel and to characterize the morphometric variation in their individual digital components. **Methods:** Forty formalin-fixed adult human cadaveric upper limbs (20 right, 20 left) were dissected. The pisiform bone served as the anatomical landmark for the proximal boundary of the carpal tunnel. The distance from the proximal border of the pisiform to the distal end of the FDS and FDP muscle bellies was measured using a digital caliper. The individual digital components of the FDS and FDP corresponding to the index, middle, ring, and little fingers were also measured using the same reference point and technique. **Results:** The mean termination distance for FDS muscle fibers proximal to the pisiform was 23.2 ± 6.4 mm on the right and 24.1 ± 7.1 mm on the left; for FDP, it was 25.1 ± 9.6 mm on the right and 32.2 ± 9.8 mm on the left. The individual digital components showed considerable variation in their termination distances across the index, middle, ring, and little fingers. In 5% of limbs (2/40), both right-sided, the FDS muscle belly extended distal to the level of the pisiform. No cases were observed for FDP. **Conclusion:** The results from these data help add to the normative anatomical literature for wrist morphology and show that extension of the FDS muscle belly into the proximal carpal tunnel is an anatomical variant (only present in 5% of this sample) rather than a common occurrence.

Keywords: anatomical variation, carpal tunnel, flexor muscles, muscle, skeletal, cross-sectional study

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Introduction

The carpal tunnel is a fibro-osseous canal at the wrist that is important for passage of the median nerve and nine tendons (Cobb et al., 1993). It is bounded dorsally and laterally by the carpal bones and ventrally by the flexor retinaculum (Cobb et al., 1993). The tendons passing through this tunnel include FDS, FDP, and flexor pollicis longus (American Society for Surgery of the Hand, 2025). The FDS is the largest of these extrinsic flexors and constitutes the middle muscle layer of the forearm, being the primary flexor of the PIP joints; the FDP is the strongest muscle of the forearm, contributing to the overall strength for gripping the hand (O'Brien and Gutierrez, 2023). Although there may be some disagreement over its

precise borders, the proximal margin is typically thought to coincide with the level of the pisiform bone's proximal border (Rotman and Donovan, 2002). While only their tendons pass through the carpal tunnel in normal anatomy, there is anatomical variation where FDS and FDP have been described to reach into the distal forearm, proximal to the carpal tunnel (Werner et al., 1997). From an evolutionary perspective, the flexor muscles of the mammalian forearm are believed to be derived from intrinsic palmar muscles that moved backward toward the wrist bone, leaving long tendons to pass through the carpal tunnel (Gowda et al., 2022; Lewis, 1989). These types of variations may represent vestiges of this

phylogenetic development (Standring, 2021).

This represents an important morphological variation as opposed to tendinous tissue alone; however, prevalence for the presence of muscle bellies extending into the carpal tunnel varies widely among previous cadaveric studies and ranges from 7.8 percent to 46 percent (Holtzhausen et al., 1998) depending on sex, with male specimens having lower rates than female specimens. Some reports have described this variation in case studies, sometimes accompanied by clinical symptoms (Androjna et al., 2011). This variation in reported prevalence highlights the necessity for further descriptive data from various populations. Although we know that such variation exists, having specific quantitative data regarding where the musculotendinous junction lies within consistent bony landmarks is useful to create a foundational database of normal human anatomy and will serve as a starting point for any future biomechanical or imaging studies. Thus, this study aimed to provide descriptive and quantitative data on the termination of the FDS and FDP muscle bellies relative to the pisiform bone and to characterize variation in their individual digital components in 40 cadaveric limbs.

Materials and Methods

Study design and setting

This descriptive, cross-sectional cadaveric study was conducted in the Department of Anatomy at our institution. The specimens were obtained through the department's body donation program, and dissections were performed during the 2023-2024 academic year.

Participants

All formalin-fixed adult human upper limb specimens without deformity or evidence of previous surgery or trauma at the wrist region were eligible for inclusion. Specimens were selected based on availability during the study period. A total of 40 eligible upper limbs (20 right and 20 left) were available and included in the study.

Variables and data sources/measurement

The primary outcome variables were the distances between the reference line established at the proximal border of the pisiform and the distal ends of the FDS and FDP muscle bellies. During cadaveric dissection, a pin was placed at the proximal border of the pisiform, and a horizontal reference line was established at this level using a second pin and thread. The distance from this reference line to the distal end of the corresponding muscle belly was measured using a calibrated digital vernier caliper and recorded in millimetres. All specimens were positioned in neutral alignment (0°) as verified by digital goniometry. Each

measurement was repeated three times by a single investigator using a calibrated digital caliper (Mitutoyo Absolute Digimatic, Japan), and the mean value was used for analysis.

Statistical methods

All measurements were recorded and tabulated using Microsoft Excel. Statistical analysis was performed using SPSS version 23.0 (IBM Corp., Armonk, NY). Descriptive statistics including mean, standard deviation, range, and percentages were calculated for all quantitative variables. The data were assessed for approximate normality before applying the t-test. Student's t-test was used to compare the right versus left sides subgroup. Missing data were addressed by excluding the single instance of an absent FDS tendon from the analysis for that measurement as a qualitative anatomical finding with all 40 specimens included in the data.

Results

Termination of FDS and FDP muscle bellies

The mean distance of termination of flexor digitorum superficialis (FDS) muscle bellies from the pisiform bone was 23.2 ± 6.4 mm (range: 13–40 mm) on the right side and 24.1 ± 7.1 mm (range: 11–35 mm) on the left side (see Table 1). For flexor digitorum profundus (FDP), the mean distance was 25.1 ± 9.6 mm (range: 12–42 mm) on the right side and 32.2 ± 9.8 mm (range: 10–52 mm) on the left side (see Table 1). The muscle bellies of FDS extended into the carpal tunnel before terminating in 5% of specimens (2 out of 40), both in right-sided specimens; no extension of FDP muscle bellies into the carpal tunnel was observed.

Comparison between right and left sides

The right and left sides did not differ significantly in the termination distance of FDS muscle bellies ($p = 0.686$, 95% CI [-5.0, 3.2]), but there was a significant difference between the sides for the termination distance of FDP muscle bellies ($p = 0.032$, 95% CI [-13.6, -0.6]).

Individual Digital component Measurements

Measurement of individual digital components: The FDS and FDP muscle bellies corresponding to the index, middle, ring, and little fingers were identified separately. The distance from the proximal border of the pisiform to the distal end of each individual muscle belly was measured using a digital vernier caliper. Measurements were recorded separately for the right and left sides. Each measurement was taken three times, and the mean value was used for analysis.

Measurements of the individual digital components showed variation in the distance of the distal ends of the FDS and FDP muscle bellies from the pisiform reference line (see Table 2 and Figure 2).

For the right limb specimens, the mean measurements for FDS muscle-belly components were:

- Index finger: 20.72 ± 10.40 mm

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- Middle finger: 20.84±10.20 mm
- Ring finger: 59.83±26.30 mm
- Little finger: 21.14±16.12 mm

For FDP muscle-belly components on the right side, the measurements were:

- Index finger: 50.98±11.28 mm
- Middle finger: 32.51±13.58 mm
- Ring finger: 38.97±20.25 mm
- Little finger: 44.19±22.12 mm

For the left limb specimens, the mean measurements for FDS muscle-belly components were:

- Index finger: 14.60±11.53 mm
- Middle finger: 13.44±12.11 mm
- Ring finger: 52.04±24.02 mm
- Little finger: 18.97±6.33 mm

For FDP muscle-belly components on the left side, the measurements were:

- Index finger: 36.94±13.52 mm
- Middle finger: 20.02±13.65 mm
- Ring finger: 24.96±12.11 mm
- Little finger: 48.25±25.97 mm

Right-sided tendons also measured longer than left specimens with statistical significance for index finger FDP measurements ($p = 0.039$, 95% CI [0.8, 27.3]), approaching significance for middle finger FDP measurements ($p = 0.072$, 95% CI [-1.1, 26.1]). No statistically significant bilateral differences were found in the other digital tendons of FDS and FDP. Comparison between FDS and FDP within each side showed no difference for the right side ($p = 0.469$, 95% CI [-7.1, 3.3]), but a highly significant difference for the left side ($p = 0.007$, 95% CI [-13.9, -2.3]).

Anatomical variations

In addition to the two specimens where FDS muscle bellies extended into the carpal tunnel, one specimen (left side) showed absence of the FDS for the little finger. This represents a 2.5% prevalence of this known anatomical variant in our total sample (1 out of 40 specimens).

Table 1: Distance from the pisiform bone to the distal muscle bellies of flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP) in right and left upper limb specimens (mm).

S No	Side (Right/Left)	Distance from pisiform to distal fibers of FDS (mm)	Distance from pisiform to distal fibers of FDP (mm)
1	Right	28	30

2	Right	19	20
3	Right	17	40
4	Right	32	42
5	Right	20	42
6	Right	21	19
7	Right	22	20
8	Right	21	36
9	Right	30	30
10	Right	13	12
11	Right	16	13
12	Right	18	20
13	Right	27	31
14	Right	30	16
15	Right	22	32
16	Right	40	20
17	Right	23	20
18	Right	20	19
19	Right	18	20
20	Right	27	20
1	Left	30	18
2	Left	26	41
3	Left	15	39
4	Left	26	26
5	Left	35	42
6	Left	11	29
7	Left	26	34

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8	Left	30	52
9	Left	16	36
10	Left	30	40
11	Left	18	20
12	Left	31	42
13	Left	21	30
14	Left	18	10
15	Left	26	30
16	Left	26	26
17	Left	35	40
18	Left	15	30
19	Left	26	30
20	Left	21	29

Table 2: Measurements (mean $\pm$ SD) (mm) of the individual digital components of FDS and FDP across digits and sides, with p-values and 95% confidence intervals for comparison between FDS and FDP within each digit.

Side	Digit	FDS (mean $\pm$ SD)	FDP (mean $\pm$ SD)	p-value (FDS vs FDP)	95% CI for difference (FDS - FDP)
Right	Index	20.72 $\pm$ 10.40	50.98 $\pm$ 11.28	<0.001	[-38.92, -21.60]
	Middle	20.84 $\pm$ 10.20	32.51 $\pm$ 13.58	0.045	[-23.05, -0.29]

	Ring	59.83 $\pm$ 26.30	38.97 $\pm$ 20.25	0.083	[-2.89, 44.61]
	Little	21.14 $\pm$ 16.12	44.19 $\pm$ 22.12	0.029	[-43.69, -2.41]
Left	Index	14.60 $\pm$ 11.53	36.94 $\pm$ 13.52	<0.001	[-31.57, -13.11]
	Middle	13.44 $\pm$ 12.11	20.02 $\pm$ 13.65	0.037	[-12.70, -0.46]
	Ring	52.04 $\pm$ 24.02	24.96 $\pm$ 12.11	0.012	[6.36, 47.80]
	Little	18.97 $\pm$ 6.33*	48.25 $\pm$ 25.97	0.006	[-49.12, -9.44]
Right vs. Left comparison					
FDS	Index	20.72 vs 14.60	-	0.120	[-1.65, 13.89]
	Middle	20.84 vs 13.44	-	0.104	[-1.58, 16.38]

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	Ring	59.83 vs 52.04	-	0.515	[-16.43, 32.01]
	Little	21.14 vs 18.97	-	0.642	[-7.11, 11.45]
FDP	Index	-	50.98 vs 36.94	0.039	[0.76, 27.32]
	Middle	-	32.51 vs 20.02	0.072	[-1.13, 26.11]
	Ring	-	38.97 vs 24.96	0.106	[-3.13, 31.15]
	Little	44.19 vs 25	-	0.743	[-28.66, 20.54]
*One specimen showed absence of FDS for little finger					

Figure 1:



Figure 1 Photograph showing pin placement at the pisiform (proximal carpal tunnel marker) and the horizontal reference line established at this level. The distal ends of the FDS and FDP musculotendinous junctions are identified, and the distance from the reference line to the musculotendinous junction is measured using a digital caliper. Scale in millimeters.

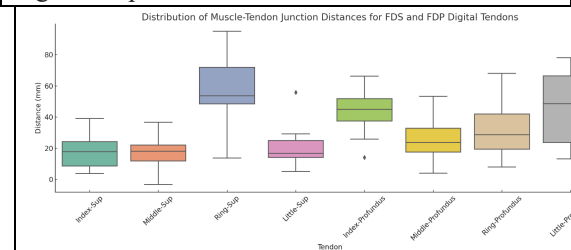


Figure 2: Box plot showing the distance of the distal ends of the FDS and FDP muscle bellies from the pisiform reference line across the index, middle, ring, and little fingers in right and left limbs. For each digit, measurements are presented for both right and left specimens. Horizontal lines within boxes represent median values; boxes show interquartile ranges (25th–75th percentiles); whiskers indicate minimum and maximum values within 1.5 times the interquartile range; and dots represent outliers. (flexor digitorum superficialis-FDS, flexor digitorum profundus-FDP)

Discussion

Key results

This descriptive anatomical study identified a distal extension of the FDS muscle belly past the pisiform bone in 5% (2/40) of limbs, with no cases of an extended FDP. The prevalence we report (5%) is at the lower end of the broad range reported in the literature. For instance, Holtzhausen et al. (1998) reported a much higher overall prevalence, which was strongly driven by a 46% prevalence in female specimens versus only 7.8% in male specimens; our lower figure may have been influenced by any number of factors, such as the demographic features (e.g., sex ratio, unknown for our sample) of the cadaver population or subtle differences in the definition of the proximal boundary of the carpal tunnel.

Interpretation

In fact, both instances of FDS muscle extension were observed in right-sided specimens, and there was a statistically significant difference in the termination distance for FDP (left: 32.2 mm vs. right: 25.1 mm; $p=0.032$). Although we cannot draw conclusions from these asymmetries definitively because of lack of data on limb dominance in our sample, they are interesting. It has been demonstrated that the majority of individuals favor their dominant hand for most tasks, which can cause some degree of asymmetrical development in forearm bones and muscles (Kim et al., 2021). Handgrip strength dominance has been positively correlated with the size of flexor muscles in the forearm (Abe and Thiebaud, 2015); therefore it is possible that chronic, increased mechanical loading on a dominant limb could impact muscle morphology throughout life, contributing to the asymmetries observed in our data.

This high degree of variability in the termination points of the individual digital components is also of anatomical and clinical interest. The musculotendinous junctions were most proximal for FDS in the ring finger component, consistent with the known muscle architecture (O'Brien and Gutierrez, 2023); such variations are significant to surgeons because the FDS tendons are commonly utilized as a tendon transfer procedure and knowledge of their individual morphology is key for effective outcomes (Boyes, 1962; Smith, 1987). In addition, this complex arrangement and potential for inter-tendinous connections limits the independent movement of fingers, which has biomechanical implications (Boyes, 1962). Although there were no clinical data included in this study, these anatomical variations have a wider range of clinical implications: An anomalous muscle belly may be felt as a soft-tissue mass that can confuse the diagnostic process for clinicians (O'Brien and Gutierrez, 2023; Bhat et al., 2016), or Unexpected muscle tissue within or near the carpal tunnel may be relevant during imaging interpretation and surgical planning (Boyes, 1962).

Based on our quantitative data, we considered classifying specimens by the measured distances of their musculotendinous junctions from the pisiform; however, without established functional or clinical correlates, any proposed distance-based thresholds would be arbitrary and not scientifically useful. Development of a clinically relevant classification system will require future studies that correlate these anatomical findings with dynamic imaging, intra-tunnel pressure measurements, or symptomatic patient populations. Therefore, we present our findings as descriptive data and refrain from proposing a formal classification at this time.

Limitations

This study has several important limitations: (1) The study used an availability-based sample of 40 upper limbs, which may limit the precision and generalizability of the findings. (2) Formalin-fixed cadaveric specimens may have tissue artifacts (shrinkage), which could affect measurements; (3) demographic data, such as sex and handedness of the cadavers were not available. Sex data were not available for comparison with sex-specific findings such as those reported by Holtzhausen et al (1998), there was no handedness data, which limits interpretation of the observed bilateral asymmetries and this was an anatomical study without any clinical information so there is no connection between the anatomy found and pathology. All these factors reduce the generalizability (external validity) of our findings to the population at large.

Conclusion

This descriptive anatomical study of 40 cadaveric limbs showed that the FDS muscle belly extended distal to the level of the pisiform in approximately 5% of cases. The study provides quantitative data on the termination of the FDS and FDP muscle bellies and the variation among their individual digital components, contributing to the baseline anatomical literature of the wrist. These findings may provide a basis for future biomechanical, imaging, and clinical studies of anatomical variation in this region.

Contributions

RSSN: Conceptualisation, methodology, validation, investigation, resources, writing—original draft preparation, writing—review and editing, supervision
APS: Data Collection, writing—review and editing
KK: Data Collection, writing—review and editing
RM: Data Collection, writing—review and editing
AP: Data Collection, writing—review and editing
Final approval of the manuscript: All authors.

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Statements and declarations:

Data availability: The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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Ethics declarations: The specimens used in this study were obtained through the institutional body donation program. The study was conducted in accordance with the institutional guidelines governing the use of donated human bodies for anatomical research.

Conflict of interest: The authors have no conflict of interest to declare.

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