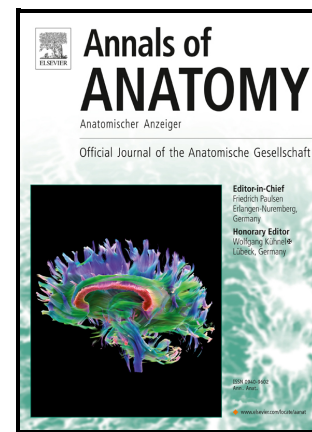


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Old name, new face: a systematic analysis of flexor digitorum superficialis muscle with “chiasma antebrachii”

Süleyman Ergün¹, Yalda Ghoreishi¹, Stefan Hübner¹, Jan-Peter Grunz², Henner Huflage², Thorsten Alexander Bley², Nicole Wagner^{1*}, Markus Naumann^{3*}

¹Institute of Anatomy and Cell Biology, Julius-Maximilians-University Würzburg, Würzburg Germany

²Department of Diagnostic and Interventional Radiology, University Hospital Würzburg, Würzburg, Germany

³Department of Neurology and Clinical Neurophysiology, University Hospital Augsburg, Augsburg, Germany

*: both authors contributed equally

Correspondence:

Prof. Dr. Süleyman Ergün

Institute of Anatomy and Cell Biology

Julius-Maximilians-University Würzburg

Koellikerstr. 6

97070 Würzburg

Phone: +49-931-3182707

E-Mail: sueleyman.erguen@uni-wuerzburg.de

Abstract:

The gross anatomy of the forearm flexors, particularly that of the flexor digitorum superficialis (FDS) muscle, has been described and graphically illustrated in several anatomical books and atlases starting in the middle of the century before last. However, in anatomical dissection studies as well as in clinical-anatomical courses training muscle-specific targeted injections due to movement disorders such as

dystonia or spasticity, it has become apparent that there is a need for a closer investigation of the complex construction of the FDS muscle. To this end, we studied the structure of the muscle bellies and tendons of FDS on 46 human body donates that have been used either in our dissection or clinical-anatomical training courses. With this, we demonstrate here the topographical configuration of the individual muscle belly for each of digits 2 through 5 and the exact paths of their tendons until their passing through the carpal tunnel. Furthermore, we demonstrate the presence of a chiasm of the FDS tendons for the digits 2 and 3, approximately 3-4 cm proximal of the carpal tunnel. Thus, we introduce herewith the terminology “chiasma antebrachii”. These findings were confirmed in situ by imaging of fixed human body donates via MRI and corroborated by MRI and ultrasound imaging in two volunteers. Taken together, the present findings enable an updated understanding of the complex organization of the heads, bellies, and tendons of FDS that is relevant not only for anatomical teaching but also clinical interventions.

Keywords:

flexor muscles of the forearm, flexor digitorum superficialis, chiasma antebrachii, dissection, MRI and ultrasound imaging

Abbreviations

AP: aponeurosis palmaris

APS: arcus palmaris superficialis

APL: abductor pollicis longus muscle

BR: brachioradialis muscle

ECRB: extensor carpi radialis brevis muscle

ECRL: extensor carpi radialis longus muscle

ECU: extensor carpi ulnaris muscle

ED: extensor digitorum muscle

EDM: extensor digitorum minimi muscle

EI: extensor indicis muscle

EPB: extensor pollicis brevis muscle

EPL: extensor pollicis longus muscle

FDP: flexor digitorum profundus muscle

FCR: flexor carpi radialis muscle

FDS: flexor digitorum superficialis muscle

FDS/2: flexor digitorum superficialis muscle/digit 2

FDS/3: flexor digitorum superficialis muscle/digit 3

FDS/4: flexor digitorum superficialis muscle/digit 4

FDS/5: flexor digitorum superficialis muscle/digit 5

FCU: flexor carpi ulnaris muscle

FPL: flexor pollicis longus muscle

IOM: interosseous membrane

MN: median nerve

MRI: magnetic resonance imaging

PB: palmaris brevis muscle

PL: palmaris longus muscle

PT: pronator teres muscle

PQ: pronator quadratus muscle

RA: radial artery

UN: ulnar nerve

ThM: thenar

Introduction

Detailed knowledge about the topographical anatomy of finger flexors, especially of the FDS, is crucial to clinicians who perform e.g., reconstructive surgery or botulinum toxin injections in movement disorders such as dystonia or spasticity. The complex anatomy of the FDS, formerly known as the flexor digitorum sublimis, is reflected by its multiple origins, the composition and the topographical order of the muscle bellies arising therefrom and the topographical course of FDS tendons until they reach the wrist. The muscles in the anterior compartment of the forearm are organized into three layers: a superficial, an intermediate and a deep layer, with the FDS occupying the intermediate layer. Broadly speaking the FDS arises from several heads, roughly said the humeral head (caput humerale), which is the most prominent head, the ulnar head (caput ulnare) and the radial head (caput radiale). The humeral and ulnar heads are often combined and referred to as humeroulnar head.

The superficial (to a major extent) contingent of the FDS, as part of the flexor-pronator-mass, originates from the medial epicondyle via a common tendon, referred to as the anterior common tendon (ACT) (Otoshi et al., 2014; Matsuzawa et al., 2021). The ACT spans from the medial humeral condyle to the anteromedial joint capsule, therefore crossing the humeroulnar joint line. Additional muscle fibers arise from the coronoid process of ulna (Caput ulnare) and from radius (Caput radiale) (Weber 1830, Gray 1858, v. Luschka 1865, Ohtani 1979, Matsuzawa et al., 2021).

Accessory sites for FDS muscle fibers were reported to originate from the medial ulnar collateral ligament (MUCL), with respect to its anterior bundle, the anterior oblique ligament (AOL) (Otoshi et al., 2014; Frangiamore 2017; Matsuzawa et al., 2021). An additional common tendon, the posterior common tendon (PCT), has been described (Otoshi et al., 2014), which is formed by the intermuscular fascia between FDS and FCU. A closer look at the structure of FDS bellies for each finger at the

origin has been performed by Matsuzawa and co-authors (Matsuzawa et al., 2021). Here, the authors state, that the muscle bellies for digits 3 and 4 originate from the radius, the ACT, and the PCT, while those of the digits 2 and 5 originate from the ACT, the PCT, the AOL, and other soft tissues of the elbow. The contribution of the radial head to the muscle belly for the digit 3 has already been described (v. Luschka 1865; Henle 1871). The FDS muscle bellies are being described different in volume. The most prominent muscle belly is that of the digit 3, followed by the digit 2 and 4. The smallest muscle belly is that of digit 5 (Weber 1830, Merkel 1907). The FDS bellies for the digits 3 through 4 have been described in several anatomy textbooks and atlases as well as recent original publications to course down the forearm with the superficial muscle bellies that merge into the tendons for the digits 3 and 4 while the deep muscle belly is reported to merge into tendons for the digits 2 and 5 (v. Luschka 1865; Henle 1871; Merkel 1907; Morris 1933; Hafferl and Thiel 1969; Hollinshead 1974; Ohtani 1979; Fanghänel et al., 2003; Benninghoff and Drenckhahn 2008; Standring, Gray's Anatomy 2020; Matsuzawa et al., 2021). Few anatomy textbooks (v. Luschka 1865; Henle 1871; Morris 1933, Fanghänel et al., 2003) and a recent publication (Matsuzawa et al., 2021) reported a digastric structure for the deep FDS belly with an intermediate tendon from which the distal belly for the digit 2 and the muscle belly for digit 5 arise. In rare cases, the FDS/5 has been reported to be missing or independent of the FDS/2 (Matsuzawa et al., 2021). It has also been demonstrated that the deep FDS belly provides short muscle fibers for the digit 4 (Ohtani 1979), and then divides into muscle bellies that merge into the tendons for the digits 2 and 5.

The complex architecture of the FDS is additionally reflected by the arrangement of its tendons before they approach the wrist. Passing beneath the transverse carpal ligament the tendons are arranged in pairs, the anterior pair corresponding to the

digit 3 and 4; the posterior pair to the digit 2 and 5 (Gray 1858; Morris 1933, Töndury 1970), which is a continuation of the superficial and deep positionings of the FDS muscle bellies (Lanz-Wachsmuth 1935; Benninghoff and Drenckhahn, 2008; Standring, 2020; Pernkopf 1964; Toldt-Hochstetter 1976; Töndury 1970) as also described above.

However, while we could confirm the aforementioned FDS topography in dissection studies to a major extent, we also realized during our clinical-anatomical courses that a) some relevant aspects of the FDS structure that were described in only few old anatomical textbooks, like the crossing tendons of the digits 2 and 3 (v. Luschka, 1865), were unfortunately not further considered in the newer textbooks (except 17th Edition of Waldeyer's Anatomy, 2003) and atlases, and b) there are still ambiguities or diffuse notions, particularly about the structure of the FDS for digits 2 and 5. To this end, we studied the anatomy of the FDS on 46 body donates, 36 of them were used in our dissection course teaching medical students and 10 body donates were examined in the frame of our clinical anatomical courses. Furthermore, two body donates were exposed to clinical imaging through MRI scans, one volunteer was objected to MRI imaging, and two volunteers underwent ultrasound analyses. The FDS and its four tendons were captured up to their passage through the carpal tunnel. By these, we provide a systematic multimodal study on the complex structure, paths, and tendons of FDS using anatomical dissection and clinical imaging by MRI and ultrasound. These analyses together also serve as basis for an updated graphical illustration of FDS.

Material and Methods

Fixation and dissection of body donors

The human body donors (n=46) were preserved initially by intra-arterial perfusion fixation with up to 4 – 4.5% formaldehyde solution containing 1.2 – 1.8 l formaldehyde 37% (depending on size and weight of the donors), Carlsbad salt (400 g), chloral hydrate (400 ml), Lysoformin (400 ml) in 8 l water for several hours. Subsequently, the body donors were transferred into an ethanol-(33%)-solution-filled metal container to achieve further preservation by ethanol vapor for 1-2 years before being used in the dissection course.

For the present study on flexor muscles, 92 forearms of 46 human body donors (20 men, 26 women, age ranging from 55 to 100 years, mean age at death, 83 ± 13 years) were dissected during the regular teaching course of macroscopic anatomy for medical and dental medicine students at the university of Würzburg. The arms showed no signs of previous major surgery or joint diseases.

The forearms of two body donors were used to prepare the flexor muscles for capturing the images presented exemplarily in the figures of our study. From the second body donor the left arm was used for preparing cross sections from the elbow to the wrist.

The use of the human material was in full compliance with the university policy for use of body donors and recognizable body parts.

Magnetic resonance imaging, ultrasound imaging and image segmentation

MRI was performed on one body donor and one volunteer. Forearms were exposed to MRI scans on a 3.0 Tesla scanner (Magnetom Prisma fit, Siemens Healthineers). A T2-weighted turbo spin echo sequence (repetition time 7560 ms, echo time 87 ms, flip angle 120° , slice thickness 4 mm, matrix 320 x 320 pixels, field of view 170 mm x 186 mm) was used for segmentation and subsequent 3D-Reconstruction of data set of the distal half of the forearm. Segmentation was performed using the TrakEM2

plug-in (Cardona et al., 2012) of Fiji (Schindelin et al., 2012). 3D rendering model was created using Tomviz Version 1.8.0 (<https://tomviz.org/>).

Ultrasound imaging was performed on two volunteers using an ultrasound device (Acuson S2000 with 9L4 Linear Array Probe, Siemens Healthineers) under repeated flexion of the fingers 2-5 to identify the individual FDS muscle bellies for these fingers and the paths of their tendons as well as their relation to each other from the middle part of the forearm to the wrist.

Results

During the examination of 36 human body donors, we first provided an overview of the left ventral forearm by anatomical dissection and demonstrated the flexor muscles including their tendons *in situ*, from their origin to the entrance into the carpal tunnel and arrival in the palmar hand (Fig. 1A). Next, the tendon of palmaris longus was dissected together with palmar aponeurosis and folded back towards the medial epicondyle to allow a first clear superficial view of the FDS (Fig. 1B, suppl. Fig. 1A). Subsequently, further superficial layer flexors such as flexor carpi radialis (FCR) and ulnaris (FCU) were sectioned at the entrance into the carpal tunnel and were also folded back to their origin. This enabled a near complete overview of FDS *in situ*, of which each individual muscle belly and tendon could be identified except of the belly and tendon for digit 2 (Fig. 1B). We have separated them from each other (suppl. Fig. 1B-C) as shown for FDS of digit 3 and tested their individual motion during flexion of the corresponding finger for the reliable assignment of the respective muscle belly and tendon to the appropriate digit.

Next, we studied the organization of the muscle bellies and tendons of the FDS in more detail. Here, we identified the muscle bellies and the tendons of the digit 3 and

4 at the level of the forearm to be the most superficial parts of the FDS in comparison to those of the digits 2 and 5 (Fig. 1C, suppl. Fig. 1B). For clarity, we introduce the following abbreviations: FDS/2: FDS for digit 2; FDS/3: FDS for digit 3; FDS/4: FDS for digit 4 and FDS/5: FDS for digit 5. The FDS/3 belly was the most radially localized part (Fig. 1B, and suppl. Fig. 1C). It contains two heads with the long head originating from the medial epicondyle via ACT (Matsuzawa et al., 2020) and the short head from the anterior radial facies (Weber 1830; v. Luschka 1865; Henle 1871) in form of a broad muscle plate that forms a fibrous arch (fibrous arcade, tendinous arch) on its cranial border (Fig. 1B, and suppl. Fig. 1B-C). The muscle belly of the FDS/3 accompanies its own tendon to the wrist at the radial side. The FDS/4-belly is located ulnar to FDS/3 muscle belly (Fig. 1B and suppl. Fig. 1B-C). The dissection in all studied cases revealed that this muscle belly has one head, that also originates from the medial epicondyle and is interconnected with the neighbored head of FDS/3 (Fig. 1B and suppl. Fig. 1B). Also noteworthy, the muscle bellies for FDS/3 and FDS/4 are densely packed together in their proximal segments (until 5-6 cm distal from medial epicondyle), but they are well separable from each other by careful dissection (suppl. Fig. 2A-B). Directly underneath, the FDS/2 belly and tendon can be identified. They lie deeper and more ulnar to that of the FDS/3 (Fig. 1C and 2A, and suppl. Fig. 2B), which could be confirmed by flexing digit 2. The FDS/2 belly is subdivided into a proximal and a distal belly by an intermediate tendon (Fig. 2A-B and suppl. Fig. 2C), which displays a rounded form in its proximal part. This intermediate tendon originates from the proximal FDS/2 belly and ends at the ulnar edge of the distal FDS/2 belly (Fig. 2B and suppl. Fig. 2C). It should be noted that in similar depth to the FDS/2 the median nerve runs from ulnar to radial in the back of the FDS/3 (Fig. 2A). Interestingly, the proximal FDS/2 belly, that displays a bipennate structure, ends on the intermediate FDS tendon, while the distal FDS/2 belly encompasses and

accompanies the flat and broadened tendon for digit 2 to the inside of the carpal tunnel. Both serve as a gutter for the FDS/3 tendon from 5-9 cm proximal of the transverse carpal ligament until the carpal tunnel (Fig. 2A-B, and suppl. Fig. 2C). Furthermore, the proximal FDS/2 belly has two heads with different origins: the more superficial head arises from the medial epicondyle and the deeper head from the coronoid process of the ulna (Fig. 2C). Starting in the distal half of the FDS/2, the distal FDS/2 tendon runs from the ulnar side towards the radial side and crosses under the FDS/3 tendon, approximately 3-4 cm proximal of the transverse carpal ligament (Fig. 3A and suppl. Fig. 3A). We appointed the terminology “chiasma antebrachii”, which, similar to the “chiasma crurale”, marks the crossing of the two tendons. Finally, the last FDS belly at the ulnar border belongs to the digit 5 and is located deeper and more ulnar than the muscle belly of the digit 4 while equally deep but more ulnar than the muscle belly of the digit 2 (Fig. 3B and suppl. Fig. 3B-C). In 35 of 36 cases of our study, the FDS/5 muscle belly took its origin from the ulnar border of the FDS/2 belly, starting immediately at the distal end of the intermediate FDS/2 tendon (Fig. 3B and suppl. Fig. 3C). The muscle belly of the FDS/5 extends to the inside of the carpal tunnel accompanying its own tendon. In 1 of 36 cases, the FDS/5 was not present in both forearms. Furthermore, we performed serial cross-sectioning through a forearm of one human body donate that was exposed to formalin fixation. As marked in the selected pictures, the existence of the “chiasma antebrachii” could also be confirmed by these analyses (suppl. Fig. 4A-C).

In order to confirm our findings from dissection studies in a clinical imaging setting, MRI scans of human body donors were performed. The results of image analyses were in line with the findings of the dissection studies (suppl. Fig. 5A-B). Moreover, these findings were also confirmed by 3D reconstruction of the MRI study of a volunteer, in which the FDS tendons for digits 2 - 5 were marked by different colors

(Fig. 4A-B). Also here, the “chiasma antebrachii” was identified at 22 ± 3.5 cm measured from the elbow (depending on the individual forearm length) or 3-4 cm proximal of the wrist. Lastly, the ultrasound imaging of the FDS of two volunteers also confirmed the topographical order of the aforementioned muscle bellies and tendons of the FDS as assigned to the digits 2 - 5 (Fig. 5A-D) by performing individual flexion of each finger.

Both methods, dissection of the body donates as well as clinical imaging by MRI and ultrasound have led to a more profound understanding of the complex anatomical structure of the FDS. Based on the matching datasets, we could successfully define the term “chiasma antebrachii” since all these analyses confirmed that the distal FDS/2 tendon crosses under the FDS/3 tendon running from ulnar-proximal to radial-distal at a certain distance proximal from the carpal region.

The individual muscle bellies of the FDS, its tendons and paths are of clinical relevance, as lesions of the central motor system may lead to disabling and painful muscle spasms as well as abnormal postures, often involving FDS, FDP or the wrist flexors (Fig. 6). Botulinum toxin (reversibly blocking the neuromuscular transmission) effectively relieves these muscle contractions when injected into the affected muscles or selectively into individual muscle bellies of the FDS (Moore and Naumann, 2003).

Discussion

In this manuscript, we revisit the complex structure of the FDS including the topographical order of its muscle bellies and tendons in anterior-posterior as well as radial-ulnar axis. Particularly, the path of each tendon was studied combining dissection studies and clinical imaging using MRI- and ultrasound analyses. In summary, we show that i) the most radial muscle belly belongs to FDS/3, while the

FDS/2 belly lies deeper and more ulnar compared to that of FDS/3, ii) the FDS/2 displays a digastric (biventer) structure with a proximal and a distal belly which are connected to each other by an intermediate tendon, iii) the proximal belly of the FDS/2 has two heads, a superficial head originating from the medial epicondyle of humerus and a deep head originating from the coronoid process of ulna, while both the distal FDS/2 belly and its tendon together form a gutter shape that serves as a splint for the FDS/3 tendon in the front of them, iv) the FDS/3 tendon descends straight to the carpal tunnel, while the distal FDS/2 tendon runs from proximal-ulnar to distal-radial and as it progresses, it crosses under the FDS/3 tendon approximately 3-4 cm proximal of the wrist and hence referred to here as the “chiasma antebrachii”, v) the FDS/4 belly lies superficial like that of FDS/3 and covers partially the muscle bellies of the FDS/2 and FDS/5; both lie deeper than the FDS/4 belly and tendon, vi) the FDS/5 belly has its origin in all cases studied here from the distal end of the intermediate tendon of the FDS/2 and lies ulnar to the distal FDS/2. These findings are summarized in the graphical representations as demonstrated in figure 7A-B. Furthermore, it is to mention that the focus of this study lies in a detailed exploration of the FDS structure in human body dissection and clinical imaging while the nerve and blood vessel supply of the forearm flexors including the FDS were beyond this focus.

First, in our clinical-anatomical courses on targeted injection of botulinum toxin into the forearm muscles, we realized that the FDS structure is more complex than known from many most frequently used anatomy textbooks and atlases (Benninghoff and Drenckhahn, 2008; Gray's Anatomy, 2020; Paulsen and Waschke, 2022; Schünke et al., 2022; Fanghänel et al., 2003). In the main body of textbooks, - covering a period from 1830 to 2022 -, the two (humeroulnar and radial) or three (medial epicondyle, coracoid process of ulna and anterior border of radius) origins of the FDS formation

are described as a broad and thick muscle mass at the proximal forearm, off which four tendons arise in the middle part of the forearm. It is also well described that these tendons pass beneath the transverse carpal ligament. Distal to this ligament, FDS tendons diverge and run towards digits 2 - 5 where each tendon divides into two bundles building up a slip, through which the corresponding FDP tendon passes towards the end phalanx (Weber, 1830; Meyer, 1861; Rüdinger, 1873; Quain, 1882; Henke, 1884; v. Gerlach, 1891; Rüdinger, 1899; Rauber, A. 1892; Piersol, 1906; Waldeyer and Mayet, 1986). A more detailed description of the FDS can only be found in a small number of textbooks during this period: the earliest comprehensive data in detail together with a graphical representation on FDS, as far as we could find in the literature, was provided by v. Luschka (v. Luschka, 1865) and few years later by Henle (1871). They described that the proximal common muscle mass of the FDS is composed of a superficial and a deep layer in its further course to the middle of the forearm: the superficial layer gives rise to two muscle bellies that merge into the tendons of the digits 3 and 4, and the deep layer also delivers two muscle bellies that merge into the tendons of the digits 2 and 5. This observation went down not in all but in diverse anatomical textbooks and atlases and was confirmed by recent publications (v. Luschka, 1865; Henle, 1871; Gegenbaur, C. 1888; Merkel, 1907; Sieglbauer, 1958; Hafferl and Thiel, 1969; Hollinshead, W. H. 1974; Ohtani, 1979; Fanghänel et al., 2003; Benninghoff and Drenckhahn, 2008; Paulsen and Waschke, 2022; Schulte et al., 2022 Waschke et al., 2019; Standring, 2020; Matsuzawa et al., 2021). Our present data also confirm this basic description of the FDS. In addition, and in line with a recently published elegant study on FDS (Matsuzawa et al., 2021), which provides a very detailed analysis on FDS origins, we demonstrate that the single muscle bellies of FDS/3 and FDS/4 (superficial layer of the FDS) as well as that of the FDS/2 and FDS/5 (deep layer of the FDS) can be easily separated from

each other until their respective origins. Based on these dissection analyses we demonstrate that FDS/3 is the most superficial and most radially positioned FDS belly that takes its origin from the medial epicondyle of humerus, the anterior border of radius (distal from the insertion of the pronator teres muscle) and the ACT that connects the two last-mentioned heads of the FDS/3 forming a tendinous arch. FDS/4, also part of the superficial FDS layer, originates mainly from the medial epicondyle while interconnected with the neighboring FDS/3 belly by fibrous tissue in its proximal part. It has the longest tendon free of muscle belly among the FDS tendons. FDS/2 is part of the deepest layer of the FDS bellies and is positioned ulnar from the FDS/3. Our data show furthermore a digastric construction of the FDS/2 displaying a proximal and a distal belly that are connected by an intermediate tendon. These findings are in line with few previous anatomy textbooks (v. Luschka, 1865; Henle, 1871; Fanghänel et al., 2003). First, it should be noted that the information about the intermediate tendon of the FDS/2 was only included in the 17th edition of Waldeyer-Anatomie des Menschen by Fanghänel et al. (2003) while not present in earlier editions. v. Luschka (1865) and Henle (1871) described the observation of an intermediate tendon arising from the deep portion of the FDS and mention three muscle bellies originating from this tendon: one connects to the muscle belly of the digit 4, another one merges into the tendon of the digit 2 and the last one merges into the tendon of the digit 5. However, such connections between different FDS bellies were also mentioned by few authors (v. Luschka, 1865; Morris, 1933; Ohtani, 1979) and could be observed in few cases in our study. Moreover, our present data are also majorly in line with recently published findings (Matsuzawa et al., 2021) demonstrating the intermediate tendon of the FDS/2 and thus its digastric structure. Furthermore, we demonstrate that the proximal FDS/2 belly has two heads, of which the superficial head originates from the medial epicondyle (via ACT) while covered by

the origin of the FDS/4 and the deep head arises from the coracoid process of ulna. These two heads display a bipennate-like structure and unify by merging into the intermediate tendon (mentioned above) in the proximal third of the forearm. These findings are to a great extent in line with the recently published data (Matsuzawa et al., 2021) with two exceptions: first, we could not find an independent FDS/5 muscle belly in the proximal forearm that originates from the medial epicondyle and second, respectively no separate intermediate tendon for FDS/5. In 35 of 36 cases of dissection in our study, the FDS/5 belly started with its origin first from the intermediate tendon of the FDS/2, approximately at the middle of the forearm. The later was also found in great majority of the elbows (18 of 20) in the study of Matsuzawa et al. (Matsuzawa et al., 2021) indicating to be the major type of the FDS/5. The minor mismatch between our study and that of Matsuzawa et al. is probably due to the regional differences to some extent.

Our data confirm the topographical order of the tendons proximal the wrist and their arrangement in pairs in carpal tunnel as already described in several anatomical textbooks and partly demonstrated in graphical representations (v. Luschka, 1865; Henle, 1871; Merkel, 1907; Oertel, 1927; Morris, 1944; Pernkopf, 1964; Toldt and Hochstetter, 1976; Fanghänel et al., 2003; Benninghoff and Drenckhahn 2008, Gray, 1858; Standring, 2020). Briefly, the radial pair is composed by the superficial FDS/3 and the deep FDS/2 tendons while the ulnar pair contains the superficial FDS/4 and deep FDS/5 tendons (Fig. 7B). In contrast, some frequently used atlases demonstrate all four FDS tendons side-by-side in the same plane (Paulsen and Waschke, 2022; Schünke et al., 2022; Netter, 2022). Furthermore, we observed in both dissection as well as imaging analyses by MRI and ultrasound that the distal belly and tendon of FDS/2 take on a gutter shape (Fig. 5B-C and Fig. 7B) beginning in the distal third of the forearm and by this, they serve as a splint for the FDS/3

tendon situated closely anterior of them. As far as we could check in the previous literature, no text description about this particular construction was found, while only two graphical representations of two anatomical textbooks (Lanz and Wachsmuth, 1935; Töndury, 1970) take this fact partially into account. Furthermore, in all dissected forearms in this study, we found that muscle bellies of FDS/2 and FDS/5 extend into the carpal tunnel by accompanying their corresponding tendons (Fig. 7A-B). This might lead to a carpal tunnel syndrome as it has been reported for the FDS/2 with compression of the median nerve (Javed and Woodruff, 2014).

In all dissection cases of our study and in the context of the clinical-anatomical training courses we observed that the distal FDS/2 tendon runs from proximal-ulnar to distal-radial. In doing so, it is crossing under the FDS/3 tendon 3-4 cm proximal to their entry into the carpal tunnel, that we named as “chiasma antebrachii”. Checking the previous literature, we only found a description of this crossing of two tendons, - and to our knowledge for the first time, in the anatomy textbook of v. Luschka (v. Luschka, 1865) in which he specified that the tendon of the digit 2 crosses under that of the digit 3. Unfortunately, this observation fell into oblivion until it found attention again in the 17th edition of Waldeyer-Anatomie des Menschen (Fanghänel et al., 2003) while missing in its earlier editions. Checking several old and new anatomical atlases, we could not find any graphical representation visualizing this chiasm, and now we record the “chiasma antebrachii” in our graph about FDS (Fig. 7A) with hope that it will find its way into all relevant anatomical textbooks and atlases and by this will not be lost again.

Beside teaching (bio)medical and dental students, anatomical training courses for clinicians are in demand worldwide, to either improve surgical skills, to teach the young surgeons in the special techniques of surgery or to implement and establish new surgical approaches. Likewise, there is a necessity for a better understanding of

various muscle structures while training in targeted injection. Surgical reconstruction, minimal invasive surgeries and insertion of joint implants also require a comprehensive understanding of muscles and their tendons. Procedures, such as target specific application of therapeutics by injections (e.g., therapeutic injection of botulinum toxin into individual muscles) have become the treatment of choice in focal dystonia and spasticity (Simpson et al., 2016). The clinical picture is often complex and requires detailed knowledge of the structural and topographical anatomy of the muscles involved to achieve the most beneficial therapeutic outcome.

In summary, our study provides an update of the complexity of the FDS bellies and topographical order of its tendons by providing new aspects and merging all pieces of knowledge into a complete picture. We incorporate this knowledge into novel graphical representations and with this unveil the previous structural appearance of the FDS and provide it a new face.

Figure legends

Figure 1: Demonstration of the flexor muscles of the ventral forearm

A) Overview of the superficial compartment of the forearm flexors including the flexor carpi radialis (FCR), the pronator teres (PT), the palmaris longus (PL), the flexor carpi ulnaris (FCU) from their visible origins (medial epicondyle of the humerus, anterior common tendon (ACT) and fascia antebrachii: PL, PT, FCR, FCU; and additionally olecranon: FCU) to the wrist or to their entrance into the carpal tunnel and arrival in the palmar hand. PB: the palmaris brevis. The paths of the FCR, the PL and the FCU are marked with black dashed lines. The medial epicondyle and the olecranon are marked with black dashed circles.

B) Clear superficial view of the FDS/3 and FDS/4 with its individual muscle bellies and tendons after dissection and back folding of the FCR, PL and FCU to the medial epicondyle. The ulnar part of the flexor digitorum profundus (FDP), which forms the deep compartment of the forearm flexors is also now visible, while the rest of it is still covered by the FDS. The median nerve (MN), the ulnar nerve (UN) and the radial artery (RA) are marked. Note that the forearm is in pronated position.

C) Demonstration of the distal part of the deeper localized FDS/2 with its intermediate tendon after radial displacement of FDS/3 and ulnar displacement of FDS/4.

FDS/2 (orange dashed line) flexor digitorum superficialis for the digit 2; FDS/3 (blue dashed lines): flexor digitorum superficialis for the digit 3; FDS/4 (purple dashed line): flexor digitorum superficialis for the digit 4; FDS/5 (green dashed line): flexor digitorum superficialis for the digit 5. APS: arcus palmaris superficialis; FCR: flexor carpi radialis; FCU: flexor carpi ulnaris; FDP: flexor digitorum profundus; MN: median nerve; PB: palmaris brevis; PL: palmaris longus; RA: radial artery; UN: ulnar nerve. Note that the forearm is in pronated position.

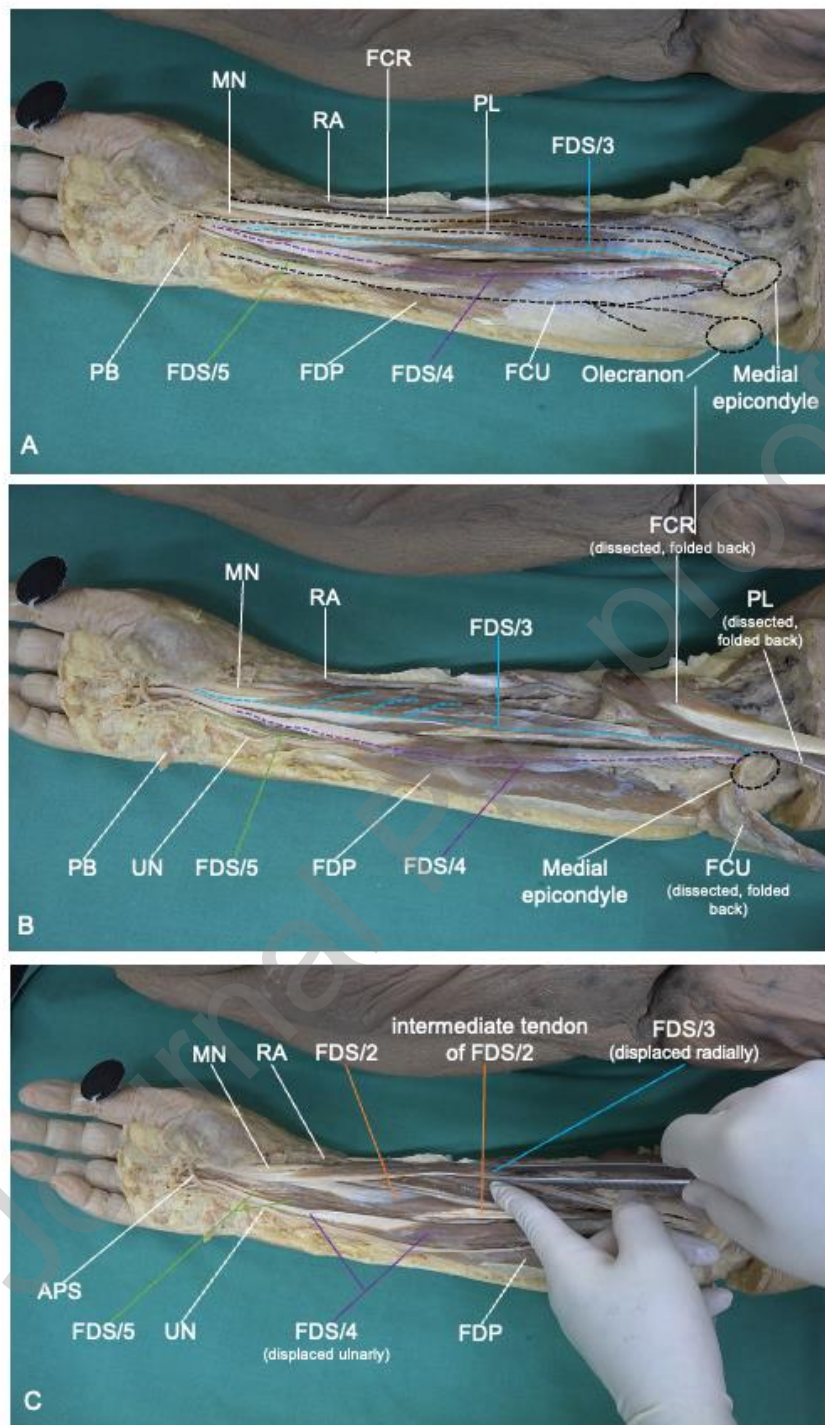


Fig. 1

Figure 2: Demonstration of the FDS/2 bellies and tendons.

A) After radial displacement of the FDS/3 and ulnar displacement of the FDS/4, the FDS/2 is now visible in its entire course. The paths of the median nerve (yellow) and the individual FDS components are marked: (FDS/2: orange dashed line; FDS/3: blue dashed line; FDS/4: purple dashed line; FDS/5: green dashed line).

B) FDS/3 is displaced radially, and FDS/4 is displaced ulnarly by which the entire FDS/2 is demonstrated with its complex organization in detail (proximal and distal bellies and intermediate tendon). Note that the intermediate tendon originates from the proximal FDS/2 belly and ends at the ulnar edge of the distal FDS/2 belly. The distal FDS/2 belly encompasses a flat and broadened tendon that serves as a gutter for the FDS/3 tendon.

C) Close up of the proximal FDS/2 belly with its two heads: the superficial head originating from medial epicondyle and the deeper head originating from the coronoid process of the ulna. The paths of both heads are marked with separate orange dashed lines until they merge into the intermediate tendon.

APS: arcus palmaris superficialis; FCR: flexor carpi radialis; FCU: flexor carpi ulnaris; FDP: flexor digitorum profundus; FDS/2: flexor digitorum superficialis/digit 2; FDS/3: flexor digitorum superficialis/digit 3; FDS/4: flexor digitorum superficialis/digit 4; FDS/5: flexor digitorum superficialis/digit 5; MN: median nerve; PB: palmaris brevis; RA: radial artery; UN: ulnar nerve. Note that the forearm is in pronated position.

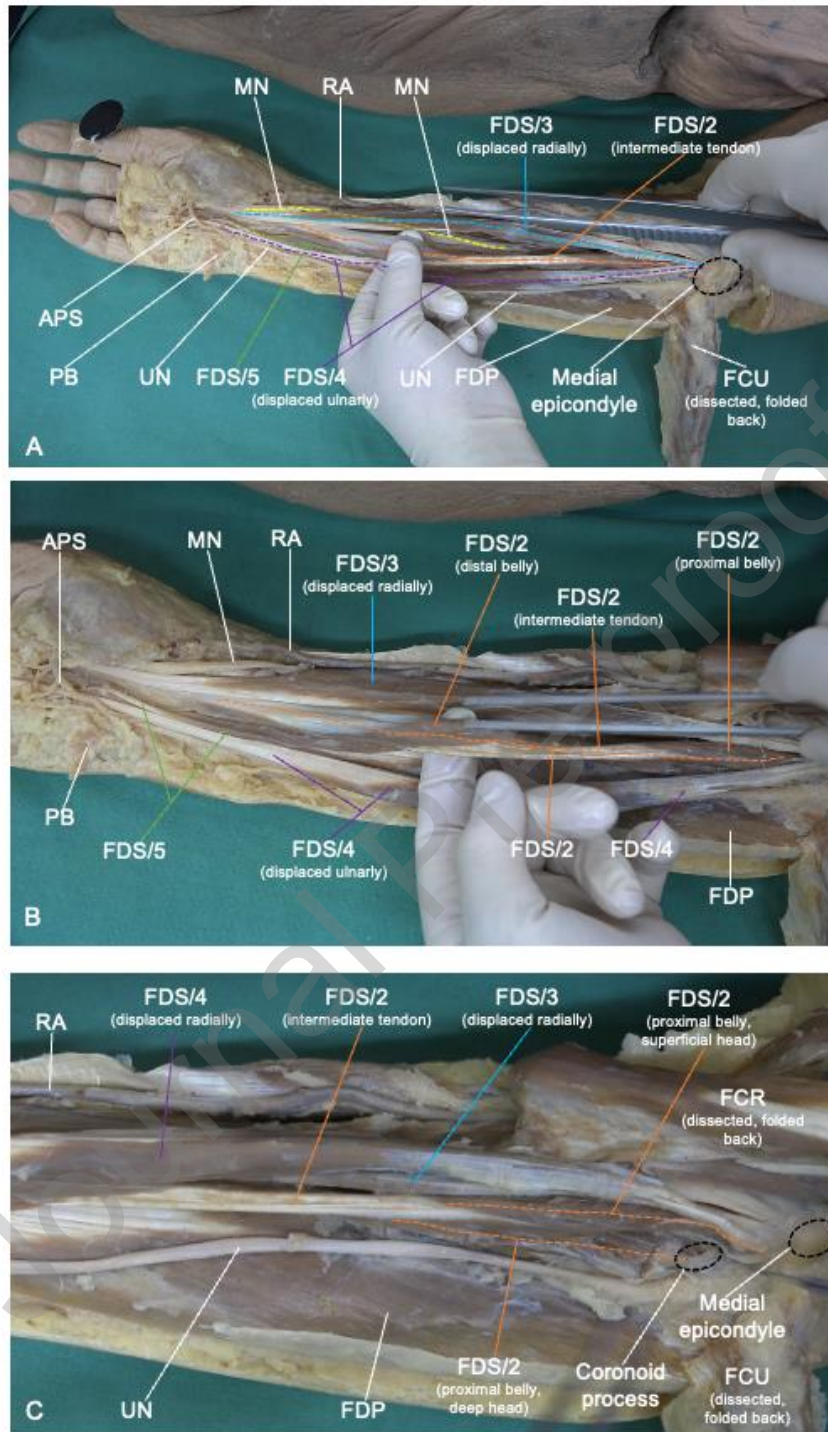


Fig. 2

Figure 3: Demonstration of the “chiasma antebrachii”

A) The distal path of the FDS/2 and its tendon is marked by an orange dashed line to visualize its crossing under the FSD/3, that is marked by a blue dashed line, demonstrating the "chiasma antebrachii" (as we termed it in this study for the first time) approximately 3-4 cm proximal of the carpal tunnel.

B) Close up of the FDS/5 and its origin from the distal end of the intermediate FDS/2 tendon at the ulnar border of the distal FDS/2 belly. Dashed orange line: intermediate tendon and FDS/2; dashed green line FDS/5.

Close up of the "chiasma antebrachii". The paths of the crossing FDS parts are marked: FDS/2: orange dashed line; FDS/3: blue dashed line. The metal probe marks the path of the distal part of the FDS/2 leading to the "chiasma antebrachii".

APS: arcus palmaris superficialis; FCR: flexor carpi radialis; FCU: flexor carpi ulnaris; FDP: flexor digitorum profundus; FDS/2: flexor digitorum superficialis/digit 2; FDS/3: flexor digitorum superficialis/digit 3; FDS/4: flexor digitorum superficialis/digit 4; FDS/5: flexor digitorum superficialis/digit 5; MN: median nerve; PB: palmaris brevis; RA: radial artery; UN: ulnar nerve. Note that the forearm is in pronated position.

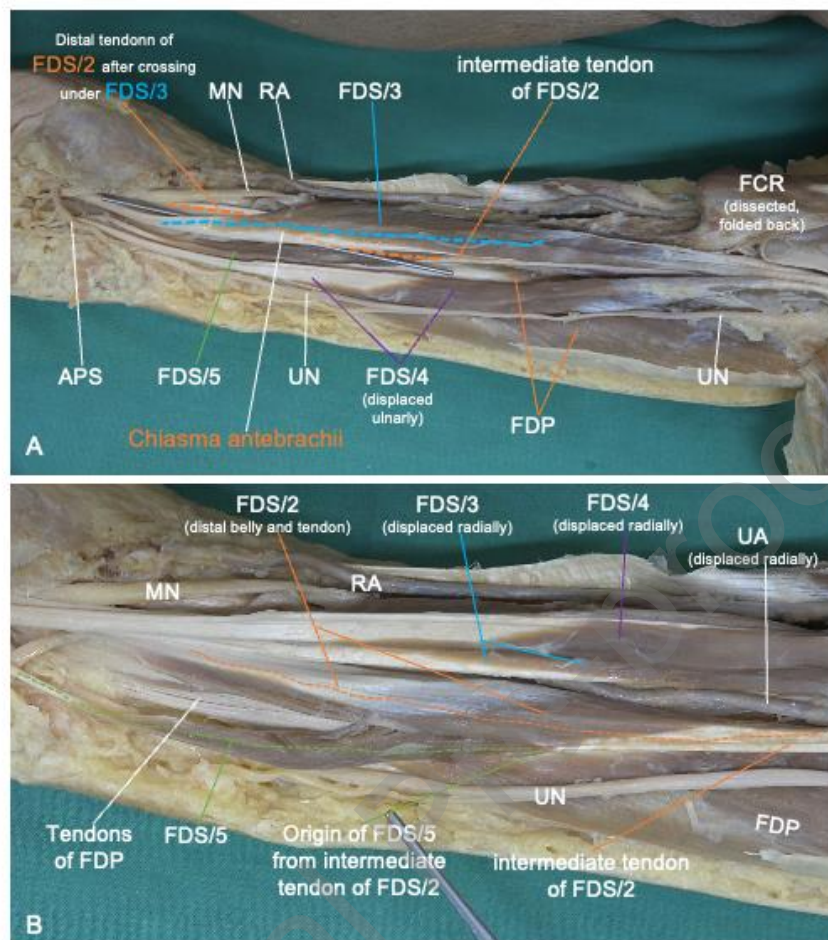


Fig. 3

Figure 4: 3D-reconstruction of the paths of the FDS tendons with “chiasma antebrachii”

(A) Large-volume 3D-reconstruction of the axial MRI dataset showing the path of the individual FDS tendons and the "chiasma antebrachii".

(B) Large-volume 3D-reconstruction of the axial MRI data set showing the path of the individual FDS tendons and the "chiasma antebrachii" in combination with the axial plane demonstrating the topographic localization of the FDS tendons (in different colors) and FDP tendons at the wrist (or in carpal tunnel).

MRI dataset of the left forearm (distal part): Reconstruction of a 22.4 cm volume: 56 sections, section thickness 4 mm, pixel size 0.5 x 0.6 mm. Source data are available for this figure.

The ulna, the radius and the proximal carpal bones are colored in yellow.

FDS/2: flexor digitorum superficialis/digit 2; FDS/3: flexor digitorum superficialis/digit 3; FDS/4: flexor digitorum superficialis/digit 4; FDS/5: flexor digitorum superficialis/digit 5; FDP: flexor digitorum profundus.

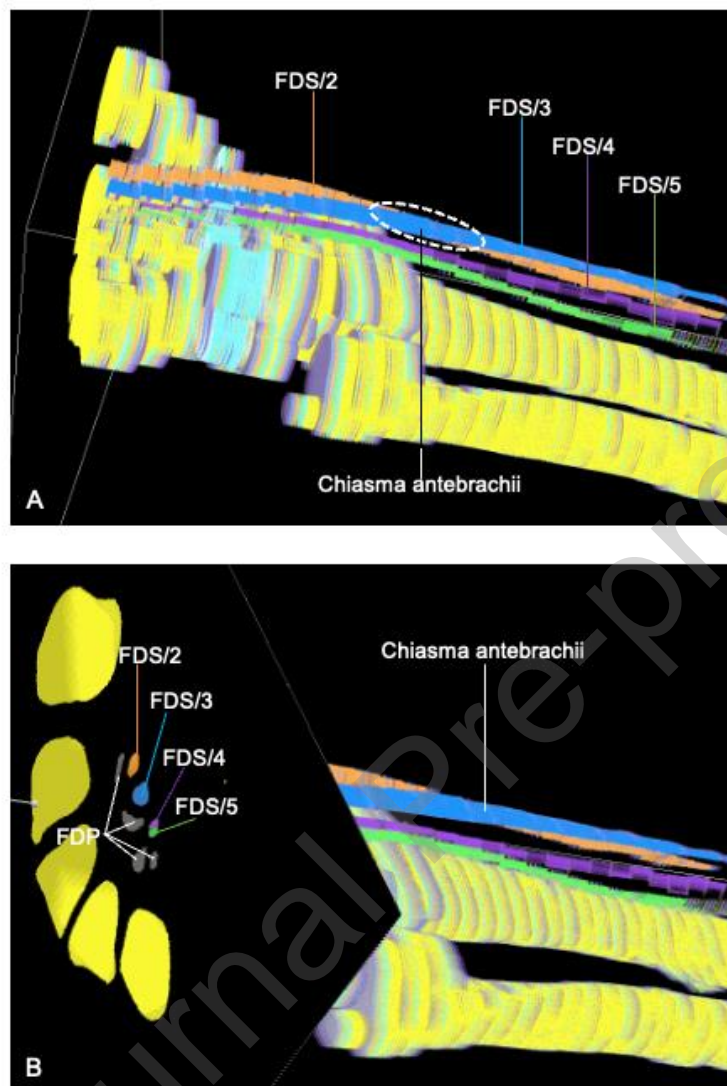


Fig. 4

Figure 5: Ultrasound imaging of the forearm and the FDS of a volunteer

A) Ultrasound image of the middle part of the forearm demonstrating the topographic relations of the flexor muscles. Note that the muscle belly and the tendon of the FDS/3 (marked by blue and numbered with 3) is localized radially to the muscle belly and tendon of the FDS/2 (marked by orange and numbered with 2).

B) Ultrasound image of the distal third of forearm. Note that the FDS/2 (marked by orange and numbered with 2) tendon is moved dorsally of the tendon of the FDS/3 (marked by blue and numbered with 3).

C) Ultrasound image of the distal third of forearm at the position of “chiasma antebrachii”. Note that the tendon of the FDS/2 (colored in orange and numbered with 2) forms a clear gutter for the tendon of the FDS/3 (colored in blue and numbered with 3).

D) Ultrasound image of the forearm proximal of the wrist and after “chiasma antebrachii”. Note the rearrangement of the FDS/2 and the FDS/3 tendons leading to radial localization of the FDS/2 tendon (colored orange and numbered with 2) in comparison to the FDS/3 tendon (colored blue and numbered with 3) due to the crossing of the FDS/2 tendon under the FDS/3 tendon from ulnar to radial.

FCR: flexor carpi radialis; FCU: flexor carpi ulnaris; FDP: flexor digitorum profundus; FDS/2: flexor digitorum superficialis/digit 2; FDS/3: flexor digitorum superficialis/digit 3; FDS/4: flexor digitorum superficialis/digit 4; FDS/5: flexor digitorum superficialis/digit 5; FPL: flexor pollicis longus; MN: median nerve; PL: palmaris longus; PQ: pronator quadratus.

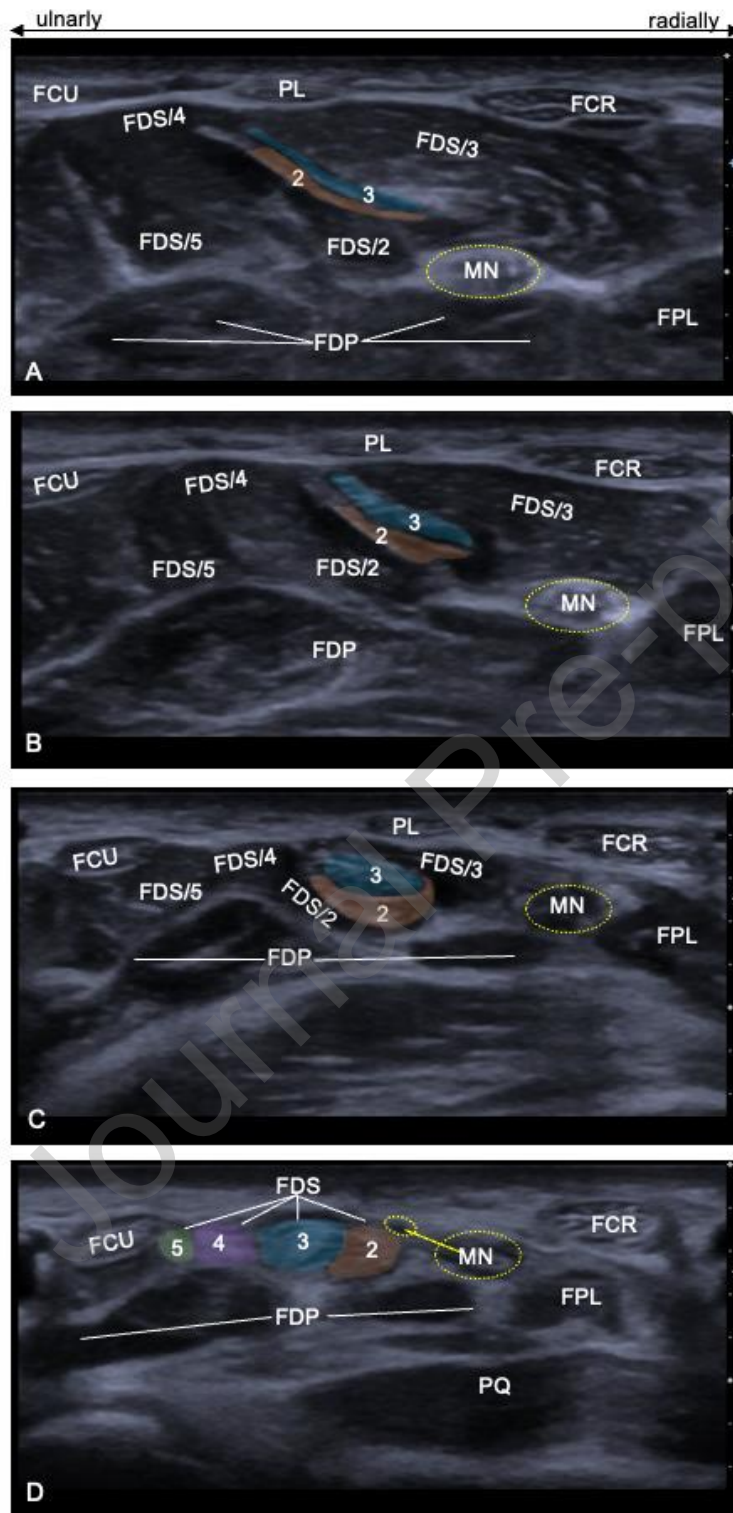


Fig. 5

Figure 6: Focal hand dystonia (writer's cramp) with involuntary activation of wrist and finger flexors during writing.



Fig. 6

Figure 7: Graphical demonstration of the ventral forearm with the flexor muscles in updated version of the FDS in its complex structure with individual bellies and tendons.

AP: aponeurosis palmaris; BR: brachioradialis; FDP: flexor digitorum profundus; FCR: flexor carpi radialis; FDS: flexor digitorum superficialis; FDS/2: flexor digitorum superficialis/digit 2; FDS/3: flexor digitorum superficialis/digit 3; FDS/4: flexor digitorum superficialis/digit 4; FDS/5: flexor digitorum superficialis/digit 5; FCU: flexor carpi ulnaris; FPL: flexor pollicis longus; PB: palmaris brevis; PL: palmaris longus; PT: pronator teres; ThM: thenar muscles; PQ: pronator quadratus muscle; ECU: extensor carpi ulnaris; EDM: extensor digiti minimi; EI: extensor indicis; EPL: extensor pollicis longus; ECRB: extensor carpi radialis brevis; ECRL: extensor carpi radialis longus; EPB: extensor pollicis brevis; APL: abductor pollicis longus; UN: ulnar nerve; UA: ulnar artery; RN: radial nerve; RA: radial artery; ACT: anterior common tendon.

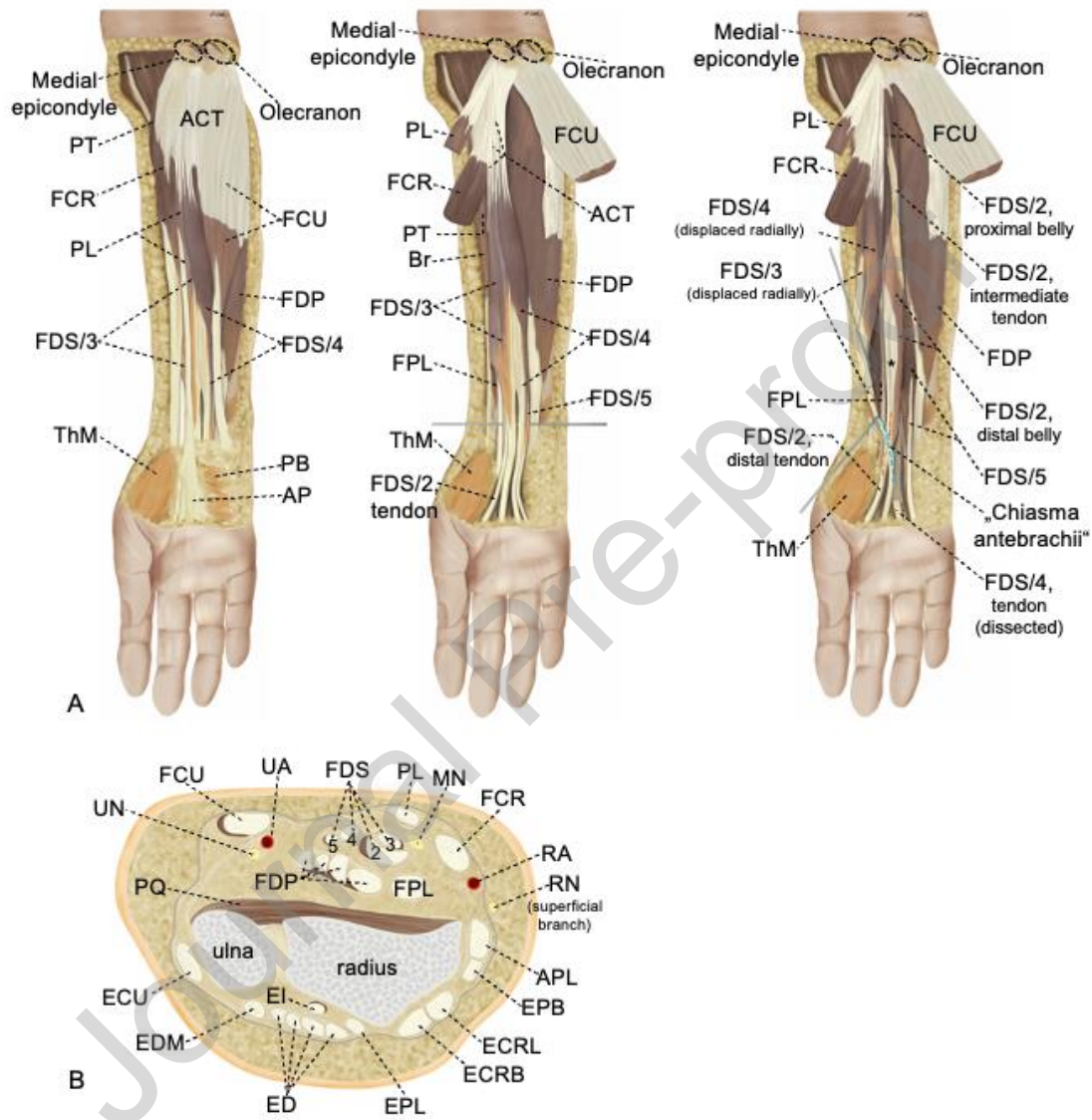


Fig. 7

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Ethical statement

The authors are accountable for all aspects of this work in ensuring that questions related to the accuracy or integrity of any part of this work are appropriately investigated and resolved.

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