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Research article

The anatomy of the tendon of abductor pollicis longus and its morphological variations: An anatomical approach emphasizing the clinical relevance

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A B S T R A C T

Purpose: The anatomical literature describes the abductor pollicis longus as a muscle with a single tendon inserting on the base of the first metacarpal bone, but investigations have shown that it often exhibits morphological variations. However, methodological approaches used to describe these variations have not been useful in a clinical context. Therefore, the purpose of this investigation was to study and relate such anatomical variations in a clinical context.
Basic procedures: Thirty upper limbs from the body donation program were dissected using standard procedures to identify the number of abductor pollicis longus (APL) tendons, their position, site of insertion, length, width and thickness. The presence or absence of the extensor pollicis brevis muscle was also noted. Inter and intra-observer reliability was analysed.
Main findings: A total number of 71 tendons from the APL muscle were found in the thirty limbs. The most frequent distribution pattern was a main tendon inserted on the base of the first metacarpal and an accessory tendon inserted into the abductor pollicis brevis muscle. These tendons could divide into various tendinous slips that could insert in different locations. Also, clustering algorithms and classical statistical tests showed tendons inserting on the first metacarpal were longer than tendons not inserting on the first metacarpal ($p = 0.03$), while medial tendons and tendons from an APL muscle with supernumerary tendons were narrower ($p < 0.001$). The absence of the extensor pollicis brevis muscle was not related to the presence of supernumerary APL tendons.
Conclusions: Radiological and surgical implications of these results are important when examining this region of the hand and wrist. The pathophysiology and treatment of de Quervain's tenosynovitis, trapeziometacarpal arthritis and trapeziometacarpal subluxation or laxity could be influenced by the results of our findings.

Abbreviations: APL, abductor pollicis longus muscle; APB, abductor pollicis brevis muscle; EPL, extensor pollicis longus muscle; EPB, extensor pollicis brevis muscle; US, ultrasounds; TMC, trapeziometacarpal joint; 1rstMTC, first metacarpal bone

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1. Introduction

Classical literature describes the abductor pollicis longus (APL) as a fusiform flattened muscle located in the deep plane of the posterior compartment of the forearm. It originates immediately distal to the supinator muscle, attached on the posterior surface of the interosseus membrane of the forearm, and crosses the wrist under the extensor retinaculum in the first extensor compartment. Eventually, it inserts on the lateral side of the base of the first metacarpal bone (Testut et al., 1979; Bergman et al., 1984; O'Rahilly, 1986; Orts, 1987; Williams, 1995; Rouvière et al., 2005). These classical textbooks mention accessory slips or tendons but fail to give consistent accounts of their possible variations. Furthermore, only Bergman et al. (1984) estimated the frequency of thumb muscle variations as *"one out of six subjects dissected"* but was not more specific.

However, during the last seventy years, several studies (Lacey et al., 1951; Coleman et al., 1953; Baba, 1954; Jackson et al., 1986; Brunelli et al., 1991; Khoury et al., 1991; van Oudenaarde, 1991; Yuksel et al., 1992; Fabrizio et al., 1996; Dos Remédios et al., 2005; Shiraishi et al., 2005; Kulthanan et al., 2007; Paul et al., 2007; Mehta et al., 2009; Bravo et al., 2010; Roy et al., 2012; El-Beshbishy et al., 2013; Thwin et al., 2014; Tewari et al., 2015; Lee et al., 2017; Palatty et al., 2018; Xu et al., 2018; Karauda et al., 2020; Deivasigamani et al., 2021; Gnanasekaran et al., 2021) have shown that the APL tendon is much more variable than reports from the classical literature suggests, reaching proportions of 74.41 % and 85 % according to Roy et al. (2012) and Bravo et al. (2010) respectively. The anatomical diversity ranges from supernumerary tendons to variations of the point of insertion or tendons that divide themselves into various tendinous slips. These variations can be detected by ultrasound (US) with a high accuracy (Rousset et al., 2010; Iriarte et al., 2021).

It is very important to be familiar with these variations since they have been found to have clinical relevance in the pathophysiology of De Quervain's tenosynovitis, especially their number, thickness and length (Melling et al., 1996) and their site of insertion (Lee et al., 2017). In addition, knowledge of the anatomy of the area is essential for treating this condition surgically by performing a tendon release after conservative treatment has failed, reaching a success rate of 96 % of patients treated (Zarin et al., 2003). Furthermore, its relationship to the pathogenesis of thumb carpometacarpal osteoarthritis has not been established (Schulz et al., 2002) although some authors describe a positive correlation (Tewari et al., 2015). Also, these tendons have been described as an excellent source of grafts for tendon reconstruction (Bravo et al., 2010; Rosas et al., 2017), improving the results of surgical treatment of trapeziometacarpal (TMC) osteoarthritis (Rab et al., 2006).

The aim of this study is to analyse the different patterns of APL variations that can be encountered, particularly regarding the dimensions and sites of insertion of the APL tendons, with a focus on relating these data clinically.

2. Material and Methods

The sample was obtained from the University of Girona's body donation program available for undergraduate and postgraduate study and investigation. From this sample comprising cadavers of both sexes, 30 non-paired formalin-fixed upper limbs (16 right and 14 left) were selected. It was not possible to identify corresponding limbs belonging to the same corpse, so no analysis of the bilaterality of the identified variations could be performed. Specimens with signs of previous surgery in the region of interest were excluded.

To assess the pattern of the APL tendon from its origin to its insertion and its relationship to the other muscles that make up the anatomical snuffbox [Extensor Pollicis Brevis (EPB) and Extensor Pollicis Longus (EPL)], a window was opened on the skin covering the thumb, the muscles of the thenar eminence and the distal radial posterior half of the forearm, keeping the upper limb in a neutral position. With this manoeuvre, optimal visualization of the APL was ensured. Tendons were isolated from the surrounding tissue from their insertion to their origin using a surgical magnifying glass (Zeiss x8), which was also used to distinguish independent tendons from tendinous slips. Independent tendons were defined as those originating directly from the muscle belly without connection to other tendons, while tendinous slips denoted the division of one tendon (usually at the insertion point) into diverse interconnected bands.

Once dissection was complete, measurements of all the tendons dissected were taken at the point where they crossed the first extensor compartment of the radius. The length, width and thickness of each tendon were measured using a calibrated sliding calliper with the upper limb held in a neutral position (TURATA® A-123, 0.01 mm resolution). The length was defined as the distance from the point of insertion to the visible origin from the muscle belly. When the tendon had an oblique origin line, a middle point of this line was taken as the visible origin. The width was the distance between the lateral and the medial sides of the tendon, while the thickness was the distance from its anterior to posterior face perpendicular to the width. In tendons composed of various tendinous slips with different sites of insertion, the mean points of insertion were used for length measurements. The position was registered on the same spot, numbering each tendon in the direction from lateral-dorsal to medial-ventral with the hand in a neutral position. The presence or absence of the EPB was also noted.

In order to account for inter-observer error, three different raters measured the three selected variables (length, width and thickness) on the first 18 out of the 30 specimens of the analysed sample (60 % of the whole sample size) i.e., 48 out of the 71 different tendons were measured for this purpose. These measurements were taken at different times by the three raters to guarantee the robustness of the test. In order to account for intra-observer error, the first author measured the 30 hands (71 tendons) and then repeated the measurements two months later. For the first round, measurements were taken one at a time concurrently with the dissection and description of the specimen. At the second round, two months later, the measurements were taken in succession.

A two-way random intraclass correlation coefficient (ICC) was calculated to test both the inter- and intra-rater reliabilities of the quantitative data. Owing to the data characteristics, an absolute agreement ICC type was used (Daniel et al., 1999). Single measurements were employed for intra-observer reliability while average measurements were used to test inter-observer reliability. According to Koo et al., ICC values less than 0.5 indicate poor reliability, values between 0.5 and 0.75 indicate moderate reliability, values between 0.75 and 0.9 indicate good reliability, and values greater than 0.90 indicate excellent reliability (Koo et al., 2016). All the reliability tests were performed using IBM SPSS Statistics 28.0.

The remaining data were recorded on an Excel spreadsheet (Microsoft Excel version 16.63.1) and analysed using Python language Jupyter Notebook which applied the data analysis libraries "*Pandas*" and "*Numpy*" for data structures, "*Sklearn*" and "*SciPy*" for statistics and "*Matplot*" and "*Seaborn*" for plots. Variables were tested for normality using the D'Agostino and Pearson's test and differences between tendons inserting o not inserting on the first metacarpal bone were assessed by Student's t-test. Correlation between the different variables recorded in this study was examined using Spearman's rank correlation coefficient. Thus, Spearman's rho coefficient indicates a weak correlation if < 0.3, a fair correlation if the result were between 0.3 and 0.5, a moderately strong relationship if between 0.6 and 0.8 and a very strong relationship if > 0.8 (Chan, 2003). The significance threshold was $p < 0.05$. Also, after data from the number, position, length, width and thickness of the APL tendons were scaled, the k-means clustering algorithm was

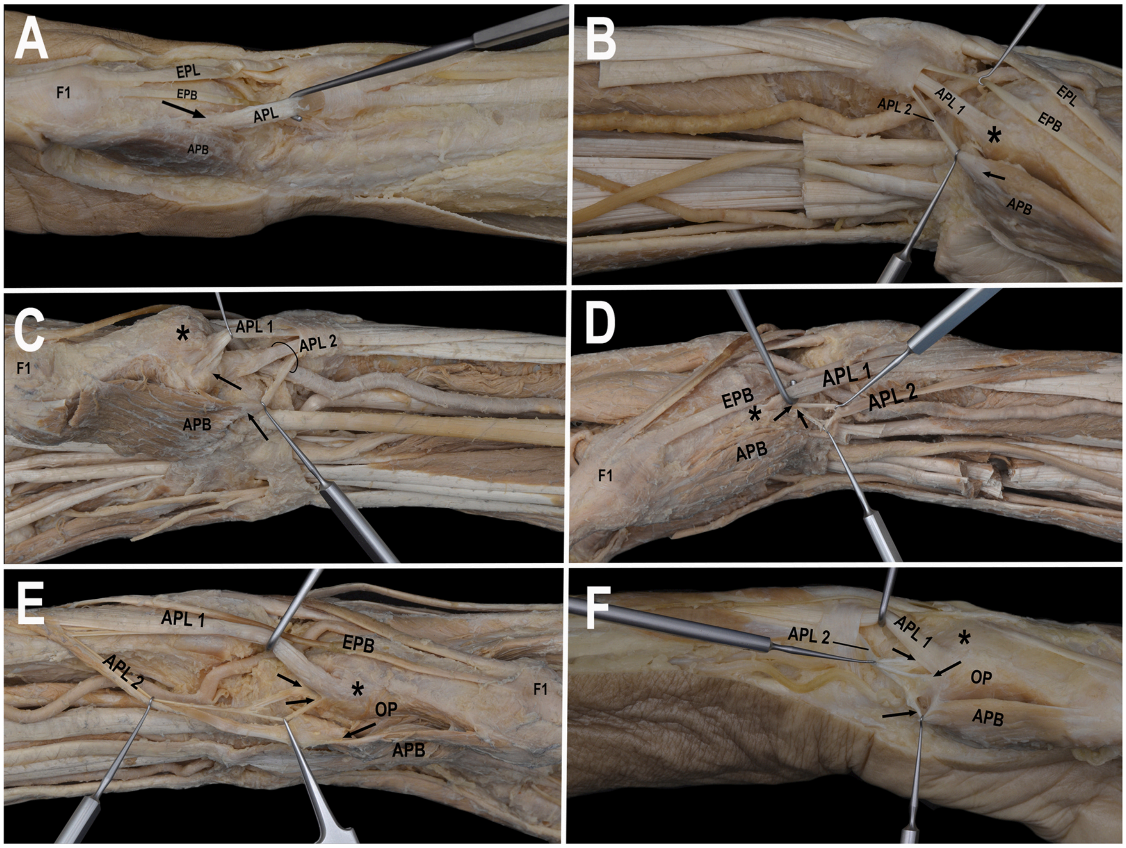

Fig. 1. Images corresponding to specimens with a single APL main tendon. 1A. Specimen (right hand) corresponding with the classical description of the APL tendon. It was single and inserted into the base of the 1rstMTC (arrow); 1B. Specimen (left hand) with an APL main tendon (APL 1) to the base of the first metacarpal bone (*), and an accessory tendon (APL 2) inserted (arrow) into the APB muscle; 1C. Specimen (right hand) showing a main APL tendon (APL 1) inserted into the 1rstMTC (*) and an accessory tendon (APL 2) with two terminal splits attached to the APB muscle and the trapezium (arrows); 1D. Specimen (right hand) characterized by a main APL tendon (APL 1) inserted into the lateral side of the base of the 1rstMTC bone (*), and an accessory tendon (APL 2) which had a bifurcated insertion (arrows) into the trapezium and the base of the 1rstMTC (arrows); 1E. Left hand with a single main APL tendon (APL 1) to the 1rstMTC (*), and an accessory tendon (APL 2) that showed three terminal slips (arrows) to the trapezium, 1rstMTC and the APB muscle; 1F. Left hand specimen with a single main APL tendon (APL 1) to the lateral aspect of the 1rstMTC (*), and an accessory tendon (APL 2) split into three terminal slips (arrows) to the trapezium, the OP muscle and the APB muscle.

applied. This test grouped variables into different clusters according to their similarities and allowed the behaviour of this data to be visualized generally before cross-correlations were tested.

3. Results

All the 30 upper limbs studied in this work presented an APL tendon inserted on the first metacarpal bone. This tendon was considered as the main tendon of the APL muscle. In relation to its morphology, the APL main tendon could be single (19 cases/63.3 %) or divided into two or three independent tendons (double type −8 cases/26.7 %-; triple type −3cases/10 %) (Figs. 1–3). Double and triple typologies corresponded to those tendons originated in the APL muscle which could be easily separated over their entire length, from their origin to their insertion in the base of the first metacarpal bone (Figs. 2, 3). In four specimens (13,33 %), the APL main tendon split into two tendinous slips before the insertion. Through these tendinous slips, the APL main tendon was also inserted into the APB muscle (2 cases/6.66 %), or into the opponens pollicis muscle (2 cases/6.66 %) (Fig. 4).

In 26 specimens (86.7 %), accessory tendons to the APL main tendon were observed. With the hand in a neutral position, accessory tendons were arranged palmarly and medially to the main APL tendon, characteristically. The number of accessory tendons was one (96.15 %) or two (3.84 %). The terminal end of each accessory tendon could be either simple (46.15 %) or split into two (46.15 %) or three tendinous bands (7.7 %). The site of insertion of these accessory tendons could be the APB muscle, the base of the first metacarpal bone, the trapezium and/or the opponens pollicis muscle, being the APB muscle the most frequent spot of insertion of these accessory tendons (Figs. 1–3). Table 1 summarizes all the APL tendon typologies and their observed frequencies.

In our sample (30 specimens), the total number of tendons originating from the APL muscle (main and accessories) was 71. Table 2 shows the points of insertion of all these tendons. If the number of APL tendons (main and accessory) found in the first extensor compartment are considered, these ranged between 1 and 5, two tendons being the most frequent pattern (56.67 %) in the studied specimens (Fig. 5).

Excellent reliability was found for inter-observer reliability tests for tendon length [0.935 (95 % CI: 0.890–0.963)] and width [0.927 (95 % CI: 0.881–0.957)] while good reliability was obtained for thickness [0.761 (95 % CI: 0.603–0.860)]. In addition, and according to the categories described in the Methods section, an excellent reliability was found in intra-observer reliability tests for length [0.953 (95 % CI: 0.925–0.970)] and width [0.952 (95 % CI: 0.925–0.970)], while a good reliability was obtained for thickness [0.891 (95 % CI: 0.831–0.931)].

The length, width and thickness of the 71 tendons dissected are shown in Table 3. They were separated into two groups according to whether they inserted (1rstMTC) or did not insert (Not 1rstMTC) solely on the first metacarpal bone, and the mean length, width and thickness in each group were tested for normality. Since all variables followed a normal distribution, variables were compared using

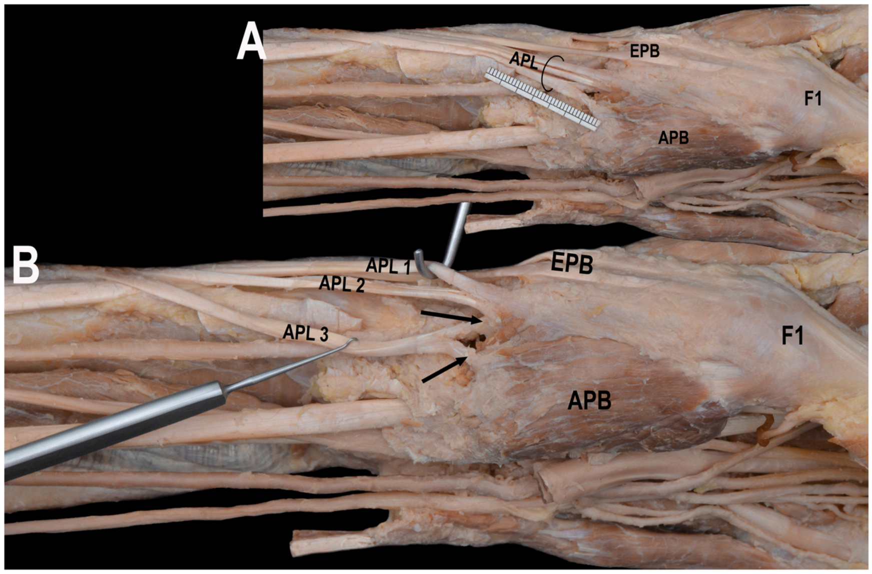

Fig. 2. Left hand specimen corresponding to an example of double APL main tendon. A. Image that corresponds to the *in situ* dissection. B. Image showing the detailed anatomical disposition of the tendons. The APL main tendon (APL) is clearly separated into two main tendons (double typology) to the 1rst MTC (APL 1 and APL 2). The specimen showed an accessory tendon (APL 3) with a terminal split in two slips (arrows), which were inserted into the 1rstMTC and the APB muscle.

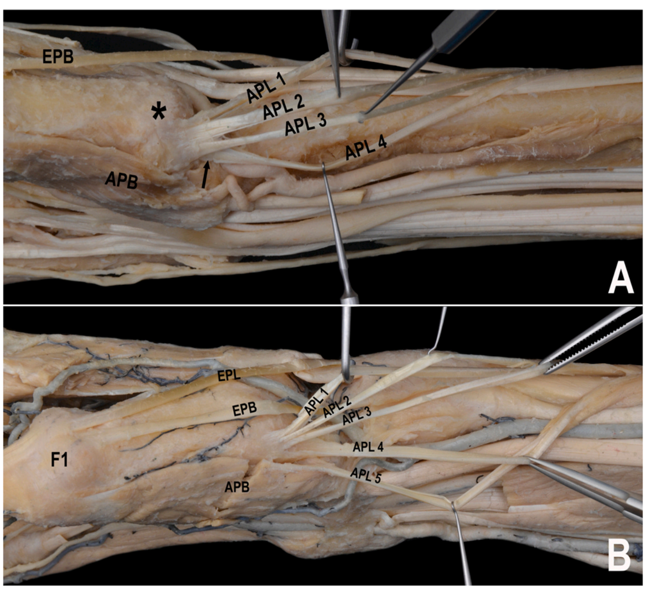

Fig. 3. Specimens corresponding to the typology of a triple APL main tendon (APL 1, APL 2, APL 3) inserted into the base of the 1rstMTC bone. A. Right hand with and accessory tendon (APL 4) to the trapezium (arrow). B. Right hand with two accessory tendons, to the trapezium (APL 4) and to the APB muscle (APL 5).

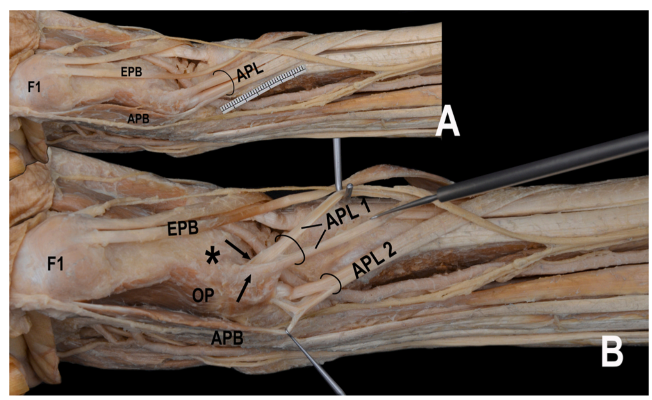

Fig. 4. Right hand characterized by a main APL tendon (APL) split into two tendinous slips (APL 1 & arrows), one to the 1rstMTC (*) and the other to the opponens muscle (OP). The specimen demonstrates an accessory tendon (APL 2) that split at the end into two slips, one to the trapezium, and the other to the trapezium and the abductor pollicis brevis muscle (APB). A. *In situ* dissection. B. Detailed anatomical depiction of the APL tendons. EPB: extensor pollicis brevis tendon; F1: proximal phalanx of the thumb.

Student's t-test (Table 4). Statistical analysis identified a significant difference between the length of 1rstMTC and Not 1rstMTC tendons, the former being longer than the latter, but no difference was observed in width and thickness between groups.

Clustering analysis (Fig. 6) allows the behaviour of these data to be visualized generally and for certain conclusions to be drawn. Wider tendons tend to belong to an APL muscle with fewer tendons and have a more lateral position, thus forming an independent cluster (blue). The red cluster comprises smaller widths and is therefore seen on the far end of the number-of-APL-tendons axis. However, when related to position, this cluster seems to spread. Tendons in the orange and green clusters tended to behave contrary to those in the blue cluster and similarly to the red cluster, remaining intermediate between those clusters, especially when width or thickness is compared with the number or position of the APL tendons. The scatterplots comparing length, thickness and width imply a weak positive relationship.

Spearman's rank correlation (Fig. 7) confirms most of the observations extracted from the cluster analysis. The negative correlation between the width and the number of APL tendons is moderately strong ($r_s = -0.72$; $p < 0.001$), which means that the more tendons there are in an APL muscle, the smaller their width will be. The relationship between the width and position of the APL tendon also shows a moderately strong negative trend ($r_s = -0.55$; $p < 0.001$), meaning that the more medial the tendon, the narrower it will be (Fig. 8). The thicknesses of the APL tendons were also negatively related to their position, although the strength of the relationship was only fair ($r_s = -0.30$; $p = 0.01$). Another statistically significant correlation was the weak positive relationship between the length and width among APL tendons ($r_s = 0.25$; $p = 0.02$). There were no statistically significant relationships between the absence or presence of the EPB tendon and the number of APL tendons ($r_s = 0.03$; $p = 0.815$), thickness and length ($r_s = 0.21$; $p = 0.076$) or thickness and width ($r_s = 0.23$; $p = 0.050$).

Table 1
Distribution of APL main and accessory tendons typologies and their observed frequencies.

APL main tendon type (percentage)	Number of accessory tendons (0, 1, 2) Site of insertion (number of cases /percentage)			
	0	1		2
		No terminal split	Tendon with terminal split	
Single (63,3 %)	1rstMTC (3/10 %) *	APB (3/10 %) T (1/3.33 %)	APB + T (7/23.33 %) * * 1rstMTC + APB (2/6.67 %) 1rstMTC + T (1/3.33 %) 1rstMTC + T + APB (1/3.33 %) T + APB + OP (1/3.33 %)	-
Double (26,7 %)	1rstMTC (1/3.33 %)	APB (4/13.33 %) * ** T (1/3.33 %)	APB + 1stMTC (2/6.67 %)	-
Triple (10 %)	-	T (2/6.67 %)	-	T & APB (1/3.33 %)

* In two specimens the APL main tendon was split and inserted in the 1rst MTC and in the APB muscle
** In one case (Fig. 4) the main APL tendon split and inserted into the 1rst MTC and the opponent muscle
*** In one case, one of the main APL tendons split and inserted into the 1rst MTC and the opponent muscle
APB: abductor pollicis brevis muscle; OP: opponent muscle; T: trapezium; 1rstMTC: first metacarpal bone.

Table 2
Distribution of main and accessory APL tendons according to their site of insertion.

Site of insertion	Number of tendons
1rst MTC	41
APB	8
Trapezium and APB	7
1rst MTC and APB	5
Trapezium	5
1rst MTC and OP	2
Trapezium, APB and OP	1
1rst MTC and Trapezium	1
1rst MTC, Trapezium and APB	1
Total Sum	71

1rst MTC: base of the first metacarpal bone; APB: abductor pollicis brevis muscle; OP: opponent muscle

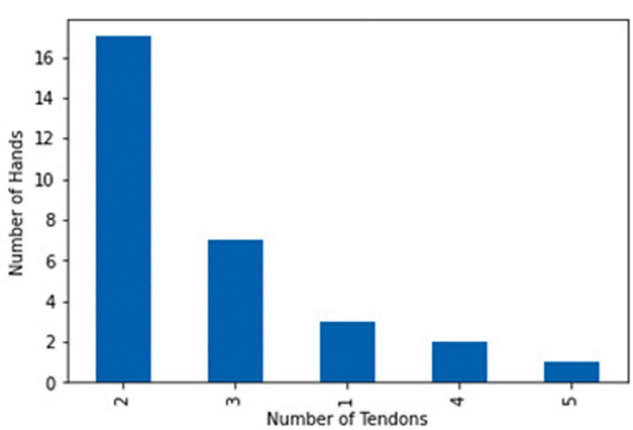

Fig. 5. Distribution of specimens according with the total number of APL tendons.

Table 3
Length, width and thickness of the 71 tendons dissected.

	Mean	SD
Length (mm)	73.38	13.15
Width (mm)	2.84	1.19
Thickness (mm)	1.91	0.80

The tendons of the left hands (3.17 mm ± 1.06) were significantly wider than those of the right hands (2.58 mm ± 1.23) (t = 2.14; df=69; p = 0.04). However, left hands had a greater mean number of APL muscles bearing two tendons than right hands, in which the APL muscles were more diverse (Fig. 9).

Concerning the EPB muscle, it was absent in 23.33 % of specimens. In those cases, where the EPB muscle was present, almost all met the standard description of this muscle. Thus, it showed one single tendon inserting on the proximal phalanx of the thumb. Only one specimen (3.33 %) showed a bifurcated EPB tendon inserting on the proximal phalanx and on the base of the first metacarpal bone. There were no statistically significant relationships between the absence or presence of the EPB tendon and the number of APL tendons (r_s = 0.03; p = 0.815).

Table 4
Mean differences between dimensions of APL tendons depending on whether they inserted (1rstMTC) or not (Not 1rstMTC) in the first metacarpal bone. Significant differences were marked in bold.

	1rstMTC		Not 1rstMTC		Student t-test	df	p-value
	Mean	SD	Mean	SD			
Length (mm)	76.25	12.23	69.46	13.54	2.21	69	**0.031**
Width (mm)	2.87	1.16	2.79	1.24	0.30	69	0.763
Thickness (mm)	1.99	0.75	1.81	0.87	0.90	69	0.370

4. Discussion

The present investigation has shown that the anatomical structure of the APL in the adult differs significantly among individuals. Of all the dissected upper limbs, only three specimens (10 %) showed a single APL tendon inserted into the base of the first metacarpal bone. Only one of these three specimens (3.33 %) followed the classical description. The other two had accessory insertions via tendinous slips that reached the lateral aspect of the base of the first metacarpal bone and the abductor pollicis brevis muscle (APB). Thus, 96.67 % showed variations in the number of tendons and their sites of insertion. There can be supernumerary tendons or tendons with different points of insertion, contrary to descriptions in the classical literature (Testut et al., 1979; Bergman et al., 1984; O'Rahilly, 1986; Orts, 1987; Williams, 1995; Rouvière et al., 2005). These observations are supported by current evidence, which implies that the percentage of APL muscle variants can range from 33 % to 100 % (Lacey et al., 1951; Coleman et al., 1953; Baba, 1954; Jackson et al., 1986; Brunelli et al., 1991; Khoury et al., 1991; van Oudenaarde, 1991; Yuksel et al., 1992; Zancolli and Cozzi, 1992; Fabrizio et al., 1996; Dos Remédios et al., 2005; Shiraishi et al., 2005; Kulthanan et al., 2007; Paul et al., 2007; Mehta et al., 2009; Bravo et al., 2010; Roy et al., 2012; El-Beshbishy et al., 2013; Thwin et al., 2014; Tewari et al., 2015; Lee et al., 2017; Palatty et al., 2018; Xu et al., 2018; Karauda et al., 2020; Deivasigamani et al., 2021; Gnanasekaran et al., 2021). These data show that the presence of accessory or supernumerary APL tendons in human anatomy is not unusual and is rather common. In this sense, with the evolution of the anthropoids (including humans) it is very common to observe this type of

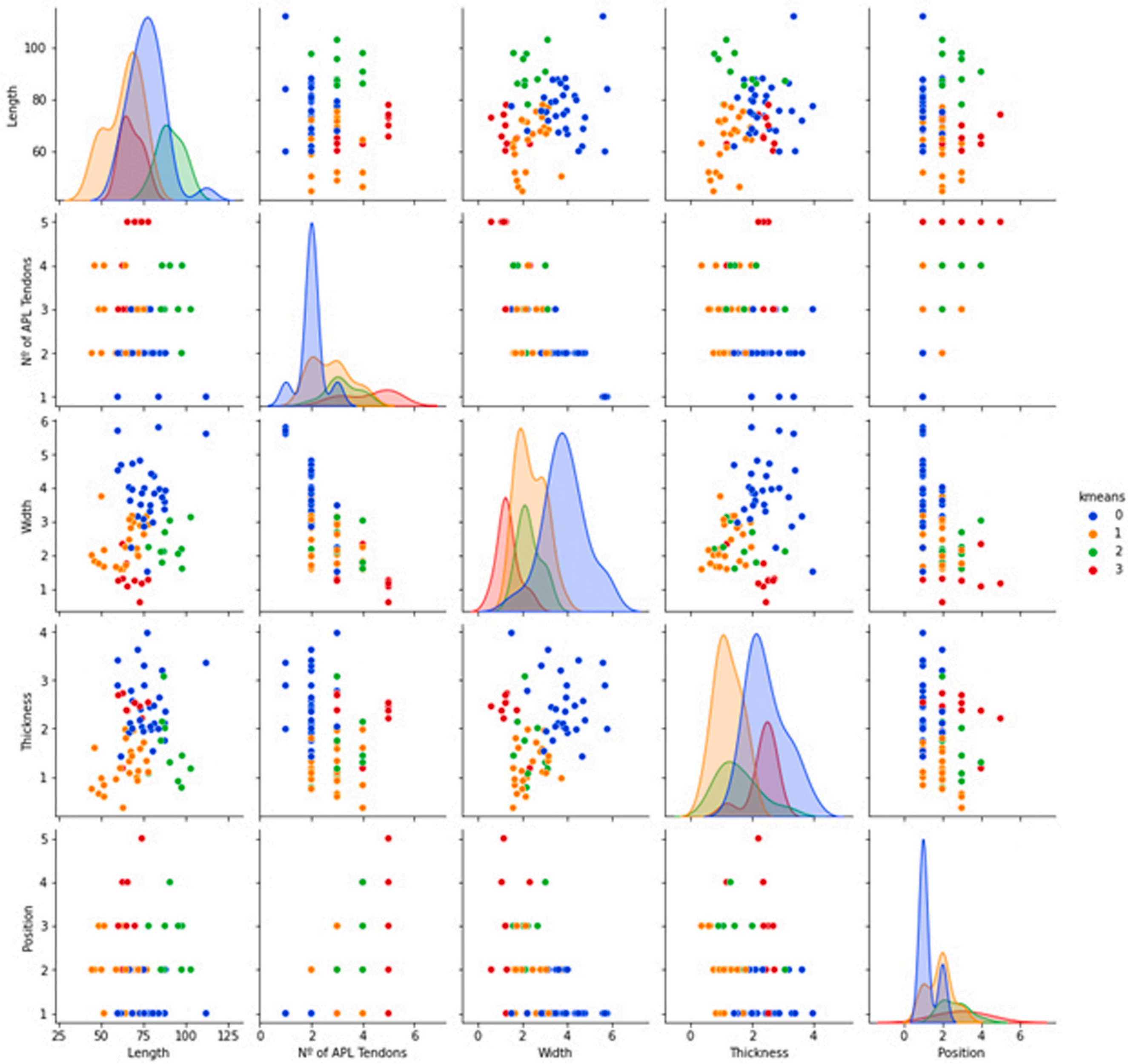

Fig. 6. Cluster analysis on the relationship between the length, width, thickness, position and number of APL tendons.

supernumerary tendon. In lower primates, it is common to find that the APL muscle presents with a single distal tendon of insertion (Wood, 1867). This fact could be related to the acquisition of opposition and a greater range of thumb movement among the anthropoids. Revision of the classical anatomy books is, therefore, recommended to include this updated evidence. Also, it is important that when the muscular structure of the thumb is taught, its wide variability should be emphasised to underline its clinical relevance and minimise negative outcomes during surgery.

When the numbers of tendons found in the studies cited above were considered, comparisons were difficult to establish since other authors failed to differentiate tendinous slips from tendons. Only a few (Coleman et al., 1953; Jackson et al., 1986; Roy et al., 2012; Deivasigamani et al., 2021) included a definition similar to, or identical to the one used in this study. Moreover, a magnifying glass or a surgical microscope was used infrequently during tendinous dissection in other studies. Only Brunelli et al. (1991) and van Oudenaarde (1991) reported their use, the latter in only 22 of their 84 samples. These two factors hinder proper comparison since intratendinous dissection could account for the supernumerary tendons recognised in the studies reviewed (Lacey et al., 1951; Coleman et al., 1953; Baba, 1954; Jackson et al., 1986; Brunelli et al., 1991; Khoury et al., 1991; van Oudenaarde, 1991; Yuksel et al., 1992; Fabrizio et al., 1996; Dos Remédios et al., 2005; Shiraishi et al., 2005; Kulthanan et al., 2007; Paul et al., 2007; Mehta et al., 2009; Bravo et al., 2010; Roy et al., 2012; El-Beshbishy et al., 2013; Thwin et al., 2014; Tewari et al., 2015; Lee et al., 2017; Palatty et al., 2018; Xu et al., 2018; Karauda et al., 2020; Deivasigamani et al., 2021; Gnanasekaran et al., 2021). Nonetheless, if the data were to be compared with the present study, the ranges observed would be similar with a mean maximum of five tendons and a two tendon APL being the most frequent pattern. These numerical differences have also been reported in foetal hands (Palatty et al., 2018).

Radiologically, supernumerary tendons can be detected by US since they are distinguished by hypoechoic bands (Iriarte et al., 2021). This procedure has an accuracy of 80 % and it is essential to

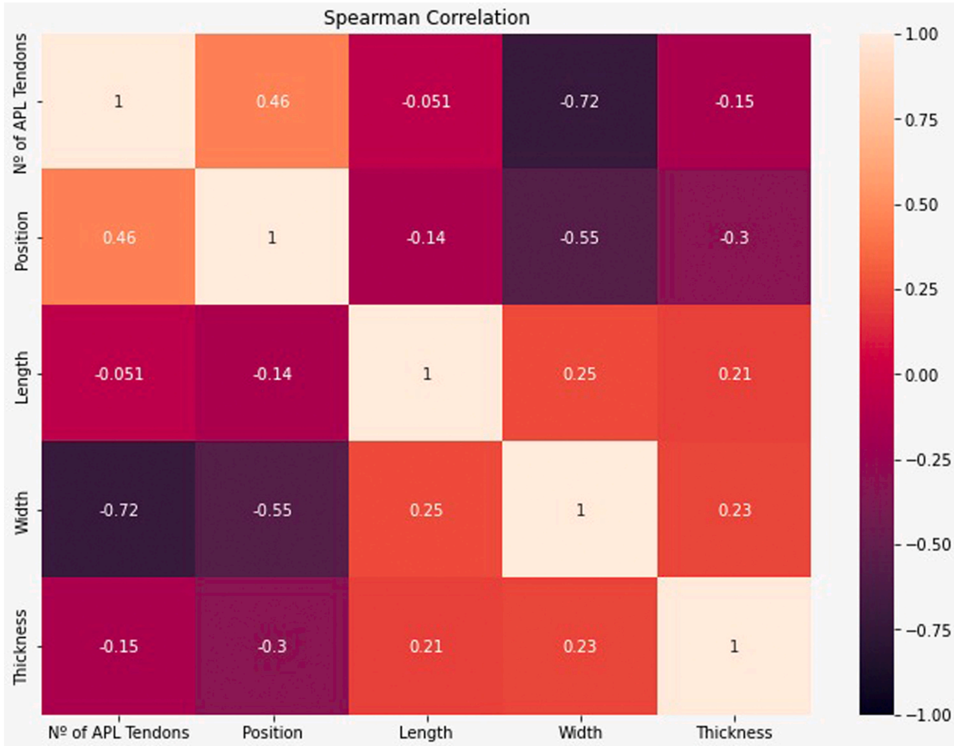

Fig. 7. Pictorial representation of Spearman's rank correlation results that shows the relationship between the length, width, thickness, position and number of APL tendons. The darkest and lightest colors represent stronger correlations.

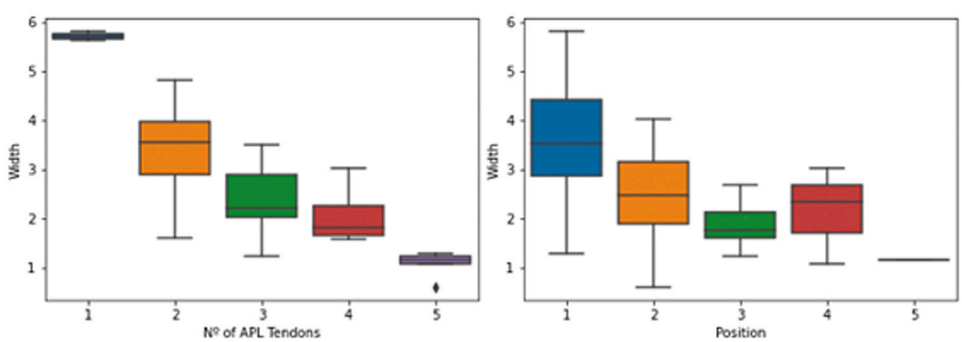

Fig. 8. Boxplots representing the relationship described between the width, the number of APL tendons and their position. Hands with 1 or 5 tendons were uncommon, thus explaining the smaller size of their boxes. This was also seen with tendons located in positions number 4 and 5 or more medialward.

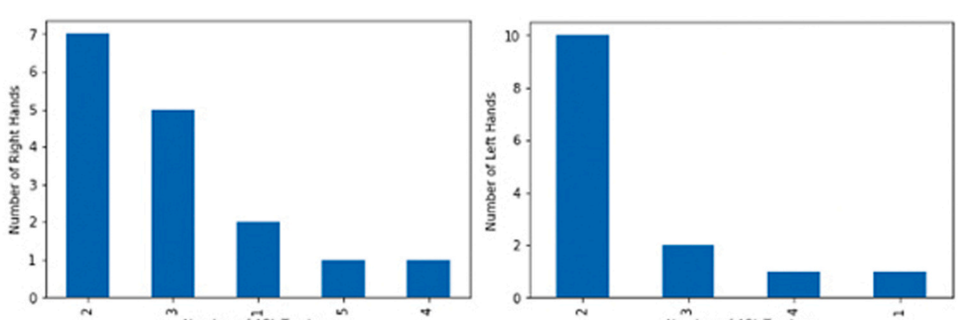

Fig. 9. Bar diagrams depict the differences in distribution for the number of APL tendons between sides. Right hands had a more diverse tendon arrangement than left hands which mostly presented with 2 APL tendons.

note this information because of its clinical relevance (Rousset et al., 2010). Supernumerary tendons must not be confused with tendinous ruptures (Iriarte et al., 2021). The presence of accessory APL tendons in the first dorsal compartment of the extensor retinaculum has been related to the development of chronic tenosynovitis conditions at this level, which can trigger de Quervain's syndrome. (Lacey et al., 1951; Melling et al., 1996). According to Zancolli and Cozzi (1992), these supernumerary tendons are separated by fibrous septa either between them or between them and the EPB tendon. The presence of these septa further compromises the normal anatomical space of the first radial groove, predisposing to the development of de Quervain's syndrome. After conventional treatments have failed, surgical release of the APL tendons has proved an excellent option for treating de Quervain's tenosynovitis (Zarin et al., 2003). This demonstrates the importance of familiarity with various anatomical findings since incomplete release could result in failure of the treatment. However, a recent systematic review revealed no significant relationship between a patient with more than one APL tendon and a predisposition to develop de Quervain's tenosynovitis (Lee et al., 2017).

In patients with TMC arthrosis, one of the techniques is the resection of the trapezium and the subsequent arthroplasty using either the APL tendon or the flexor carpi radialis (FCR) tendon. Some studies have presented highly satisfactory results with the APL procedure (Rab et al., 2006). Although it is not well known why the APL procedure is better than the FCR one, from a biomechanically point of view, the APL tendon is the main muscle of the radial group of muscles that is responsible of the complete abduction and axial rotation of the thumb, which is necessary for the first step in the opposition movement (Zancolli and Cozzi, 1992). The FCR terminal tendon orientation is parallel to the APB and opponens muscles, which only participate in the second phase of the opposition movement. Therefore, considering the range of numbers currently found, the use of accessory APL tendons is recommended for grafting rather than other tendon fragments, always taking into account their point of insertion and mechanical orientation.

The diversity of insertions found in the present sample gives a general view of the most frequent sites of insertion of APL tendons. Universally, all APL muscles have a main tendon that inserts on the base of the first metacarpal bone, with slight variations in the insertion. An extensive bibliographical review revealed that accessory APL tendons insert on the trapezium, first metacarpal, APB muscle, OP muscle, flexor pollicis brevis muscle, thenar fascia, volar carpal ligament and TMC joint. However, many of these articles failed to note the presence of double or triple insertions of single tendons, possibly because there was no clear differentiation between tendinous slips and tendons (Lacey et al., 1951; Baba, 1954; Brunelli et al., 1991; Khoury et al., 1991; van Oudenaarde, 1991; Yuksel et al., 1992; Fabrizio et al., 1996; Dos Remédios et al., 2005; Shiraishi et al., 2005; Kulthanan et al., 2007; Paul et al., 2007; Mehta et al., 2009; Bravo et al., 2010; El-Beshbishy et al., 2013; Thwin et al., 2014; Tewari et al., 2015; Lee et al., 2017; Palatty et al., 2018; Xu et al., 2018; Karauda et al., 2020; Gnanasekaran et al., 2021). When the difference was reported, the sites of insertion were identical to those described in the Results section (Coleman et al., 1953; Jackson et al., 1986; Roy et al., 2012; Deivasigamani et al., 2021).

Numerical data on the frequency of insertion of APL tendons were also difficult to extract since most investigations expressed this variable as the number of cases instead of the number of tendons. However, the most frequent sites of insertion of accessory tendons were the trapezium and the APB muscle, with disagreements about which is the most frequent. Overall, attempts have been made to classify this insertional variability (Coleman et al., 1953; Brunelli et al., 1991; Karauda et al., 2020), but no proposed method accounts for all the combinations observed here, so a simple description seems to be the most effective way for recording surgical or radiological findings. If a classification were necessary, cluster analysis indicates that parameters such as the width and thickness could best differentiate populations of APL tendons and could be useful preoperatively, as explained below.

The embryological development of the upper limb could explain this wide insertional diversity of the APL. Morphogenesis of the hand begins between six and 14 weeks of gestation (Raszewski et al., 2021) with the digits arising as single chondrogenic condensations approximately 36 days after conception (Cole et al., 2009). Thumb development starts at six weeks and rotates during weeks eight and 10 (Raszewski et al., 2021). During this period, the APL tendon begins as an undivided mass that cannot be differentiated proximally from the surrounding mesenchyme and continues to evolve to a three-slip tendon with insertions on the trapezium, the first metacarpal and a distal site, typically on the OP muscle. Lastly, as the thenar muscles develop, the OP tends to lose its connection with the APL tendon while the APB gains it, taking into account that the APB muscle originates independently from the APL (Cihák, 1972).

Some authors have assigned special functions to tendons depending on their insertion. For example, Brunelli and Brunelli (1991) affirmed that tendons inserting on the trapezium abducted the carpus rather than the first metacarpal and stabilized the trapeziometacarpal joint (TMC). Similar observations were made by van Oudenaarde and Oostendorp (1992), who suggested that the APL muscle should be structurally and functionally divided into superficial and deep divisions, the latter contributing to stabilising the joint and the former participating in thumb kinetics. This was discussed by Dos Remédios et al. (2005), who suggested that the systematic division of the APL into superficial and deep divisions was inappropriate. The present study, along with other publications (Lacey et al., 1951; Karauda et al., 2020), found a low percentage of tendons inserting on the trapezium in the general population, and Britto and Elliot (2002) found that total absence of the APL muscle had only a minimal effect on thumb function. Therefore, APL tendons inserting on the trapezium probably contribute to TMC stabilization but should not be considered a major or principal factor.

Clinically, in regard to APL insertions, a systematic review by Lee et al. specified that de Quervain's tenosynovitis could be related to the precise site of insertion of the APL tendons (Lee et al., 2017), which could be explained by the increased friction endured by accessory tendons during activity and their greater vulnerability to trauma (Baba, 1954). Another anatomical factor closely related to the development of de Quervain's tenosynovitis was a septum in the first extensor compartment (Lee et al., 2017). This latter finding can be detected by US with excellent accuracy (95 %) (Rousset et al., 2010), but to the authors' knowledge, there has been no previous investigation on the ability of US to detect the exact point of insertion of the APL tendons.

Brunelli and Brunelli (1991) suggested, without statistical analysis, that the absence of trapezium insertions contributes to the development of TMC arthritis, but this does not agree with Schulz et al. (2002) who found no evidence of a relationship between TMC arthritis and the insertion of the APL tendons. Similarly, Roh et al. (2000) found no clear relationship between the presence of thenar insertions and the development of TMC arthritis, although Martinez and Omer (1985) reported that thenar insertions alone do not guarantee a stable TMC joint since active movement of the thumb resulted in subluxation. This type of insertion has also been related to retention of the capacity for opposition in patients with median nerve injuries (Deivasigamani et al., 2021). Zancolli and Cozzi (1992) established a close relationship between the presence of supernumerary APL tendons inserted into the thenar muscles and the development of TMC osteoarthritis. They hypothesised that the longitudinal compressive effect of these tendons along the thumb column predisposes one to TMC arthrosis. The so-called Zancolli's surgical procedure for the treatment of TMC osteoarthritis includes tenotomy of these accessory or supernumerary APL tendons (Ebelin and Hérisson, 2021). Ultimately, when accessory APL tendons are harvested as grafting material for resection-suspension-interposition-arthroplasty, the tendon to be grafted must be chosen carefully; tendons inserting on the trapezium would not be eligible for this procedure.

The APL tendons have been measured in six other previous studies (Coleman et al., 1953; Palatty et al., 2018; Bravo et al., 2010; El-Beshbishy et al., 2013; Karauda et al., 2020; Gnanasekaran et al., 2021), but to the best of our knowledge, there have been no previous references to inter- and/or intra-observer tests in similar descriptive analysis of APL variability, so this is the first of its kind, guaranteeing the accuracy of the current data and the reliability of the study. Also, these six studies all took the measurements mainly from the point of insertion and not on the spot used in the present study. Measurements of APL tendons after they exit the first extensor compartment are more clinically relevant than those taken from the point of insertion, since US evaluations and surgical procedures begin and proceed from this area (Atroshi et al., 1997; O'Neill, 2008). This also makes comparisons difficult to achieve since measurements, especially of the width and thickness, can differ significantly from the exit of the first corridor to their point of insertion.

In addition, none of these studies found differences between sides or sex except for Karauda et al. (2020), who reported differences in accessory tendon lengths between males and females with a p-value on the borderline of conventional statistical significance. The observations by El-Beshbishy and Abdel-Hamid (2013) concur with our results, showing a progressive decrease of width and thickness as the tendons became more medial. An example of this progression was seen in the spreading of the red cluster when relating width and position. Most of the tendons in the red group belong to a hand with 5 tendons; therefore, more medial tendons tend to be narrower than those located more laterally, showing a trend towards a negative linear relationship between tendons belonging to the same hand.

In addition, the fact that APL muscles with supernumerary tendons have narrower tendons could explain why supernumerary tendons are not related to the development of Quervain's tenosynovitis (Lee et al., 2017). Supernumerary tendons would occupy the same space as a single APL tendon, so the pressure on a normal first extensor compartment would not be increased. This hypothesis is also supported by data from Deivasigamani et al. (2021), who concluded that the cross-sectional area of the APL tendons decreased as the number of tendons increased. These same authors reported differences in length between tendons that did and did not insert on the first metacarpal as the present study also demonstrated.

Data on the dimensions of APL tendons have clinical relevance, mainly for US evaluation or surgical procedures. As Bravo et al. (2010) observed, APL tendons are suitable for TMC arthroplasty since their mean length in this sample was 7 cm, and the recommended length for tendon grafts in this technique is 5 cm (Atroshi et al., 1997). Also, the length of the tendon would indicate whether it inserts on the first metacarpal, suggesting the most suitable grafts for the surgical procedure. Despite this, it can be difficult to identify their precise point of insertion, though imaging techniques such as US could help. In addition, width could be useful for characterizing an APL muscle; a narrow tendon would most probably be a medial tendon belonging to a muscle with supernumerary tendons. This information could easily be revealed by US and would be relevant preoperatively for any procedure in the anatomical snuffbox region, especially when the APL tendon is involved.

The present study has some limitations. First, although past evidence showed no relevant sex differences in the anatomy of the APL tendons, inability to ascertain the sexes of the upper limbs used in this investigation could detract from the clinical relevance as some pathologies such as de Quervain's tenosynovitis affect women more often with a prevalence of 77.5 % (Hassan et al., 2022). Secondly, the bilaterality of the presented variations could not be analysed. Thirdly, a relatively small number of upper limbs were examined, though when the number of individual tendons is considered, the sample on which the main analysis was performed was considerably larger. Also, this sample size was sufficient for essential statistical analysis not reported in other similar investigations, such as intra- and inter-observer variability, which showed our data to be reliable, and cluster analysis, which provided a visual representation of data behaviour and the relationships among variables. However, owing to the methodological differences between investigations on this topic, it is sometimes challenging to compare studies. For this reason, it is recommended that future analyses follow the present methodology since it ensures optimum anatomical description that can be extrapolated to the clinical field. In the future, as a continuation of the present research, it would be interesting to analyse the efficacy of US for detecting the point of APL insertion, which could then be used to define its potential role in the development of pathologies in the area and enhance different surgical approaches.

5. Conclusions

This study has shown that the variability of the APL muscle can range from supernumerary tendons to variable sites of insertion, most frequently on the first metacarpal bone, the APB muscle and the trapezium. The ontogenesis of the APL muscle could account for these numerical and insertional variations and could also explain how the muscular apparatus of the thumb seems still to be evolving; the functional role of each tendon or tendinous slip is yet to be decided.

Significantly, it is clinically important to recognise these anatomical variations and the relationships found during this investigation. Tendons that inserted on the first metacarpal were significantly longer, while medial tendons and tendons belonging to APL muscles with supernumerary tendons were narrower. In addition, absence of the EPB was not statistically related to the presence of multiple APL tendons. Its relevance to the pathophysiology and treatment of conditions such as de Quervain's tenosynovitis, TMC arthritis and TMC subluxation or laxity needs to be understood within this anatomical framework.

Ethical statement

The authors state that every effort was made to follow all local and international ethical guidelines and laws that pertain to the use of human cadaveric donors in anatomical research (Iwanaga et al., 2021; Iwanaga et al., 2022).

CRediT authorship contribution statement

Jesús Marí-Gorreto: conceptualization, methodology, formal analysis, investigation, writing – original draft, **Marta San-Millán**: methodology, validation, formal analysis, writing – review and editing, **Anna Carrera**: conceptualization, resources, data curation, **Shane Tubbs**: conceptualization, writing review and editing, **Joe Iwanaga**: formal analysis, writing review and editing, **Aïda Cateura**: investigation, data curation, **Laura Acquabona**: investigation, data curation, **Miguel A Reina**: writing review and editing, **Francisco Reina**: conceptualization, methodology, writing review and editing, supervision.

Declaration of Competing Interest

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.

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