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Morphological Variations of the Proximal Fusions Between the Superficial Flexor Muscles of Forearm: Its Clinical Significance

Variaciones Morfológicas de las Fusiones Proximales Entre los Músculos Flexores Superficiales del Antebrazo: Su Importancia Clínica

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SUMMARY: Forearm Compartment Syndrome (FCS) is a severe condition that can result in functional loss of the hand. The primary treatment for FCS is fasciotomy, which involves incision of the fascia over the forearm's superficial flexor muscles (PT, FCR, PL, FCU, FDS). This study examined 58 forearm specimens from 40 cadavers to investigate the morphological characteristics and fusion points between these muscles. The superficial flexor groups of the forearm varied in morphology among 58 specimens. Specifically, the lowest fusion points between the muscles were as follows: 9.6±1.3 cm between PT and FCR, 8.1±1.5 cm between FCR and PL, and 6.3±2.6 cm between PL and FCU. For FDS, the fusion points with FCR, PL, and FCU were 10.5±1.6 cm, 7.8±1.9 cm, and 6.9±1.6 cm. Additionally, some specimens exhibited anatomical variations, including absent fusion points, missing muscles, or the presence of accessory muscles. These findings provide valuable anatomical insights that help inform clinical approaches to the treatment of FCS.

KEY WORDS: Forearm Compartment Syndrome; Forearm's superficial flexor muscles; Fasciotomy; Forearm function; The fusion points.

INTRODUCTION

The superficial flexor muscles of the forearm play a critical role in the function of both the forearm and the hand, especially in fine motor control and strength. This group primarily includes the pronator teres (PT), flexor carpi radialis (FCR), palmaris longus (PL), flexor digitorum superficialis (FDS), and flexor carpi ulnaris (FCU) (Rodrigues *et al*., 2019). These muscles originate from the medial epicondyle of the humerus via a common tendon, with additional fusion at the intermuscular fascia. The intermuscular fascia between the PT, FCR, PL, and FDS muscles converges proximally, forming a shared tendon that attaches to the medial epicondyle and the anterior joint capsule of the elbow. Similarly, the intermuscular fascia between FDS and FCU forms another common tendon, which attaches to the lower part of the medial epicondyle and the medial joint capsule (Otoshi *et al*., 2014). As these muscles transition through the forearm, their intermuscular fascia converges again at their insertion points (Fig. 1).

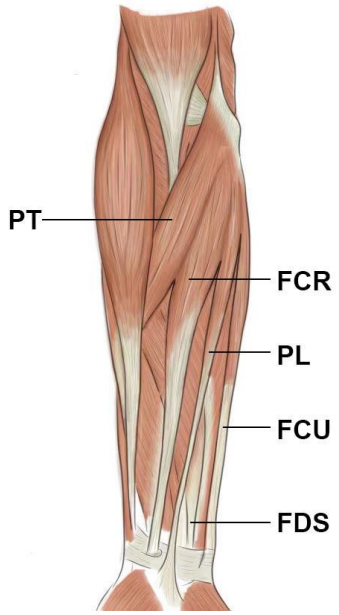

Fig. 1. Anatomical structure of the superficial muscles of the forearm.

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FCS is a condition associated with significant morbidity and mortality, typically presenting with swelling in the forearm, and in severe cases, leading to permanent loss of hand function (Kistler *et al*., 2018). The primary treatment for acute compartment syndrome (ACS) in the forearm is fasciotomy (Oliver, 2019). Studies report that the fasciotomy rate for ACS ranges from 2 % to 24 % (Jimenez & Marappa-Ganeshan, 2024). Decompression is usually performed through two incisions—one on the palmar side and one on the dorsal side of the forearm (Friedrich & Shin, 2007). In the palmar approach, it is often necessary to release the superficial muscle compartment via the FCU and FDS (Ronel *et al*., 2004). However, the degree and morphology of the proximal fusion between these muscles can vary, which may present technical challenges during surgery in this region (Eaton & Green, 1972). The objective of this study is to explore the morphological variations in the proximal fusion of the superficial flexor muscles.

MATERIAL AND METHOD

Specimens and methods of measurement. Forty adult cadavers (58 forearms; 25 males, 15 females, with an average age of 79 years at the time of death) were used in this study. The skin was incised to expose the superficial muscles, which were arranged from lateral to medial as follows: PT, FCR, PL, and FCU, with the FDS visible on the deep surface. The muscle origins were carefully cleaned, and the forearm length was measured using a digital caliper (Mitutoyo, Tokyo, Japan) from the medial epicondyle to the styloid process of the ulna. The fusion point distance was defined as the vertical distance between the medial epicondyle and the lowest fusion point (Fig. 2). Unless otherwise specified, all data are presented as mean ± standard deviation (SD).

Statements. The authors hereby confirm that every effort was made to comply with all local and international ethical guidelines and laws concerning the use of human cadaveric donors in anatomical research.

Statistical analysis. Analysis of statistical and data visualization in this study were conducted using GraphPad Prism 9.0.

RESULTS

The average forearm length was 24.4 ± 1.4 cm. The PT, FCR, PL, FCU, and FDS were distinguished by their distal tendons. The minimum fusion points between PT and FCR, FCR and PL, and PL and FCU were 9.6 ± 1.3 cm, 8.1 ± 1.5 cm, and 6.3 ± 2.6 cm, respectively, corresponding to the upper 2/5, 1/3, and 1/4 of the forearm. The fusion between PT and FCR originates from the bicipital aponeurosis or the medial epicondyle, formed by the muscle belly and aponeurosis (Fig. 3). A tendinous membrane was consistently observed between PL and FCR, with the muscle fibers of PL originating from the membrane (Fig. 4). In 13.8 % of the specimens, PL fused with FCU.

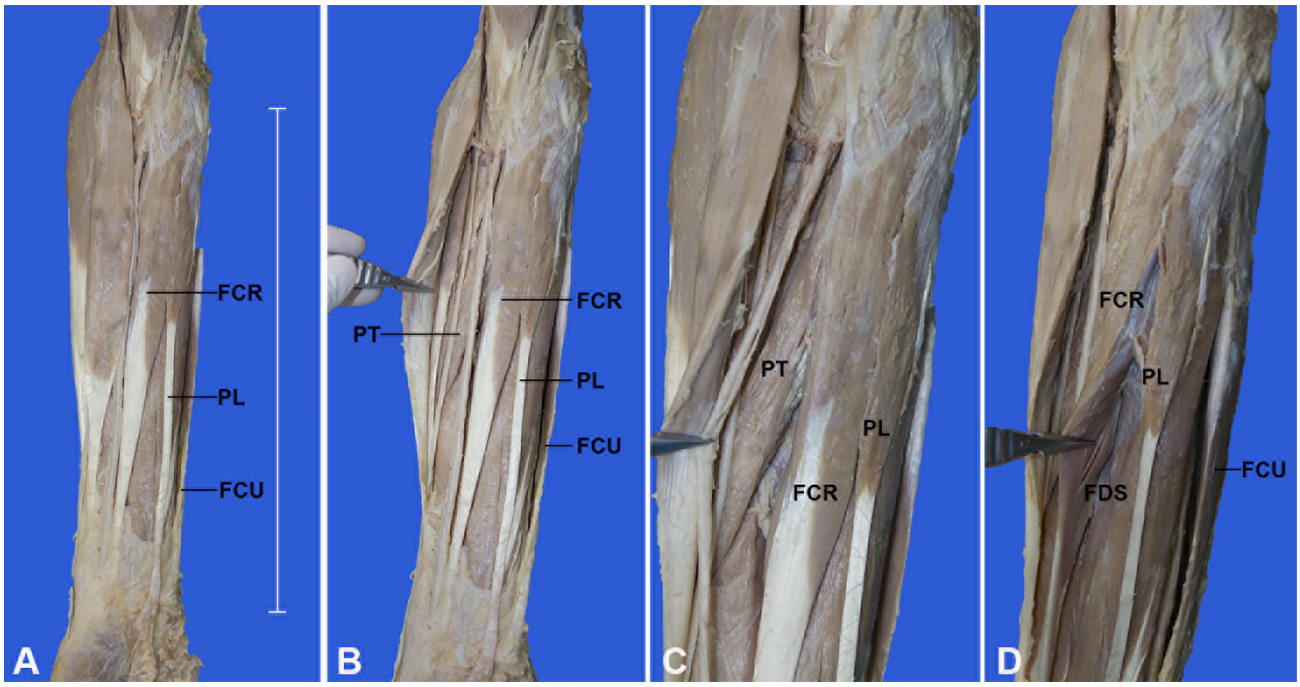

Fig. 2. Illustrations of the measurement of forearm length and the lowest point of fusion. A. Schematic diagram of measuring forearm length. B-D. Anatomical diagram of the superficial flexor muscles of the forearm.

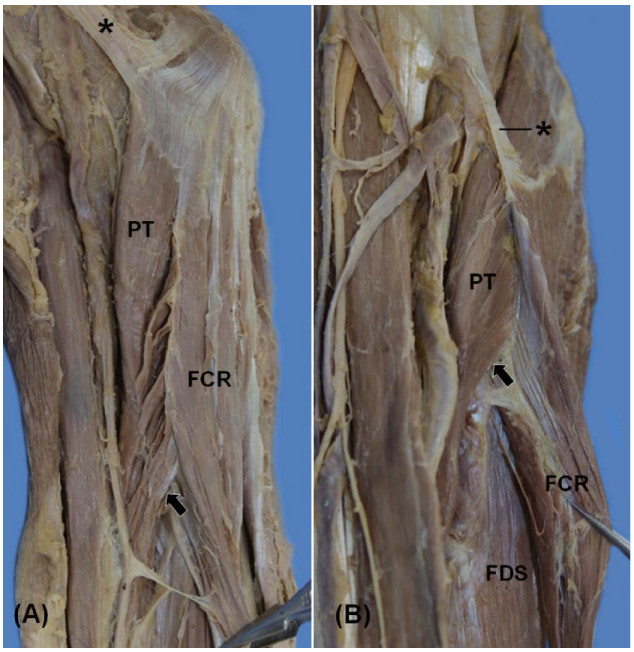

Fig. 3. The proximal fusion between the PT (Pronator teres) and FCR (Flexor carpi radialis). The lowest margin (arrows) of the fusion between the PT and FCR appears as muscular bundles and a tendinous membrane. The bicipital aponeurosis (*) is connected with the PT only (A) or with both the PT and FCR (B).

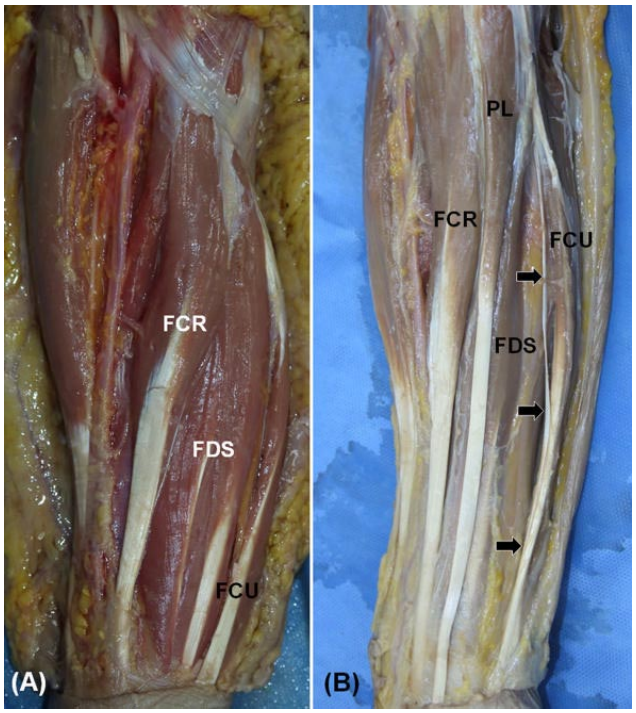

Fig. 5. Absence of the PL (Palmaris longus) (A) and existence of an accessory FCU (Flexor carpi ulnaris). (B) An accessory FCU (Arrows) appears at the lowest point of the proximal fusion between the FUC and FDS, and conjoins the distal tendon of FCU.

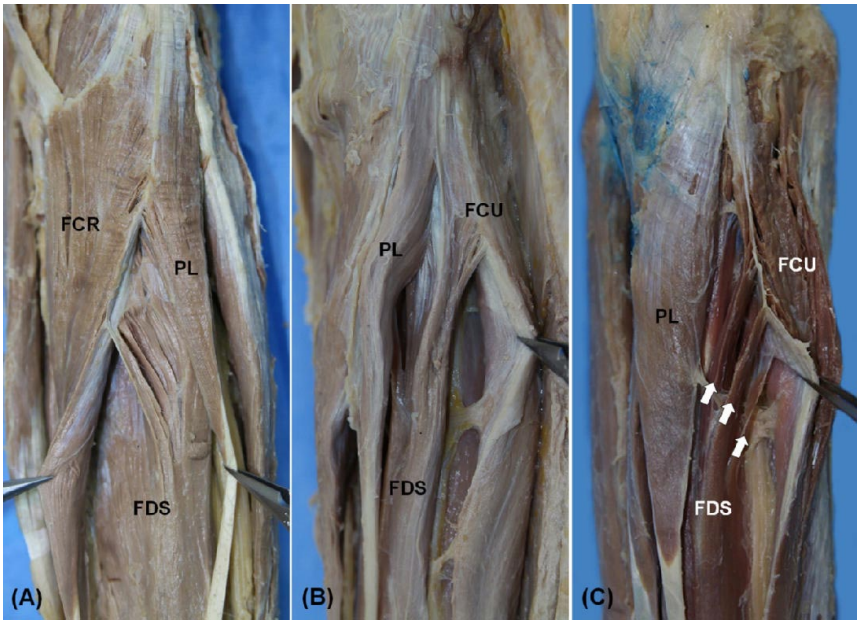

Fig. 4. The proximal fusions: (A) between the FCR (Flexor carpi radialis) and PL (Palmaris longus) or FDS (Flexor digitorum superficialis); (B) among the PL, FCU (Flexor carpi ulnaris), and FDS; (C) between the FCU and FDS.

The minimum fusion points of FDS with FCR, PL, and FCU were 10.5 ± 1.6 cm, 7.8 ± 1.9 cm, and 6.9 ± 1.6 cm, respectively, located at the proximal 3/7, 1/3, and 1/4 of the forearm. At these points, the deep lateral muscle fibers of FCR (Fig. 4A) and the deep medial part of PL (Fig. 4B) fused with the tendon of FDS. FCU fused with FDS at five additional muscle bundles (Fig. 4C). Below the fusion point of PT and FCR, a tendon attachment was observed between FCR and FDS. Interestingly, one specimen lacked PL and instead exhibited an accessory FCU.

A tendinous membrane appears between the FCR and PL, and between the PL and FCU. The deep lateral tendinous membrane of FCR and deep medial muscular bundle of PL is connected with the tendinous membrane of FDS at the lowest point of their proximal fusion. Arrows indicate muscular bundles of the FDS arising from the FCU (Fig. 5).

Figure 6 shows the absence of the palmaris longus muscle and the presence of an accessory flexor carpi ulnaris, which originates at the lowest point of the proximal fusion between the flexor carpi ulnaris and the flexor digitorum superficialis, and joins the distal tendon of the FCU.

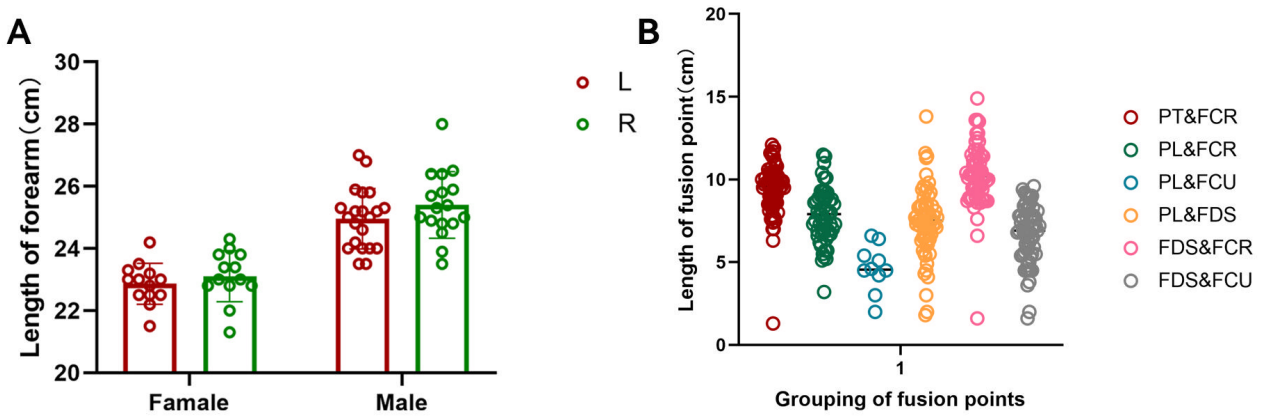

Fig. 6. Statistical analysis of forearm length and lowest fusion point. A. Statistical analysis of the length of the left and right forearms in male and female subject. B. Statistical analysis of the lowest fusion points in PT & FCR, PL & FCR, PL & FCU, PL & FDS, FDS & FCR, and FDS & FCU across all samples.

DISCUSSION

In anatomical texts, the muscles PT, FCR, PL, FDS, and FCU are often described as arising from a common origin at the medial epicondyle of the humerus (Goldwyn, 1985). The origin of PT consists of two heads: a superficial head from the medial epicondyle of the humerus, and a deep head from the coronoid process of the ulna. PT runs obliquely across the forearm, inserting on the lateral surface of the radius in the middle third. The median nerve passes between the superficial and deep heads of PT as it enters the forearm, where its primary function is forearm pronation. Anatomical variations in the heads of PT, along with fibrous bands, can narrow the space through which the median nerve passes, potentially leading to nerve compression (Caetano *et al*., 2017b). FCR, the largest superficial flexor muscle, originates from both the medial epicondyle of the humerus and the antebrachial fascia. It inserts at the base of the second metacarpal and functions to flex the elbow, wrist, and cause radial deviation of the wrist (Luong *et al*., 2014). With the evolution of human upper limb function, FCR has become a critical stabilizer of the wrist joint, which shifted from primarily supporting posture to enabling manipulation. Recent studies have also highlighted an accessory muscle on the radial side of FCR, a rare variation associated with wrist-crossing syndrome (Hongsmatip *et al*., 2019). PL typically originates from the medial epicondyle of the humerus, but may also have contributions from FDS, FCR, or FCU. It passes into the palmar aponeurosis beneath the skin of the palm. PL's primary role is wrist flexion, as well as tightening the palmar aponeurosis to prevent compression of blood vessels and nerves when the hand grips objects for extended periods (Dowdy *et al*., 1994). FDS arises from the medial epicondyle of the humerus and the proximal portions of the ulna and radius. The muscle belly divides into four tendons that insert into the middle phalanges of the 2nd to 5th fingers. Situated between the superficial and deep muscle layers, FDS contributes to flexion of the proximal interphalangeal joints, flexion of the metacarpophalangeal joints, and wrist flexion (Sadeghifar *et al*., 2020). Variations of FDS are common, with five primary types: tendon connections, connections to the flexor retinaculum, bifurcated muscle bellies, distal extensions of the muscle belly, and other anomalies (Caetano *et al*., 2017a). FCU originates from the medial epicondyle of the humerus, the antebrachial fascia, and the olecranon of the ulna, as well as the intermuscular septum between the olecranon and FDS. It inserts at the pisiform bone, and the ulnar nerve typically passes between its two heads. FCU functions in wrist flexion and ulnar deviation of the wrist (Lee *et al*., 2023). Anatomical abnormalities of FCU, such as accessory muscles, can compress the ulnar nerve, resulting in nerve entrapment symptoms. During imaging or surgical exploration of the forearm, various muscular abnormalities may be encountered. While multiple techniques are available to identify such anomalies, a comprehensive understanding of forearm muscle anatomy and its variations is essential for accurate diagnosis and treatment planning (Andring *et al*., 2018). In our study, we examined 40 adult cadaveric specimens (58 forearms) from 25 male and 15 female cadavers, with an average age of 79 years at the time of death. The average forearm length in these specimens was 24.4 ± 1.4 cm, with male forearms being longer than female forearms, correlating with differences in height and sexual dimorphism. Interestingly, regardless of sex, the right forearm was slightly longer than the left, suggesting anatomical differences in forearm muscle length and positioning. We then focused on the superficial muscle

group of the forearm, noting that fusion points between PT, FCR, PL, FDS, and FCU exhibited varying degrees of anatomical variation. Specifically, we examined the fusion points between PT & FCR, FCR & FDS, PL & FDS, FCU & FDS, FCR & PL, and PL & FCU. Our findings revealed that fusion points between PT & FCR and FDS & FCR were present in all specimens. However, we found that 6 specimens lacked a fusion point between PL & FCR, 50 specimens lacked a fusion point between PL & FCU, 1 specimen lacked a fusion point between PL & FDS, and 5 specimens lacked a fusion point between FCU and FDS.

FCS refers to the elevation of pressure within a fascial compartment of the forearm, which can impair circulation and lead to nerve damage, potentially resulting in loss of limb function if untreated (Zhang *et al*., 2019). FCS is generally classified into ACS and Chronic Exertional Compartment Syndrome (CECS).CECS is a condition caused by repetitive use, where the rigid fascial compartment cannot accommodate muscle contraction and swelling, leading to an increase in compartment volume (Sindhu *et al*., 2019). CECS is rare in the forearm. Treatment for forearm CECS generally includes both non-surgical and surgical options, with surgical intervention often yielding good results in about 80 % of cases by simply releasing the superficial flexor compartment (Marwan *et al*., 2021). ACS, in contrast, is a rapidly developing and more severe condition commonly associated with fractures, soft tissue injuries, and vascular damage. Studies indicate that fractures account for 65.4 % of ACS cases, soft tissue injuries for 30.7 %, and vascular injuries for 3.9 % (Khoshhal *et al*., 2022). The primary treatment for ACS is fasciotomy, aimed at relieving intra-compartmental pressure. A typical skin incision begins at the medial epicondyle of the humerus and extends toward the middle of the palm. The superficial musculature is then exposed, and the deep fascia is examined to determine if further muscle decompression is needed (Frane *et al*., 2020). If pressure remains high after fasciotomy, additional release of individual muscle fascial compartments may be required. In some cases, certain muscles, such as the superficial flexors, may need to be partially detached from their origin or the attachment sites near neighboring muscles to fully expose the radius and ulna. Research also suggests that the radial incision (a palmar incision to release the flexor tendons followed by a Henry approach for deeper structures) significantly impacts ACS treatment and prognosis (Abihssira *et al*., 2021). Additionally, ulnar incisions (longer incisions along the ulnar side to release the FCU and extensor carpi ulnaris (ECU) have been reported in treating ACS associated with displaced ulnar fractures, with satisfactory long-term outcomes and minimal complications. In these studies, the superficial flexor muscles were noted as crucial in the fasciotomy procedures for ACS, underscoring the importance of understanding their anatomical variations (Suzuki *et al*., 2016). In our specimens, the average location of the fusion points of the following muscles were as follows: PT and FCR: 9.6±1.3 cm, located at 2/5 of the forearm length; FCR and PL: 8.1±1.5 cm, located at 1/3 of the forearm length; PL and FCU: 6.3±2.6 cm, located at 1/4 of the forearm length; FDS and FCR: 10.5±1.6 cm, located at 3/7 of the forearm length; FDS and PL: 7.8±1.9 cm, located at 1/3 of the forearm length; FDS and FCU: 6.9±1.6 cm, located at 1/4 of the forearm length. The proximal fusion points of the superficial flexor muscles exhibit significant variation, with marked differences in their location and morphology. The lowest fusion points between PT and FCR, as well as between PL and FDS, are generally located above the midpoint of the forearm, though this is not always the case. The attachment points of the tendon sheaths form cohesive structures at the proximal fusion site, with additional muscular bundles emerging distal to this junction.

The results of this study are expected to provide helpful information when the superficial flexor muscles are separated for the treatment of forearm compartment syndrome or bone exposure of forearm.

CONCLUSION

FCS is a serious condition that often requires fasciotomy, particularly in cases of ACS (Shiraz *et al*., 2022). The anatomical structure of the superficial flexor muscles plays a critical role in determining the approach for fasciotomy. It is essential for clinicians to be familiar with the anatomy of the superficial flexor group and its potential variations. Our study demonstrates that the length, morphology, and lowest fusion points of the superficial flexor muscles differ across specimens. In some cases, we observed muscle agenesis, significant variations in fusion points, and the presence of accessory muscles. These findings provide valuable insights into anatomical variations and surgical approaches for fasciotomy, offering a more comprehensive understanding for clinical practice.

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PEI, Y; WON, H-S.; ZHANG, L.; ZHAO, D.; ZHANG, N.; XU, Q. & LIU, H. Variaciones morfológicas de las fusiones proximales entre los músculos flexores superficiales del antebrazo: Su importancia clínica. *Int. J. Morphol. 43(4)*:1288-1293, 2025.

RESUMEN: El síndrome compartimental del antebrazo (SCA) es una afección grave que puede provocar la pérdida funcional de la mano. El tratamiento principal para el SCA es la fasciotomía, que consiste en la incisión de la fascia sobre los músculos flexores superficiales del antebrazo (PT, FCR, PL, FCU, FDS). Este estudio examinó 58 muestras de antebrazo de 40 cadáveres para investigar las características morfológicas y los puntos de fusión entre estos músculos. Los grupos flexores superficiales del antebrazo variaron en morfología entre las 58 muestras. Específicamente, los puntos de fusión más bajos entre los músculos fueron los siguientes: 9,6 ± 1,3 cm entre PT y FCR, 8,1 ± 1,5 cm entre FCR y PL, y 6,3 ± 2,6 cm entre PL y FCU. Para FDS, los puntos de fusión con FCR, PL y FCU fueron 10,5 ± 1,6 cm, 7,8 ± 1,9 cm y 6,9 ± 1,6 cm. Además, algunas muestras presentaron variaciones anatómicas, incluyendo la ausencia de puntos de fusión, la ausencia de músculos o la presencia de músculos accesorios. Estos hallazgos proporcionan información anatómica valiosa que ayuda a fundamentar los enfoques clínicos para el tratamiento del SCA.

PALABRAS CLAVE: Síndrome compartimental del antebrazo; Músculos flexores superficiales del antebrazo; Fasciotomía; Función del antebrazo; Puntos de fusión.

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