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ORIGINAL RESEARCH

Ultrasonographic study of the thumb pulleys and their entheses: correlations with anatomy and histology

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ABSTRACT

Objectives The entheseal nature of digital annular pulleys insertion was recently described, with high resolution ultrasound (US) reliably identifying these submillimetre structures with impressive accuracy. Since the thumb was not examined, the aim of the present study was to characterise the thumb annular pulley system, including entheses, from an anatomical, histological and ultrasonographic perspective.

Methods US assessment and gross anatomical dissection were performed on cadaveric thumbs to investigate the thickness and structural features of the four thumb pulleys, including the identification of their entheses. US and anatomical measurements were correlated. Entheses identified by US were verified by histology. All thumb pulleys in healthy controls (HC) were detected and thickness was measured by US. A reliability exercise on US identification and anatomical study of thumb pulleys was carried out.

Results 20 cadaveric thumbs and 40 thumbs from HC were examined. A total of 240 thumb pulleys (80 cadaveric, 160 HC) were analysed. The cadaveric study demonstrated good correlation between anatomical and US measurement of thumb pulleys thickness (r=0.8). Histology confirmed the entheseal nature of thumb pulleys insertions, with both fibrous and fibrocartilaginous features. 267/480 (55.6%) entheses were detected by US. A1 pulley entheses were always visualised while oblique pulley and A2 pulley entheses were seldom identified. The intrarater and inter-rater reliability showed good correlation among participants.

Conclusions US is an effective and reliable tool to detect and study thumb pulleys, even though the identification of their entheses may be challenging and require advanced US skills.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ The digital annular pulleys of triphalangeal fingers have recently been characterised through anatomical, histological and ultrasonographic study. Their insertions have been identified as anatomical entheses, and ultrasound proved effective to evaluate these submillimetre structures.

WHAT THIS STUDY ADDS

⇒ For the first time, the thumb pulley system, including the entheses, was comprehensively evaluated by high-frequency ultrasound. The fibrous/fibrocartilaginous nature of the entheses was highlighted by histology. A1 pulley entheses were shown to be the most suitable for ultrasound routine evaluation.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Ultrasound effectively assesses thumb pulleys, potentially helping to distinguish mechanical from inflammatory changes, even involving their entheses. A1 pulley may be a valuable target for future studies on hand pulley involvement in rheumatic diseases like spondyloarthritis and psoriatic arthritis.

INTRODUCTION

Finger annular pulleys are fundamental anatomical structures implicated in biomechanics and musculoskeletal health of the hand complex. These fibrous structures encircle the flexor tendons, guiding and stabilising their movement to prevent tendons from bowstringing and guarantee effective force transfer during flexion and extension. Pulleys are present across all fingers, with the thumb pulleys presenting unique anatomical features due to its unique anatomy and differential function.

From a macroscopic perspective, the thumb is composed of two phalanges, proximal and distal, lacking the middle one. As a result, the joints identified are the first metacarpophalangeal (MCP) joint and the interphalangeal (IP) joint. The flexor pollicis longus (FPL) is the flexor tendon of the thumb, which presents reinforcements constituting the proper thumb pulley system.[1] To date, four anatomically different pulley configurations have been described: (1) the A1 pulley runs over the MCP joint, (2) the variable annular (Av) pulley presents with transverse or oblique fibres located

between A1 and the Oblique (Obl) pulleys,[2] (3) Obl pulley, that usually displays a Y-shaped fibres arrangement running from the ulnar side of the proximal phalanx to the radial side of the base of the distal one and[3] (4) A2 pulley, that overlies the IP joint with a characteristic annular structure with the two proximal thirds inserting into the volar plate and the distal third into the base of the distal phalanx.

As stated, thumb pulleys are not always all present, and a recent study, performed in cadaveric thumbs,[4] described variable patterns of thumb pulley appearance, with the most frequent configuration being the presence of all four pulleys with a variable orientation of Av pulley fibres, ranging from parallel to A1 pulley to an oblique/triangular morphology.

Thumb pulleys hold special interest for their pathology consisting mainly of rupture or entrapment, so-called 'triggering'. The latter is also known as stenosing tendinopathy and is a common condition,[5] mostly occurring in the thumb and, less frequently, in the ring finger of the dominant hand.[6] The clinical presentation is characterised by pain when flexing the thumb, associated with locking or clicking, and it is typically produced due to discrepancy in size between the flexor tendon and A1 pulley. Aside from these mechanical conditions, recent evidence suggests that pulleys may be implicated in rheumatic conditions, such as psoriatic arthritis (PsA).[7] Interestingly, the entheseal nature of pulley insertion sites has been described along with the validity of high-frequency ultrasound (US) in the study of these structures in triphalangeal fingers.[8]

To date, literature involving the thumb pulley system and its study by US, focusing on the evaluation of pulley insertions, is lacking.[9 10] Thus, the present study aimed to perform a complete assessment of thumb pulleys and their entheses by US, assessing their reliability and validating the results by anatomical and histological study.

METHODS

Thumb pulley identification by US in cadavers and HC

A LOGIQ P9 US unit (GE Ultrasound Korea, Seongnam, Republic of Korea) equipped with an 8–18 MHz hockey stick transducer and an Aplio i800 Prism Edition (Canon Medical Systems, Tustin, California, USA) US unit equipped with an 8–22 MHz hockey stick transducer were used for thumb pulleys assessment on cadaveric specimens and HC, respectively. A proper amount of gel was delivered to ensure no pressure was exerted during the examination. US-specific parameters, that is, focus and gain, were adjusted according to the region of interest. All examinations were performed by the same investigator (LC). A reliability exercise was performed with a senior musculoskeletal sonographer (IM).

US study in cadavers

The US study was conducted on 20 thumbs (12 right and 8 left) from adult cadavers (11 women, 9 men; mean age 81±9 years) cryopreserved at −20°C in the Dissection Laboratory of the Faculty of Medicine and Health Sciences at the University of Barcelona. All the specimens were donations to the Faculty of Medicine and Health Science. No signs of traumatic injuries nor surgical scars were noted; in the available medical records, no history of relevant diseases was reported. The samples were coded with a univocal number to allow identification according to the dissection order and the sonographic examination. Each thumb was positioned in full palmar abduction to identify thumb pulleys, and examination was conducted at both dorsal and volar aspects.

The thickness of each pulley, namely A1, Av, Obl and A2 pulleys, was measured twice at their thickest site within the main body of the pulley corresponding to its mid-portion, both in transverse and longitudinal views. The measurements were performed between the two hyperechoic interfaces, delimitating the superficial and deep limits of the pulleys (online supplemental figure 1), and the mean value was considered the final result.

Four cadaveric thumbs were evaluated consecutively by two sonographers (LC and IM), blinded to the others' examination, to assess intraobserver and interobserver reliability. The intrarater reliability exercise was performed only by LC.

The entheses of A1, Av, Obl and A2 pulleys were assessed in B mode in a transverse scan (online supplemental figure 2), with respect to the major axis of the thumb, at both the ulnar and the radial level and scored absent/present (0/1). Specific superficial anatomic landmarks were used to identify the entheses of thumb pulleys: the MCP skin fold, volar plate and sesamoid bones for A1 and Av pulleys, which was just distal to A1 pulley; the proximal phalanx ridge for the Obl pulley and the IP joint skin fold and volar plate for A2 pulley.[1 9]

US study in HC

A total of 20 HC (15 women, 5 men; mean age 47±15 years) recruited at the Rheumatology Unit of the Vall d'Hebron Hospital of Barcelona underwent the US examination of thumb pulleys. Exclusion criteria for HC were the presence of diseases possibly affecting the pulley, especially musculoskeletal disorders/rheumatic diseases, the history of hand/thumb trauma and the practice of hand sports or manual works. During scanning, individuals were seated in front of the examiner with their hands resting on the examination table. HC were asked to keep the thumb in a fully palmar abducted position to optimise the US examination, which was performed at both volar and dorsal aspects as in cadaveric specimens.

Anatomical study of thumb pulleys

In the cadaveric thumbs, a needle was inserted into each pulley detected by US before dissection. The skin was incised along the midline of the thumb that overlays the FPL tendon from the pulp to the base of the MCP joint.[11] The skin, deep fascia, soft tissues and neurovascular bundles around the tendon sheath were removed, and individual pulleys were identified using a surgical microscope. The tendon sheath of the FPL tendon was removed between pulleys. Each pulley

was measured twice at the point of maximal thickness with a Vernier digital calliper (absolute Solar Caliper Series 500, Mitutoyo, Aurora, Illinois, USA), using the mean value as the final result. Eight cadaveric pulleys of two thumbs were measured consecutively by LC and MMP, professor of anatomy, blinded to each other to obtain intraobserver (performed only by LC) and interobserver reliability.

Histological study of thumb pulleys

Paraffin-embedded sections of four thumbs at the pulley level were obtained. The tissue was prepared with H&E staining as previously described.[12] Entheses appeared as fibrous or fibrocartilaginous tissue in the transition zone between pulleys and bone/volar plates. The entheses of A1, Av, Obl and A2 pulleys were assessed at both the ulnar and radial sides, and the presence of fibrocartilage at the entheses was scored as absent/present (0/1). Each enthesis was evaluated, and the histological description of the tissue structure as fibrous, fibrocartilaginous or mixed was reported. All preparations were observed under a DMD 108 microscope (Leica Microsystems, Deerfield, Illinois, USA) at ×10 magnification.

Statistical analysis

Quantitative demographic variables were summarised as means and SD, whereas qualitative variables were summarised as frequencies and percentages. Variables were compared across groups using independent samples, Student's t-test and χ^2. The intraclass correlation coefficient (ICC) with 95% CI was calculated to evaluate intrarater and inter-rater reliability for repeated thumb pulley measurements with US and digital calliper. Reliability was qualified with the ICC as bad or null (ICC<0.20), poor (ICC=0.21–0.40), moderate (ICC=0.41–0.60), good (ICC=0.61–0.80) or very good (ICC=0.81–1.00). All tests were two-sided and p values <0.05 were considered statistically significant. Statistical analyses were performed using RStudio V.2022.12.0+353 (Posit Software, Boston, Massachusetts, USA).

RESULTS

Assessment of pulley thickness in cadavers and HC

A total of 240 thumb pulleys (160 in HC, 80 in cadavers) were assessed by US with the 80 cadaveric by anatomical dissection. The mean values of pulley thickness detected by US were analysed for each pulley: A1, Av, Obl and A2, in both specimens and HC.

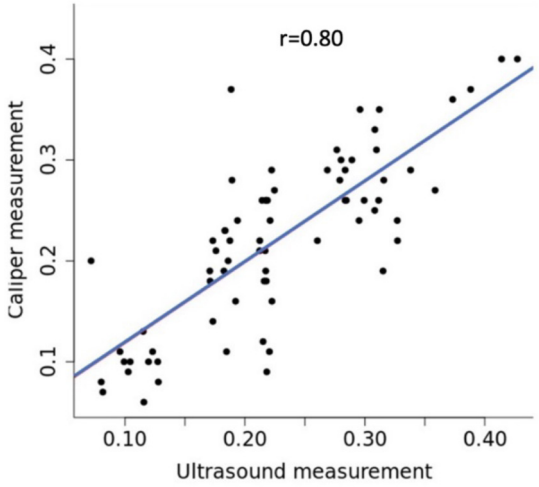

Figure 1 Correlation between US and digital calliper measurements of the thumb pulleys. US, ultrasound.

In HC, the mean thickness by US was lower than in cadavers, with statistically significant differences for A1, Av, and Obl pulleys (p<0.05). Detailed results are presented in table 1.

The results of the thumb pulley US assessment in cadavers were confirmed in the anatomical study (table 1), with no significant differences between US and digital calliper measurements. A positive good correlation (r=0.8) between the two measurement techniques for thumb pulleys in specimens was outlined (figure 1).

7.5% (6/80) of pulley measurements in the specimen group were lost because of technical difficulties related to cryopreservation or to the physiological configuration of pulleys in the different thumbs. The six lost pulleys were 3 Obl and 3 A2 pulleys. Of note, five pulleys that were not detected by US but were identified in the dissection study, while on the other hand, one pulley was evident only in US.

The ICC for the intrarater reliability for pulley measurements by US was 0.7 (95% CI 0.712 to 0.93) and by digital calliper was 0.98 (95% CI 0.854 to 0.999). The ICC for

Table 1 Pulleys thickness for all pulleys in thumbs measured by US, in both HC and cadavers, and by digital calliper, in cadavers

	Ultrasound		Digital calliper
	HC	Cadavers	Cadavers
A1, mean (SD), mm	0.242 (0.058)	0.284* (0.078)	0.273 (0.076)
Av, mean (SD), mm	0.178 (0.079)	0.242* (0.051)	0.244 (0.051)
Obl, mean (SD), mm	0.204 (0.047)	0.241* (0.053)	0.251 (0.068)
A2, mean (SD), mm	0.125 (0.042)	0.127 (0.046)	0.103 (0.029)

Quantitative data are expressed in mean and SD.
*p<0.05, statistically significant thicker pulleys in cadavers versus HC.
HC, healthy control; US, ultrasound.

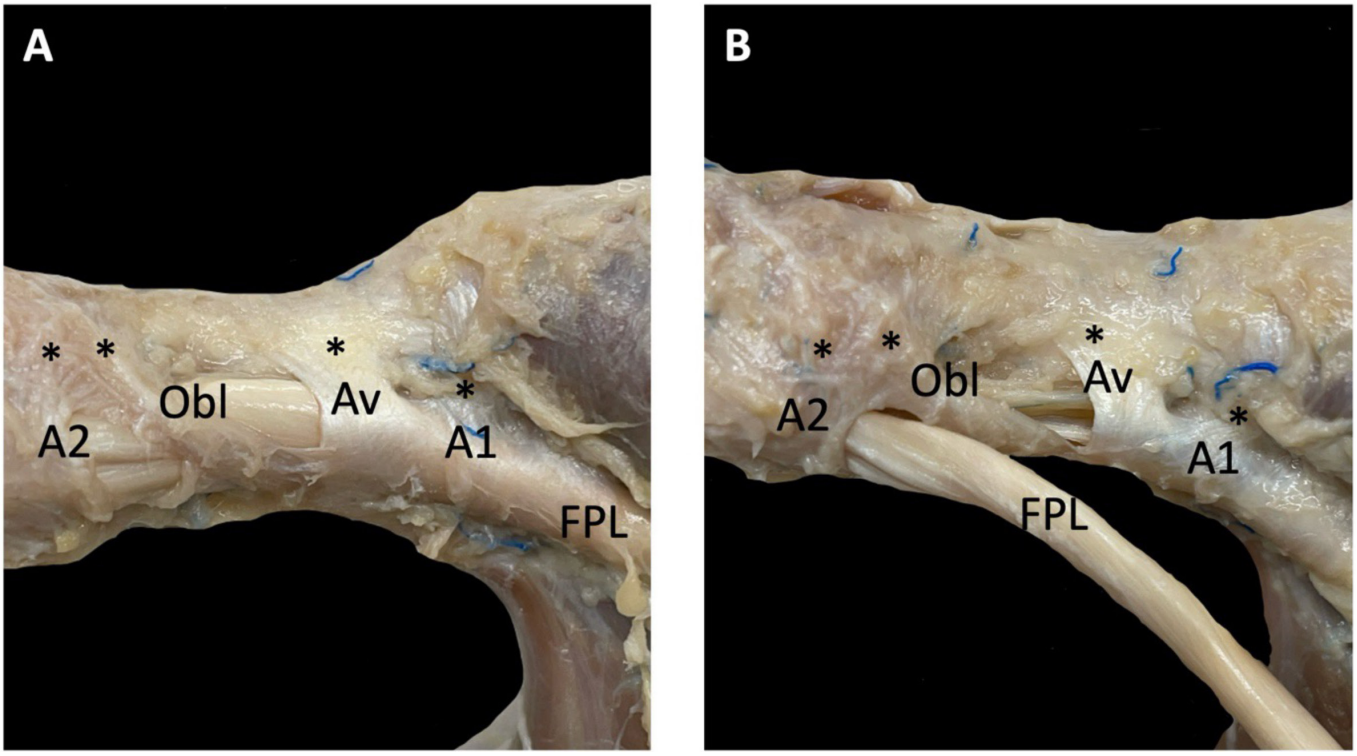

Figure 2 Anatomy of the thumb pulley system. Dissection of the pulley system of the thumb showing A1, Av, Obl and A2 pulleys and their radial insertions pre (A) and after (B) the removal of the FPL tendon from its anatomical position. *Pulley enthesis. A1, A1 pulley; A2, A2 pulley; Av, variable pulley; FPL, flexor pollicis longus; Obl, oblique pulley.

the inter-rater reliability by US was 0.96 (95% CI 0.82 to 0.992) and by digital calliper was 0.98 (95% CI 0.842 to 0.999).

Thumb pulley entheses evaluation by anatomy, histology and US

The anatomical study of thumb pulleys revealed that A1 pulley entheses were consistently at the volar plate and sesamoid bones in the thumbs.

Av entheses were located at the base of the proximal phalanx shaft, medially and laterally. The lateral enthesis of the Obl pulley was at the proximal phalanx at the level of bony ridges, with the medial insertion being more challenging to detect because of the conjunction with fibres from the adductor pollicis tendon. A2 pulley entheses were at the volar plate at the level of the IP joint (figure 2).

The main histological characteristics of the different thumb pulley entheses are summarised in table 2; both fibrous and fibrocartilaginous tissue were detected (figure 3A). A2 pulley entheses were unavailable for the histological study due to difficulty in isolating the A2 pulley.

The US study of thumb pulley entheses detected 267/480 (55.6%) entheses, medially and laterally, in cadaveric specimens and HC combined, resulting in 44.4% being undetectable. Sesamoid bones were retrieved in 100% of cases at both radial and ulnar aspects of the thumb MCP joint, and insertions of A1 pulley were confirmed always to involve the volar plate and sesamoid bones (figure 3B).

Table 2 Histological characteristics of the thumb pulley system

	Presence of fibrocartilage at the enthesis			
	Yes	No	Not available	Description of the enthesis
A1	6	2	/	Fibrous and fibrocartilaginous enthesis (volar plate/sesamoid bone)
Av	3	1	4	Fibrous and fibrocartilaginous enthesis
Obl	5	2	1	Fibrous and fibrocartilaginous enthesis
A2	/	/	8	

Four hands (2 right/2 left), 4 thumbs, 16 pulleys.
Not available: data lost due to cutting, sample preparation, staining and processing.

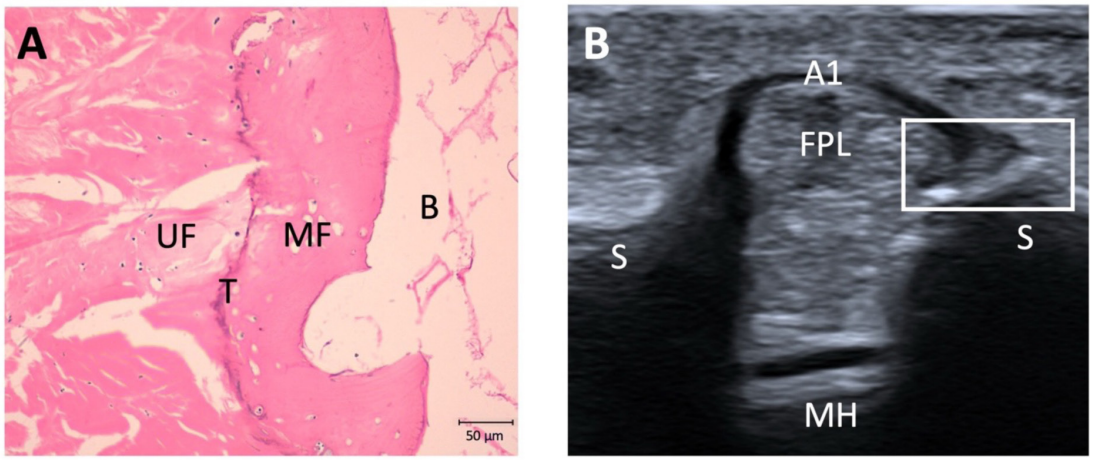

Figure 3 Histological and US assessment of thumb pulleys entheses. (A) Representative histology picture (H&E) showing the insertion of A1 thumb pulley to sesamoid bone. (B) US transverse scan at the level of A1 thumb pulley enthesis, the insertion on the sesamoid bone is clearly visualised (white box). A1, A1 Pulley; B, bone; FPL, flexor pollicis longus tendon; MF, mineralised fibrocartilage; MH, metacarpal head; S, sesamoid bone; T, Tidemark; UF, unmineralised fibrocartilage; US, ultrasound.

The Av and Obl pulleys entheses were better visualised in cadavers than in HC (30%–65% in HC vs 60%–90% in cadavers).

The A2 pulley entheses were poorly visualised at the thumb IP joint's ulnar and radial aspects. A complete description of the US assessment of thumb entheses for each pulley is detailed in table 3.

DISCUSSION

Pulleys function is crucial to allow the smooth gliding of the flexor tendons and provide mechanical advantage to accomplish precise motor tasks without triggering or pain.[13] Considerable literature can be found in regard to mechanical pathologies affecting these structures. Still, recent works focusing on inflammatory changes have raised their potential involvement in rheumatic diseases such as PsA.[8 14] Pulley inflammation has been recognised as a significant and early feature, potentially serving as a distinguishing marker between PsA and other inflammatory conditions, such as rheumatoid arthritis.[15–18]

Different imaging techniques can be used for pulley detection, that is, MRI and US, with the latter being probably the best choice because of its accessibility, dynamic nature and higher spatial resolution, especially when working with high-resolution probes in experienced hands.[19–22]

Most data have focused on digital pulleys of triphalangeal digits, with the thumb being a neglected finger to study due to its different motor tasks and anatomy. There has been new interest in the thumb pulley system, and the US was recently validated as a valuable tool to accurately identify all four pulleys.[9 23] In this article, differently from other reports,[9] we present, for the first time, a systematic multistep approach based on US, anatomy and histology to completely characterise the thumb pulley system, with a particular focus on their entheses which represents a significant novelty. In particular, high-frequency US was able to detect A1, Obl and Av pulleys, including their enthesis. The fibrous and fibrocartilaginous nature of the entheses was highlighted by histology. Among thumb pulleys, A1 entheses were shown to be the most suitable for US routine evaluation.

Initially, we assessed pulley thickness which revealed significantly higher values in the cadaveric group than in the HC group. This is consistent with literature data suggesting that pulley thickness may increase with age due to the continuous biomechanical stimulation related to flexor tendon friction.[24] As previously described,

Table 3 Thumb pulley entheses visualisation by US in HC and cadavers

	HC		Cadavers	
	Medial (n=160)	Lateral (n=160)	Medial (n=80)	Lateral (n=80)
A1, n (%)	40 (100)	40 (100)	20 (100)	20 (100)
Av, n (%)	19 (47.5)	24 (60)	14 (70)	18 (90)
Obl, n (%)	12 (30)	26 (65)	12 (60)	16 (80)
A2, n (%)	2 (5)	2 (5)	1 (5)	1 (5)

320 entheses were analysed in HC and 160 in cadavers, considering both medial and lateral insertions.
HC, healthy control; US, ultrasound.

A1 was the thickest pulley, followed by the Obl pulley, while A2 pulley was confirmed to be the thinner.[2] Data about Av pulley are scarce as it has been described only recently.[4 25 26] Indeed, detecting the gap between A1 and Av pulleys requires more technically advanced US equipment, which could have affected previous studies.

Interestingly, US measurements showed a strong correlation with anatomical measurements obtained using a digital calliper, which is considered the gold standard technique. This finding empathises the potential of US as an excellent tool for the in vivo assessment of submillimetric structures with impressive precision.

The primary goal of the present research was to evaluate the insertions of thumb pulleys to disclose their characteristics by both US and histology, as has been done with triphalangeal finger pulleys. In this context, the US was able to identify A1, A2 and A4 annular pulley entheses after implementing a newly described manoeuvre, granting the optimal pulley attachment exposition.[8]

The evaluation of thumb pulleys allowed the visualisation of 55.6% of insertion sites, in contrast with almost 100% for A1, A2 and A4 pulleys in triphalangeal fingers.[8 27] Analysis of our evidence revealed that A1 pulley entheses were always visible in both HC and cadavers, probably because of the size and the constant presence of the radial and ulnar sesamoid bones at the first MCP joint. Av and Obl pulleys entheses were more clearly visualised in cadavers compared with HC, likely due to the increased thickness in the cadaveric group, which facilitated their detection up to the bone insertion. In addition, the Obl pulley ulnar entheses were less visible than the radial ones, most likely due to the overlapping of structures at that level, where the cojoined insertion of A1 pulley, together with the contribution of the adductor pollicis tendon and muscle, is found. Ultimately, A2 pulley entheses were rarely identified due to their smaller size.

Thus, the striking difference in enthesis identification between triphalangeal digits and the thumb underscores the critical difference in evaluating these structures in a more complex anatomic scenario. Additionally, very high-frequency transducers (>24 MHz) may be required to ascertain the presence of entheses and differentiate them from neighbouring structures. Standardising thumb assessment and high-level US skills are indispensable to studying all thumb pulleys.

The histological analysis of the thumb pulley entheses was novel as no previous data were available. All four pulleys were evaluated, demonstrating the presence of fibrocartilage at the insertion point of the pulley in A1, Av and Obl pulleys. A2 pulley was not analysed owing to inability to retain adequate specimens during its preparation. These findings confirm the entheseal nature of thumb pulley insertions, as previously demonstrated in the triphalangeal digits, making the thumb an additional US target to study in enthesis-driven diseases, such as PsA and other spondyloarthropathies. Enthesitis, a hallmark feature of these conditions, is frequently detected at fibrocartilaginous entheses,[28] and the thumb pulley system may represent an under-recognised but clinically relevant site of pathology, amenable to high-resolution US study for diagnostic purposes.

Interestingly, in PsA, swelling of the IP joint of the thumb has been identified as a characteristic finding in MRI studies,[29 30] while its severe structural damage is commonly reported in mutilans PsA.[31] In this context, assessing the pulley system may provide additional insights into the clinical presentation of PsA, potentially contributing to a more comprehensive understanding of disease manifestations.

Several limitations of this study should be acknowledged, starting with the age difference between donors and HC that may have significantly impacted pulley morphology. Age-related changes, potentially caused by chronic mechanical stress,[14] could influence pulley thickness and the appearance of entheses,[32] making specimens an imperfect mirror of younger individuals' anatomy. Additionally, tissue preparation affected certain specimens and may reflect on the quality and representativeness of the samples. However, the samples analysed were sufficient to address the primary hypothesis.

The main strength of this study lies in the ability to systematically study the thumb pulleys, including their entheses, with US. US has been confirmed to be a valuable tool for analysing the enthesis organ, even in submillimetre structures, stressing its superiority to clinical examination.[33 34] Moreover, our findings were validated histologically. Therefore, A1 pulley, the pulley that obtained the best results in terms of US visualisation of its entheses, could possibly be proposed to be included in future studies or scoring systems of hand pulleys in rheumatic diseases, such as the recently published Global OMERACT Ultrasound DActylitis Score.[35]

In this regard, the identification and definition of the inflammatory changes that may occur at this level in diseases like PsA and the potential differences between alterations under mechanical vs inflammatory conditions deserve further investigation and represent future investigative possibilities. The Obl pulley, for instance, intertwines its fibres with the adductor pollicis longus tendon, whose muscle originates from the radial side of the third metacarpal bone. This creates a continuous anatomical complex, suggesting that pathology involving the Obl pulley could affect the muscle's biomechanical properties, potentially influencing the third finger.

The comprehensive description of the thumb pulley system has wider implications as hand surgeons, radiologists, and rehabilitation physicians may benefit from a deeper understanding of pulley biology, appearance and function to better detect and treat pathological conditions affecting these structures.

In conclusion, our study demonstrates the presence of fibrocartilage at the entheses of A1, Av and Obl pulleys, confirming the entheseal nature of their insertions. Thumb pulleys are amenable to US examination, which is confirmed to be a valuable, reliable and consistent

technique to measure thumb pulley thickness with a high correlation with anatomical measurements.

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Contributors All authors meet the authorship criteria. Study conception and design: LC, CR, MAD'A and IM. Acquisition of data: LC, CR, MMP, JB, DAB, JAPG and IM. Analysis of data: LC, CR, JAPG and MAD'A, IM. All authors were substantial contributors to the interpretation of the data. All authors were involved in drafting the article or revising it critically for important intellectual content, and all authors approved the final version to be published. LC and IM are guarantors and accept full responsibility for the work and the conduct of the study.

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Patient consent for publication Not applicable.

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Data availability statement All data relevant to the study are included in the article or uploaded as supplementary information.

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